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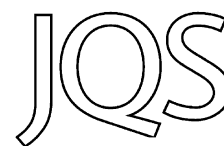
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A new radiocarbon chronology of Baumkirchen, stratotype for the onset of the Upper Würmian in the Alps



CHRISTOPH SPÖTL,^{1*} PAULA J. REIMER,² REINHARD STARNBERGER¹ and RON W. REIMER²

¹Institute of Geology, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria

²Centre for Climate, the Environment & Chronology (14CHRONO), School of Geography, Archaeology and Palaeoecology, Queen's University, Belfast, Belfast, UK

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ABSTRACT: The start of the Upper Würmian in the Alps was marked by massive fluvioglacial aggradation prior to the arrival of the Central Alpine glaciers. In 1984, the Subcommission on European Quaternary Stratigraphy defined the clay pit of Baumkirchen (in the foreland of the Inn Valley, Austria) as the stratotype for the Middle to Upper Würmian boundary in the Alps. Key for the selection of this site was its radiocarbon chronology, which still ranks among the most important datasets of this time interval in the Alps. In this study we re-sampled all available original plant specimens and established an accelerator mass spectrometry chronology which supersedes the published 40-year-old chronology. The new data show a much smaller scatter and yielded slightly older conventional radiocarbon dates clustering at ca. 31 ¹⁴C ka BP. When calibrated using INTCAL13 the new data suggest that the sampled interval of 653–681 m in the clay pit was deposited 34–36 cal ka BP. Using two new radiocarbon dates of bone fragments found in the fluvioglacial gravel above the banded clays allows us to constrain the timing of the marked change from lacustrine to fluvioglacial sedimentation to ca. 32–33 cal ka BP, which suggests a possible link to the Heinrich 3 event in the North Atlantic.

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KEYWORDS: Alps; Middle Würmian; radiocarbon chronology; stratotype; Upper Würmian.

Introduction

The Inn Valley, one of the most prominent orogen-parallel valleys, is a classical area of Quaternary research in the Alps. During the Last Glacial Maximum (LGM) the Inn Valley was occupied by one of the major ice streams that transported ice from the high Central Alps into the northern alpine foreland (Fig. 1). During the Middle Pleniglacial, however, the N–S width of the valley floor was roughly twice as large as today and was at least periodically filled by a large fjord-like lake, as already suggested by Penck and Brückner (1909). Today, terraces form a characteristic feature especially in the central and eastern parts of the Inn valley, stretching over a distance of ca. 50 km east and west of Innsbruck. These terraces mark an ancient lacustrine and fluvial accretion level that was situated about 250–300 m above the present level of the Inn River. They consist of lacustrine, fluvial and glacial sediments which are an important archive for reconstructions of climate and landscape during the last glacial period in the Alps (Würmian).

The terrace of Gnadenwald, ca. 15 km east of Innsbruck on the northern side of the Inn Valley, hosts the stratotype locality for the onset of the Upper Würmian in the Alps. The coarsening-upward succession of this terrace is currently exposed in two outcrops, the abandoned clay pit of Baumkirchen and the Absam gravel pit (formerly known as Pfanzelter gravel pit; Fig. 2). At Baumkirchen, a clay pit exposes fairly monotonous clayey silts known as ‘Bändertone’ (banded clays) which grade into thin sand overlain by thick fluvioglacial gravel (‘Vorstoßschotter’ *sensu* Penck and Brückner, 1909). Up to 20 m thickness of basal till of the LGM caps this sequence. Clay mining has yielded a series of wood fragments (Fig. 3) with radiocarbon ages ranging from 25.5 ± 0.6 to 32.4 ± 0.6 ¹⁴C ka BP (Fliri, 1970, 1976; Fliri *et al.*, 1971, 1972). These dates, when corrected for changes in the ¹⁴C production rate (Reimer *et al.*, 2013), imply that

the central Inn Valley was ice-free between approximately 28 and 38 ka and filled by a large perennial lake. The transition from the banded clays into the gravel was seen to reflect a major climatic deterioration triggering fluvioglacial sedimentation at the transition from the Middle Pleniglacial to the LGM. Therefore, the Baumkirchen site was selected by the Subcommission on European Quaternary Stratigraphy as the stratotype of the onset of the Upper Würmian within the Alps (Chaline and Jerz, 1984).

