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Subdecadal-scale vegetation responses to a previously unknown late-Allerød climate fluctuation and Younger Dryas cooling at Lake Meerfelder Maar (Germany)

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ABSTRACT: Lake Meerfelder Maar (MFM) is the northernmost Western European sediment record with annual laminations across the Younger Dryas (YD), and the onset of the YD in the record of MFM has previously been defined as an increase in non-arboreal pollen abundance at ca. 12 680 varve a BP. Here we present a palynological record at unprecedented subdecadal resolution for MFM, covering the Allerød–YD transition. Our results show a fluctuation in pollen accumulation rates (PARs) before the onset of the YD, with lower rates between ca. 12 725 and 12 685 varve a BP. The fluctuation in PARs occurs simultaneous with a previously undescribed short fluctuation in sediment composition and varve thickness, as well as with changes in biogeochemical proxies. The combined evidence indicates signs of climatic instability ca. 45 years before the onset of the YD. The PAR records of *Betula* and *Pinus* furthermore show earlier and more abrupt changes at the onset of the YD than the percentage-records do. Finally, heliophilous herbaceous taxa show a delayed increase following the onset of the YD of ca. 145 years. This paper illustrates the potential to identify previously unrecognized climate variability and vegetation change when using subdecadal-resolution analyses. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: climate instability; Lateglacial; Meerfelder Maar; pollen accumulation rates; vegetation change.

Introduction

The onset of the Younger Dryas (YD) represents the last major cold period in the circum-Atlantic region (e.g. Goślar *et al.*, 1995; Björck *et al.*, 1996; Rasmussen *et al.*, 2006) and led to large-scale environmental changes on the European continent (e.g. Isarin *et al.*, 1998; Brauer *et al.*, 2008). Chironomid-based estimates of July air temperatures at the transition from the Allerød to the YD indicate a decrease of 3–4 °C for Western Europe (Heiri *et al.*, 2007; van Asch *et al.*, 2012; Brooks and Langdon, 2014), while other studies suggest that the onset of the YD was mainly characterized by a decrease in winter season temperatures (Lücke and Brauer, 2004; Denton *et al.*, 2005). In Greenland, the onset of Greenland Stadial-1 shows a centennial-scale decrease in $\delta^{18}O$ and the deuterium-excess record of the NGRIP ice core indicates an abrupt reorganization of the Arctic atmospheric circulation at this transition (Steffensen *et al.*, 2008).

Lake Meerfelder Maar (MFM), located in central-Western Europe (50°6′N, 6°45′E), is the northernmost Western European sediment record with annual laminations across the YD. The onset of the YD is defined by an increase in non-arboreal pollen (NAP) percentages and concurrent decreases in the abundance of *Betula* and *Pinus* pollen (Litt and Stebich, 1999; Litt *et al.*, 2003). The onset of the YD in the MFM records has been placed at the point of strongest change of NAP percentages between two adjacent pollen samples at 12 680 varve a BP (Litt and Stebich, 1999). An abrupt shift in micro-facies also occurred at ca. 12 680

varve a BP. This major lithological change (Brauer *et al.*, 1999; Lücke and Brauer, 2004) coincided with the onset of the YD as observed in the palynological record, given the 30- to 40-year sampling resolution used by Brauer *et al.* (1999), Litt and Stebich (1999) and Lücke and Brauer (2004). The onset of the YD furthermore coincided with an abrupt and strong increase in varve thickness in the MFM record, interpreted to have resulted from a decrease in water depth as well as an increase in winter wind strength (Brauer *et al.*, 2008).

Rach *et al.* (2014) studied the hydrogen isotope values (δD) of lipid biomarkers extracted from the sediments of MFM to reconstruct palaeohydrological changes. They show that a stepwise decrease in biomarker δD values already started at 12 850 varve a BP, ca. 170 years before the onset of the YD as defined by biostratigraphy. The results of Rach *et al.* (2014) indicate that climate change across the Allerød/YD transition in Western Europe does not represent a simple shift in temperatures but that it is composed of a complex succession of climatic and ecosystem changes, including shifts in temperature and evapotranspiration, as well as in precipitation and wind regimes. The most prominent of these shifts was the one at ca. 12 680 varve a BP, which coincides with the onset of the YD as defined by the increase in NAP percentages and the change in micro-facies in the MFM record. These climatic changes probably had a range of different impacts on the physical environment and the vegetation, and therefore on the pollen assemblages.

Palynological records with a subdecadal to decadal resolution can reveal complex and dynamic changes in pollen percentage assemblages and pollen accumulation rates (PARs) in response to abrupt changes in environmental

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conditions during the Lateglacial (e.g. Ralska-Jasiewiczowa et al., 2003; Ammann et al., 2013). Lotter et al. (1992) identified the occurrence of two centennial-scale climate oscillations in the Swiss Alps during the Bølling/Allerød interstadial, termed the Aegelsee fluctuation during the earlier part of the interstadial and the Gerzensee fluctuation towards the end of the Allerød. The Aegelsee fluctuation was expressed as a change in both oxygen-isotope ratios as well as in the palynological records (as an increase in NAP), whereas the Gerzensee fluctuation could initially only be observed in the oxygen-isotope data presented by Lotter et al. (1992). Ammann et al. (2000) applied high-resolution multi-proxy analyses (including stable isotope and pollen analysis) to the Lateglacial record of Lake Gerzensee. Their results showed that although palynological evidence of a vegetational response to the minor climatic change associated with the Gerzensee fluctuation is not conspicuous, there is a statistically significant change in the palynological record just after the onset of the isotopic oscillation corresponding to the Gerzensee oscillation (Ammann et al., 2000). Furthermore, the chironomid and cladocera records presented by Ammann et al. (2000) also show variation around the isotopic oscillation associated with the Gerzensee oscillation. Ammann et al. (2013) re-analysed the Lateglacial record of Lake Gerzensee (Switzerland), previously studied by Lotter et al. (1992) and Ammann et al. (2000). Ammann et al. (2013) used a subdecadal-scale sampling resolution and their new palynological results provided more detail of the sequence of events during the climate transitions into and out of the YD, especially when focusing on the response time of vegetation to changes in climate.

Litt and Stebich (1999), Litt et al. (2003) and Brauer et al. (1999) describe a decadal-scale palynological record for the Lateglacial period of MFM. However, the relatively low sedimentation rate of 0.2–0.3 mm a^{-1} in the late Allerød (when compared to the sedimentation rates during the YD) and the 1-cm-thick samples investigated by Litt and Stebich (1999) resulted in a ∼30- to 40- year sampling resolution in the late Allerød, preventing the detection of decadal-scale fluctuations in vegetation.

Here we present the first palynological record for MFM with a subdecadal resolution covering the Allerød–YD transition with a particular focus on the last 400 years before this major environmental shift. Our increased sampling resolution allows the detection of short-term variability, even during the late Allerød, which in the MFM record is characterized by a relatively low sedimentation rate. The main research aim of the present study is to improve on the current paradigm that the vegetation shift at the Allerød–YD transition occurred as a simple shift in the arboreal pollen (AP)/NAP ratio by analysing the well-dated sequence of MFM in more detail. We will compare changes in vegetation to lithological (Brauer et al., 1999, 2008), high-resolution element composition (this study) and biogeochemical (Rach et al., 2014) shifts in the MFM sediment record.

