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# An Early Würmian age for the inneralpine Halldorf site, Salzach Valley, Austria

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## Abstract

The Salzach Valley is one of the major valleys in the Eastern Alps which was occupied by a large ice stream during glacial maxima. In contrast to the Inn and Enns valleys, dated Pleistocene sediments predating the last glacial maximum are rare in the interior of this valley. The only known site is a former gravel pit near Halldorf, close to the conspicuous turn of the valley, where reworked lignite fragments were previously dated to 32 to 55 ka BP. In this study we re-examined these and additional lignite fragments in order to clarify the chronostratigraphic position of this site.

Observations made at the time when the quarry was in operation showed that the lignite fragments were well rounded and compressed, and occurred in poorly sorted and poorly bedded deltaic foresets which lacked evidence of over-consolidation. The lignite also contains wood which is also compressed. Radiocarbon analyses performed on twelve individual wood samples yielded infinite $^{14}$C dates (with one exception) indicating that they were most likely older than the Middle Würmian. Pollen showed high arboreal pollen percentages including *Picea* (dominant), *Alnus*, *Pinus*, as well as low percentages of *Quercus*, *Fagus*, *Abies* and *Corylus* in some samples. *Osmunda* was also found in some samples. Wood anatomical studies performed on fourteen samples revealed a dominance of *Pinus*, which, however, likely reflects the poorer preservation potential of soft wood genera such as *Picea*. The pollen data confirm the radiocarbon dates and document the former presence of a forest vegetation, consistent with Early Würmian records from the northern alpine rim including Mondsee. Although the pollen data do not permit to unequivocally assign these lignite samples to a known stratigraphic interval, they favour a First Early Würmian Interstadial age, whereby different samples record different parts of this long period during which the former peat bog formed. Strong compaction of the peat and wood probably reflects ice loading during the last glacial maximum, while subsequent erosion, transportation and re-deposition by meltwater streams occurred during the deglaciation phase.

Das Salzachtal ist eines der großen Täler der Ostalpen und beherbergte einen großen Eisstrom wähernd glazialer Maxima. Im Gegensatz zum Inn- und Ennstal sind datierte pleistozäne Sedimente aus der Zeit vor dem Hochwürm im Inneren dieses Tales sehr selten. Die einzige bislang bekannt gewordene Lokalität ist eine ehemalige Kiesgrube bei Halldorf, nahe dem markanten Knick des Tales, wo aufgearbeitete Lignitgerölle gefunden wurden, die auf 32-55 ka BP datiert wurden. In der vorliegenden Studie wurden diese und weitere Lignitkomponenten neu untersucht um deren chronostratigraphische Stellung zu klären.

Feldbeobachtungen aus der Zeit, als die Kiesgrube noch zugänglich war zeigen, dass die Lignitgerölle gut gerundet und stark kompaktiert waren und in schlecht sortierten und schlecht geschichteten Deltakiesen eingebetten waren, die ihrerseits keinerlei Anzeichen von Überkonsolidierung aufwiesen. In den Lignitkomponenten fanden sich ebenfalls gepresste Hölzer. Radiokarbonanalysen an zwölf Holzproben ergaben infinite $^{14}$C Alter (mit einer Ausnahme), d.h. diese Proben sind älter als Mittelwürm. Palynologische Untersuchungen zeigten hohe Baumpollenanteile mit *Picea* (dominant), *Alnus*, *Pinus*, und geringen Anteilen an *Quercus*, *Fagus*, *Abies* und *Corylus* in einzelnen Proben. *Osmunda* wurde ebenfalls in einigen Proben gefunden. Holzanatomische Analysen wurden an vierzehn Proben durchgeführt und ergaben eine Vorherrschaft von *Pinus*. Dies dürfte jedoch das schlechtere Erhaltungspotential von Weichholzarten wie *Picea* reflektieren. Die Pollendaten bestätigen somit die Radiokarbonwerte und dokumentieren das Vorkommen einer Waldvegetation, was mit frühwürmzeitlichen Referenzprofilen vom Nordrand der Alpen übereinstimmt, z.B. Mondsee. Auch wenn die palynologischen Ergebnisse keine eindeutige biostratigraphische Zuordnung zulassen, so sprechen sie doch in Summe für das Erste Frühwürm-Interstadial, wobei einzelne Proben verschiedenen Abschnitten dieser längeren klimagünstigen Phase zugeordet werden können, in der sich das damalige Moor bildete. Die starke Kompaktion des Torfs

und der Hölzer wird auf Eisauflast während des Hochwürms zurückgeführt, während die nachfolgende Erosion, der Transport und die Ablagerung durch Schmelzwässer im frühen Spätglazial erfolgte.

## 1. Introduction

The last glacial period, i.e. the interval between the end of the Last Interglacial and the onset of the Holocene, was a time of drastic and often abrupt climate change. Most of these ca. 119 ka are continuously recorded in the deep ice of Greenland, where 25 interstadials have been identified, interrupted by variably long stadials (North Greenland Ice Core Project members, 2004). Recent research has revealed that the same pattern of high-frequency high-magnitude climate change also affected the Alps during this period (Spötl et al., 2006; Boch et al., 2011; Moseley et al., 2014). These data were obtained from speleothems using the same oxygen isotope proxy as in ice-core studies. The speleothem archive offers a superior chronology, but lacks a direct proxy for land surface conditions including vegetation. Palaeovegetation data are best preserved in lacustrine sediments and peat bogs, but studies of these archives in the Alpine realm face several challenges. Firstly, remains of Late Pleistocene palaeolake successions are not widespread in the Alps due to the pervasive erosion associated with the Last Glacial Maximum (LGM) ice advance and collapse. Secondly, these sediments are difficult to date because they commonly either lack well-preserved plant macrofossil remains or they are close to or beyond the limit of radiocarbon dating. Finally, these successions commonly comprise short time spans only. Still, there are a number of lacustrine records known in the Alps, and they are best preserved in the foreland and close to the margin of the mountain range. These data provide a robust picture of the palaeovegetation that prevailed during the Last Interglacial (Rissian/Würmian or Eemian) and during the two subsequent forested interstadials referred to as the First and Second Early Würmian Interstadials. The best-known example in Austria are the deltaic sediments of the former Mondsee preserved near the northern tip of modern lake Mondsee. This record starts at the very end of the Penultimate glacial period (Rissian) and extends almost continuously until the end of the Second Early Würmian Interstadial (Klaus, 1976; Drescher-Schneider, 2000; Oeggl & Unterfrauner, 2000). The same stratigraphy was reported from other lacustrine records along the northern rim of the Alps, including Samerberg and Füramoos (see Preusser, 2004 and Heiri et al., 2014 for reviews). The Middle Würmian record, however, is highly fragmentary at Mondsee and discontinuous even at the most complete foreland record at the site Füramoos (Müller et al., 2003).

Within the Alps lacustrine successions of Early to Middle Würmian age are known from the Inn Valley (Fliri, 1973; Starnberger et al., 2013; Barrett et al., 2017) and the adjacent area between Wildschönau and Kitzbühel (Reitner et al., 2015), the Enns Valley (Draxler & van Husen, 1978), the Gail Valley (Draxler, 2000) and more recently also from Berchtesgaden (Mayr et al., accepted). These data largely confirm observations from peri-alpine sites and show that closed forests disappeared from the Alps at the end of the Second Early Würmian Interstadial giving rise to a tundra vegetation with only scattered stands of trees, particularly during the short interstadials of the Middle Würmian. In this respect, the discovery of reworked lignite (compressed peat) fragments in gravel at Halldorf (Fig. 1) is of interest, because it is the only known record of wood-bearing Würmian sediments in the inner alpine Salzach Valley, a major valley which hosted the easternmost outlet glacier in the Alps. Surprisingly, radiocarbon dates sug-