The above-mentioned radiocarbon data were produced four decades ago, before the advent of accelerator mass spectrometry (AMS) techniques. At that time radiocarbon ages of ca. 30 ka were close to the upper dating limit of the method. All except one of these specimens were found during operation of the clay pit, largely thanks to the efforts of Professor Franz Fliri from Innsbruck University, who was a resident of the village of Baumkirchen. Chances of finding new organic material have rapidly diminished over the years as the clay pit was closed in the 1980s and has since been back-filled. Only one additional radiocarbon-dated wood sample was reported (but not properly published) after Fliri's pioneering work (Patzelt, 1996). The fact that Baumkirchen is still the only site within the Eastern Alps with a fairly comprehensive radiocarbon chronology of pre-LGM sediments provided the key motivation to re-date the original specimens using state-of-the-art AMS techniques to refine the chronostratigraphy of this stratotype locality.

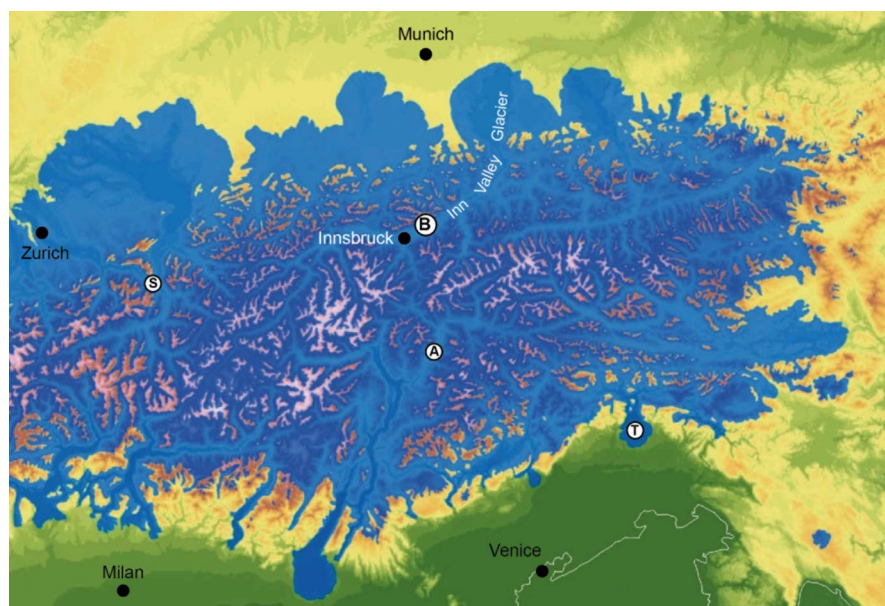
Stratigraphy and samples

At the time when the Baumkirchen clay pit was in operation the deepest mining horizon was between 645 and 648 m and the highest clay was exposed at 707 m a.s.l. (Fliri *et al.*, 1970; Patzelt and Resch, 1986). North of the mine the banded clays can be mapped up to an elevation of ca. 730–740 m a.s.l., where they are overlain by sand followed by gravel and capped by basal till (Fig. 3). Drilling performed at the base of the clay pit a few decades ago found banded clays at least

*Correspondence: C. Spötl, as above.

E-mail: christoph.spoetl@uibk.ac.at

Figure 1. The central and eastern part of the alpine ice stream network during the Last Glacial Maximum (from Stüwe and Homberger, 2012, after Ehlers, 2011; used with permission) and the location of the Baumkirchen type locality (B) as well as other sites mentioned in the text: A, Albeins; S, Sargans; T, Tagliamento. This figure is available in colour online at wileyonlinelibrary.com.



down to ca. 550 m a.s.l., resulting in a minimum thickness of these lacustrine sediments of 200 m (Fliri, 1999; Fig. 3).

The existing Baumkirchen radiocarbon chronology is based on wood and other plant samples (Fig. 4) found between 655 and 681 m a.s.l. in the clay pit and 69 m of banded clays are present above the highest sample. Table 1 provides an overview of wood and other organic macro remains along with their published radiocarbon dates.