Materials and methods

Sediment record and chronology

We analysed sediment cores that were retrieved from the deepest part of MFM using a UWITEC piston corer during fieldwork in 2009 (Martín-Puertas et al., 2012; Rach et al., 2014). Core sequences MFM09-A and -D were combined to form the MFM09 composite profile (Martín-Puertas et al., 2012; Rach et al., 2014), which has been matched with the older MFM-6 composite profile using microscopically defined

marker layers. The MFM chronology is based on varve counting and varve thickness measurements on 10-cm-long thin sections of the MFM-6 profile using a petrographic microscope (Brauer et al., 1999; Lane et al., 2015).

The varve chronology for the interval above the Laacher See Tephra (LST) is identical to the previously published one (Brauer et al., 1999), while for the part below the LST a revised version has been established (MFM-2015 chronology; Lane et al., 2015), which, however, in the interval shown here does not differ from the previous MFM-6 chronology (Brauer et al., 1999). The chronological anchor point is the LST dated at 12 880 ± 40 varve a BP, which is within uncertainties in agreement with the modelled age estimate of 12 937 ± 23 cal a BP of Bronk Ramsey et al. (2015). All ages in this paper are given as numbers that are rounded to the nearest multitude of 5. The uncertainty of ± 40 varve years is not repeated every time for better readability.

Palynological analysis

We significantly increased the sampling resolution compared to previous pollen analyses of Lateglacial sediments from MFM (Litt and Stebich, 1999), using 3-mm-thick samples for the late Allerød interval, and 5-mm-thick samples for the early YD. Supporting Information Table S1 provides details of the obtained samples and their ages. The difference in sampling resolution within our record follows the increase in varve thickness at the onset of the YD. We analysed 94 samples across the Allerød–YD transition interval (ca. 13 060–12 480 varve a BP) with a subdecadal sampling resolution for 80% of our palynological samples. The samples were obtained by first pressing transparent L-shaped containers into an opened core-half (cores MFM09-D4 and −A5, where the 5-cm-thick LST deposit was used as the boundary) in the laboratory. Marker layers were indicated on the container and pins were used to demark 1-cm intervals before sampling the L-shaped container using standard laboratory equipment (knives, forceps). Samples were immediately transferred to glass vials for processing and prepared following the techniques described in Faegri and Iversen (1989) and Moore et al. (1991). The samples were first boiled in KOH (10%) and subsequently in HCl (10%) and sieved over a 212-μm mesh. After washing and centrifuging, the samples were dehydrated using 96% acetic acid and subsequently treated with an acetolysis mixture for 10 min. After cooling, the samples were washed repetitively, and organic material was separated from the clastic material by heavy liquid separation using a bromoform–alcohol mixture. Routine checks of the heavy fraction did not reveal any selective loss of pollen during the separation process. A Lycopodium tablet was added to the samples to enable the calculation of pollen concentrations and PARs (Stockmarr, 1971). A pollen-percentage diagram (Fig. 1) was calculated using a pollen sum ($n_{average} = 290$) that included pollen of trees, shrubs and upland herbs, and the diagram was plotted using TILIA v 1.7.16 (Grimm, 2004). A pollen diagram with per cent abundances plotted against core depth is provided in the Fig. S1; a diagram showing pollen concentrations against varve age is provided in Fig. S2.