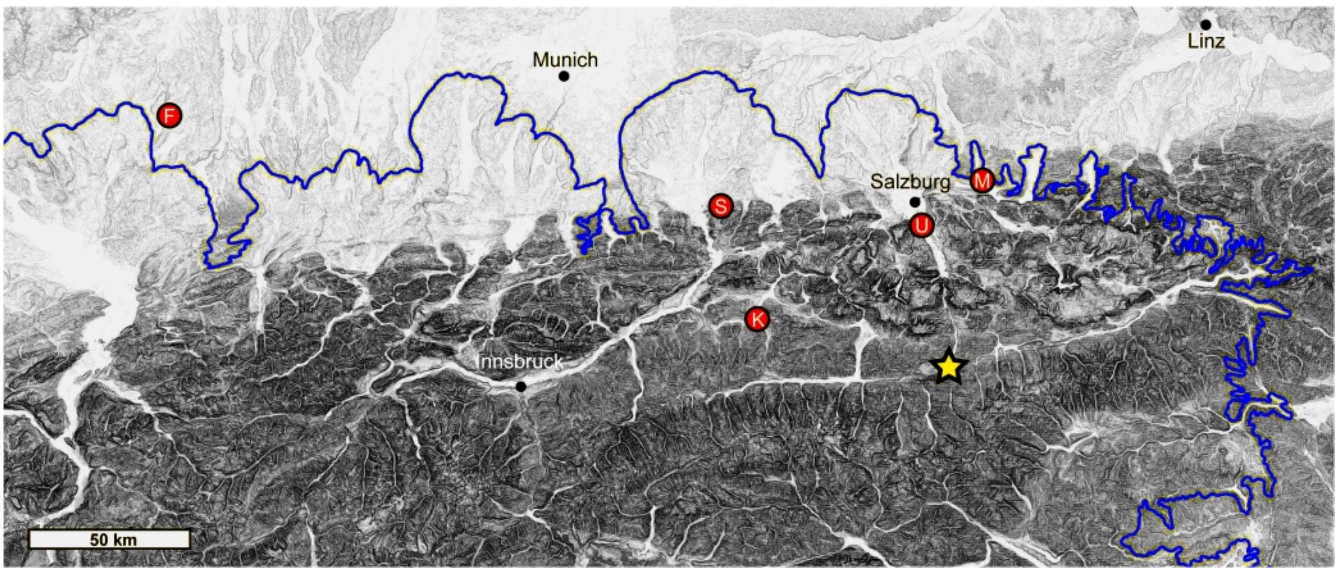


**Figure 1:** Relief map of the northern part of the Eastern Alps showing the location of the study area (Halldorf, marked by an asterisk), Pleistocene lacustrine references sites mentioned in the text (M..Mondsee, K..Kitzbühel/Lebenberg, S..Samerberg, F..Füramoos, U..Urstein; not shown is Gondiswil in Switzerland) and the maximum ice margin during the Upper Würmian.

gested a Middle Würmian age of these deposits (Slupetzky, 1975), which is difficult to reconcile with the evidence from the other inner-alpine valleys mentioned above. The aim of the present study was to re-examine the original lignite samples using a combination of radiocarbon, pollen and wood analyses and to re-assess their chronostratigraphic position and palaeovegetational implications.

## 2. Site description and previous research

Between St. Johann and Schwarzach im Pongau the Salzach valley turns from a primarily W-E oriented valley into an essentially S-N trending one. On the left (northwestern) side of the valley just south of Halldorf, a hamlet of St. Johann im Pongau, a ridge (Klingelberg) terminates close to the Salzach river (Figs. 1 and 2). This spur is composed of calcareous schists and marbles of the Greywacke Zone. On its northern edge the terrace of Stalln is present about 30 m above the level of the Salzach. In the 1970s, the lower and upper parts of this terrace were exposed in a gravel pit (47.33207 °N, 13.18645 °E), which was repeatedly visited and documented at that time (by HS). These sediments have largely been removed and the quarry has been abandoned since then. Figure 3a summarises the available geological information which reveals a twofold internal architecture of the terrace: an upper unit 1 composed of horizontally bedded, fluvial gravel (Fig. 3B), and a lower unit 2, which was at that time exposed down to 5-6 m below the level of the adjacent road (578 m a.s.l.). Unit 2 comprised a succession of very poorly sorted gravel containing boulders up to about 0.5 m in diameter and intercalated sand beds. The bedding was commonly inclined but varied and was disturbed in places (Slupetzky, 1975), pointing towards a deltaic sediment body with foresets dipping towards the NE (Fig. 3C). The sediments were stained brown in places indicating oxidation processes in the groundwater. Individual lignite fragments and less commonly wood pieces were embedded in the more sandy layers and lenses. The lignite fragments were almost black and moist when freshly exposed (Figs. 3D and 3E) and uniformly characterised by a high degree of rounding (Fig. 4A). Wood fragments also showed rounding. The lignite components ranged from a diameter of few centimetres up to 80 x 40 x 20 cm.

A key feature of the lignite cobbles and the isolated wood pieces was their high degree of compaction. The former also contain macroscopically visible wood remains which likewise are strongly compressed (Figs. 4B and 4C). One specimen of a well preserved cone was found inside a lignite fragment

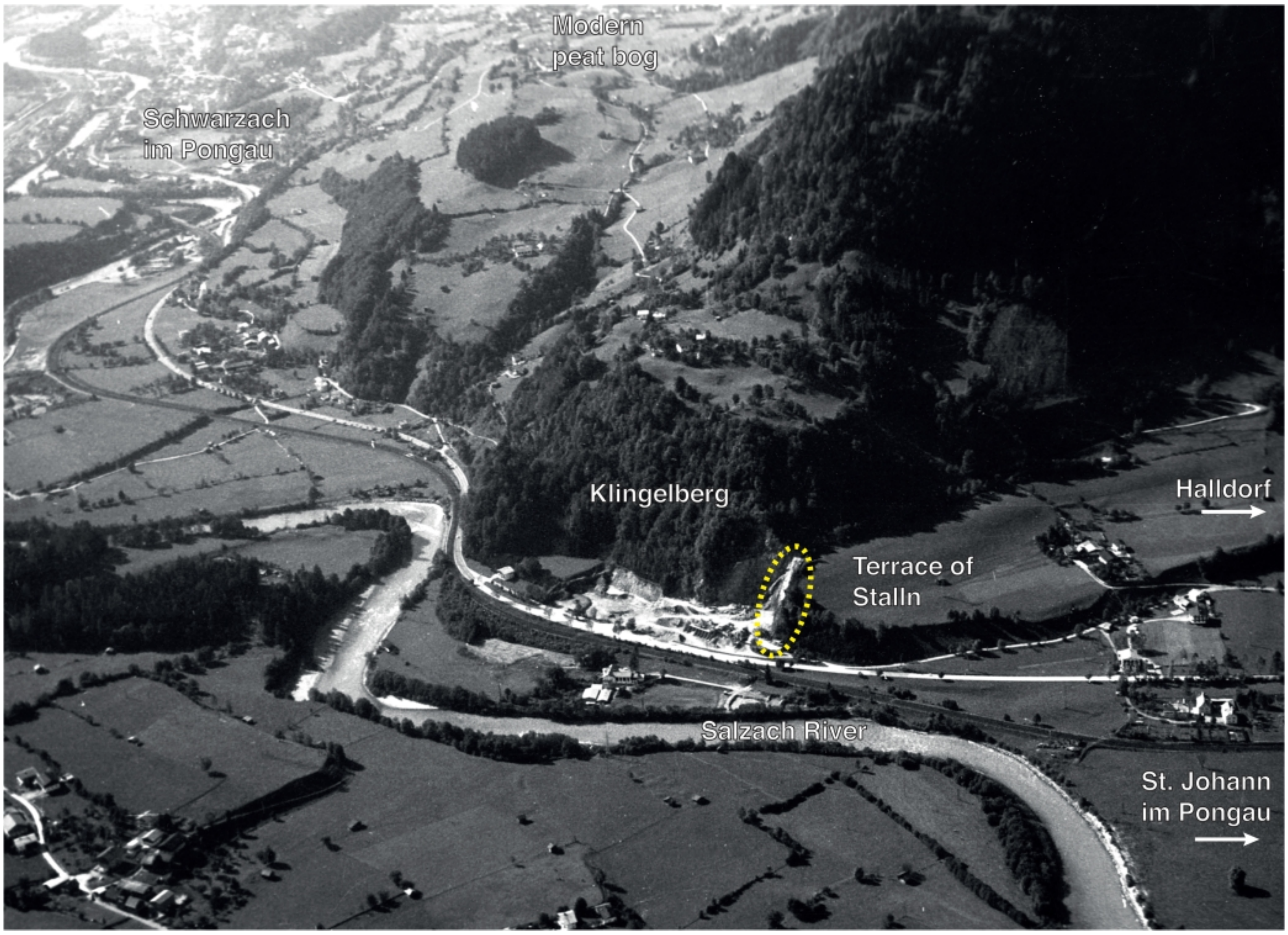


**Figure 2:** Historical oblique aerial photo from the east onto the spur of Klingelberg, the southern part of the terrace of Stalln and the location of the former gravel pit marked by a yellow stippled ellipse.