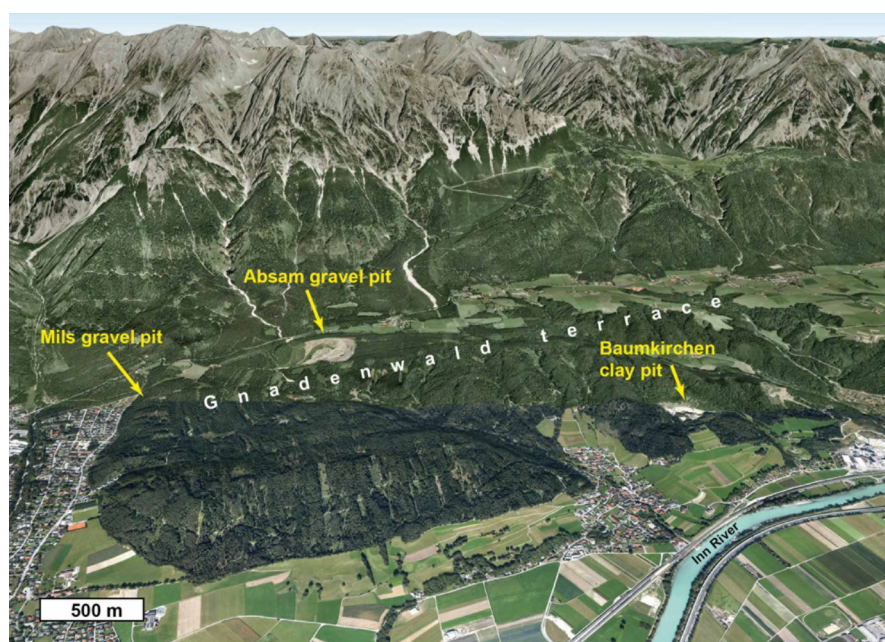
The second artificial outcrop in the Gnadenwald terrace, the Absam gravel pit, exposes fluvioglacial gravel between ca. 760 and 840 m a.s.l. (Figs 2 and 3). Sands were encountered in drillings below the gravel, but they are not exposed in the gravel pit. Only one finding of a wood fragment was reported from this large outcrop, but unfortunately this sample was lost (Fliri, 1971).

A third outcrop, the Mils gravel pit (Fig. 2), existed until the early 1980s and has been re-filled since then. Heiel (1954), Mayr (1968) and Fliri (1971) provided descriptions of the section exposed in this gravel pit, which is comparable to the succession of the Absam gravel pit but also contains a

discrete layer of large limestone blocks, most likely originating from a rockfall or debris-flow from the adjacent Karwendel Mountains (Fig. 3). The succession at Mils was also capped by the LGM basal till. The base of the gravel in the former Mils gravel pit occurred at a slightly lower elevation than in the Absam pit and coincided with the elevation of the upper part of the banded clays at Baumkirchen (Fig. 3). This suggests that the upper part of the banded clays was either eroded west of Baumkirchen before the deposition of the sand and gravel (Fig. 3) or that the gravel was deposited as lateral equivalent to the upper lacustrine sediments. As geological field mapping (e.g. Poscher and Lelkes-Felvri, 1999) did not yield evidence of an interfingering between alluvial (gravel) and lacustrine (banded clays) facies we regard the first model as more likely, which therefore calls for an unconformity between the lake sediments and the sand and gravel succession above.

Scarce wood fragments were found in the gravel at Mils, but they were lost (Heiel, 1954; Fliri, 1971). Heiel (1954), however, reported the discovery of thigh bones probably

Figure 2. Oblique aerial view of the MIS 3 and 2 terrace of Gnadenwald located some 250 m above the Inn River and the adjacent Karwendel Mountains to the north (Google Earth Pro image). The Baumkirchen clay pit is located near the southern (erosional) rim of the terrace, whereas the Absam gravel pit is situated on the plateau. The former Mils gravel pit opened on the western side of the terrace and was later back-filled and re-vegetated. This figure is available in colour online at wileyonlinelibrary.com.