PARs were calculated for each pollen taxon by first multiplying the number of encountered pollen by the ratio of the number of added Lycopodium spores and the number of spores encountered during analysis. This number was then divided by the known surface of each sample (3.6 cm^2 for the samples below the LST, and 5.0 cm^2 for the samples above the LST) and the number of varves included in each sample (range: 5–13 varves per sample; Table S1). A PAR diagram (Fig. 2)
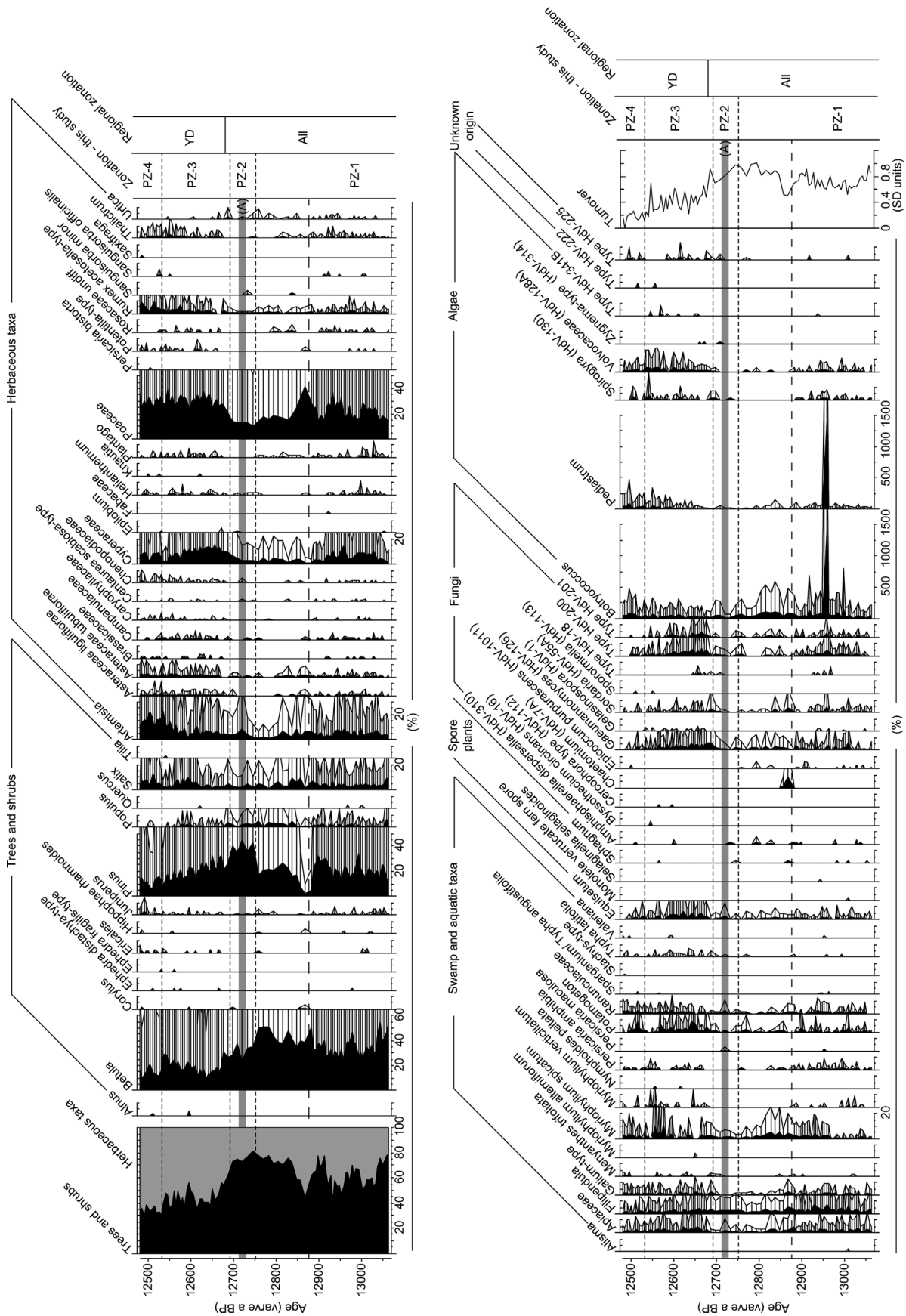
Figure 1. Pollen percentage diagram for the Late Allerød–early Younger Dryas transition at Lake Meerfelder Maar. The samples are expressed as percentages of the total pollen sum, which includes pollen from trees, shrubs, Ericales and upland herbs and are plotted on a varve age scale (varve a BP). The graph entitled 'Turnover' shows the estimated compositional turnover (β diversity) expressed as standard deviation (SD) units (cf. Birks and Birks, 2008; see text). The dashed line at 12 880 varve a BP marks the presence of the 6-cm-thick Laacher See Tephra (LST). The grey band marked '(A)' indicates the time interval of the formation of calcite-diatom varves (see text and Fig. 5). Pollen zones (PZ-x) show the statistically significant pollen zones calculated using the data presented in this study. The regional zonation with the horizontal line at 12 679 varve a BP marks the onset of the YD as defined by Litt and Stebich (1999).
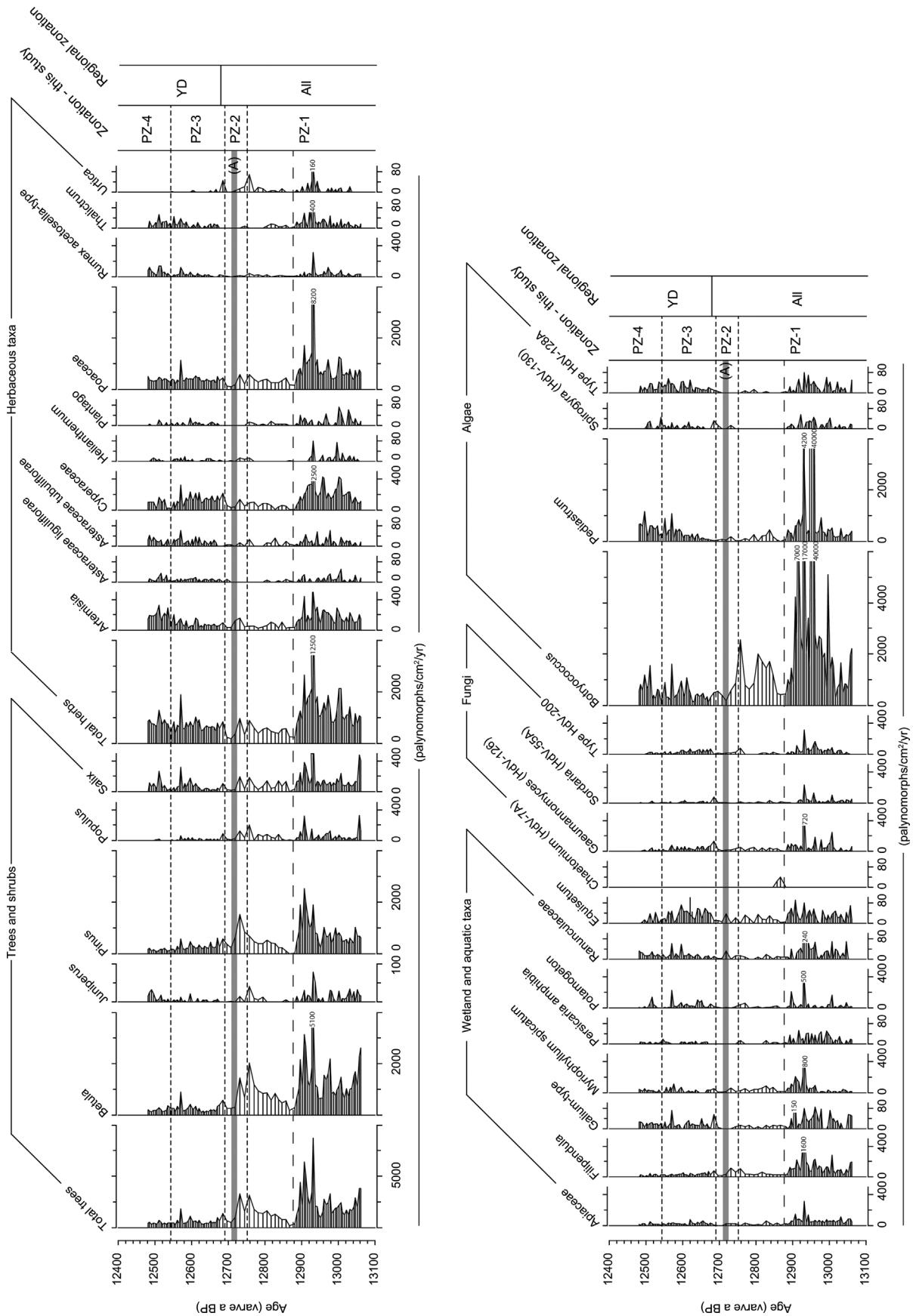
Figure 2. Pollen accumulation rate (PAR) diagram for the Late Allerød–Younger Dryas transition at Meerfelder Maar on a varve age scale (varve a BP). Selected taxa are shown in palynomorphs cm^{-2} a^{-1}. Note the different x-scales used in the diagram. Zonation is based on the percentage diagram: see Fig. 1 and text for more information.

showing the number of palynomorphs cm^{-2} a^{-1} was constructed in C2 (Juggins, 2003).

Numerical analysis

Zonation of the pollen diagram was carried out using the constrained hierarchical clustering method (Grimm, 1987) as included in the rioja-library (Juggins, 2015) in the R environment. We used the percentage abundance data set in our analysis, only including the taxa that are included in the pollen sum. We used a broken stick model (Bennett, 1996) to assess the significant number of zones, and we plot our results alongside the regional zonation for the Eifel as published by Litt and Stebich (1999).

We estimated the amount of palynological compositional change ('turnover') following the methods presented by Birks and Birks (2008). We ran a detrended canonical correspondence analysis (DCCA) using sample age as the only constraining variable on the square-root-transformed percentage data of all the taxa included in the pollen sum, without down-weighting of rare taxa, with detrending by segments and with non-linear scaling using CANOCO v4.56 (ter Braak and Šmilauer, 2002) to obtain results that are comparable to those presented in Birks and Birks (2008). The sample scores [scaled in standard deviation (SD) units of compositional change or turnover with time] are interpreted to represent the beta-diversity or between-habitat diversity (Birks, 2007; Odgaard, 2007; Birks and Birks, 2008). We repeated our analysis with a palynological datasheet where we obtained equally spaced time intervals (of 10 varve years) by linearly interpolating the pollen percentage data. As the results of this time-standardized analysis are very similar to the results obtained on the unstandardized dataset, we only present the latter in Fig. 1.

