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Geochronology of *Betula* extensions in pollen diagrams of Alpine Late-glacial lake deposits: A case study of the Late-glacial deposits of the Gasserplatz soil archives (Vorarlberg, Austria)

Jan M. van Mourik [a,*], Ruud T. Slotboom [a], Johannes van der Plicht [b,c], Harm Jan Streurman [b], Wim J. Kuijper [c], Wim Z. Hoek [d], Leo W.S. de Graaff [e]

[a] Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, The Netherlands
[b] Centre for Isotope Research, Groningen University, The Netherlands
[c] Faculty of Archaeology, Leiden University, The Netherlands
[d] Department of Physical Geography, Utrecht University, The Netherlands
[e] Research Foundation for Alpine and Subalpine Environments, Amsterdam, The Netherlands

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ABSTRACT

Pollen diagrams of Alpine Late-glacial calcareous lake deposits show several extensions of *Betula*. The geochronology of these extensions cannot be based on radiocarbon dating due to reservoir effects of such lakes on the radiocarbon ages. A robust geochronology can be based on the oxygen isotope stratigraphy. Additionally, recognition of 12,920 calBP LST in the sediment cores provides a secure time marker. The combined results of pollen, macro-remains and stable isotope analyses of the Gasserplatz cores point to a correlation of the *Betula* extensions with the oscillations in the oxygen isotope curve and are related to global climatic oscillations. This is sustained by the correlation of the Gasserplatz isotope oscillations with the oscillations as registered in the Greenland ice cores. Comparison of the results of the Gasserplatz cores with the results of similar Alpine lake deposits makes clear that the fluctuations in the *Betula* curve are not a local but a regional phenomenon.

1. Introduction

The Late-glacial is a period of rapid climate changes that marks the transition from the last Glacial to the present Interglacial. The Late-glacial can be sub-divided into interstadial and stadial phases that were clearly recognized in the Greenland Ice core records (Johnsen et al., 2001). In various palynological studies, these climate changes are recorded in the pollen diagrams. The subdivision into warm interstadials and cold stadials is classically based on palynology.

In numerous pollen diagrams of Late-glacial deposits, sampled in north-western and central Europe, vegetation changes are discernible even within the warm Bølling-Allerød interstadial. These changes may be the reflection of a climatic alternation dry/warm, moist/cool, dry/warm. These fluctuations can usually be deduced from the combined pollen curves of *Pinus*, *Betula* and non-arboreal pollen (Riezebos and Slotboom, 1984; de Graaff and de Jong, 1995; Hoek, 1997). The climatic fluctuations can also be reflected in the lithofacies of Late-glacial deposits (Zolitschka, 1989; van Mourik and Slotboom, 1995).

Climate changes during the Late-glacial interstadial can be reconstructed using various proxies such as Coleoptera (Coope et al., 1998), Chironomids (Brooks and Birks, 2001), and stable isotopes in lake sediments (Lotter et al., 1992). Especially the ice-core records show details on an annual basis and are, therefore, chosen as a template for climate change during the Last Glacial–Interglacial transition (Lowe et al., 2008). Moreover, the Greenland ice cores provide accurate age estimates for the climate shifts in this period of rapid climate change. The aim of the Gasserplatz case study was to establish a robust geochronology of the Alpine environmental oscillations during the Late-glacial, based on palynology and isotope stratigraphy.

2. The Gasserplatz cores

The geomorphological impact of the Weichselian deglaciation has been studied for a long time in Vorarlberg by researchers and

* Corresponding author.
E-mail addresses: j.m.vanmourik@uva.nl, janmvanmourik@gmail.com (J.M. van Mourik).

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students of the University of Amsterdam (Simons, 1985) and members of the Research Foundation for Alpine and Subalpine Environments (de Graaff et al., 2007). During the field inventories sites as Gasserplatz (Fig. 1) were found with high quality soil archives for palaeoecological analysis.

Gasserplatz is a shallow basin in the rather flat, glacially eroded confluence area of the former Rhine and Ill glaciers. This area became ice-free during the Feldkirch stadium (around 15,500 calBP) and developed as a tiny ice-marginal lake in a sheltered position at an elevation of 559 m above sea level. During the Late-glacial lacustrine carbonate (calcareous gyttja) was deposited, in the Holocene peat accumulated. To unlock information about the Late-glacial environmental oscillations palynology, radiocarbon dating and isotopic analyses have been applied on the Late-glacial lacustrine carbonates.

In the Oldest Dryas the lake sedimentation started with clay deposition (glacier milk), followed by the rhythmic deposition of calcareous clay and humic calcareous gyttja. During the Holocene the lake transferred into a bog with peat accumulation. In a preliminary study of the Gasserplatz archives, aimed at dating of the limnic deposits, a diagram of pollen and macro remains of the limnic deposits has been published (de Graaff et al., 1989). In this diagram the sequence of Late-glacial palyno-chronozones was observed from the Oldest Dryas to the Younger Dryas and this confirms the retreat of the glacier at around 15,500 calBP.

An interesting phenomenon in this diagram was the behavior of the *Betula* pollen curve. The authors connected the expansions of *Betula* in the Gasserplatz diagram with the temperature oscillations as found in the $\delta^{18}O$ curves from the Arctic Dye 3 Ice core and the Swiss Gerzensee sediments (de Graaff et al., 1994; de Graaff and de Jong, 1995). However, the resolution of the *Betula* pollen curve (vertical sampling distance 10 cm) was insufficient to correlate the Gasserplatz *Betula* oscillations with the Dye 3 and Gerzensee $\delta^{18}O$ oscillations satisfactorily.

For that purpose, resampling was required to create a pollen and isotope diagram with a higher resolution (vertical sample distance 2 cm) to correlate the *Betula* and $\delta^{18}O$ oscillations within the Gasserplatz sediment core. Firstly we resampled with a Dachnowsky auger. Unfortunately, the quality of the Dachnowsky samples did not allow precise description of the profile, and it was impossible to collect reliable deeper samples. For that reason we resampled a second time with a mechanical auger (Fig. 2). The quality of these samples (Gasserplatz-2) allowed to distinguish various initial histosols accurately, a lithological reflection of short-lived periods with relatively low water levels. In the present study correlations could be made to the more recent NGRIP isotope record (Rasmussen et al., 2006) and various Swiss lake studies (e.g. Lotter et al., 2012) following the INTIMATE protocol (Lowe et al., 2008). For this, the regional chronostratigraphy of the Alps is used in comparison with the INTIMATE event stratigraphy.