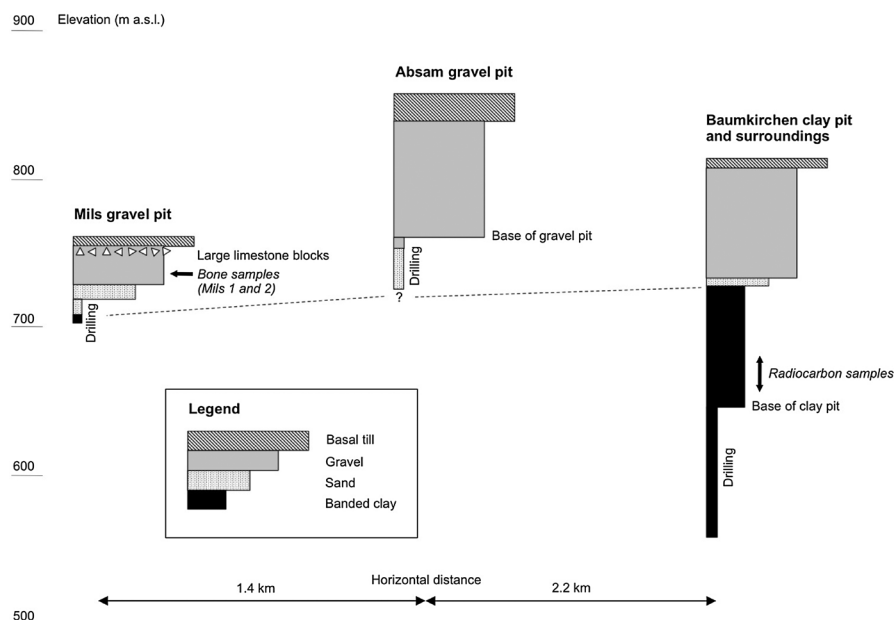


Figure 3. Simplified stratigraphic logs of the three large artificial outcrops in the Gnadewald terrace compiled from the literature (see text for references). The top of the banded clay sequence dips slightly westward (stippled line). The locations of both the original Fliri specimens from Baumkirchen and the bone fragments from the former Mils gravel pit are indicated (italics).

from *Alces cf. alces* (elk) from the middle part of the fluvioglacial gravel. Fragments of this specimen are archived in the fossil collection of the Institute of Geology and Palaeontology of Innsbruck University (Fig. 5) and were included in our dating campaign.

Materials and methods

Most of Fliri's original wood specimens are archived in the fossil collection of the Institute of Geology and Palaeontology at Innsbruck University. For some of his samples he reported that all material had been used up for radiocarbon preparation and analyses (Fliri *et al.*, 1971, 1972). Small samples were taken from the remaining specimens for AMS dating. We also sampled one original wood specimen stored in the Botany Institute and provided by S. Bortenschlager and a wood sample found in 1996 (Patzelt, 1996) provided by G.

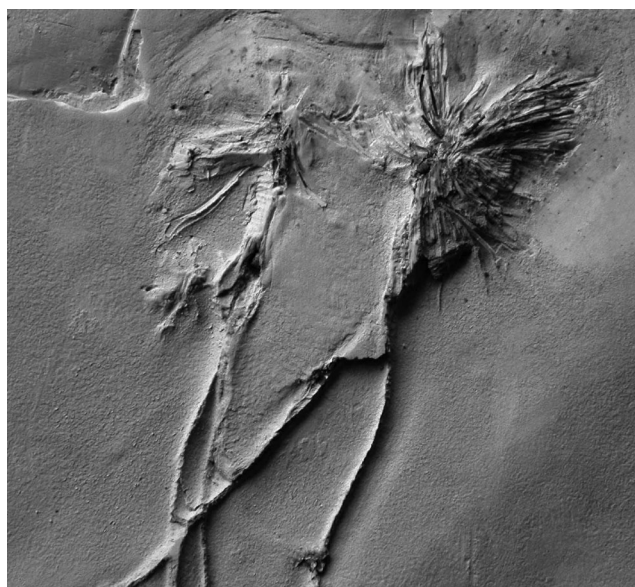


Figure 4. Example of *Pinus mugo* twigs with needles found in the banded clays of Baumkirchen. Width of image 17 cm. This is part of the large specimen F4 of F. Fliri, which also contained trace fossils of fish (e.g. Fliri *et al.*, 1971).

Patzelt. To check for intrasample heterogeneity we sub-sampled several specimens.

Samples were prepared at the ^{14}C CHRONO Centre, Queen's University, Belfast, and analysed using AMS. Wood samples were aggressively cleaned with a three step acid–base–acid pretreatment with H_2SO_4 as the final instead of the routine HCl pretreatment (Hatté *et al.*, 2001). For the background (blank) correction, Kauri (*Agathis australis*) wood from Marine Isotope Stage 7 (MIS 7), kindly provided by A. Hogg, University of Waikato, was used. Protein ('collagen') was extracted from the bone samples after demineralization in 2% HCl and gelatinization in weak HCl using the ultrafiltration method (Brown *et al.*, 1988; Bronk Ramsey *et al.*, 2004). Anthracite processed with acid–base–acid pretreatment was used as the background correction for the bone dates due to the lack of well-preserved bone older than 50 000 ^{14}C years. However, for comparison samples of whalebone with an international consensus age of 8831 ± 6 ^{14}C a BP (Table 7 in Scott *et al.*, 2010) were analysed by the same method, with results within 1 standard deviation. Ages were calculated according to Stuiver and Polach (1977) using the AMS-measured $^{13}\text{C}/^{12}\text{C}$, which accounts for both natural and machine isotope fractionation. Ages were calibrated using the INTCAL13 (Reimer *et al.*, 2013) calibration curve and the Calib 7.0 software. Calibrated ages are reported with two standard deviations (2σ).