Elemental analysis

The element composition of the sediments was analysed non-destructively every 0.2 mm on the composite profile MFM-09 using an ITRAX X-ray fluorescence (XRF) core scanner at GFZ-Potsdam, Germany. The XRF core scanner irradiated the split core surface with an Mo X-ray source during 20 s, operated at 30 kV and 40 mA, generating energy dispersive fluorescence radiation. The element intensities of Si, K, Ca, Ti, Mn, Fe, Ni, Rb, Sr and Zr as well as relative variations of the coherent and incoherent radiation were acquired non-destructively. The acquired chemical composition of the sediment is expressed as element intensities (counts per second, cps).

Results

Palynological analysis

Four statistically significant pollen zones have been identified in our percentage abundance data (Fig. 1). The pollen spectra of zone PZ-1 (ca. 13 060–12 750 varve a BP) were dominated by *Betula* and *Pinus*. The increase of *Pinus* from values of ca. 20% during PZ-1 to values over 40% probably indicates the local expansion of pine during PZ-2 (ca. 12 750–12 690 varve a BP). The late Allerød vegetation (PZ-1 and −2) around MFM therefore probably consisted of birch–pine woodlands (Fig. 1). Relatively low percentage abundances of heliophilous herbs such as *Artemisia* indicate that some open habitats were present in a predominantly forested landscape (Litt and Stebich, 1999). Our new high-resolution pollen data show clear evidence for the effects of the Laacher See Eruption (LSE) (12 880 varve a BP) on the local vegetation.

The birch–pine woodlands surrounding MFM underwent a reorganization of the vegetation following the LSE as pine temporarily disappeared from the region. A rapid succession of grassland to birch to birch–pine woodlands took place in the first 150 varve years after the LSE. A detailed analysis of the effects of the LSE on the vegetation around MFM and beyond is presented in Engels *et al.* (2015). For a more detailed description of the general vegetation development during the Allerød/YD period in the Eifel region we refer to Litt and Stebich (1999). Below, we focus on previously unrecognized features of vegetation change visible in our high-resolution record.

A major decrease in the AP/NAP ratio from 46 to 27% occurs between 12 695 and 12 675 varve a BP (Figs 1 and 3), reflecting the transition from the late Allerød to the YD. Our numerical analysis places the zone boundary (PZ-2 to PZ-3) that marks the onset of the YD in our new high-resolution record at 12 690 varve a BP. This is a decade earlier than the published onset of the YD by Litt and Stebich (1999) and this difference is probably the result of different sampling resolution. We comply with the published date for the definition of the onset of the YD because the age difference of only 10 years falls within the dating uncertainty, and we use the conventional date of 12 680 varve a BP (Litt and Stebich, 1999) for the definition of the onset of the YD in the remainder of this paper.

High percentage abundances of, for example, Poaceae, Cyperaceae and *Equisetum* are characteristic for PZ-3 (ca. 12 690–12 545 varve a BP). The final transition that can be seen in our percentage record is observed at the onset of PZ-4 (12 545–12 480 varve a BP), which is characterized by an increase in abundances of *Artemisia* and *Rumex acetosella*-type and a decrease in pollen of *Betula*.

A DCCA with sample age as the sole constraining variable indicates that there is almost no compositional turnover visible during the late Allerød interval of our record. The exception is formed by a decrease of 0.4 SD units around the time of the LSE (Fig. 1), which is followed by an increase to pre-disturbance values within a few decades. A second decrease in turnover can be seen at the Allerød–YD transition, after which the compositional turnover shows a nearly linear change throughout the remainder of our record.

PARs of the most abundant taxa (Fig. 2) show a distinct decline that already starts between ca. 12 730 and 12 720 varve a BP, several decades before the onset of the YD (12 680 varve a BP). The total PAR of herbaceous taxa decreases from 500 to 1000 pollen cm^{-2} a^{-1} before ca. 12 725 varve a BP, to a minimum of ~175 pollen cm^{-2} a^{-1} at 12 710 varve a BP, and recovers to pre-disturbance values by ca. 12 685 varve a BP. This trend can be observed for the curves of most of the individual herbaceous taxa as well (e.g. Cyperaceae, Poaceae), but there are a few herbaceous taxa that show more or less stable PAR values throughout the interval 12 800–12 685 varve a BP (e.g. Asteraceae tubuliflorae). *Artemisia* and Apiaceae show a decrease in PAR that starts ca. 15 varve years later than the general decrease in PAR as observed for most of the herbaceous taxa. Figure S2 shows the concentrations of the same taxa that are presented in Fig. 2 and shows a decrease in pollen concentrations that also occurs between ca. 12 730 and 12 720 varve a BP and a recovery by ca. 12 685 varve a BP for most but not all taxa.