(probably *Picea* – K. Oeggl, written comm. – Fig. 4D). Two lines of evidence indicate that the lignite acquired its high degree of compaction prior to erosion and re-deposition in unit 2: (a) not only components whose internal bedding was oriented parallel to the bedding of the surrounding sediment showed a high degree of compaction, but also fragments whose internal bedding formed a steep angle relative to the sediment bedding. (b) The surrounding sediment of unit 2 showed no signs of over-consolidation. The high degree of compaction of these lignite and associated wood fragments therefore demonstrates that these former peat sediments experienced (over)compaction, possibly by ice loading, prior to erosion and re-deposition in the deltaic sediments of unit 2. Given that the latter lack clear signs of over-consolidation, this last depositional event took place during the early part of the Late Glacial, probably associated with the down-wasting of the Salzach glacier. A possible scenario involves erosion of these sediments by a subglacial stream and re-deposition in the small delta of a temporary lake in the Salzach valley. Alternatively, erosion occurred by a subaerial meltwater stream. In any case, these processes most likely took place during the final stages of downwasting of the Salzach glacier when abundant meltwater was available; the good rounding of all lignite fragments indicates a (short) fluvial transport. A likely source region of the lignite is the area near St. Veit on the northern side of the valley some 160 m above the Salzach valley floor (Fig. 2), which also hosts a peat bog today, located c. 2.2 km from the Halldorf gravel pit. Further up valley,

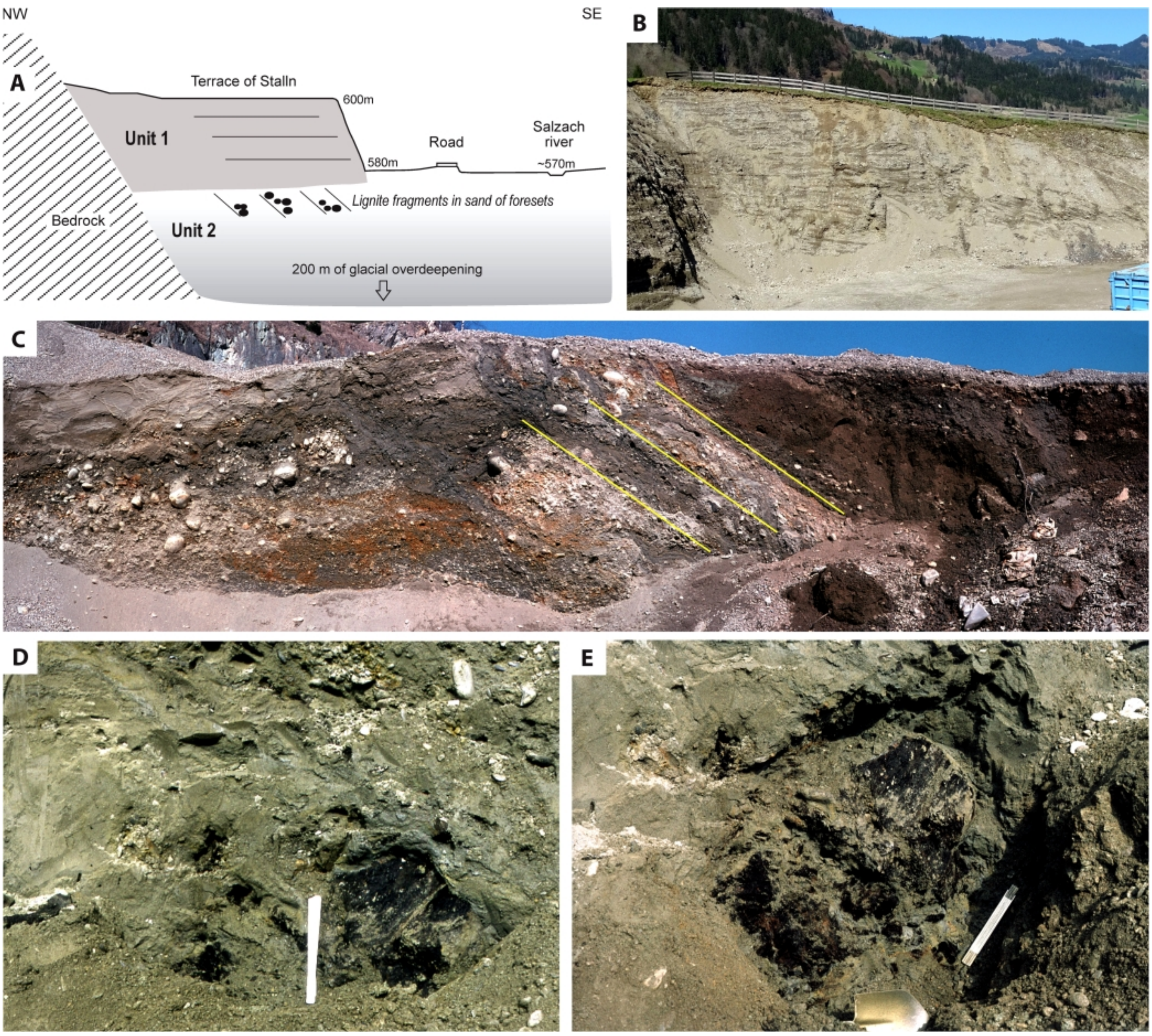


**Figure 3:** Outcrop situation at the former gravel pit at Halldorf. (A) Simplified cross section showing fluvial gravel of a left-lateral terrace of the Salzach river (unit 1) underlain by gravel, sand and boulders showing commonly inclined bedding and containing reworked lignite fragments (unit 2). (B) Horizontally bedded fluvial gravel of unit 1, (C) panoramic view of unit 2 showing the wide range of sediment types in this deltaic body. Yellow lines indicate foresets. Most lignite components were found in sandy layers near the center of the picture. Average height of outcrop 6 m. (D) and (E) close-ups of individual lignite fragments embedded in coarse sand and gravel. White scale bars 25 cm.

two bogs exist 6.5 and 11 km to the west (Goldegg Lake Weng and Böndl Lake, respectively – Schantl-Heuberger, 1994) and similar topographic conditions for peat growth may have existed in interstadial/interglacial periods in the past.

In a first study, twelve wood fragments were examined. Six were *Picea abies*, one *Pinus sylvestris* and four samples did not allow any identification (Slupetzky, 1975). Two radiocarbon dates obtained in the former radiocarbon laboratory at the Institut für Radiumforschung und Kernphysik in Vienna yielded variably old ages: lignite sample 1 (VRI-444) >36,500 BP and wood sample 19D (VRI-452) 35,470 +2,580/-1,950 BP (Slupetzky, 1975). A laboratory report by Felber (1978) includes two additional finite dates for samples Halldorf 2 (*Juniperus* wood, VRI-449, 32,000 ±1,200 BP) and Halldorf B9 (lignite fragment, VRI-489, 31,000 ±1,000 BP). These dates were then summarised in a later field trip report (Slupetzky, 1990), which also reported a new radiocarbon date for lignite sample 1 (GrN-8513-C; 55,000 +3,900/-2,600 BP) as well as a date of a *Pinus sylvestris* wood sample (GrN-8720; 46,300 +2,600/-1,900 BP), both measured in the Groningen laboratory.

A piece of the Halldorf lignite was checked for its pollen content. Abundant fern spores and *Picea* pollen were found, suggesting a considerably older age than indicated by the radiocarbon dates (R. Krisai, written communication to HS, 2009).

The potential modern natural vegetation would consist of a montane beech and fir forest along the lower altitudinal belt and a spruce and fir forest in the upper parts of the valley slope. As a result of forestry management, however, spruce forests and meadows dominate the valley slope today. The floodplain area along the Salzach river was originally vegetated by alder (Wagner, 1989) and is now used as arable land and building area.

## 3. Methods

As the original outcrop at Halldorf has largely been removed, this study had to rely on the existing archive of 29 lignite fragments, which were collected from the outcrop in the 1970s (by HS). The samples had been stored under conditions avoiding contamination. For the present examinations the specimens were macroscopically inspected and photographed.

