Przegląd Geologiczny, vol. 73, no. 2, 2025; doi: http://dx.doi.org/10.7306/2025.14

Climate change and environmental responses over the last 13,000 years deduced from analysis of annually laminated lake deposits of north-central Europe

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Abstract. We describe annually laminated deposits from the bottoms of Lake Czechowskie and Lake Gościąż in Poland, Lake Tiefer in Germany and the palaeolake Trzechowskie in Poland, as analysed by a Polish-German multidisciplinary research team. For each site, absolute dating and varve chronology provided the basis for an age-depth model, with palaeoecological and geochemical analyses being carried out. The results allowed us to characterize the responses of the natural environments around these lakes to global climate changes of the last 13,000 years. Techniques including microlithofacies analyses, XRF scanning, beryllium-10 analyses and, above all, tephrochronological analyses, allowed precise cross-correlation of the stratigraphic profiles in the lakes studied. This made it possible to determine leads and lags in the various environmental responses to global climate change in the Central European Lowland in an east–west transect, taking into account the degree of climate continentalism. The results indicated the high utility of annually laminated lake deposits in palaeoclimatic and palaeoenvironmental analyses, including those reflecting the influence of human activity. The results may be helpful in developing effective measures for adapting natural environments to projected climate changes.

Keywords: *postglacial, climate change, annually laminated lake deposits, north-central Europe*

INTRODUCTION

One of the most important challenges facing Earth sciences is to address current global climate change and related changes in the natural environment (Jary, Błaszkiewicz, 2024). The scientific discussion on this topic must be firmly grounded in knowledge of the Earth's climatic and environmental past (Bradley, 2015). Such an approach is consistent with a reversed principle of uniformitarianism, which indicates that only on the basis of knowledge of the past can we fully understand contemporary climate-environment interactions and build reliable models for the near future (Elias, 2018). Because instrumental measurements and meteorological observations began only in the 17th century (Ćurić, Siridonov, 2023), our knowledge of the Earth's climatic past is primarily based on indirect (proxy) data obtained from various sedimentary environments. Such archives of past climatic changes include marine sediments (Lisiecki, Raymo, 2005), ice cores (Rasmussen *et al.*, 2014), cave speleothems (Dreybrodt, 1999), and tree rings (Briffa *et al.*, 2004). Detailed analyses of sedimentary successions have allowed considerable recognition of both large-scale glacial-interglacial cycles and short-term variability in the Quaternary (past Interglacials…, 2016).

Although lake deposits usually contain shorter time records than ocean sediment profiles or ice cores from Greenland and Antarctica, they are of special importance among the natural archives of past climate and environmental changes. This is primarily due to their very diverse biotic composition, which provides great potential to analyse a large variety of different and complementary proxies in the context of a multiproxy approach (Bradley, 2015). Also important are the wide distribution of lakes around the globe (Brosius *et al.*, 2021) and their presence in the immediate living space of humans. These factors allow detailed analysis of lake deposits not only to gain knowledge about past climate changes and corresponding environmental responses, but also to consider the role of humans in these interactions (Brauer *et al.*, 2009). Of particular importance in palaeoenvironmental studies are annually laminated lake deposits because of their potential to record even seasonal changes and their chronological potential for robust high-resolution age–depth models (Brauer, 2004; Zolitschka *et al.*, 2015). New research techniques, such as microlithofacies analyses and tephrochronology (cryptotephra) further enable to precisely correlate proxy time series from sedimentary records at great distance from each other. This is fundamental for investigating regional differences in environmental response to climate change and to identify even brief leads and lags in the response of environment to climate change (Lane *et al.*, 2013). Due to the specific nature of the formation of annual sedimentary laminations in lakes and their preservation (Ojala *et al.*, 2012), only few varved sedimentary records spanning a period of more than 10,000 years have been documented (Zolitschka *et al.*, 2015). Among these sites, the varved deposits of Lake Czechowskie and Lake Gościąż in Poland and Tiefer See in Germany are iconic records. They were the subject of detailed research within the German–Polish project: Integrated Climate and Landscape Evolution Analyses (ICLEA) and two National Science Centre (NCN, Poland) projects led by the authors of this article.