3. Materials and methods

3.1. Sampling

The sample site Gasserplatz is indicated in the geomorphological map of the Gasserplatz area (Fig. 1). The first sediment core was taken with a Dachnowsky sampler from the surface down to

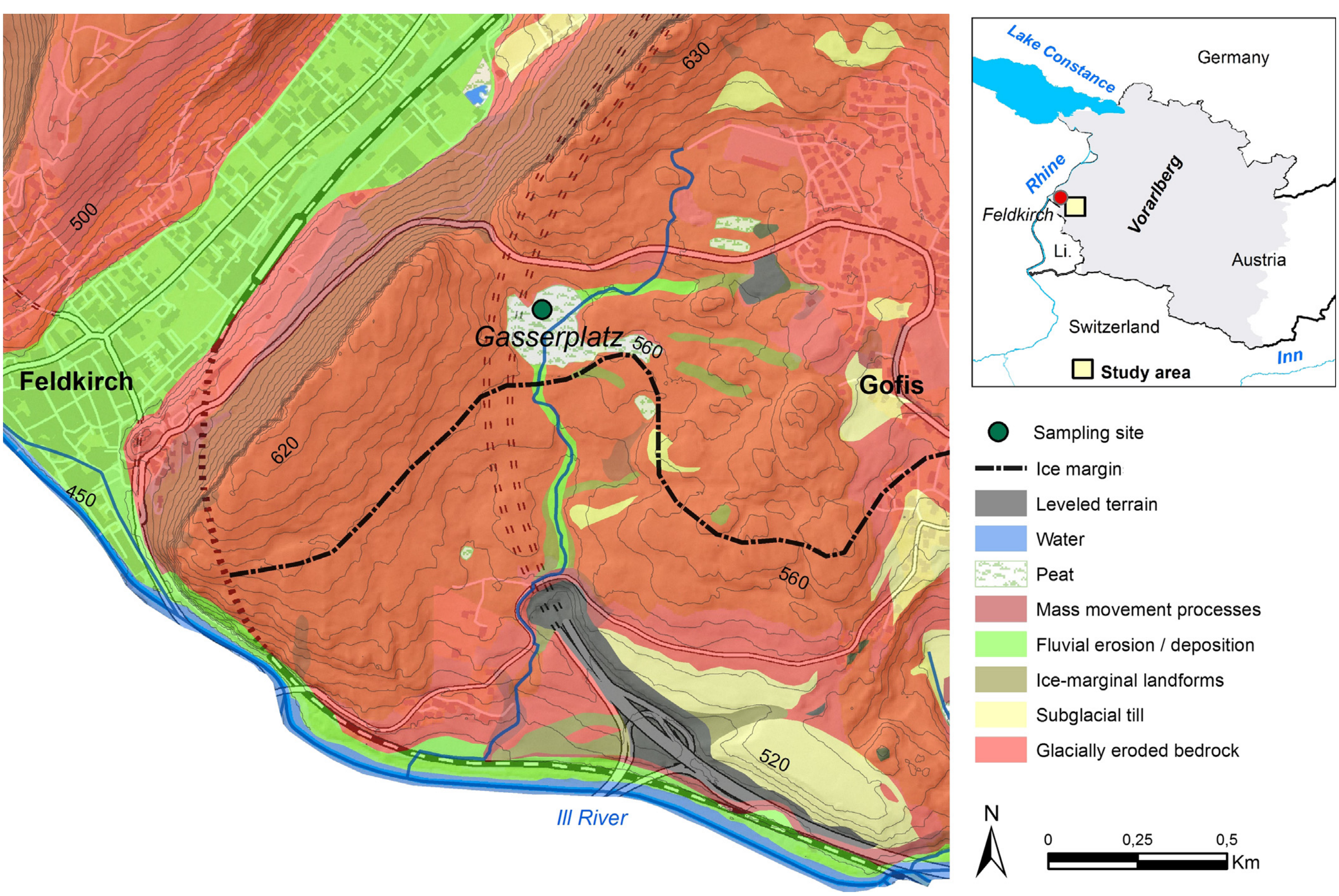

Fig. 1. Gasserplatz in geomorphological context. The ice-margin indicates the boundary of the Ill glacier shortly after the beginning of the Late-glacial sedimentation in the Gasserplatz lake.

Fig. 2. Sampling of the Gasserplatz records with the mechanical auger in March 2002); sampling site is indicated in Fig. 1.

510 cm. The samples from 300 to 465 (vertical sampling distance 2 cm) have been used for pollen and isotope analysis and radiocarbon dating (Gasserplatz-1).

The second core was taken very close to the same site with a mechanical auger from the surface down till the 590 cm The samples from 330 to 530 cm (vertical sampling distance 2 cm) have been used for extractions for (absolute) pollen and isotope analysis, Laacher See Tephra (LST) recognition and a macro remains check (Gasserplatz-2). Also some thin sections have been produced to control the presence of LST, the quality of the limnic carbonates and the initial histosols and the distribution of pollen in the sediments.

3.2. Pollen analysis

For pollen analysis 2 ml samples were collected from the sediment cores with a vertical sampling distance of 2 cm. Initial histosols and lacustrine carbonate sediments are considered to contain syn-sedimentary pollen records and the pollen diagrams to reflect the characteristics of the local and regional vegetation development (van Mourik, 2001). Pollen extractions were carried out using the tufa extraction method (Moore et al., 1991, p. 50). To distinguish between mainly long distance pollen transport and local pollen production, the exotic marker grain method was applied (Moore et al., 1991, p. 53) for estimation of the pollen densities in the lacustrine carbonate sediments. The pollen extractions were performed in the palynological laboratory of IBED, University of Amsterdam. For the identification of pollen grains the pollen key of Moore et al. (1991, p. 83–166) was applied. Pollen grains occur as single grains in the limnic sediments (Fig. 7c); the

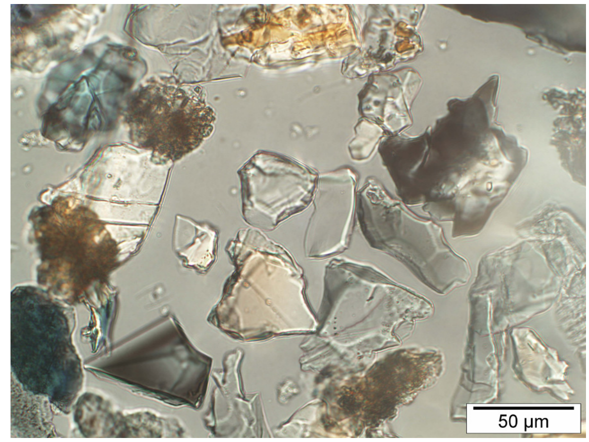

Fig. 3. Gasserplatz-2 383 cm; micrograph of extracted tephra minerals.

conservation rate condition was good, only a small part of the grains show some damage due to mechanical or chemical corrosion.

3.3. Isotope analysis

Organic ^{14}C samples are chemically pretreated with AAA: Acid/Alkali/Acid. The first step removes carbonates and fulvic acids; the second step removes humic acids; the final acid step removes any CO_2 adsorbed during the previous step (Mook and Streurman, 1983). This applies to both conventional (bulk peat) samples as to AMS (dated snails). Snails and carbonates were dissolved in HCl to extract the CO_2, which is used for isotopic analysis.

Conventional Radiocarbon samples were counted by Proportional Gas Counting after the pretreatment and CO_2 production (Cook and van der Plicht, 2006). For AMS samples, the isolated fraction was combusted into CO_2 and purified using an Elemental Analyser/Mass spectrometer (EA/MS) combination (Aerts et al., 2001). The CO_2 was then collected cryogenically for off-line graphitisation. The graphite powder was pressed into targets which were placed in the sample carousel of the ion source of the AMS. The AMS system measured the isotopic ratios $^{14}C/^{12}C$ and $^{13}C/^{12}C$ of the graphite (van der Plicht et al., 2000).

The ^{14}C activities are reported in 'years BP'. These are conventional dates, based on the conventional half-life of 5568 years, and include the correction for sample $\delta^{13}C$ normalized to a $\delta^{13}C$ value of $-25‰$.