Results

Seventeen AMS dates was produced from the original specimens, covering a depth range from 653 to 681 m a.s.l. (Table 1). The samples comprise arboreal taxa such as *Pinus mugo* (mountain pine), and *Alnus viridis* (green alder), shrubs such as *Hippophae rhamnoides* (sea-buckthorn) and *Juniperus* sp. (juniper) next to undetermined plant macro remains. The corresponding dates range from $30\,346 \pm 204$ to $31\,351 \pm 303$ ^{14}C a BP with a mean of $30\,790$ ^{14}C a BP (Fig. 6). Six AMS dates were obtained from individual pieces of Fliri's sample No. 4 (F4 in Table 1), a large collection of wood remains from a single layer at 661 m a.s.l. (part of which is shown in Fig. 4), and the results cluster between $30\,561 \pm 255$ and $31\,136 \pm 274$ ^{14}C a BP.

Table 1. Summary of old and new radiocarbon data from the Baumkirchen area.

Sample (F. Fliri)	Elevation (m a.s.l.)	Original specimens and radiocarbon data of Fliri and co-workers			New radiocarbon data (this study)			
		Material	Lab code	Radiocarbon age (¹⁴ C a BP)	Calibrated age (cal a BP) (2σ) ⁺	δ ¹³ C (‰)	Radiocarbon age (¹⁴ C a BP)	Calibrated age (cal a BP) (2σ) ⁺
F1	681	<i>Pinus mugo</i>	VRI-161	26 800 ± 1300	28 339–33 602		UBA-10863	33 887–34 751
F25 [†]	678	<i>Pinus</i> (root)	VRI-343	27 300 ± 1100	29 168–33 701	–22.3	UBA-10864	34 062–35 013
F26	675	<i>Alnus viridis</i>	VRI-359	27 200 ± 900	29 427–33 341	–22.6		
F24 [†]	671	<i>Hippophae rhamnoides</i>	VRI-339	27 400 ± 900	29 666–33 503			
F22 [†]	667	<i>Alnus viridis</i>	VRI-334	28 300 ± 1 000	30 656–34 304			
F12	665	Plant remains (indet.)				–24.9	UBA-11674	34 141–35 048
(From G. Patzelt) [‡]	663	<i>Hippophae rhamnoides</i>	VRI-394	28 100 ± 800	30 854–33 778	–26.6	UBA-10858	34 571–35 691
	661.5	Twigs (indet.)				–21.6	UBA-10859	34 216–35 405
F14	661	<i>Hippophae rhamnoides</i>	VRI-226	28 000 ± 1000	30 258–34 093			
F18 [†]	661	<i>Pinus sylvestris</i>	VRI-273	25 500 ± 600	28 455–30 877	–26.7	UBA-10865	34 102–35 271
F4	661	<i>Pinus mugo</i>	VRI-193/131	000 ± 1300	32 295–38 268	–24.7	UBA-10860	34 202–35 298
F4	661	<i>Pinus mugo</i>	VRI-193/229	700 ± 1100	31 341–35 711	–28.8	UBA-10862	34 171–35 236
F4	661	<i>Pinus mugo</i>	Hv-4672	32 370 ± 600	35 046–38 101	–25.9	UBA-10866	34 289–35 402
						–23.4	UBA-10867	34 522–35 643
						–23.7	UBA-10861	34 036–34 964
						–26.6	UBA-10868	34 548–35 671
F2	660	<i>Hippophae rhamnoides</i>	VRI-173	28 900 ± 700	31 369–34 166	–22.9	UBA-10857	34 150–35 211
(Patzelt, 1996)	658	<i>Juniperus sp.</i>	VRI-1735	28 340 ± 630	31 180–33 650	–23.2	UBA-14428	33 962–34 729
						–25.6	UBA-14429	33 761–34 501
F6 [†]	655	<i>Pinus</i> (bark)	VRI-199	30 600 ± 1 300	31 603–37 498			
F20	653	Plant remains (indet.)				–29.2	UBA-11672	34 541–35 521
						–32.2	UBA-11673	34 657–35 907
Mils 1 [§]	–	Thigh bone (<i>Alces cf. alces</i> , Mils gravel pit). 13.7% collagen, C/N = 3.23				–19.8	UBA-11679	31 207–31 927
Mils 2 [§]	–	Thigh bone (<i>Alces cf. alces</i> , Mils gravel pit). 2.0% collagen, C/N = 3.29				–19.0	UBA-11680	31 088–31 585

*Using INTCAL13 (Reimer *et al.*, 2013).†No material left (Fliri *et al.*, 1971, 1972). Sample F6 was erroneously listed as F7 in Fliri *et al.* (1972, their Table 2); cf. Fliri *et al.* (1971, their Table 1).