Betula and *Pinus* PARs also decrease at ca. 12 725 varve a BP, but they do not show a recovery similar to the herbaceous taxa. *Betula* shows a decrease from 1000 to 2000 pollen cm^{-2} a^{-1}, before ca. 12 725 varve a BP, to 250–400 pollen cm^{-2} a^{-1} between ca. 12 720 and 12 670 varve a BP, and a second decrease to values of 90–250 pollen cm^{-2} a^{-1} at ca.
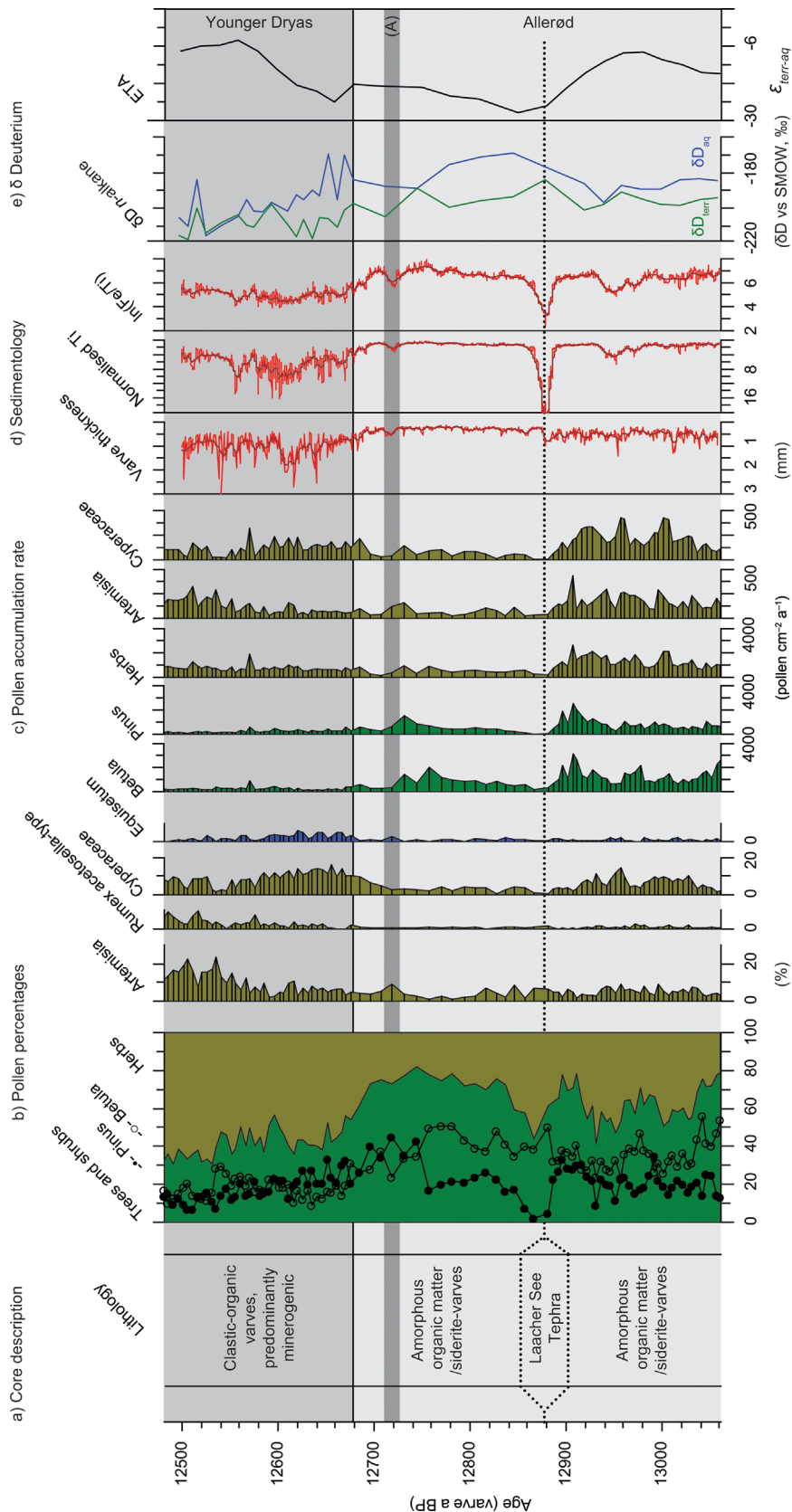
Figure 3. The Allerød–YD transition in Meerfelder Maar: (a) core description; (b) main pollen diagram and selected percentage abundance curves of arboreal taxa (dark green), non-arboreal taxa (beige) and *Equisetum* (blue) (%); (c) PAR values of selected taxa (pollen cm^{-2} a^{-1}) (the sample at 12 932 varve a BP has been removed for plotting purposes as it showed extreme values, probably because of laboratory issues); (d) varve thickness (mm) record (Brauer *et al.*, 2008), normalized titanium (Ti) variability and element ratio *ln*(Fe/Ti) determined using a μ-XRF core scanner, all with a LOESS smoother; (e) hydrogen isotope measurements (expressed as δD) on compound-specific lipid biomarkers − the blue line shows measurements on the *n*C$_{23}$ alkane probably derived from aquatic plants (δD$_{aq}$), while the green line shows δD values of the *n*C$_{29}$ alkane derived from higher terrestrial plants (δD$_{terr}$; Rach *et al.*, 2014). ε$_{terr-aq}$ is the difference between δD$_{terr}$ and δD$_{aq}$ and interpreted to reflect terrestrial evapotranspiration (ETA; Rach *et al.*, 2014). The grey shading indicates the classical biostratigraphical zonation of Litt and Stebich (1999) based on the decrease in NAP and the change in lithology at 12 679 varve a BP (Brauer *et al.*, 2008), and the dark band marked '(A)' indicates the time interval of the formation of calcite-diatom varves (see text and Fig. 5).
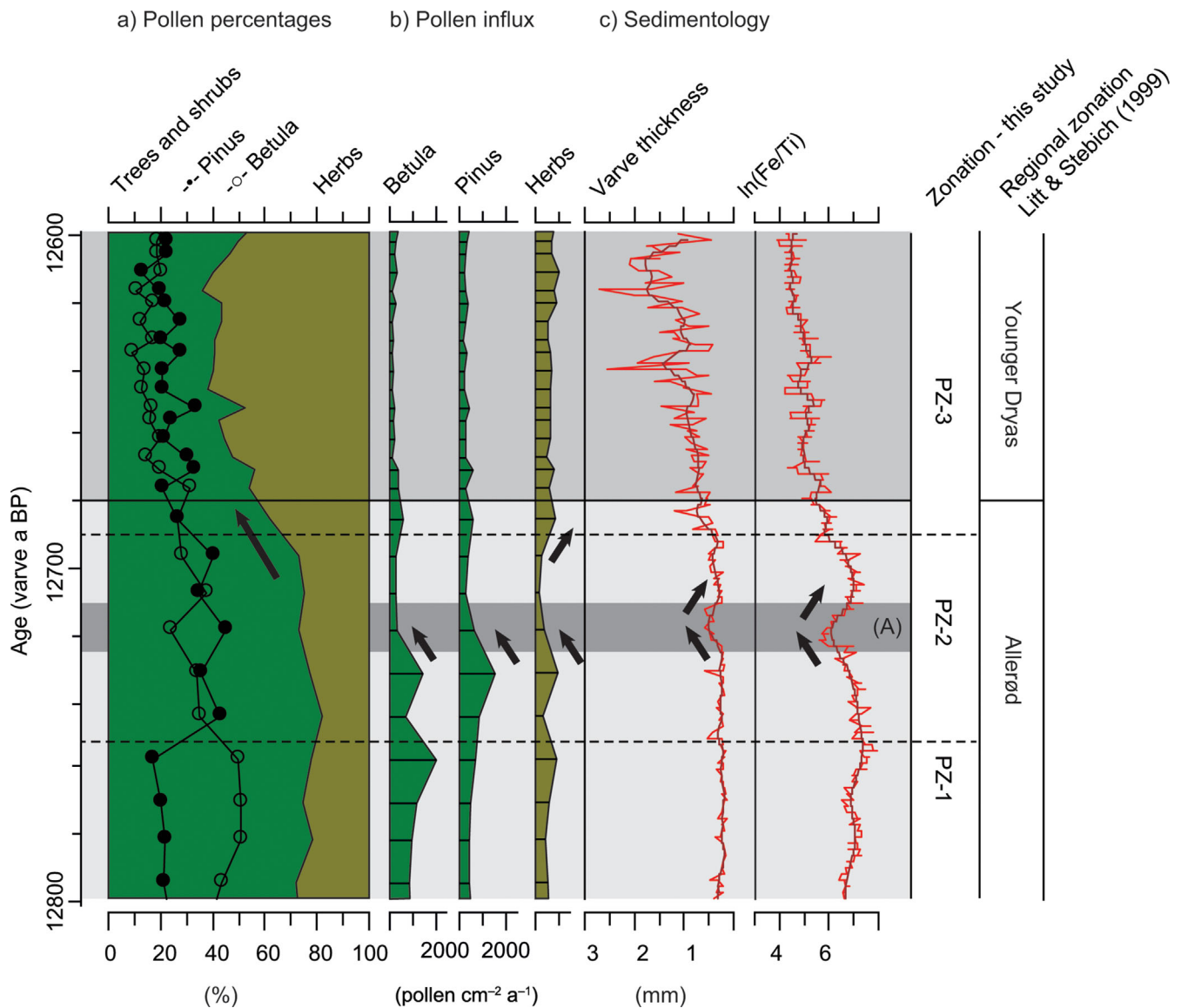
Figure 4. Detail of the 12 800–12 600 varve a BP interval of the MFM record presented in this study: (a) main pollen diagram; (b) PAR values of selected taxa; (c) sedimentological data. Zonation is based on the percentage diagram: see Fig. 1 and text for more information. See caption of Fig. 3 for more details.