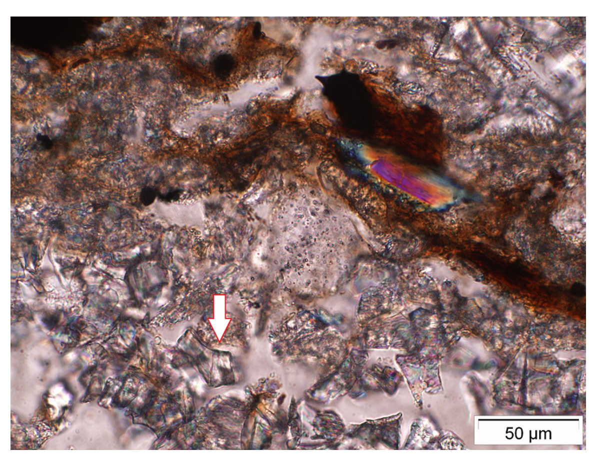

Fig. 4. Gasserplatz-2 383 cm; micrograph of tephra minerals in a thin section (arrow), deposited in a winter lamella.

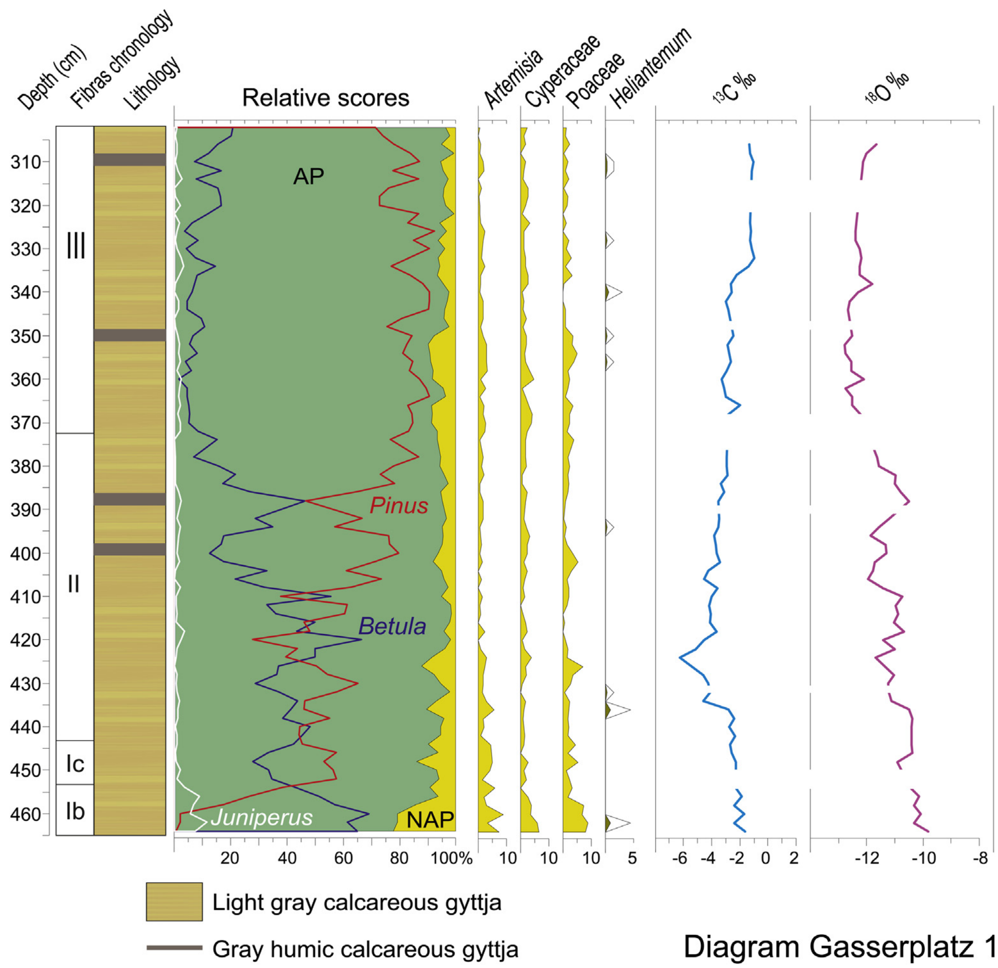

Fig. 5. Gasserplatz records, pollen and isotopes (only relative pollen scores).

Conventional samples (bulk peat and wood) were counted by Proportional Gas Counting after the pretreatment and CO_2 production and purification (Mook and Streurman, 1983). For both the conventional and the AMS laboratory, the background level corresponds to ^{14}C dates of about 50,000 BP. The Radiocarbon dates are calibrated into numerical ages using the latest recommended calibration curve Intcal09 (Reimer et al., 2009).

Stable isotopes are measured by Isotope Ratio Mass Spectrometry. The stable isotopic content of materials is expressed in delta (δ) values, which are defined as the deviation (expressed in per mil) of the rare to abundant isotope ratio from that of a reference material:

$$^{13}\delta = \frac{(^{13}C/^{12}C)_{sample}}{(^{13}C/^{12}C)_{reference}} - 1(\times 1000‰) \quad \text{and}$$

$$^{18}\delta = \frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{reference}} - 1(\times 1000‰)$$

For carbon and oxygen, the reference material is carbonate in the shell of fossil belemnite from the PeeDee Formation (so-called PDB) in the USA. The analytical error is about 0.1‰.

For the $^{13}C/^{18}O$ analyses, the fractions <200 μm are selected from all sediments in order to prevent contamination by e.g. primary carbonates. The selected fraction is converted to CO_2 using 98% H_3PO_4 at room temperature. The CO_2 is trapped and analysed for stable isotopes.

3.4. *Tephra recognition*

Because of the recent discoveries of tephra far beyond the distribution of visible tephra layers by using micro-tephra analysis (Turney et al., 2004; Lane et al., 2012) we decided to investigate the part of the sequence before the clearly defined onset of Younger Dryas for the presence of Laacher See Tephra (LST). According to Riede et al. (2011) the MLST-C2 fallout phase must have reached Vorarlberg. The recognition of LST in the sediment core provides a possibility to acquire a numerical dating point of 12,920 calBP (Riede, 2008). For this purpose, the mineral fraction was extracted from 25 ml samples of the core of profile Gasserplatz-2 of the section 370–390 cm, with a vertical distance of 2 cm. $CaCO_3$ was dissolved in HCl and removed together with the clay fraction, the organic fraction was removed in two steps; the first step was dissolution in H_2O_2, the second step was loss of ignition to 550 Co. Separation of light and heavier minerals was executed in a liquid with a density of 2.45. Tephra minerals were identified using a polarisation microscope (Fig. 3) and tested by application of SEM/EDX microscope (Brucker equipment) in the SAIT laboratory of the Technical University of Cartagena (Spain). Ryolitic glass shards corresponding to LST tephra were recognized in the samples of 383 cm (high concentration) and 381 cm (low concentration) (Figs. 3 and 4). Because the samples were pretreated, no distinct geochemistry could be obtained. However, the shard morphology and especially stratigraphic position supports the identification of LST in the sequence at 383 cm.