Pollen work was split between two laboratories: 11 lignite fragments were prepared in Innsbruck (by DF), but only six of them yielded sufficiently high pollen counts which were further studied. One pollen sample each was analysed. Two lignite fragments were examined in Graz (by RDS). Halldorf (Hd) 26 was 19 x 14 cm in diameter and 7 cm high. It consisted of strongly pressed peat containing wood pieces. This block was subdivided into eight subsamples (Hd26/1 to Hd26/8, 3-8 mm thin each) which were separated according to the bedding cleavage. The second sample, Hd35, was significantly smaller (8 x 6 x 1 cm) and only one sample was analysed for pollen. The chemical processing followed the same standard preparation protocol involving 10% KOH, HF, HCl, acetolysis, KOH and glycerol. Pollen and other microfossils were identified and quantified using a light microscope at 400x magnification, if necessary using phase contrast and 1000x magnifi-


**Figure 4:** Lignite fragments and plant remains. (A) Large well-rounded lignite component showing internal near-horizontal bedding. Width of component 40 cm. (B) Cut lignite fragment showing internal layering and branch near bottom. Width of the lignite fragment 12 cm. (C) Cross section of a strongly compacted stem of spruce (*Picea abies)*, longer diameter of section 20.5 cm. (D) Cone embedded in lignite. Length of cone 11 cm.

cation. The pollen identification followed mainly Beug (2004) and Moore et al. (1991). Due to the often broken pollen grains, a solid differentiation of *Pinus cembra* and *Pinus sylvestris/mugo* was not possible. Therefore *Pinus* is indicated as *Pinus* sp. A total of 421-740 pollen grains per sample were counted. The percentage calculation is based on the sum of the arboreal plus non-arboreal pollen (AP + NAP). Aquatics, spore plants and the non-pollen palynomorphs (NPPs) were excluded from the pollen sum. Their values refer to the pollen sum (AP+NAP). The software TILIA 2.0.33 (Grimm, 1994-2014) was used for calculation and creating the diagram. To facilitate the legibility of the diagram, only pollen types that were found at least twice in all samples are shown.

Wood remains from 14 lignite specimens were selected for anatomical studies. These wood samples with lengths varying between 3 and 4 cm were soaked in 60°C water and rehydrated for 24 h to soften them. Then, anatomical sections (cross-section, tangential, radial) were made using a razor blade. The thin sections were examined under a transmitted-light microscope at magnifications up to 500x, using standard identification literature (Schweingruber, 1990) and an interactive identification key (Heiss, 2009).

Twelve wood samples (nine of which were also studied microscopically, see above) were analysed at the 14CHRONO Centre, Queen's University Belfast, using accelerator mass spectrometry (AMS). The wood was pre-treated following the standard acid-alkali-acid procedure (de Vries and Barendsen, 1952). The sample AMS $^{14}C/^{12}C$ ratio was background corrected with an anthracite blank and normalised to the HOXII standard (SRM 4990C; National Institute of Standards and Technology). The $^{14}C/^{12}C$ ratio was corrected for isotopic fractionation using the concurrently measured $^{13}C/^{12}C$ ratio which accounts for both natural and analytical isotope fractionation. Ages were calculated according to Stuiver and Polach (1977) and were calibrated using the IntCal13 (Reimer et al., 2013) calibration curve and the Calib 7.1 software. Calibrated ages are reported with two standard deviations (2σ).

## 4. Results

### 4.1 Sample characterisation

Lignite fragments ranged in size from less than 10 cm to as large as 40 cm. Despite the fact that all fragments were completely dried out during storage and tended to break apart along bedding planes, most of the components still show clear evidence of a well-rounded outer surface. Macroscopic wood remains were found in most of the 27 studied lignite fragments, mostly compressed twigs up to a few cm in diameter.

### 4.2 Pollen analysis

The six lignite fragments analysed in Innsbruck are characterised by AP percentages between 90 and 95%. *Picea* is dominant in samples Hd8 and Hd17 and the values of *Alnus* reach 30% and 20%, respectively, while those of *Pinus* sp. stay below 10%. Thermophilous tree species of a mixed oak forest (*Quercus*, *Ulmus*, *Tilia*) are absent with the exception of *Quercus*. *Abies* reaches 3-4% and *Corylus* (< 1%) and *Lonicera* (± 3%) are present in Hd17. *Osmunda* is present in Hd8 and Hd17. The pollen content of the following three samples (Hd13, Hd15 and Hd22) is also dominated by *Picea*, but the presence of *Alnus* (5-8%) and *Abies* (± 1%) is lower, whereas *Pinus* sp. reaches 25-30%. Thermophilous trees are rare and *Fagus* and *Osmunda* are present in two samples. Single grains of Scrophulariaceae and *Valeriana* also occur but are not indicated in the pollen diagram. Hd9 shows high values of arboreal pollen, dominated by *Pinus* sp. Values for *Picea* and *Larix* are about 35% and 2%, respectively. Only a few grains of *Quercus*, *Abies*, *Fagus* and *Lonicera* were found. *Sphagnum* spores reach about 44%. *Osmunda* spores, as well as *Artemisia* pollen are present and individuals of the *Cystopteris fragilis*-type were also found. Finally, all samples contain very low values of microcharcoal particles.

Lignite block Hd26 was split into eight subsamples according to bedding. AP values never surpass the limit of 80% in these layers. Two different pollen zones (PZ) can be distinguished, A and B (Fig. 5).

PZ A: *Picea* increases from 25 to 42% in the lower zone (Hd 26/8-Hd 26/6) and *Pinus* sp. is frequent (±20%) as well as *Alnus* (10-15%). The presence of alder trees in the surrounding of the former peat bog is documented by perforation plates of *Alnus*. Thermophilous species of a mixed oak forest (especially *Ulmus*) are regularly found. Moreover, these samples are characterised by high percentages of Poaceae and monolete fern spores. Single pollen grains not indicated in the diagram are *Juniperus*, Gentianaceae and *Sparganium*.

PZ B: the upper part (Hd26/5-Hd26/1) reveals a clear decrease in the abundance of *Picea* and *Pinus* sp., an increase in *Ulmus* and *Quercus* and slightly rising values of *Corylus*. *Abies* and *Fagus* are present as well. Cyperaceae are abundant and are accompanied by *Gaeumannomyces* (saprophytes on sedges). Monolete fern spores are distinctly less abundant than in the layers below, although sporanges are commonly present. The three uppermost subsamples show conspicuously high values of charcoal particles. Single grains not indicated in the diagram include *Cirsium*-type, *Heracleum*, *Lygeum* and oogonia of the Neorhabdocoela species *Gyratrix hermaphroditus* and *Microdalyellia armigera* (according to Haas, 1995). *Osmunda* spores are missing, in contrast to samples Hd8-9-15-17-22.

The last sample (Hd35) yielded a pollen spectrum similar to the upper layers of Hd26 including a high abundance of charcoal particles. Single grains not indicated in the diagram are Rubiaceae and *Potamogeton*.

### 4.3 Wood identification

The wood samples showed varying degrees of preservation. About half of the specimens still bore well-preserved anatomical structures, while the other half (samples Hd2A, Hd7A, Hd7B, Hd9A, Hd17A, Hd22A) displayed clear signs of decomposition (e.g., cell walls decaying and folding in, or cells enti-

| | Samples | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hd1A | Hd2A | Hd7A | Hd7B | Hd8A | Hd8B | Hd9A | Hd10A | Hd15A | Hd17A | Hd19A | Hd22A | Hd27A | Hd27B | Sum |
| *Juniperus* sp. | - | - | - | - | - | 1 | - | 1 | - | - | 1 | - | - | 1 | 4 |
| *Pinus mugo/nigra/sylvestris/uncinata* | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 2 |
| *Pinus* cf. *mugo/nigra/sylvestris/uncinata* | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 |
| cf. *Pinus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 |
| Conifer wood indet. | - | - | 1 | - | - | - | 1 | - | - | - | - | 1 | - | - | 3 |
| Indeterminata | - | 1 | - | 1 | - | - | - | - | - | 1 | - | - | - | - | 3 |

**Table 1:** Anatomical analyses of compressed wood specimens embedded in lignite from Halldorf.

rely collapsed). Only evidence of coniferous wood was found (11 out of 14 samples, Table 1). Samples allowing identification to at least genus level are divided more or less equally between *Juniperus* and *Pinus*. Juniper wood is characterised by cupressoid cross-field pits, the lack of resin canals and the abundance of axial parenchyma. No further discrimination of the two locally occurring *Juniperus* species is possible by their wood anatomy. Central European *Pinus* species, on the other hand, display fenestrate cross-field pits and rather abundant large resin canals. Three of the *Pinus* samples allowed exclusion of *P. cembra* due to the clearly visible dentate wood ray tracheid walls. The central European species in question (*P. mugo/uncinata*, *P. sylvestris*, *P. nigra*) can, however, not be distinguished any further by their wood anatomy.