‡Collected in 1978 and provided to us by G. Patzelt.

§These dates were already reported in a previous publication (Stamberger *et al.*, 2011) but due to a re-assessment of the radiocarbon blank used in the Belfast laboratory these dates and their uncertainties have been adjusted slightly.



Figure 5. Fragments of thigh bones of *Alces cf. alces* found in the first half of the 20th century in fluvioglacial gravel of the former gravel pit Mils (reported by Heißel, 1954). Width of image is 20 cm.

Three aliquots of the thigh bone fragments from the Mils gravel pit were analysed for their nitrogen content. One sample had a nitrogen content $<0.79\%$ and was not processed further but collagen extracted from the two others (Mils 1 and Mils 2) had C/N_{atomic} ratios of 3.2 and 3.3, respectively, which are within the range of recommended C/N_{atomic} ratios (van Klinken, 1999; Bronk Ramsey *et al.*, 2004) suggesting sufficient preservation of bone protein (collagen). These two samples gave dates of $27\,792 \pm 100$ and $27\,526 \pm 107$ ^{14}C a BP (Table 1).

Discussion

The new radiocarbon data from the Baumkirchen site and the surrounding Gnadenwald terrace substantially improve and partly revise the late-Middle Würmian chronology of Fliri and co-workers in three aspects. (i) The new dates are consistently older and overlap at two standard deviations only with the oldest ages of the original chronology. This cannot be due to the 40-year-long storage of these samples as any exchange with modern carbon would cause the opposite effect. Fliri's samples were processed during the early 1970s in the then newly established radiocarbon laboratory at the Institut für Radiumforschung und Kernphysik of the Austrian Academy of Sciences in Vienna (e.g. Felber, 1971). Sample preparation,

purification and radiocarbon measurement techniques have changed dramatically since then and it does not come as a surprise to see this moderate shift of the ages. (ii) The new AMS dates are significantly more precise than the original dates, again reflecting the analytical improvements since the early 1970s. (iii) The new dates cluster around 31 ka compared with the large spread of the original dates between 26 and 32 ka, which had already raised concerns about their validity (e.g. Klasen *et al.*, 2007). The heterogeneity of the old dates can be explained by large sample sizes, which make it more difficult to remove contamination, and less advanced preparation techniques used in the 1970s. Unfortunately, only one sample in the upper half of the section could be re-measured (at 681 m a.s.l.), but its duplicate dates are consistent with the rest of the dates, seriously questioning the significantly younger dates of the old chronology (as young as 25.5 ka; Fig. 6). Sample F4 (at 661 m a.s.l.) was dated five times by Fliri and co-workers (four dates made in Vienna and a fifth one produced in Hanover), yielding a spread of dates larger than the range of the entire sediment succession (Fig. 6; Table 1). The new dates – six subsamples from this large specimen – cluster much more tightly and again cast doubts on the accuracy of the old dates (Fig. 6).

While calibration of the old chronology using INTCAL13 (Reimer *et al.*, 2013) results in calendar ages ranging from 28.3 to 38.3 cal ka BP (2 sigma range), the new data from this study yield ages between 33.8 and 35.9 cal ka BP (2 sigma range; Table 1 and Fig. 7). Our new results thus suggest a much shorter time interval for the deposition of the 28 m of banded clays represented by these radiocarbon samples (Fig. 6). This was already suggested by Bortenschlager and Bortenschlager (1978) based on pollen analysis. In their detailed study of an 86-cm-long section at ca. 655 m a.s.l., these authors found evidence of 17 subsequent vegetation periods and calculated a mean sedimentation rate of ca. 5 cm a^{-1} . A linear regression of the new data suggests a similar mean sedimentation rate of ca. 6 cm a^{-1} . This means that the package of banded clays represented by the radiocarbon-dated samples may have been deposited in roughly 500 years.