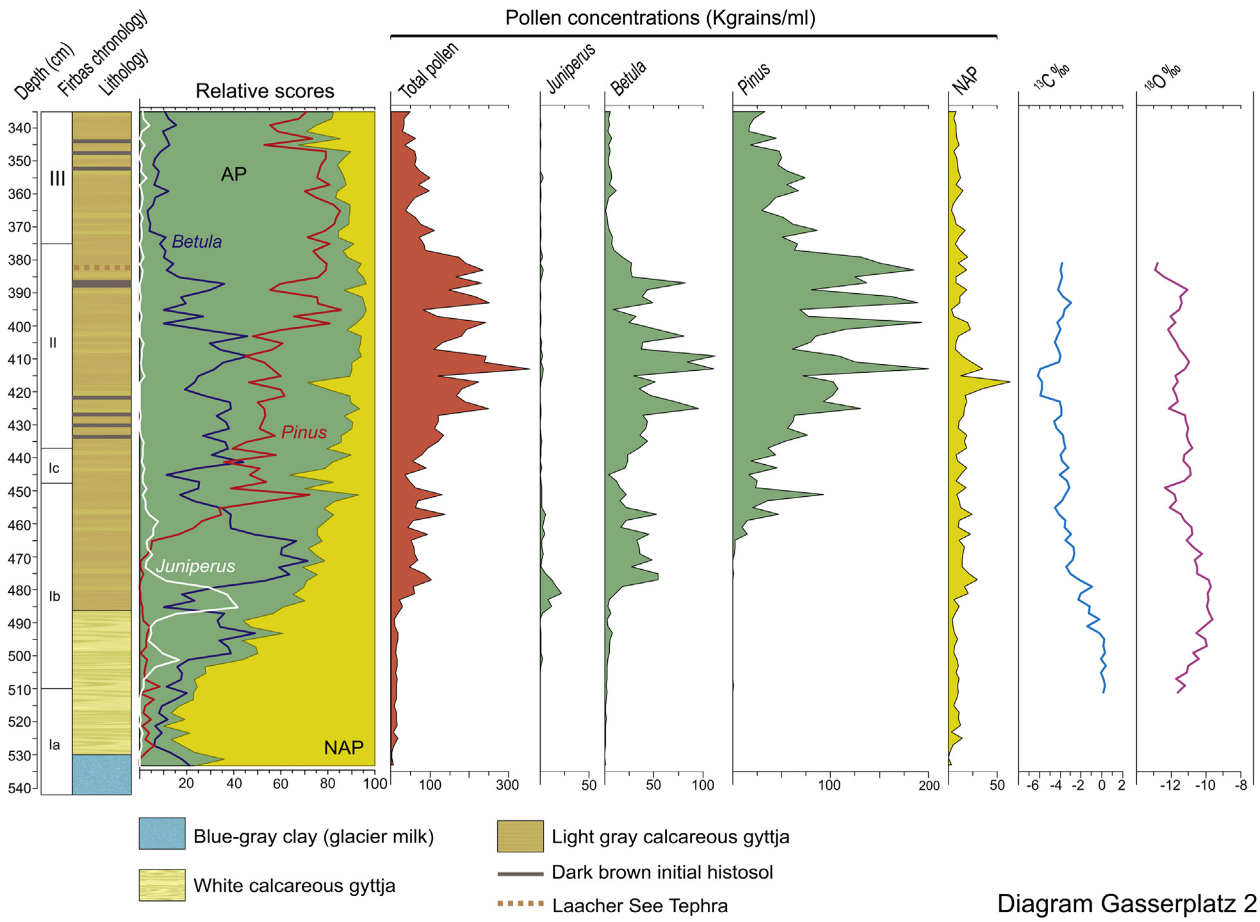

Fig. 6. Gasserplatz records, pollen and isotopes (relative and absolute pollen scores).

3.5. Macro remains analysis

Macro remains ware extracted from 36 samples of ≈20 cm^3, vertical distance 2 cm, of the section 449–520 cm of the core of profile Gasserplatz-2. After sieving, the wet residue was microscopically analyzed on seeds and other plant remains, after drying the same sample was analyzed on molluscs. The aim of the macro remains analysis was firstly to check the similarity with the preliminary results (de Graaff et al., 1989), secondly to substantiate the palynological interpretation that *Betula* arrived not before the middle of the Bølling in the Gasserplatz area. For regular macro remains analysis as applied in archaeology, the volume of the Gasserplatz samples was too small.

4. Results

4.1. Palynology

4.1.1. The Late-glacial chronozones of the Gasserplatz records

The diagrams Gasserplatz-1 (Fig. 5) and Gasserplatz-2 (Fig. 6) of the Late-glacial deposits show similar trends in pollen and isotope fluctuations and distinguish various oscillations during the Late-glacial. The chronozones are well expressed in the palyno and the isotope stratigraphy.

4.1.1.1. Oldest Dryas (GS-2). The sedimentation of white laminated calcareous gyttja on sterile blue-grey clay started in the Oldest Dryas. The pollen concentrations of the white gyttja are very low (<200 grains/ml). In the relative pollen diagrams, the Oldest Dryas is dominated by non-arboreal pollen (mainly *Artemisia*, Cyperaceae, *Helianthemum*, Poaceae). The low pollen concentrations indicate that the pollen precipitation was mainly the result of long distance transport. The biomass production in and around the Gasserplatz lake was very low, considered the relatively high values of the $\delta^{13}C$ curve.

4.1.1.2. Bølling (GI-1e). In the $\delta^{18}O$ curves this interstadial is clearly recognizable as a relatively warm time. The deposition of white gyttja with low pollen concentrations continued till 485 cm. The relative pollen diagrams show a first increase of *Betula* after the beginning of the Bølling, followed by an expansion of *Juniperus*. The pollen concentration curve of *Betula* in Fig. 6 provides additional information. Together with the start of deposition of light grey humic gyttja and decreasing $\delta^{13}C$ values from 485 cm, the pollen concentrations increase drastic. That means that firstly *Juniperus* followed by *Betula* and later by *Pinus*, arrived in the Gasserplatz area and started to contribute to the local pollen production and dispersion. Consequently, the oldest peak in the relative pollen diagrams must be considered as a reflection of a *Betula* expansion on distance; evidently it took time after the deglaciation before firstly *Juniperus*, followed by *Betula* and *Pinus*, arrived at the Gasserplatz site.

4.1.1.3. Older Dryas (GI-1d). The Older Dryas is reflected in the diagrams by a decrease of *Betula* and $\delta^{18}O$ and an expansion of non-arboreal pollen.