### 4.4 Radiocarbon dating

Eleven out of twelve samples yielded infinite ages, and one sample yielded a very high age of 51,893 ± 4,796 BP (Table 2).

## 5. Discussion

### 5.1 Pollen spectra: vegetation reconstruction

Samples of PZ A (of block Hd26) record a wet, fern-rich environment, similar to a modern riverine forest with *Ulmus* and *Alnus*. *Picea* and *Pinus* trees probably grew on a drier soil at the foot of the mountain slope. The understory consisted of ferns, grasses and Cyperaceae (mainly sedges).

| Sample | Lab code | $^{14}$C age BP |
|---|---|---|
| TG1A | UBA-26505 | >49,005 |
| TG7A | UBA-26506 | >52,922 |
| TG8A | UBA-26507 | >48,092 |
| TG9A | UBA-26508 | 51,893 ±4,796 |
| TG10A | UBA-26509 | >49,707 |
| TG13A | UBA-26510 | >52,922 |
| TG15A | UBA-26511 | >48,798 |
| TG17A | UBA-26512 | >49,081 |
| TG22A | UBA-26513 | >51,358 |
| TG27A | UBA-26514 | >52,922 |
| TG_NR1 | UBA-26736 | >49,058 |
| Halldorf17 | UBA-26737 | >48,941 |

**Table 2:** Radiocarbon dates of wood specimens from Halldorf. All samples are from twigs except Hd17, which a bulk sample of lignite. Sample TG_NR1 was previously analysed in the former Vienna laboratory (VRI-444, >36500 BP; Felber, 1978) and subsequently in the Groningen laboratory (GrN-8513-C, 55000 +3900/-2600; Slupetzky, 1990).

Samples of PZ B document a development towards a riverine *Alnus* forest with grasses, Cyperaceae and ferns. The lack of perforation plates of *Alnus* implies that no *Alnus* trees grew directly adjacent to the peat bog. The pollen data also indicate the development of a mixed *Picea-Quercus* forest with increasing proportions of *Tilia* and *Corylus* along the base of the mountain slopes. Whether the traces of *Abies* and *Fagus* already mark the onset of their immigration into the study area remains unclear, because the short succession stops here.

Lignite fragment Hd35 records a similar vegetation and it is possible that it formed at the same time as the upper part of Hd26 (between Hd26/2 and Hd26/3?) given the high abundance of charcoal particles.

A quite different vegetation pattern is indicated by samples Hd8 to Hd22, which reflect three types of closed forests. (i) Hd8 and Hd17 indicate a *Picea* forest with a few *Abies* stands. *Alnus* was probably growing in the vicinity of the depositional site as its pollen is second in abundance only to *Picea*. (ii) Samples Hd13, Hd15 und Hd22 indicate a *Picea* forest. The elevated counts of *Pinus*, *Betula*, rare grains of *Larix* and in particular the presence of *Huperzia selago* and *Selaginella selaginoides* indicate a subalpine *Picea-Pinus* forest close to the upper timberline. Assuming that all samples (Hd8 to Hd22) were deposited at the same site (i.e. the same altitude), these data suggest a colder climate with a lower timber line as compared to samples Hd8 and Hd17. Rare grains of *Quercus*, *Ulmus*, *Corylus* and *Fagus* probably represent long-distance transport from lower altitudes. (iii) Lignite sample Hd9 was deposited close to a *Pinus-Larix* forest mixed with *Picea*, typical of a timberline situation. The occurrence of a Poaceae and other herbs, as well of spores of the *Cystopteris fragilis*-type, indicate that the forest was open, which is compatible with the proximity of the timberline. High values of *Sphagnum* und Ericaceae imply that this sample formed in a raised bog where herbs were not abundant.

To conclude, lignite samples Hd26 and 35 record a vegetation of a climatically benign period in proximity to a river. The other samples (Hd8 to Hd22) reflect different climate intervals, which were generally cooler.

### 5.2 Pollen spectra: biostratigraphic considerations

Dense and/or open *Picea* forests with varying proportions of other tree species constituted the main vegetation type in the Eastern Alps and their northern and southern foreland from the Eemian until the Middle Würmian (Füramoos – Müller, 2001, Azzano Decimo – Pini et al., 2009, Lago di Fimon – Pini et al., 2010). Strong cooling during intervening stadials and a general trend towards cooler interstadials during this time span reduced the chances for the re-immigration of thermophilous woody plants leading to a decrease in plant diversity. As a result, diagnostic index species are absent in the post-Eemian period. It is therefore difficult to use pollen data from the last glacial period to draw firm biostratigraphic conclusions (e.g., Grüger, 1996; Wegmüller, 1997). In the case of Halldorf, the task is even more daunting given (a) the lack of a nearby reference section, and (b) the fact that only single samples and one short pollen sequence dominated by *Picea* are preserved. Nevertheless, provided that the Halldorf samples are not older than the Eemian, they can still be compared to reference sections on the northern rim of the Eastern Alps: Mondsee located at 560-580 m a.s.l. (Drescher-Schneider, 2000) and Samerberg at 600-670 m a.s.l. (Grüger, 1979). In addition, the sections at Füramoos (560 m a.s.l.; Müller, 2001) and Jammertal (578 m a.s.l.; Müller, 2000), both of which are located in the foreland of the Rhine palaeoglacier, yielded lacustrine sediments of Eemian and younger age. The latter section, however, lacks Alnus, which renders a comparison difficult. Finally, Eemian to Early Würmian sediments were also described from Gondiswil (Beerenmösli, 639-649 m a.s.l.; Wegmüller, 1992), where lignite layers alternate with clay, silt and sand beds. These five sites show similar present-day mean annual air temperature values as Halldorf (8.0°C): Mondsee 8,4°C, Samerberg 7.5°C, Füramoos 7.4°C and Jammertal 8.2°C, Gondiswil 8,1°C. As far as precipitation is concerned, only Mondsee (1303 mm/yr) shows values slightly higher than Halldorf (1267 mm/yr).

An important question is how the large lignite block (Hd26) was originally oriented. All lignite blocks show clear evidence of fluvial transport and rounding. Close inspection, however, revealed a slight U-shaped depression on one side of Hd26. Studies of reworked Holocene peat fragments at the Pasterze glacier in central Austria showed that such a depression is commonly