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ANNUALLY LAMINATED LAKE DEPOSITS – FORMATION AND PRESERVATION

The seasonal nature of laminations in lake deposits was first recognized by Gerard de Geer more than a hundred years ago (De Geer, 1912) in Late Glacial palaeolake sedimentary profiles formed in proglacial lakes in southern Sweden. These laminations are characterized as silt-clay couplets and reflect the seasonal glacier melt in spring and summer when fine-grained minerogenic material was transported into the lake. Different settling velocities of the particles due to their different grain-sizes lead to deposition of typical silt-clay couplets, with clay only deposited when the lake was frozen again. The succession of these seasonal couplets known as clastic varves (from Swedisch 'varvig lera' = layered clay) has been mainly used as chronological tools that allowed absolute dating of the ice retreat at the termination of the last glaciation. Today, the term 'varves' is used for all kinds of laminated deposits for which the seasonal nature has been proven. Not all types of lamination reflect strictly seasonal deposition. A large variety of varve facies types with different numbers of seasonal sublayers has been described from all climate zones and various geological catchments (Brauer, 2004) including evaporitic varves from arid climates, iron-rich varves in boreal environments and calcite varves in mid-latitude temperate climates. A precondition for varve formation is at least two different sediment deposition processes related to seasonal changes in the lake system. The main processes are allochthonous, *i.e.* minerogenic material transported from the catchment by wind or water, and autochthonous, *i.e.* biogenic (e.g., diatoms) or minerals (e.g., calcite) formed in the water column. As important as seasonal layer formation is varve preservation since the small thickness of seasonal sublayers, commonly <1 mm, makes them highly susceptible for postdepositional destruction, for example through bioturbation, sediment degassing, and wind- or wave-triggered water turbulence. These processes occur less frequently in deep lakes of small surface area and predominantly anoxic deep water. The common varve facies in the formerly glaciated southern Baltic lowlands are calcite varves (e.g., Tylmann *et al.*, 2013; Ott *et al.*, 2017) in different variations. Sediment monitoring studies have revealed repeating cycles of three predominantly autochthonous deposition processes starting with (1) diatom blooms during spring warming that trigger (2) calcite precipitation until summer, followed by sediment resuspension from the littoral zone during autumn and winter (Roeser *et al.*, 2021). Major climate changes such as related to the Younger Dryas have caused variations in the seasonal deposition of calcite varves (Müller *et al.*, 2021).

METHODOLOGY OF RESEARCH ON ANNUALLY LAMINATED LAKE DEPOSITS

A great advantage of varved deposits is that they can be used both as chronological tool and archive for past climate and environmental change. Since varve thickness/sedimentation rate commonly is low, at mm-scale or less, high-resolution analytical tools are crucial for robust data acquisition. First of all, depositional processes must be understood in order to prove the seasonal nature of fine laminations. Therefore, micro-facies analyses on thin-sections using petrographic microscopes are essential. For the preparation of large-scale thin-sections (100 × 20 mm) the wet sediment must first be shock-frozen with liquid nitrogen and freeze-dried before impregnation with resin. The resulting hard sediment blocks can be treated like rock samples for thin-section preparation. The entire sedimentary profile must be covered with overlapping (2 cm overlap) thin-sections for varve thickness measurements and counting for establishing long and continuous varve chronologies. In addition, microfacies analyses provide basic information on sedimentary structure and composition for climate and environmental information. Since this information is predominantly qualitative and semi-quantitative, complementary high-resolution methods such as μ-XRF multi-element scanning have to be applied. This allows the combination of microscope data and optical information with geochemical data.

An at least equally important feature of annually laminated deposits is the ability to construct an independent, absolute chronology (Brauer, Casanova, 2001). The deposits being annually laminated with the development of volcanic ash detection opens up new research possibilities (Blockley *et al.*, 2005), firstly by determining the number of years between eruptions (Ott *et al.*, 2016) and secondly by allowing us to correlate sites located at great distant from each other. Precisely correlating proxy records over geographically large regions allows one to trace the response of a catchment or the lake ecosystem, for example, to some abrupt climatic shift or local disturbance on a regional basis (Wulf *et al.*, 2013, 2016; Ott *et al.*, 2017). Tracking the lead and lags of various proxies for abrupt climate change e.g., at the onset of the Younger Dryas, was possible because of the seasonal resolution combined with a robust and accurate "internal" time scale in calendar years based on varve counting (Słowiński *et al.*, 2017). The high time resolution is essential for deciphering the exact timing, spatial expression and driving mechanisms of climate variations. The range of research methods applied in these studies of laminated deposits is broad and can be divided into destructive and non-destructive methods. Non-destructive methods include semi-quantitative geochemical analysis from μ-XRF core scanning and magnetic susceptibility scanning (Wulf *et al.*, 2013; Dietze *et al.*, 2016; Dräger *et al.*, 2016; Bonk *et al.*, 2021). Destructive methods can be divided into analyses based on bioindicators and those that are based on geochemistry. Bio-proxies such as pollen, Cladocera, Chironomidae, diatoms, or macrofossils allows one to decipher causes and rates of change of environmental conditions in the past through changes in characteristic species or relationships between species (Wulf *et al.*, 2013; Słowiński *et al.*, 2017; Dietze *et al.*, 2018; Dräger *et al.*, 2019). From such bio-proxy analyses quantitative and qualitative palaeoecological information can be obtained. A good example of such bioindicators comprises non-biting midges (Chironomidae) as a proxy for summer temperatures (Płóciennik *et al.*, 2022) or pollen data and the REVEALS model for quantitative vegetation reconstruction (Dietze *et al.*, 2019; Słowiński *et al.*, 2021; Theuerkauf *et al.*, 2021). On the other hand, geochemical proxies such as oxygen or carbon isotopes and biomarkers of leaf wax n-alkanes provide information about past temperatures, productivity, redox potential and oxygen conditions in the water column (Aichner *et al.*, 2018; Müller *et al.*, 2021). An important element of the work on varved deposits is an independent confirmation of varve counts by radiometric dating methods such ^{137}Cs and ^{210}Pb, but also new methods for the correlation of sedimentary records such as cosmogenic ^{10}Be, as successfully demonstrated in correlating the varved sedimentary records from Tiefer See and Lake Czechowskie (Czymzik *et al.*, 2015, 2018).