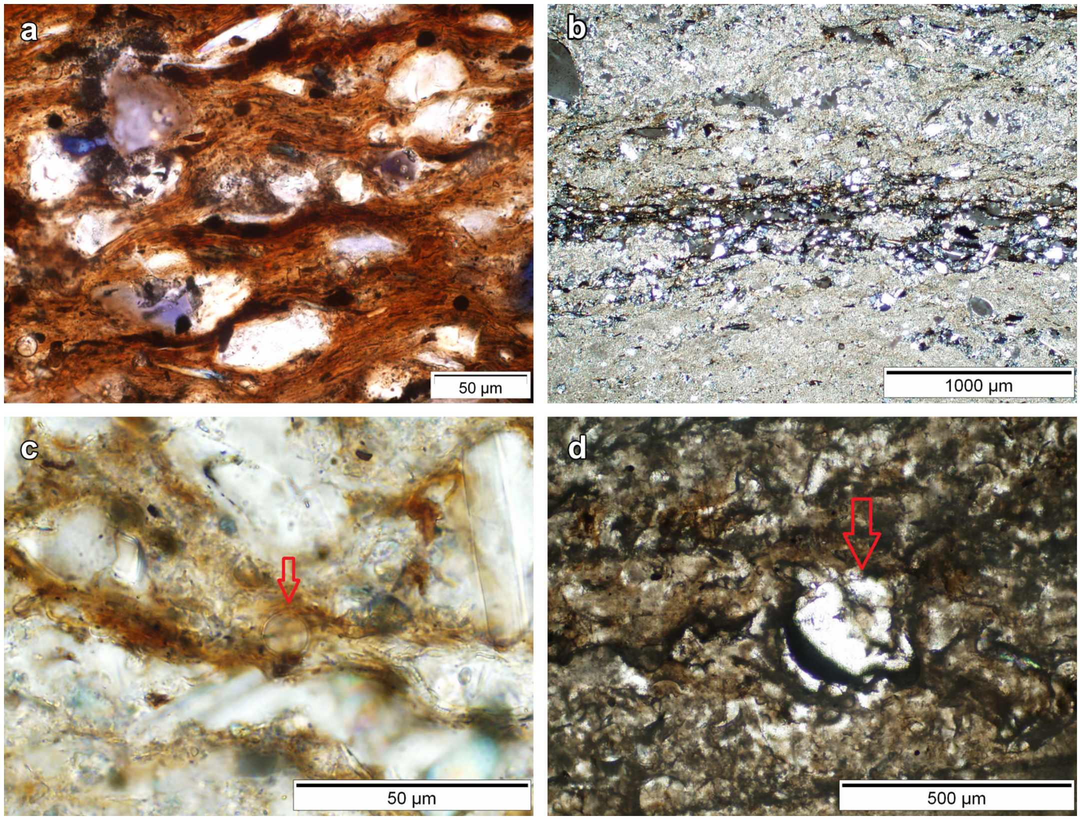

Fig. 7. Micrographs of peat (a), calcareous gyttja (b,c) and mollusk (d), used for radiocarbon dating. The graphs are from thin sections of Gasserplatz-2, the samples for radiocarbon dating are from Gasserplatz-1. a. Gasserplatz-2, 386 cm. Organic matrix of the initial histosols. The $\delta^{13}C$ of the peat is −32.4‰, indicative for a mixture of biomass, produced by underwater plants (as *Chara*) and some plants in contact with the atmosphere (as *Carex*) (The values of the Holocene terrestrial peat are around −28‰). b. Gasserplatz-2, 505 cm. Laminated calcareous gyttja; light colored lamellae are winter deposits, lamellae rich in organic matter summer deposits. The $\delta^{13}C$ of the carbonates used for radiocarbon dating is around −3.1‰. c. Gasserplatz-2, 505 cm. Detail of a humic summer lamella with a pollen grain (arrow). The $\delta^{13}C$ of the organic fraction is −38.00‰, indicative for biomass produced by aquatic plants (*Chara*). d. Gasserplatz-2, 468 cm. Mollusc (arrow) in laminated calcareous gyttja. The $\delta^{13}C$ of a mollusc is around −8.5‰.

4.1.1.4. Allerød (GI-1abc). During the Allerød we can distinguish 3 oscillations in the *Betula* and $\delta^{18}O$ curves, reflecting three periods with expansion and retreat of *Betula* likely as a reaction on temperature change. During these oscillations we observe also a response in the lithology, the deposition of calcareous gyttja is interrupted by the formation of initial histosols. The characterization of such initial soils was based on the $\delta^{13}C$ value of around −32 (Table 1), pointing to a combination of subaqueous and subarial conditions (Fig. 7a,c).

Table 1
Results of Radiocarbon measurements (The laboratory codes for AMS dates is GrA, for conventional dates it is GrN).

Lab code	Sample	Depth	^{14}C age BP	Error (BP)	Calibrated age (calBP)	$\delta^{13}C$ (‰)
GrN-32143	Peat	41	1800	60	1820–1630	−28.1
GrN-32144	Peat	65	3370	35	3690–3490	−27.9
GrN-32145	Peat	99	3780	50	4240–4020	−28.8
GrN-15918	Peat	256	8650	70	9675–9540	−27.6
GrN-15919	Peat	283	9500	200	11,125–10,570	−27.8
GrN-31212	Carbonate	309	11480	100	13,420–13,260	−1.2
GrN-31208	Carbonate	353	11780	180	13,790–13,440	−2.6
GrN-31206	Carbonate	364	11920	110	13,890–13,660	−3.1
GrN-31656	“Peat”	386	11300	100	13,270–13,120	−32.4
GrA-11476	Snails	468	12790	70	15,200–15,090	−8.5
GrA-11479	Carbonate	468	13010	70	15,840–15,240	−3.1
GrN-31210	Carbonate	505	16840	120	19,790–19,450	+1.1

4.1.1.5. Younger Dryas (GS-1). During the Younger Dryas, we can distinguish two phases with a short lived increase of the temperature, separating three colder periods, as recorded in the $\delta^{18}O$ curve and reflected as a slight increase in the *Betula* curve.

4.1.1.6. Reconstruction of the Late-glacial development of Betula forest. Based on fluctuations in the pollen concentrations, it is clear that birch trees did not arrive before the middle of the Bølling in the Gasserplatz area. From this time on the *Betula* fluctuations are records of regional temperature fluctuations. *Betula* is a pioneer species with a high ecological tolerance and few demands to growth place factors like temperature, soil, nutrients, water and solar radiation. The tree is able to survive period with ecological stress.

The pollen diagrams show that during the Allerød three *Betula* maxima alternate with two minima, associated with colder phases. Based on the $\delta^{18}O$ curve, the temperature during these short-lived colder phases is just a fraction higher than the temperature during the Older Dryas (Lotter et al., 2012).

In the Younger Dryas, *Betula* reacted on the temperature fall, but did not disappear from the Gasserplatz area. Also during the Younger Dryas, two *Betula* maxima indicate two short-lived warmer phases. Comparison of the Gasserplatz records with results of similar Alpine lake deposits makes clear that the *Betula* fluctuations are not a local but a regional phenomenon (Bortenschlager, 1984; Lotter et al., 1992, 2012).

4.1.2. Comparison of the Gasserplatz records with other Alpine studies

In Swiss lacustrine sediments, clear Late-glacial climatic fluctuations have been recorded (Lotter et al., 1992, 2012). Based on pollen and oxygen-isotope stratigraphy, the authors distinguish in the Late-glacial oxygen-isotope stratigraphy the main Aegelsee and Gerzensee oscillations. Beside these main shifts, the $\delta^{18}O$ curves show several minor shifts, not expressed in fluctuations in the pollen diagrams. The authors suggest a close relation between temperature shifts as recorded by the oxygen-isotope stratigraphy and adjustment of the vegetation as recorded by palynostratigraphy. In fact, the fluctuations, found in the Swiss lacustrine sediments should be comparable with the fluctuations, recorded in the Gasserplatz deposits. The comparison is complicated by differences in topographical altitude and differences in vertical sample distance but at least the Faulensee diagram, altitude 590 m, shows *Betula* fluctuations in the Allerød chronozone rather similar to the Gasserplatz diagrams. In the Gasserplatz records, the Aegelsee oscillation has the stratigraphic position of the Early Dryas (GI-1d) and the Gerzensee oscillation is recognizable at a similar stratigraphic position (GI-1b) just before the LST deposition. During the Younger Dryas the *Betula* curves show minor fluctuation, most probably the palynological registration of temperature fluctuations.

The Late-glacial climatic oscillations have also been recorded in the lacustrine sediments in the Lansersee, altitude 840 m (Tyrol, Austria, Bortenschlager, 1984). The *Betula* stratigraphy in the Lansersee diagram is rather similar to the Gasserplatz diagrams. The chronology of the published Lansersee diagram is based on radiocarbon dating. However, the radiocarbon ages of calcareous gyttja overestimate the sediment ages due to reservoir effect as established in the Gasserplatz research (see above). After correction of the radiocarbon ages, the Lansersee chronology might be better comparable with the chronology of the Gasserplatz records. The oscillations during the Allerød, three warmer phases separated by two colder phases, are comparable with the Egesen fluctuation (Ivy-Ochs et al., 2008).