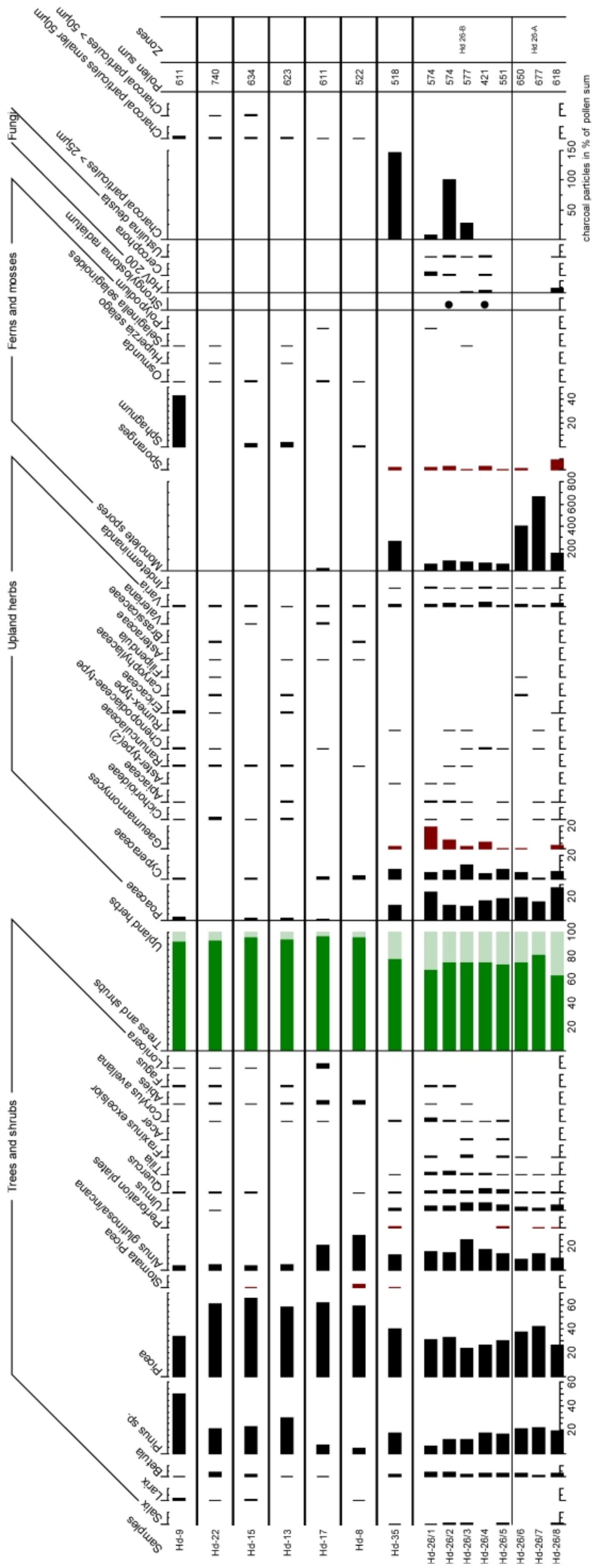


**Figure 5:** Pollen diagram. Note that only the eight subsamples of the large lignite block Hd26 represent a continuous succession, whereas the remaining samples are from individual smaller lignite fragments whose original stratigraphic position is uncertain.

present on the lower side of compressed peat fragments (Drescher-Schneider & Kellerer-Pirklbauer, 2008), and can be used as an indicator for the stratigraphically older part. We therefore used the presence of this depression to orient the lignite block and its eight subsamples (Fig. 5). This orientation is consistent with the vegetation trends known from Early Würmian interstadials, i.e. *Picea* with *Pinus*, *Alnus* and *Ulmus* (PZ A) followed by *Quercus* with *Tilia* and *Corylus* (PZ B). *Abies* and *Fagus* are only present in low amounts towards the end of these interstadials. In contrast to the large block Hd26, the orientation of the other, smaller lignite fragments (where no subsampling was performed) is uncertain. Apart from the occurrence of *Osmunda* (see below) only samples Hd8 and Hd17 with slightly elevated *Abies* counts provide some biostratigraphic guidance. The remaining four samples lack diagnostic pollen assemblages and may represent cooler intervals during interstadials. We emphasise that their position within the overall pollen diagram (Fig. 5) is therefore speculative.

Only the three lignite blocks Hd26 (*Picea* forest with abundant *Pinus* and *Alder*, mixed oak forest - mainly *Ulmus* - with *Corylus* and traces of *Abies* and *Fagus*) and Hd8 and Hd17 (*Picea* forest with *Alnus* and *Abies*, but no thermophilous trees) allow a more robust biostratigraphic interpretation. Forests dominated by *Picea* are known from several intervals in the last interglacial-glacial cycle, which will be now discussed and evaluated in stratigraphic order.

a) The first option is the end of the Eemian, as recorded at Mondsee (PZ 10), Samerberg (DA 10), Füramoos (between 12.9 and 12.6 m, at this site with dominating *Pinus*) and at Gondiswil (LPAZ 10c and 10d). Provided that the slight climatic differences between the study site and these other localities were similar to today, four lines of observation argue against a (late) Eemian age for the Halldorf lignite samples in general and sample Hd26 (and Hd35) in particular: (i) Hd26 records a change from a cool *Picea-Pinus* forest containing a few thermophilous species towards a warmer *Picea* forest with *Ulmus* and *Tilia*. Such a succession is unknown from Eemian reference sections. (ii) The percentage of *Abies* pollen grains is too low compared to the late Eemian at Mondsee and Samerberg. (iii) *Ulmus* and in particular *Tilia* are too abundant for the late Eemian, and (iv) *Carpinus* is not present in Hd26. We also argue that the other lignite fragments did not form during the Eemian, because the *Abies* counts are too low and *Carpinus* is missing. Moreover, the low values of *Pinus* argue against a deposition during the Late Eemian transition period from fir-rich spruce forests to pine forests as present in Mondsee (end of PZ 10b) and Samerberg (DA 11).
b) A second option is the early part of the First Early Würmian Interstadial (Brørup), which is recorded at Mondsee (PZ 14a and 14c), Samerberg (older part of DA 18), Füramoos (roughly between 12.0 and 11.8 m, but at low resolution) and Gondiswil (LPAZ 16). Apart from *Carpinus*, which was still present at Mondsee, Samerberg and Füramoos, but is not at Halldorf, these pollen spectra match the ones from Hd26 pretty well. *Alnus* counts, which are higher in Halldorf than at the other sites, can be explained by nearby *Alnus* stands. The same applies for samples Hd8 and Hd17, which, like Hd26, also shows no evidence of *Carpinus*.
c) A third option is the late part of the First Early Würmian Interstadial, as recorded at Mondsee (PZ 14f), Samerberg (younger part of DA 18) and Gondiswil (younger part of LPAZ 18). In contrast to Mondsee, Hd26 lacks *Larix* and *Pinus cembra* (only one pollen grain). The absence of the latter tree species may be a consequence of the preservation state of the pollen grains, which, although not poor, did not allow identification of *Pinus cembra*. Furthermore, *Ulmus* and *Tilia* counts are too high and those of *Abies* are too low compared to Mondsee and Samerberg, arguing against a late Brørup age for the Hd26 succession. In contrast, the very low abundance of mixed oak forest species and *Corylus* as well as the abundance of *Abies* and *Larix* in samples Hd8 and Hd17 are in good agreement with pollen data from the late Brørup sequences at Mondsee and Samerberg. An Odderade index species (see below), *Osmunda*, is however, present in both samples with one pollen grain each. Spores of this fern may also be present in other time periods, albeit at low abundances (Mondsee PZ 8, 14c, 14d, Samerberg DA18).
d) A fourth option is the Second Early Würmian Interstadial (Odderade), recorded at Mondsee (PZ 18), Samerberg (DA 24), Füramoos (between 10.7 and 8.4 m) and Gondiswil (LPAZ 20). The pollen spectra of Hd26 resemble those of Mondsee and Samerberg, with the exception that *Tilia* is largely absent at those sites and at Füramoos, and that *Larix*, *Pinus cembra* and *Osmunda* are missing in Hd26. Although *Osmunda* spores are occasionally found in other periods, it appears to be a reliable index species for the Second Early Würmian Interstadial along the eastern and central part of the northern alpine rim. *Osmunda* spores are regularly present at Füramoos, irregularly present at Samerberg (at both sites <1%) and regularly present at values of to 2% at Mondsee. A sample from a drill core at Urstein south of the city of Salzburg, dated by luminescence techniques to the Second Early Würmian Interstadial, yielded almost 100% *Osmunda* spores (with respect to AP+NAP – M. Fiebig et al., pers. comm.). As a consequence, this fern should be expected also at Halldorf further upstream in the Salzach Valley.

The above discussion shows that although the pollen data do not permit to unequivocally assign these isolated lignite fragments to a known stratigraphic interval, they support a First Early Würmian Interstadial age. Hd26 and H35 probably formed during the early to middle, and Hd8 and Hd17 during the middle to late part of this interstadial. The other lignite samples cannot be reliably correlated to known pollen sequences. Still, it is likely that all samples were derived from the same interstadial peat complex given their close spatial association within unit 2 (cf. Fig. 3). Samples Hd13, Hd15 and

Hd22 probably record the older part, whereas Hd9 was deposited during the end of this interstadial.

An interesting comparison can be made between Halldorf and Lebenberg, a site near Kitzbühel, some 60 km WNW of Halldorf. There, a sedimentary succession dated to the First Early Würmian Interstadial was studied by S. Bortenschlager and published by Reitner et al. (2015). These sediments were also deposited in proximity to a riverine *Alnus* forest and revealed an older pollen zone (LB-2) with *Picea*, mixed oak forests (primarily *Ulmus* and *Tilia*) and *Corylus*, and a middle and upper part (LB-3 and LB-4) dominated by *Picea* with *Abies* and *Fagus*. In contrast to Halldorf, however, pollen grains of *Taxus*, *Hedera* and *Ilex* were found in LB-3 and LB-4 next to *Carpinus* grains. The former three species are thermophilous, mainly known from interglacials and are absent at Mondsee (except one *Taxus* grain) and Samerberg (one grain each of *Taxus*, *Hedera* and *Ilex*). Only Füramoos recorded somewhat higher abundances of *Ilex*, while *Hedera* is also missing there. Provided that the stratigraphic assignments of the lignite samples from Halldorf and Lebenberg are correct, these data suggest a climatic difference between these two inner-alpine sites, i.e. cooler and/or more continental conditions at Halldorf compared to Lebenberg/Kitzbühel. This may also be the reason why *Carpinus* was not found at Halldorf.