12 665 varve a BP. *Pinus* decreases from a maximum PAR of $\sim$1500 pollen cm^{-2} a^{-1} at ca. 12 730 varve a BP to values of 200–600 pollen cm^{-2} a^{-1} around 12 480 varve a BP, which is the end of the studied interval. These trends differ from those observed for most herbaceous taxa: the recovery of the arboreal taxa at 12 685 varve a BP does not lead to PARs that are as high as before the decadal-scale decrease at 12 725 varve a BP, whereas most herbaceous taxa do show similar PARs before and after the decadal-scale decrease. Heliophilous herbs such as *Artemisia* and *Rumex acetosella*-type only reach maximum percentage abundances and PAR numbers at around 12 535 varve a BP, some 145 varve years after the onset of the YD.

Micro-facies analysis and element composition

The major shift in varve micro-facies from siderite varves in the late Allerød to diatom–clastic varves in the YD has been previously described in detail by Brauer *et al.* (1999) and Lücke and Brauer (2004), who state that the increase in varve thickness at the onset of the YD is due to (i) massive diatom blooms (interpreted as caused by nutrient remobilization due to increased water circulation) and (ii) re-deposition of littoral

sediments due to wave activity on the shorelines combined with a lake water level decline.

Here, we report a previously undescribed brief fluctuation in varve micro-facies during the late Allerød, lasting for only 11 varve years at ca. 12 720 varve a BP (Fig. 3), and occurring ca. 40 varve years before the main shift in varve micro-facies at the onset of the YD (12 680 varve a BP; Brauer *et al.*, 2008). This short interval is characterized by an increase in mean varve thickness from $\sim$0.2–0.3 to $\sim$0.4–0.6 mm (Fig. 4) mainly caused by thicker organic sub-layers that contain higher abundances of small diatom frustules (spring/summer). Similar to the facies change at the onset of the YD, siderite sub-layers vanish almost completely as the result of deeper lake-water circulation that increased oxygen availability in the deep water. Some of the layers contain biochemically precipitated calcite (Fig. 5). Typically, in mid-latitude lakes calcite forms in the epilimnion triggered by CO_2 consumption during spring and early summer algal blooms (Kelts and Hsü, 1978). In MFM this is a rarely observed process because there are no carbonate rocks outcropping in the catchment. Nevertheless, calcite precipitation in this interval is confirmed by thin section analyses and coincides with an increase in the occurrence of diatom frustules in these varves. Therefore, we
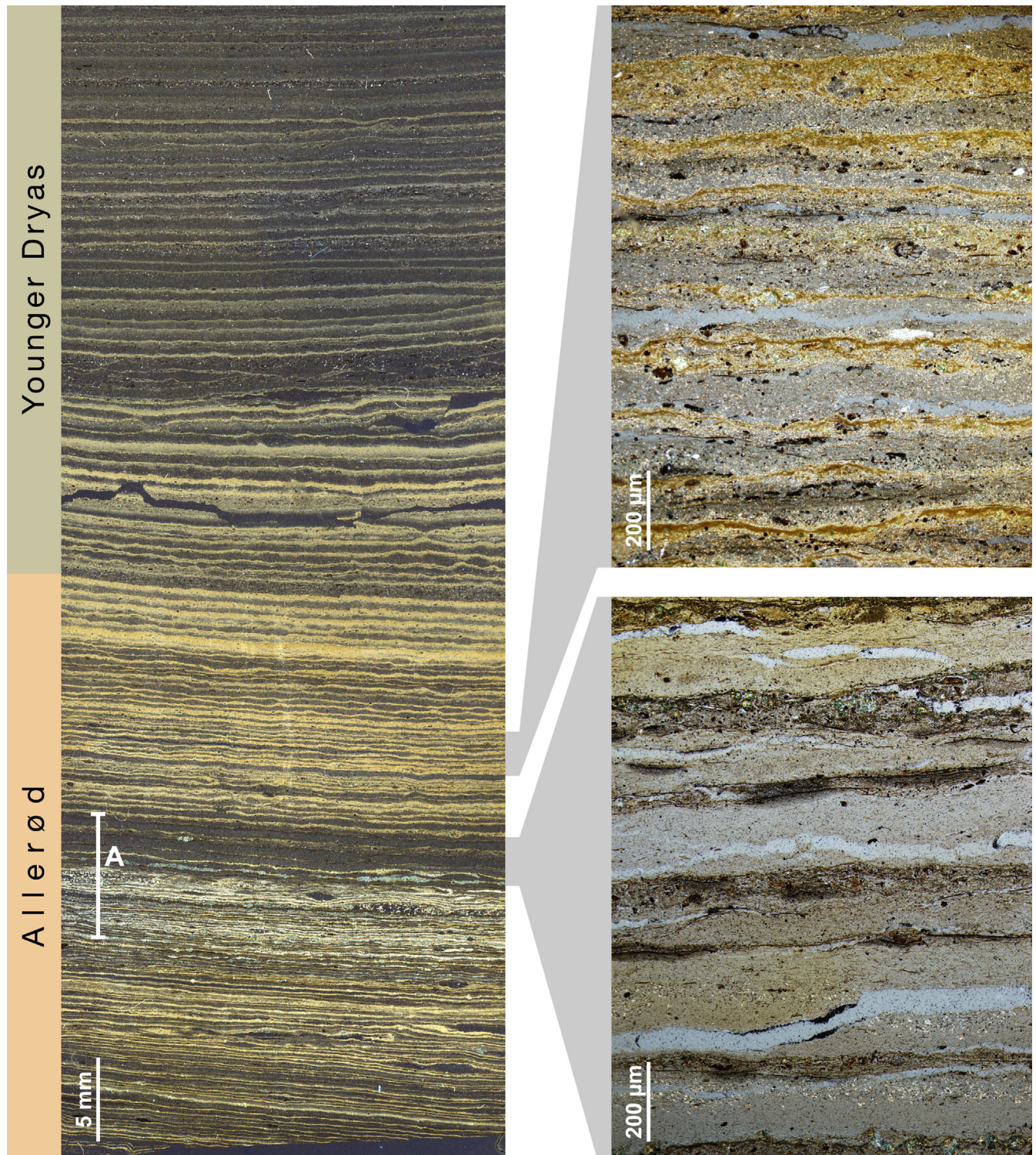
Figure 5. Left: thin section image (polarized light, flatbed scanner without microscopic magnification) showing late Allerød siderite (yellowish layers) varves and darker clastic-organic Younger Dryas varves. The indicated section (A) shows a short interval of endogenic calcite (whitish layers) and diatom-rich (dark layers) varves. Right: thin section images (polarized light) of late Allerød siderite varves (upper image) and a detail of the short intercalated interval of calcite-diatom varves (lower image).

interpret the formation of these varves as a short period of increased water circulation which, however, was less intense and, as a result, not as long-lasting as the increased circulation observed at the onset of the YD.