The new Baumkirchen radiocarbon chronology is in better agreement with independent age control provided by

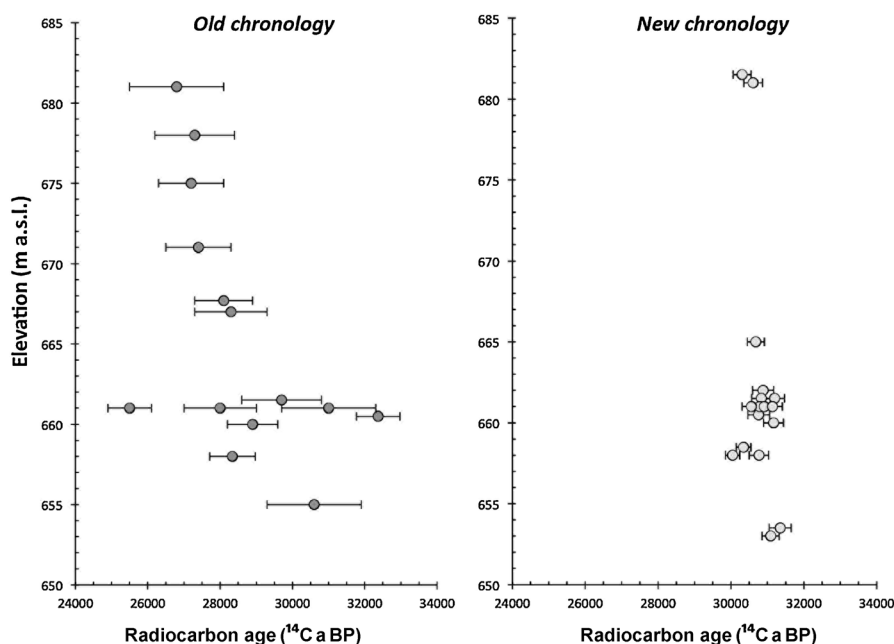


Figure 6. Comparison of the original Baumkirchen uncalibrated radiocarbon chronology (Fliri *et al.*, 1971, 1972; Fliri, 1976; Patzelt, 1996) and the new AMS-based chronology (this study). A few symbols were shifted by 0.5 m along the vertical axis to avoid overlapping error bars of replicates of the same elevation.

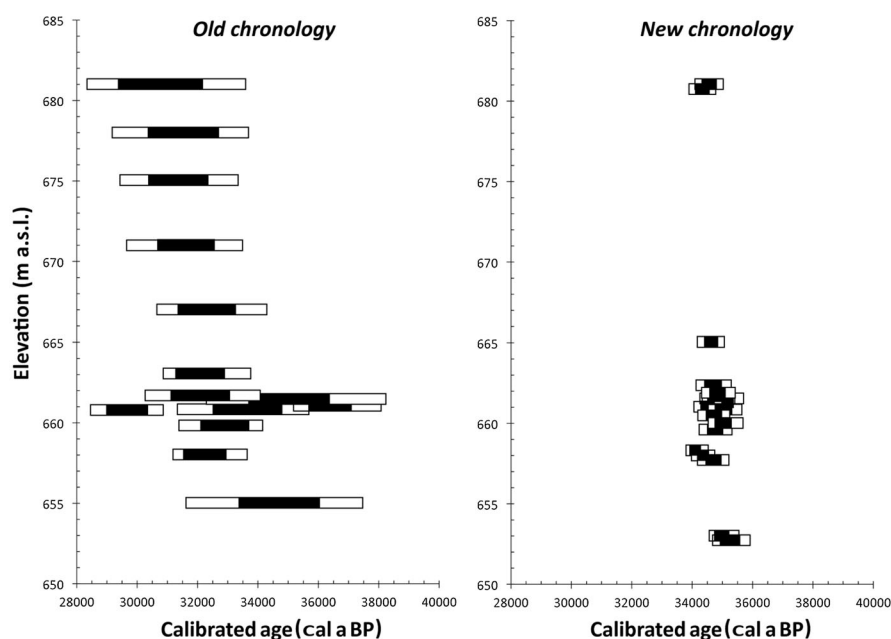


Figure 7. Comparison of the original Baumkirchen chronology (Fliri *et al.*, 1971, 1972; Fliri, 1976; Patzelt, 1996) and the new AMS-based chronology (this study) using the INTCAL13 calibration. The filled and open boxes represent the 1 and 2 sigma probability ranges, respectively.

luminescence dating than the original Fliri chronology. Klasen *et al.* (2007) analysed four samples of the banded clays between 690 and 660 m a.s.l. using luminescence techniques, covering most of the sequence geochronologically constrained by radiocarbon data. Infrared-stimulated luminescence yielded mean ages of 37.3 ± 3.5 ka (UV) and 37.8 ± 3.6 ka [post-IR optically stimulated luminescence (UV)], whereas infrared-stimulated luminescence (by blue light) gave a higher mean age of 45.0 ± 4.3 ka (Klasen *et al.*, 2007; all uncertainties of these pooled luminescence ages are quoted at the 1 sigma level).