### 5.3 Wood analysis

The taxa identified in the wood samples (*Pinus*, *Juniperus*) most probably represent a subset of the vegetation growing on-site. However, due to the small overall number of available wood specimens (N=14), no quantitative evaluation of the data is feasible. Against this background, the lack of *Picea* in the wood record (while its pollen is highly abundant in the lignite samples) has no significance.

### 5.4 Radiocarbon age constraints

The new set of samples yielded consistently high radiocarbon dates which indicate that the wood remains are older than at least some 50 ka. As even a tiny amount of contamination by modern carbon can shift the age of very old material (as apparently the case with sample TG9A) we regard this dataset as robust.

These new data seriously call into question some of the previously reported radiocarbon dates, in particular those obtained in the former Vienna laboratory. Sample preparation, purification and radiocarbon (AMS) measurement techniques have changed dramatically since the 1970s and it does not come as a surprise to see this shift towards older ages (which was already seen in wood samples from the Middle Würmian Baumkirchen site – Spötl et al., 2013). The two samples analysed in the Groningen laboratory yielded ages close to the limit of the radiocarbon method, and although they were reported as finite ages, they are more consistent with our new dates. They are both pre-AMS dates and it is questionable if in particular the older of the two is really above background (J. van der Plicht, pers. comm. 2016).

### 5.5 Sedimentation and erosion history at Halldorf

The reworked lignite clasts embedded in proglacial deltaic sediments document the former presence of a peat bog of most likely Early (rather than Middle) Würmian age. This is currently the first – though highly fragmentary – record of sediments of this age in the inneralpine Salzach Valley. So far, only two sites with organic-rich sediments predating the Upper Würmian have been known from the northern terminus of this valley. A peat layer, 1.5 m thick, encountered in a drilling at Urstein on the eastern side of the Salzach Valley (Fig. 1) yielded $^{14}$C dates of >38,600 BP and >43,400 BP (Herbst & Riepler, 2006). Tichy (1980) reported a lignite seam of about 1 m thickness within the city of Salzburg, whose pollen spectra suggest an interstadial origin, backed by a single $^{14}$C date (35,400 ± 4,100 BP). This scarcity of Early to Middle Würmian sediments in the Salzach Valley contrasts to the Inn Valley or the area between Kitzbühel and Wildschönau in Tyrol, where such sediments are more wide-spread and have not been completely removed by subsequent glacier advances.

The organic-rich sediments and enclosed wood remains at Halldorf acquired a high degree of mechanical compaction prior to erosion and transport as the surrounding sediment is not over-consolidated. The most likely mechanism causing the high degree of compaction is ice loading. During the Upper Würmian the ice surface of the Salzach glacier was about 2000 m a.s.l. at Halldorf (van Husen, 1987; Gamerith & Heuberger, 1999), i.e. the ice thickness was at least about 1.5 km, clearly sufficient to cause significant compaction in particular of peat sediments and enclosed wood. Earlier ice loading at the end of the Early Würmian is regarded as unlikely, as there is currently no evidence of a major glacier advance during this time interval which reached the main longitudinal valleys and resulted in significant ice build-up therein (Starnberger et al., 2013; Barrett et al., 2017).

We favour a model of erosion of these Early Würmian peat-bearing sediments by a subglacial meltwater stream during the last deglaciation, which resulted in re-deposition in a local delta. This sediment body was subsequently buried beneath a few metres of fluvial sediments and shaped into a terrace by subsequent incision of the Salzach River. Although there are no direct constraints on the age of this terrace of Stalln and in particular its lower unit 2 (Fig. 3), its presumed Late Glacial age is consistent with data from the next terrace (of Schwarzach – Fig. 2) 2.6 km upstream at a similar elevation (ca. 605 vs. ca. 600 m a.s.l.). There, temporary outcrops exposed weakly and commonly cross-bedded gravel sharply overlain by up to 6 m-thick banded clayey silts which were capped by sand and gravel. Wood fragments (*Juniperus*) from the base of the lacustrine silts yielded $^{14}$C dates between 13,900 ± 200 and 12,500 ± 170 BP (Felber, 1974, 1978; Slupetzky, 1975, 1990; calibrated time span: 17,432-14,085 cal BP). A Late Glacial origin of these terrace sediments is also consistent with radiocarbon and pollen data from a modern peat bog in Goldegg a few kilometres to the west, where peat accumulation commenced 12,870-13,459 cal BP (Schantl-Heuberger, 1994).

## 6. Conclusions

The re-examination of some of the original and a set of previously untouched samples of lignite from the currently inaccessible gravel pit at Halldorf clarified the chronostratigraphic position of this reworked peat and provides new insights into the Pleistocene paleovegetation of the inner Salzach Valley:

- New radiocarbon dates strongly argue against a Middle Würmian age, thereby solving the conundrum of forests at this inneralpine site during the Middle Würmian (as previously postulated).
- Although the isolated lignite fragments do not allow to piece together a continuous record, the assemblage of taxa strongly suggests that the peat bog formed during an Early Würmian interstadial, most likely the First Early Würmian Interstadial (Brørup), when closed forests dominated by *Picea* grew adjacent to the peat bog.
- In comparison with Early Würmian reference sections at the northern margin of the Alps, individual lignite samples can be tentatively assigned to the early, the middle and the late part of this long interstadial.
- In contrast to the next closest Early Würmian section (at Kitzbühel) the palynological data from Halldorf suggests a cooler and more continental climate.

  Erosion and re-deposition of this peat-bearing succession most likely occurred during the early Late Glacial phase of ice decay.

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## References

Barrett, S., Starnberger, R., Tjallingii, R., Brauer, A., Spötl, C. (2017): The sedimentary history of the inner-alpine Inn Valley (Austria): extending the Baumkirchen type section further back in time with new drilling. Journal of Quaternary Science, 32, 63-79. http://dx.doi.org/10.1002/jqs.2924

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil Verlag, Munich, 542 pp.

Boch, R., Cheng, H., Spötl, C., Edwards, R.L. Wang, X., Häuselmann, P., 2011. NALPS: a precisely dated European climate record 120-60 ka. Climate of the Past, 7, 1247-1259. http://dx.doi.org/10.5194/cp-7-1247-2011

de Vries, H., Barendsen, G.W., 1952. A new technique for the measurement of age by radiocarbon. Physica, 18, 652.

Draxler, I., 2000. Pollenanalytische Untersuchung der schieferkohleführenden Sedimentfolge von Nieselach bei St. Stefan im unteren Gailtal, Kärnten. In: van Husen D (ed.): Klimaentwicklung im Riß/Würm-Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12, 155-179.

Draxler, I., van Husen, D., 1978. Zur Einstufung innerwürmzeitlicher Sedimente von Ramsau/Schladming und Hochentauern (Steiermark). Zeitschrift für Gletscherkunde und Glazialgeologie, 14, 105-114.

Drescher-Schneider, R., 2000. Die Vegetations- und Klimaentwicklung im Riß-/Würm-Interglazial und im Früh- und Mittelwürm in der Umgebung von Mondsee. Ergebnisse der pollenanalytischen Untersuchungen. In: van Husen D (ed.): Klimaentwicklung im Riß/Würm-Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12, 39-92.

Drescher-Schneider, R., Kellerer-Pirklbauer, A., 2008. Gletscherschwund einst und heute. – Neue Erkenntnisse zur holozänen Vegetations- und Klimageschichte der Pasterze (Hohe Tauern, Österreich). In: Reitner J. M., Fiebig M. C., Neugebauer-Maresch C., Pacher M., Winiwarter V. (eds.): Veränderter Lebensraum – Gestern, heute und morgen. Abhandlungen der Geologischen Bundesanstalt, 62, 45-51.

Felber, H., 1978. Altersbestimmungen nach der Radiokarbonmethode am Institut für Radiumforschung und Kernphysik XIV. Anzeiger der Österreichischen Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, 1978, 7-9.

Felber, H., 1974. Altersbestimmungen nach der Radiokarbonmethode am Institut für Radiumforschung und Kernphysik XI. Anzeiger der Österreichischen Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, 1974, 3-7.