Changes in the element composition of the sediments agree with the observed micro-facies changes. Due to the predominantly basaltic composition of the MFM catchment (Irion and Negendank, 1984), we consider titanium (Ti) a suitable indicator for the clastic component of the sediment. Variations in the thickness of the siderite layers as inferred from

micro-facies analyses correspond well to relative changes in the detrital-normalized iron represented here by ln(Fe/Ti) ratios (Brauer et al., 2008). The Allerød–YD transition is characterized by an increase in detrital input (higher Ti values) and lower ln(Fe/Ti) ratios because of reduced authigenic iron-minerals precipitation (siderite varves) (Fig. 3). Similar changes, but at much lower amplitude, are observed between ca. 12 725 and 12 715 varve a BP corresponding to the brief fluctuation described above (Fig. 4). The LST at 12 880 varve a BP is characterized by the highest Ti values

(Fig. 3). The 15-year-long Ti peak preceding and following the air-fall ash deposit reflects ash material that penetrated into the underlying sediments corresponding to the 5 years before the volcanic eruption as well as reworked ash material during the first decade after the eruption (Fig. 3).

Discussion

Identification of a previously unrecognized decadal-scale climate oscillation before the onset of the YD

Our PAR data show that values of *Betula*, *Pinus* and most of the herbs show a distinct fluctuation starting at ca. 12 725 varve a BP (Fig. 3c), ~55 years before the onset of the YD (Litt and Stebich, 1999). This decrease in PAR was not previously observed at MFM, nor is it evident in other palynological records with a high sampling resolution (e.g. Wick, 2000; Ammann *et al.*, 2013). It also does not coincide with to the so-called Gerzensee oscillation (e.g. Lotter *et al.*, 1992), which ended shortly after the LSE, ca. 150 years earlier than the oscillation we observe in our record.

The PAR decrease that we observe in our record could have been the result of decreased pollen production under less favourable climatic conditions, such as a decrease in temperature, which has been suggested to have started as early as 12 850 varve a BP based on lipid biomarker δD data (Rach *et al.*, 2014; Fig. 3e). Notably, the decrease in δD values of the higher plant-derived nC_{29} n-alkane (probably derived from *Betula*, with possible contributions from *Salix* and Poaceae) from ca. −189 to −205‰ between 12 750 and 12 710 varve a BP was coincident with the decrease in PAR values.Rach *et al.* (2014) interpret the decrease in δD as an indication of regional cooling in Western Europe combined with a change in δD values of North Atlantic surface waters.

The varve thickness record and the element composition of the sediments also show evidence for the presence of a shorter oscillation occurring before the onset of the YD. Minor time lags at the onset of the oscillation and differences in the duration of the response observed between palynological and micro-facies data can be the result of different proxy-sensitivity to the relatively weak forcing that might have driven the observed changes. Annual layer counting reveals a fluctuation of 11 varve years at ca. 12 725–12 715 varve a BP that was characterized by relatively thicker varves (Fig. 3d). This increase in varve thickness is due to the sudden appearance of discrete diatom sub-layers and a slight increase in the minerogenic input into the lake (relatively higher Ti values). The intensification of diatom blooms, together with an increase in reworked littoral sediment and the cessation of siderite formation in varves at the beginning of the YD, was interpreted as an indicator of more intense water circulation that led to nutrient upwelling and increased lake productivity (Brauer *et al.*, 2008). For the precursor fluctuation at 12 725–12 715 varve a BP, the reduced siderite precipitation and lower *ln*(Fe/Ti) ratios (Fig. 3d), both indicative of less anoxic bottom water conditions, also support wind-induced deeper lake water circulation. Therefore, the attenuated proxy response, compared to the onset of the YD, suggests a similar mechanism (increased wind activity) but with lower magnitude than at the onset of the YD. Moreover, unlike the long-lasting shift in the depositional system at the onset of the YD, this short period of change represents a true oscillation: siderite varves occur before the fluctuation and the same varve type (siderite varves) recurs after the fluctuation, and PAR decreases at the onset of the fluctuation, and

increases again afterwards. This further indicates that the driver of this short oscillation was less intense and/or of shorter duration than the one at the onset of the YD. We hypothesize a short-lasting, non-stable change in atmospheric circulation causing increased windiness as a possible driver for this fluctuation. To prove this hypothesis, additional data from other sites in Europe are needed, providing better information about its spatiotemporal signature. Reconstructions of small-scale climate variability that may have preceded large climatic shifts such as the onset of the YD might provide vital clues to improve our understanding of potential drivers of climate change and ecosystem response. A strong chronological control as well as a very high sampling resolution is needed to be able to identify climate instability such as the decadal-scale oscillation discussed here.

The definition of the Allerød–YD transition: biostratigraphy and climate change

Many sedimentary records that are available for palaeoclimatologists and palaeoecologists lack the chronological control or the sedimentation rate that is needed to allow for the identification of (sub-) decadal-scale ecosystem and climate change. However, these records do, for example, allow the reconstruction of spatial patterns of change on longer (centennial to millennial) timescales (e.g. Giesecke *et al.*, 2014), or of continental-scale changes in distribution patterns of specific taxa (e.g. Giesecke *et al.*, 2011). As such, palynological records that lack a (sub-) decadal sampling resolution are important for palaeoecological and palaeoclimatological reconstructions.

The continental-scale analysis of European vegetation change during the Holocene by Giesecke *et al.* (2011) shows that with a centennial-scale temporal resolution the expansion of, for example, *Corylus avellana* was broadly synchronous at far apart sites. However, high-resolution results by Ammann *et al.* (2013) and van Raden *et al.* (2013) suggest that changes in climate and especially the subsequent ecosystem responses might not be synchronous on a (sub-) decadal scale. Furthermore, while the mid-point of change is often easily defined and as such a robust tool to use in characterizing, for example, biostratigraphical zones, high-resolution annually laminated records such as MFM indicate that the mid-point of change is not the best option to define the onset of climate change or the timing of ecosystem response to such changes. Only by high-resolution studies of time intervals representing climate change and by establishing detailed independent chronologies, avoiding 'correlations' through curve matching, can the differences in timing of the onset of climate change and the start of ecosystem response be identified and quantified (e.g. Björck *et al.*, 1998; Blockley *et al.*, 2012). A record such as MFM with its robust chronology and its availability of many high-resolution and high-quality proxy records (e.g. Martín-Puertas *et al.*, 2012; Rach *et al.*, 2014; Engels *et al.*, 2015) can play a key role in the process of better understanding leads and lags that may occur on a (sub-) decadal scale (Ammann *et al.*, 2000, 2013; Lane *et al.*, 2013; Wick, 2000; this study). Our high-resolution record shows that previously unrecognized climate instability is evident in three independent proxy records (i.e. palynology, sedimentology and biogeochemistry), several decades before the Allerød–YD transition. Small-scale differences observed in these proxy records suggest that individual climate-proxy records are not synchronous in their initial reactions (passing thresholds at different moments), which is probably the effect of (i) sampling resolution and (ii) proxy-sensitivity.