Based on the diagrams Faulensee, Gasserplatz and Lansersee we can conclude that the *Betula* expansions during the Allerød and Younger Dryas are not a local but a regional reaction to short-lived temperature fluctuations.

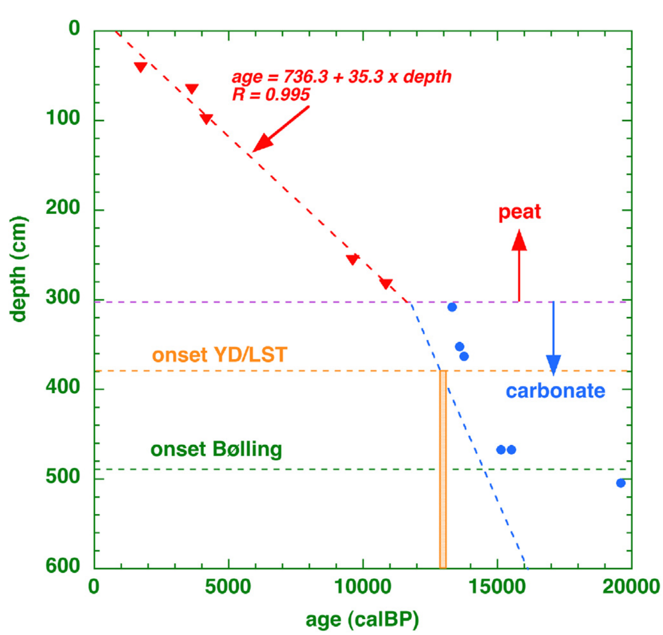

Fig. 8. Gasserplatz records, calibrated ^{14}C dates as a function of depth.

Absolute as well as relative pollen curves of *Betula* react synchronous on the short-lived climatic changes during the Late-glacial, in contrast to *Pinus*, because pine forests may not be as sensitive to climatic changes as a pioneer birch forest. Interspecific competition may lead to a favoring of *Betula* for a short period (Lotter et al., 1992).

4.2. Radiocarbon stratigraphy

Radiocarbon dating of calcareous gyttja is problematic because it easily overestimates ages due to reservoir effects (Mook and Streurman, 1983) which are difficult to quantify. We

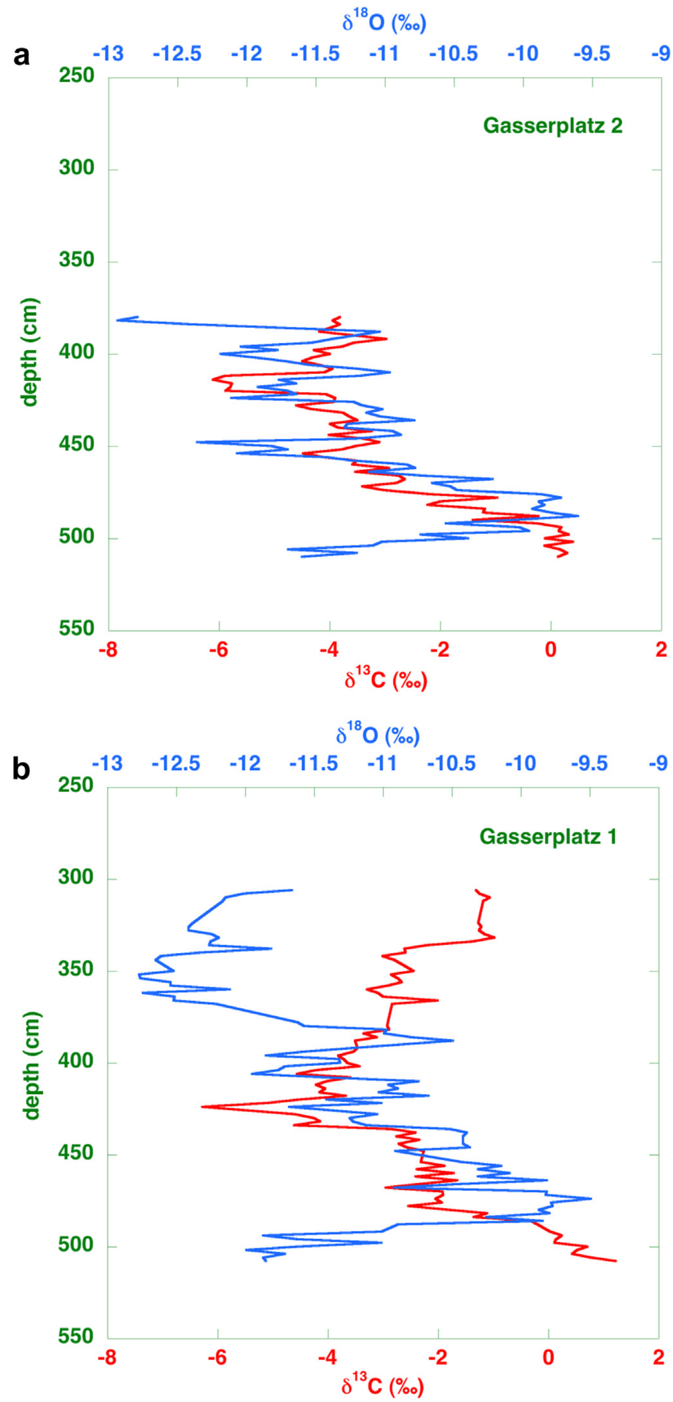

Fig. 9. a. Isotope stratigraphy of Gasserplatz-1. b. Isotope stratigraphy of Gasserplatz-2.

could obtain reliable dates for a few (bulk) peat samples of the Gasserplatz core 2 and in addition we could use two "anchor points" (the onset of the Younger Dryas and the Laacher See Tephra at 380 and 383 cm, respectively) to obtain a reliable chronology.

Various samples of the Gasserplatz core 1, consisting of peaty gyttja (Fig. 7a), calcareous gyttja (Fig. 7b and c) and molluscs (Fig. 7d) were selected for radiocarbon dating. The results are shown in Table 1 and Fig. 8. The table shows the depth, the ^{14}C ages in BP, their corresponding calibrated ages, 1-sigma uncertainties of the measurements, and stable isotope ratios.

The peat sequence (red in Fig. 8) shows a linear relation with time (calibrated ^{14}C dates). The starting time of the peat is at a depth of 306 cm, corresponding to a calibrated age of 11,550 calBP. This point is also the end point of the carbonate set of dates obtained from the gyttja. The timeline for the carbonates can be constructed from this point and the other horizons: the Younger Dryas (onset)/Laacher See Tephra at 380 and 383 cm, respectively, the onset of Bølling (490 cm depth, 14,500 calBP).

The Laacher See Tephra (LST) is located in the sequence at a depth of 383 cm. From the laminated Meerfelder Maar sequence in the Eifel, it appears that LST is deposited some 190 years before the onset of the Younger Dryas (Brauer et al., 1999).

All carbonates (blue (in the web version) in Fig. 8) are subjected to reservoir effects, as can be seen from their deviation from the deposition line. Even a peat sample at 386 cm depth shows a (small) reservoir effect. It has a very negative δ^{13}C value of −32.4‰ because of the submerged plants.

4.3. Stable isotope stratigraphy

For both Gasserplatz series, the stable isotope ratios (δ^{13}C and δ^{18}O) of the carbonate fractions are shown in Fig. 9a,b as a function of depth. They show overlap, and the YD cold reversal is clearly visible. These data lead to the following observations:

In general terms, the organic production (plant growth) determines the δ^{13}C of the carbonate in the system, and thus the size of the reservoir effect for ^{14}C dates. Plants are in isotopic equilibrium with the carbonates. More biological production leads to higher CO_2 concentration and consequently a more negative δ^{13}C for submerged plants and carbonates. For example, for the sample at a depth of 422 cm, the δ^{13}C for the organic material was −38‰, and for the carbonate −6‰.