The new radiocarbon data significantly reduce the analytical uncertainties associated with the previous chronology and suggest that the interval between 653 and 681 m a.s.l. was rapidly deposited ca. 34–36 cal ka BP (using the new INTCAL13 calibration dataset). These findings have consequences for the timing of the major, probably climate-induced change from fine-grained lacustrine to coarse fluvio-glacial sediments up-section of the clay pit. Sixty-nine metres of undated banded clays and a few metres of sand overly the highest dated sample (at 681 m a.s.l.). Extrapolating the age of this sample to the top of the banded clays succession at ca. 740 m a.s.l. and assuming a mean sedimentation rate of $5\text{--}6$ cm a^{-1} results in an age of 33–35 cal ka BP for the termination of the lake phase.

The dates of the thigh bone fragments from the Mils gravel pit are of high relevance as they provide the only currently available radiometric age constraint for the overlying gravel. The age of the bones (31–32 cal ka BP; Table 1) is consistent with the interpretation that the gravel is younger than the banded clays and not a lateral facies equivalent of the latter (cf. Fig. 3). The onset of the massive aggradation ('Vorstoßschotter') thus probably occurred ca. 32–33 cal ka BP at the study site, associated with localized erosion of the underlying lake beds. This figure represents the best available age estimate for the boundary between the Middle and the Upper Würmian as defined by Chaline and Jerz (1984). We note that this boundary coincided within age uncertainties with the onset of the Heinrich 3 event (as summarized in Starnberger *et al.*, 2011) and is in good agreement with the timing of the transition from the Middle to the Upper Pleniglacial as defined in central European loess–palaeosol sequences (e.g. Kadereit *et al.*, 2013).

No age control is available for the duration of this fluvio-glacial aggradation period in the Inn Valley until the final ice advance across this valley sander. In this context, a wood fragment found in fluvio-glacial gravel overlain by LGM basal till in the former gravel pit of Albeins in the southern Brixen basin of the Southern Alps (Fig. 1) provides an important anchor point. Dated to $24\,000 \pm 210$ ^{14}C a BP (Fliri, 1988; Hanover radiocarbon laboratory; 27 694–28 518 cal a BP) and confirmed by a second more recent dating (K. Nicolussi, personal communication) this *Pinus cembra* piece demonstrates that the inneralpine Brixen basin was still ice-free ca. 28 cal ka BP. This is consistent within the uncertainty of the age determination and calibration with radiocarbon dates from the Rhine-Linth glacier, probably the best studied LGM glacier system on the northern side of the Alps. Its ice advance from the bifurcation of the two glacier branches at Sargans (Fig. 1) across Lake Constance into the foreland occurred between ca. 28 and 26 cal ka BP (summarized in Preusser *et al.*, 2011). Re-calibrating using INTCAL13 shifts these values by a few hundred years towards younger ages. A high-quality radiocarbon-based chronology was reported from the south Alpine Tagliamento glacier, which arrived in the Friulian plain also between ca. 28 and 26 cal ka BP (Monegato *et al.*, 2007; Fig. 1).

Conclusions

This study provides a set of 17 internally consistent AMS radiocarbon ages which supersedes the 40-year-old chronology of the Baumkirchen type locality. The new dates were obtained on original plant specimens and represent 28 m of banded clay deposition in a large, fjord-type lake which occupied the Inn Valley during MIS 3. The new ages, when calibrated using INTCAL13, cluster around 35 cal ka BP and suggest a mean sedimentation rate of ca. 6 cm a^{-1} , which is in good accordance with palynological observations. No evidence of younger ages as suggested by some of the original Fliri data was found. Consequently, the rather large spread in the published ages reflects the type of sample preparation at that time and not sample heterogeneity. Neither the previous nor the new dates directly date the transition from the topmost lake sediments into sand and gravel, probably marked by an erosional unconformity. The

new dates, however, allow us to constrain this likely climate-induced change in the sedimentation regime – defined as the Middle to Upper Würmian boundary (Chaline and Jerz, 1984) – to ca. 32–33 cal ka BP, anchored by bone fragments in fluvio-glacial outwash gravel.

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