Difference in trends of percentage abundance curves and PAR curves

The lithological record of MFM showed an abrupt change in varve thickness and a major shift in micro-facies from one year to the next at 12 680 varve a BP (Brauer et al., 2008). Percentage abundances of Pinus showed a decrease of 20% within a 20-year period (Fig. 3b) across this transition. Pinus pollen that is persistently present after that date and throughout the YD might mainly represent long-distance transported pollen, as increased windiness (Brauer et al., 2008) may have favoured the accumulation of allochthonous (long-distance transported) pollen. The percentage abundance diagram suggests that Betula showed a more gradual response to decreasing temperatures across the transition into the YD than Pinus, as percentage abundances of Betula started to decrease already as early as at 12 710 varve a BP. Compositional turnover (Fig. 1), calculated using the percentage data, shows its strongest decrease just after 12 680 varve a BP.

PARs of both Pinus and Betula, however, already decrease at ca. 12 725 varve a BP, which is ~35 and ~15 years before the decreases in percentage abundances of Pinus and Betula, respectively. The difference in timing of the decrease in percentage abundance of Pinus and Betula therefore does not seem to reflect the vegetation development in the area around MFM, but seems to result from the different ability of the remnant vegetation to produce pollen under cooling climate conditions. The decrease in percentage abundances of Betula (from 31 to 19% between 12 675 and 12 670 varve a BP) just after the onset of the YD might reflect a change in the vegetation, as PARs of Betula decrease from 350 to 220 pollen cm^{-2} a^{-1} at this time as well.

Theuerkauf and Joosten (2012) present PAR values for a large number of sites in Germany that span (part of) the YD. Reconstructed PAR values for the YD at MFM are similar to the results of Theuerkauf and Joosten (2012) for many of the common taxa, including Betula, Artemisia and Poaceae. The PAR values of Pinus presented by Theuerkauf and Joosten (2012) for their southernmost sites are between 6000 and 10 000 grains cm^{-2} a^{-1}, which is an order of magnitude higher than the values obtained for Pinus in the present study (200–400 grains cm^{-2} a^{-1} during the YD). The low values that are observed at MFM, however, do corroborate the results of Theuerkauf and Joosten (2012) which show a strong east-to-west gradient in Pinus pollen abundance across Europe during the YD.

These results illustrate the advantages of calculating PARs when analysing short-term changes in palynological results, as the decrease in pollen production around 12 725 varve a BP is not reflected in the percentage diagram. However, detailed chronological information is needed to enable the distinction between fluctuations that might be due to short-term fluctuations in sedimentation rates (which might not be visible in non-laminated sediments) from real fluctuations in PAR.

Delayed increase in heliophilous herbaceous taxa following the onset of the YD

Several taxa that are typically considered pioneer taxa with a preference for open, mineral soils (Birks, 1986) take a long time to increase in PAR after the onset of the YD. For instance, Artemisia and Rumex acetosella-type take ca. 145 varve years before reaching their maximum pollen-abundances after the onset of the YD (Fig. 3), and a statistically significant transition in the pollen percentage data of these taxa is identified at 12 545 varve a BP (PZ-3 to PZ-4 boundary).

The delayed increase in pollen percentages and PAR might have been an effect of the (partly dead) trees and thermophilous herbaceous taxa that were still present in the landscape around MFM as relicts of the Allerød vegetation. Habitats for heliophilous pioneer plant communities might have only become available after the disappearance of the relict vegetation and the development of open, mineral soils. A similar observation has been made in the subdecadal pollen record from Lake Gerzensee (Switzerland), which exhibits a ~100-year delay in the increase of percentage abundances of, for example, Artemisia after the onset of the YD (Ammann et al., 2013). This supports our interpretation of a competition effect across the Allerød–YD transition as an explanation for the delayed increase of heliophilous herbaceous taxa.

Conclusions

We used a subdecadal-resolution palynological record retrieved from the annually laminated sediment record of Lake Meerfelder Maar to test the current paradigm that the vegetation shift at the onset of the YD was expressed as a multi-decadal shift in the AP/NAP ratio. Our new high-resolution data show that PARs decreased between ca. 12 725 and 12 685 varve a BP. This previously unobserved 40-year-long fluctuation occurs several decades before the onset of the YD as defined by biostratigraphy (sensu Litt et al., 2003). The decrease in PAR coincides with an increase of varve thickness and a change in micro-facies between 12 720 and 12 710 varve a BP, as well as with a decrease in the δD values of the higher plant-derived nC$_{29}$ n-alkane. Together, these records provide evidence for the occurrence of a previously unknown decadal-scale climate fluctuation during the late Allerød.

Our results furthermore show a difference in timing between the percentage abundance curves and the PAR curves of the most important taxa (i.e. Betula, Pinus). This suggests that although biostratigraphy remains a useful tool for upscaling individual proxy records to regional patterns of change, high-resolution proxy analyses on well-dated records provide a means to additionally decipher even (sub-) decadal ecosystem and climate change. Finally, our records indicate a delayed increase in heliophilous taxa after the onset of the YD. This delay of ca. 145 varve years might be the result of time-demanding competition effects with plant species that were components of the vegetation during the late Allerød period.

This study illustrates the potential to identify small-scale and low-amplitude climate variability when using ultra-high-scale-resolution analyses on suitable records such as MFM. Our results show that subdecadal palaeoecological data can provide an improved understanding of the complex changes in climate and vegetation associated with the onset of the YD.

Supporting Information

Fig. S1. Pollen percentage diagram for the late Allerød–early Younger Dryas transition at Lake Meerfelder Maar plotted on a relative depth scale (cm).

Fig. S2. Diagram showing concentration values (pollen cm^{-3}) for selected taxa for the late Allerød/Younger Dryas transition at Meerfelder Maar on a varve age scale (varve a BP).

Table S1. Varve chronology and sampling details of the Meerfelder Maar sequence presented in this paper.

Abbreviations. AP, arboreal pollen; DCCA, detrended canonical correspondence analysis; LSE, Laacher See eruption; LST, Laacher See Tephra; MFM, Lake Meerfelder Maar; NAP, non-arboreal pollen; PAR, pollen accumulation rate; YD, Younger Dryas; XRF, X-ray fluorescence.

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