There is a clear relationship between δ^{13}C and δ^{18}O (Fig. 9). Lower temperatures (lower δ^{18}O values) correlate with more negative δ^{13}C values, related to higher water levels in the system caused by more rain- and groundwater input. In contrast, the warmer periods mean less water input, a lower water level and evaporation, yielding more positive δ^{13}C and δ^{18}O values. During the cold period before 16,000 there is no biological activity in the system, which is consistent with higher reservoir effects as observed (Fig. 8).

The oxygen isotope stratigraphy shown in Fig. 9b is consistent with the one shown in Fig. 9a. The climate proxy signals show a similar trend in both cores. Together with the ^{14}C derived deposition plot, the stratigraphic framework of the stable isotopes is used to support the chronology of the Late-glacial section of the Gasserplatz records. This approach has been used successfully at other locations (Von Grafenstein et al., 1999; Schwander et al., 2000; Hoek and Bohncke, 2001; Lotter et al., 2012).

4.4. Macro remains analysis

4.4.1. The Gasserplatz record in overview

4.4.1.1. Plants. In preliminary research of the Gasserplatz records (de Graaff et al., 1989) it was demonstrated that in Late-glacial

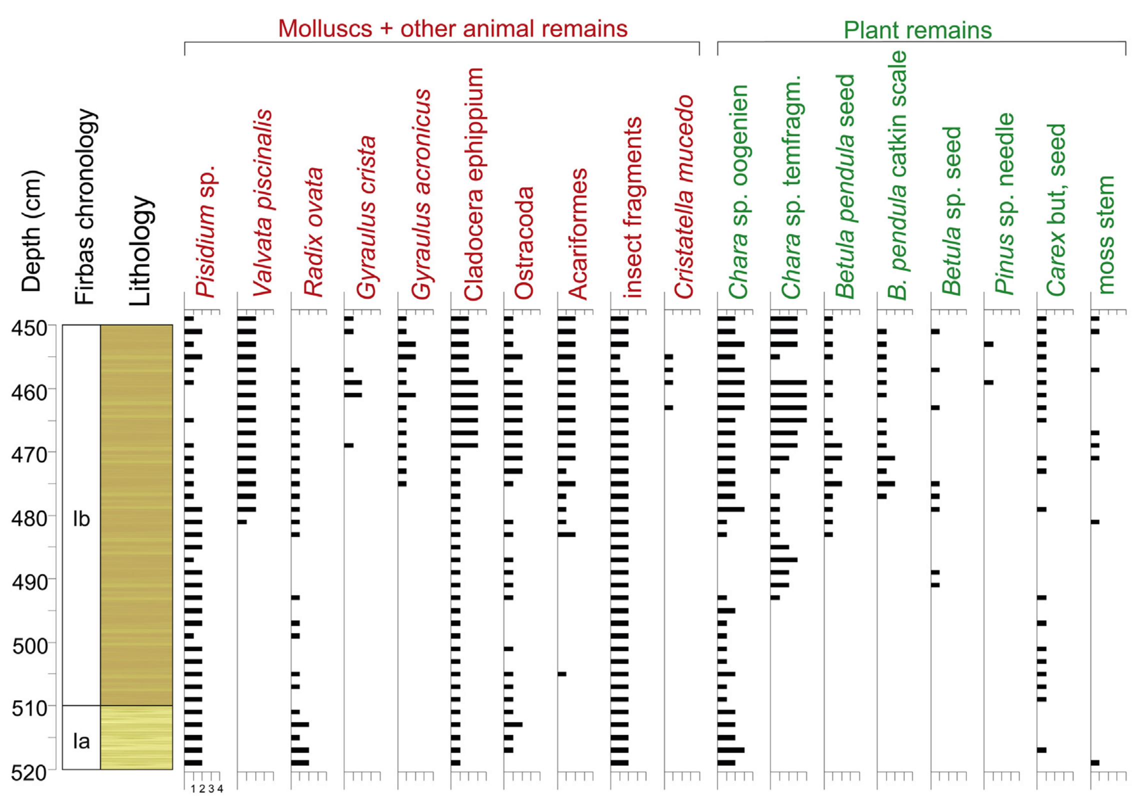

Fig. 10. Gasserplatz records, macro remains in Gasserplatz-2 between 510 and 460 cm depth (Horizontal scale: 1 = 1–9 true observations, 2 = 10–99 observations, 3 = 100–1000 estimated observations 4 = >1000 estimated observations).

calcareous gyttja deposits oospores and stem fragments of stonewort species (*Chara* sp.) occur frequently. This suggests that immediately after the clay sedimentation at the base of the record (at ≈547 cm depth) the lake was free of an ice cover during summer (in Oldest Dryas). Plants that have a preference for marshy areas are under-represented. Of the surrounding higher areas the remains of *Betula* (fruits, catkin scales) and *Pinus* (seeds, needles, bark) were blown or washed into the lake. Remarkable is the very low number of identified species. The sediment of Bølling age yielded some remains of *Betula* and *Pinus*. A continuous representation of these two species was found in the sediments above a depth of 430 cm; firstly appears *Betula*, 15 cm higher in the sediments followed by *Pinus*. It is plausible that the vegetation with these two taxa has established it selves in the area around the lake. Pollen of these two taxa dominated the pollen influx in the lake.

4.4.1.2. Molluscs. Directly after the clay deposition there are shells of some freshwater molluscs present. This is around 547 cm depth and goes right on with the sedimentation of the calcareous gyttja. The animals were living in a *Chara* vegetation. Shortly after the arrival of the first species (*Pisidium* sp. and *Radix ovata*) some others complemented the fauna. Due to the extreme environment, the fauna stays however poor during the whole Late-glacial (max. 5 *Pisidium*, 1 *Sphaerium* and 7 gastropod species). Changes in numbers of fossils and numbers of species are difficult to relate to climate or environmental change. The fauna is a characteristic one of a cold period. In the Allerød deposits from 440 to 350 cm there is a clear increase of species and individuals.

4.4.2. The macro remains of profile Gasserplatz-2 (Fig. 10)

4.4.2.1. Plants. Except for the oospores of the stoneworts, the lower part (490–520 cm) contained extremely few plant remains. The aquatic vegetation is comparable with the preliminary results (de Graaff et al., 1989): large numbers of oospores and fragments of the stem of stonewort species (*Chara* sp.). *Carex* has probably grown on the marshy bank. The vegetation on the higher area around the lake consisted mainly of *Betula* and *Pinus*. Their remains are mainly found in the upper part of the investigated part of the core. From 490 cm depth onwards Betula is present, above 460 *Pinus* appears with 5 remains. These observations fit with the increase of pollen of these plants in the absolute pollen diagram.

4.4.2.2. Molluscs. The sediments yielded the same species as in the preliminary study. The freshwater fauna concerns *Pisidium* species, *Valvatapiscinalis*, *R. ovata* (syn. *Radix balthica*), *Gyraulus crista* (syn. *Armiger crista*) and *Gyraulusacronicus*. In the lower part shells of *Pisidium* sp. and *R. ovata*, and only one *Valvatapiscinalis* are present. A very poor fauna, in the upper part supplemented with the two *Gyraulus* species (Fig. 10).

4.4.2.3. Reconstruction of the development of vegetation and aquatic fauna. During the deposition of the gyttja stonewort vegetation (*Chara* species) was present. Other aquatic plants are very rare.