Fliri, F., 1973. Beiträge zur Geschichte der alpinen Würmvereisung: Forschungen am Bänderton von Baumkirchen (Inntal, Nordtirol). Zeitschrift für Geomorphologie N.F., Suppl., 16, 1-14.

Gamerith, W., Heuberger, H., 1999. Daten zur Eisstromhöhe des eiszeitlichen Salzachgletschers im Salzachquertaal zwischen Schwarzach-St.Veit und Salzburg. Mitteilungen der Gesellschaft für Salzburger Landeskunde, 139, 317-339.

Grimm, E.C., 2004-2014. http://www.tiliait.com (last accessed Dec 27, 2016).

Grüger, E., 1979. Spätriß, Riß/Würm und Frühwürm am Samerberg in Oberbayern – ein vegetationsgeschichtlicher Beitrag zur Gliederung des Jungpleistozäns. Geologica Bavarica, 80, 5-64.

Grüger, E., 1996. Über die Datierung pleistozäner Ablagerungen mit Hilfe von Pollenanalysen. Eclogae Geologicae Helvetiae, 89, 977-990.

Heiri, O., Koinig, K.A., Spötl, C., Barrett, S., Brauer, A., Drescher-Schneider, R., Gaar, D., Ivy-Ochs, S., Kerschner, H., Luetscher, M., Moran, A., Nicolussi, K., Preusser, F., Schmidt, R., Schoeneich, P., Schwörer, C., Sprafke, T., Terhorst, B., Tinner, W., 2014. Palaeoclimate records 60-8 ka in the Austrian and Swiss Alps and their forelands. Quaternary Science Reviews, 106, 186-205. https://doi.org/10.1016/j.quascirev.2014.05.021

Heiss, A.G., 2009. Anatomie europäischer und nordamerikanischer Hölzer — ein interaktiver Bestimmungsschlüssel. Innsbruck.

Herbst, P., Riepler, F., 2006. $^{14}$C evidence for an early to pre-Würmian age for parts of the Salzburger Seeton, Urstein, Salzach Valley, Austria. Austrian Journal of Earth Sciences, 99, 57-61.

Klaus, W., 1976. Das Riß/Würm-Interglazial vom Mondsee. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1, 14-24.

Mayr, C., Brandlmeier, B., Diersche, V., Stojakowits, P., Kirscher, U., Matzke-Karasz, R., Bachtadse, V., Eigler, M., Haas, U., Lempe, B., Reimer, P.J., Spötl, C., 2017. Nesseltalgraben, a new reference section of the Last Glacial period in southern Germany. Journal of Paleolimnology, DOI 10.1007/s10933-017-9972-0

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen analysis. 2nd ed., Blackwell Scientific, Oxford.

Moseley GE, Spötl C, Svensson, A., Cheng, H., Brandstätter, S., Lawrence Edwards, R., 2014. Multi-speleothem record reveals tightly coupled climate between Central Europe and Greenland during MIS 3. Geology, 42, 1043-1046. http://dx.doi.org/10.1130/G36063.1

Müller, U., 2000. A Late-Pleistocene pollen sequence from the Jammertal, south-western Germany with particular reference to location and altitude as factors determining Eemian forest composition. Vegetation History and Archaeobotany 9, 125-131.

Müller, U., 2001. Die Vegetations- und Klimaentwicklung im jüngeren Quartär anhand ausgewählter Profile aus dem südwestdeutschen Alpenvorland. Tübinger Geowissenschaftliche Arbeiten, D7, 1-118.

Müller, U.C., Pross, J., Bibus, E., 2003. Vegetation response to rapid change in central Europe during the past 140,000 yr based on evidence from the Füramoos pollen record. Quaternary Research, 59, 235-245. https://doi.org/10.1016/S0033-5894(03)00005-X

North Greenland Ice Core Project members, 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. Nature, 431, 147-151. http://dx.doi.org/10.1038/nature02805

Oeggl, K., Unterfrauner, H., 2000. Die Pflanzenreste des Riss/Würm-Interglazials und des Würmglazials von Mondsee. In: van Husen D (ed.): Klimaentwicklung im Riß/Würm-Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 93-121.

Pini, R., Ravazzi, C., Donegana, M. 2009. Pollen stratigraphy, vegetation and climate history of the last 215 ka in the Azzano Decimo core (plain of Friuli, north-eastern Italy). Quaternary Science Reviews, 28, 1268-1290. http://dx.doi.org/10.1016/j.quascirev.2008.12.017

Pini, R., Ravazzi, C., Reimer, P.J. 2010. The vegetation and climate history of the last glacial cycle in a new pollen record from Lake Fimon (southern Alpine foreland, N-Italy). Quaternary Science Reviews, 29, 3115-3137. https://doi.org/10.1016/j.quascirev.2010.06.040

Preusser, F., 2004. Towards a chronology of the Late Pleistocene in the northern Alpine foreland. Boreas, 33, 195-210. http://dx.doi.org/10.1111/j.1502-3885.2004.tb01141.x

Reimer PJ, Bard E, Bayliss A. et al., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon, 55, 1869-1887. https://doi.org/10.2458/azu_js_rc.55.16947

Reitner, J.M., Draxler, I., Bortenschlager, S., Pestal, G., 2015. 6.4. Quartär. In: Heinisch, H., Pestal, G., Reitner, J.M., Geologische Karte der Republik Österreich 1:50 000. Erläuterungen zu Blatt 122 Kitzbühel, 165-204, Vienna, Geological Survey of Austria.

Schantl-Heuberger, H., 1994. Pollenanalytische Untersuchungen zur spät- und postglazialen Geschichte der Vegetation im Saalach- und Salzachtal (Salzburg/Austria). Berichte des naturwissenschaftlich-medizinischen Vereins Innsbruck, 81, 61-84.

Schweingruber, F.H., 1990. Anatomie europäischer Hölzer. Ein Atlas zur Bestimmung europäischer Baum-, Strauch- und Zwergstrauchhölzer. Bern, Haupt.

Slupetzky, H., 1990. Haltepunkt Halldorf. – Unpublished Handout Exkursion am 16. Juni 1990. Symposium Spät- und Postglazial im Bereich der Alpen der Arbeitsgemeinschaft für Vergleichende Hochgebirgsforschung, 15.-17. Juni 1990, Salzburg.

Slupetzky, H., 1975. Erste Radiokarbondatierungen in Quatärablagerungen im Pongau im Bereich des inneralpinen Salzachgletschers (Vorbericht). Anzeiger der Österreichischen Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, 1975, 154-160.

Spötl C, Mangini A, Richards DA., 2006. Chronology and paleoenvironment of Marine Isotope Stage 3 from two high-elevation speleothems, Austrian Alps. Quaternary Science Reviews, 25, 1127-1136. https://doi.org/10.1016/j.quascirev.2005.10.006

Spötl, C., Reimer, P.J., Starnberger, R., Reimer, R., 2013. A new radiocarbon chronology of Baumkirchen, stratotype for the onset of the Upper Würmian in the Alps. Journal of Quaternary Science, 28, 552-558.

Starnberger, R., Drescher-Schneider, R., Reitner, J., Rodnight, H., Reimer, P.J., Spötl, C., 2013. Late Pleistocene climate change and landscape dynamics in the Eastern Alps: the inner-alpine Unterangerberg record (Austria). Quaternary Science Reviews, 68, 17-42. http://dx.doi.org/10.1016/j.quascirev.2013.02.008

Stuiver, M., Polach, H.A., 1977. Reporting of C-14 data – Discussion. Radiocarbon, 19, 355-363.

Tichy, G., 1980. Das Würm-Interstadial Kohle-Vorkommen von Mülln (Stadt Salzburg). Zeitschrift für Gletscherkunde und Glazialgeologie, 16, 107-110.

van Husen, D., 1987. Die Ostalpen in den Eiszeiten. Vienna, Geological Survey of Austria.

Wagner, H., 1989. Die natürliche Pflanzendecke Österreichs. - Österreichische Akademie der Wissenschaften, Kommission für Raumforschung. Beiträge zur Regionalforschung, 6, 1-63.

Wegmüller, S., 1992. Vegetationsgeschichtliche und stratigraphische Untersuchungen an Schieferkohlen des nördlichen Alpenvorlandes. Denkschriften der Schweizerischen Akademie der Naturwissenschaften, 102, 1-82.

Wegmüller, S., 1997. Palynostratigraphische Untersuchungen an jungpleistozänen Ablagerungen von Kölliken (Schweizerisches Mittelland). Eclogae Geologicae Helvetiae, 90, 133-141.

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