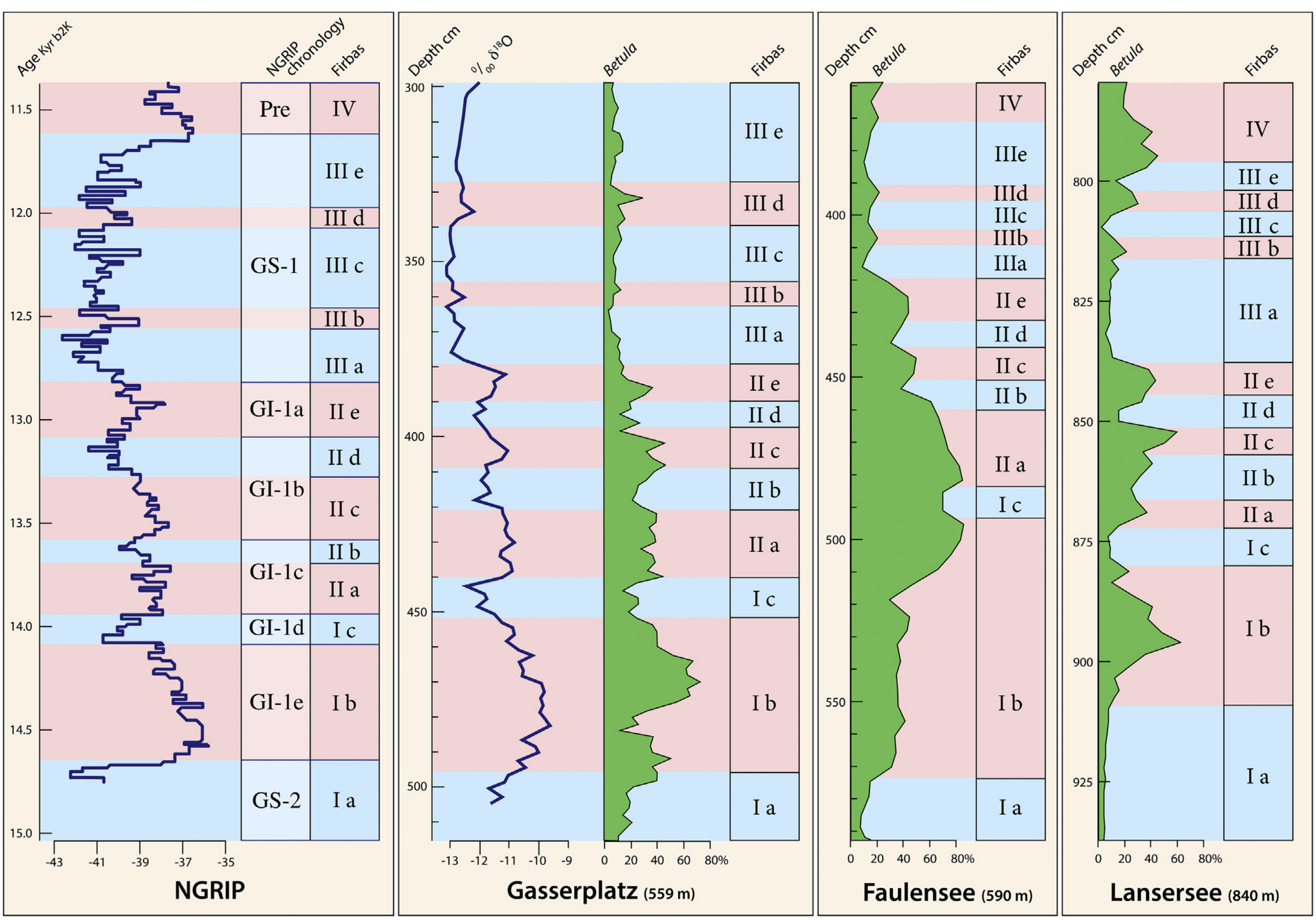

Fig. 11. Comparison of the *Betula* fluctuations of Gasserplatz, Faulensee and Lansersee calcareous gyttja deposits with the Late-glacial oxygen isotope stratigraphy of Gasserplatz and NGRIP.

Land plants are represented by only a few species. Along the banks a zone with sedges (*Carex* sp.) is supposed to be present. In the lowest part of the profile the remains of land plants are very scarce. Higher up there is a clear increase of birch (*Betula* sp.), followed by pine (*Pinus* sp.).

A similar behavior is observed in the mollusc population. The *Pisidium* species, *Valvatapiscinalis*, *R. ovata*, *Gyraulus crista* and *Gyraulusacronicus* characterize the fauna; they lived between the vegetation of *Chara*. The fauna is poor, but characteristic for this kind of calcareous freshwater lakes in the Late-glacial in this part of Europe. Besides the shells of mollusks we found many ephippia of water flies (*Cladocera*), ostracods (*Ostracoda*), mites (*Acariformes*), insect fragments and some statoblasts of the moss animal *Cristatellamucedo*. All these organisms inhabited the same environment as the mollusks. During the Late-glacial the lake was filled with clear, standing, calcareous water. The continuous precipitation of carbonates during the Late-glacial indicates a continuous water input, most probably a mixture of fluvial and groundwater.

5. Discussion

Late-glacial global temperature oscillations have been recorded in the lake carbonate deposits of Gasserplatz cores as shown by pollen and isotope stratigraphy (Fig. 11). Relative dating of the sediments, based on pollen diagrams, is not very reliable and radiocarbon dates are not very useful because they overestimate significantly the age of calcareous sediments, due to the reservoir effects of the lake environment. The only reliable chronological marker was the sediment layer with a high concentration of LST minerals.

A robust geochronology for the Late-glacial could be established, based on the oxygen isotope stratigraphy. Because of the correlation between the *Betula* extensions and the warmer phases of the oxygen isotope curves, it is clear that the behavior of *Betula* is a response on temperature changes.

The environmental fluctuations were optimal reflected in the *Betula* pollen curves. This tree did not arrive in the Gasserplatz area before the middle of the Bølling (GI-1e). This is confirmed by the results of macro remains analysis, showing that during the whole Late-glacial period stonewort species were present but macro remains from *Betula* were found from the middle of the Bølling. *Betula* is a pioneer species with a high ecological tolerance and able to survive period with ecological stress.

During the Allerød, three *Betula* maxima alternate with two minima, associated with colder phases, recognized in other studies of similar Alpine lake deposits and in Greenland ice cores. In the Younger Dryas, *Betula* reacted on the temperature fall, but did not disappear from the Gasserplatz area.

The combined results of pollen analysis, isotope stratigraphy and macro remains analysis improve the knowledge of the Late-glacial environmental oscillations in the Alpine region. In Fig. 11 the chronology of these oscillations as found in the Gasserplatz records and recognized in the Faulensee (Lotter et al., 1992) and Lansersee (Bortenschlager, 1984) deposits is linked with the NGRIP stratigraphy (Lowe et al., 2008).

6. Conclusions

- The pollen diagrams of the Late-glacial lake deposits of Gasserplatz show *Betula* oscillations.
- Due to reservoir effect, radiocarbon dating cannot be used to establish the geochronology of these oscillations.
- The oxygen isotope chronology of these sediments correlates with the Betula oscillations and with the oxygen isotope stratigraphy of the Greenland ice cores.
- Similar *Betula* oscillations are also found in pollen diagrams of Late-glacial lake sediments in Lansersee and Gersensee, showing that these fluctuations are not a local but a regional phenomenon.

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