STUDY SITE LOCATIONS AND MAIN RESEARCH RESULTS

All sites described in this publication are located in the Southern Baltic Lowlands, within the range of the last, Upper Vistulian Fennoscandinavian ice sheet (FIS) (Fig. 1).

Lake Gościąż

Lake Gościąż is located in the Płock Basin, part of the Toruń–Eberswalde spillway, at the back of the end moraines of the Last Glacial Maximum (LGM). Lake Gościąż is positioned at the bottom of a tunnel valley dissecting the surface of a spillway terrace (Wiśniewski, 1976). The tunnel valley developed during a retreat of the last glacial ice sheet about 18,000 years ago (Poznań phase) as a result of channel erosion by subglacial water flow. Subsequent to the ice retreat, the tunnel valley was filled with dead ice covered by glacio-fluvial sediments which, under permafrost conditions, prevented the dead ice from melting. The buried ice blocks were preserved until rapid warming at the onset of the Late Glacial (Błaszkiewicz *et al.*, 2015). Lake Gościąż developed as a result of the buried dead ice melting at the Bølling–Allerød transition (Ralska-Jasiewiczowa *et al.*, 1998). In the area around the Lake Gościąż tunnel valley, sand and gravel deposits of the spillway terrace are covered by numerous dunes, the genesis of which is related mainly to aeolian processes in cold periods of the Late Glacial (Rychel *et al.*, 2018; Kruczkowska *et al.*, 2020).

Today, Lake Gościąż is 24 m deep and covers 41.7 ha. The lake is part of the River Ruda river-lake system, which connects several smaller lakes and discharges into the River Vistula. The lake is dimictic, but shows some features of bradymixing with longer winter ice cover and pronounced summer thermal stratification.

The laminated deposits of Lake Gościąż were firstly recognized by K. Więckowski in 1985 (Więckowski, 1991) and were studied in 1986–1996 by a large, interdisciplinary team (Ralska-Jasiewiczowa *et al.*, 1998). In 2016–2020, a research project financed by the National Science Centre was led by M. Błaszkiewicz with the main objective of using new research techniques to analyse these annually laminated deposits to allow them to be more fully included in a central European palaeoclimatic and palaeoenviron-

Fig. 1. Location of the study area in relation to the Last Glacial Maximum (LGM) and Pomeranian Phase (Pm) – Weichselian (Vistulian) Glaciation (modified after Marks *et al.*, 2022)

mental transect. Palaeoclimatic reconstructions were based on multiproxy analyses of selected sediment cores, constituting a composite profile (master core) including >12,800 varves. Based on microlithofacies analyses on thin-sections as basis for varve counting, Caesium ^{137}Cs measurements, and AMS radiocarbon dating of plant macroremains, a revised independent chronology was developed (Bonk *et al*., 2021). It includes 1,500 varve years which were not counted in previous research (Ralska-Jasiewiczowa *et al*., 1998) due to their insufficient preservation. Based on this robust age–depth model a comprehensive multiproxy approach (XRF scanning, magnetic susceptibility, carbon and oxygen isotopes, palynology, cladocerans, diatoms, dipterans, plant macroremains) has been applied for palaeoenvironmental reconstruction encompassing multiple lines of evidence (Fig. 2). In general, five main lithofacies types of varves have been distinguished and linked to environmental factors determining changes in the nature and rate of sedimentation during the Late Glacial and Holocene (Bonk *et al*., 2021). For the first time in Poland, average air temperatures were quantitatively reconstructed based on high-resolution analyses (annual to decadal) of Late Glacial and Holocene deposits (Müller *et al*., 2021; Płóciennik *et al*., 2022). In addition to the palaeolimnological studies, sediment monitoring has been applied to shed light on the present-day depositional environment at the lake bottom (Fojutowski *et al*., 2021). An important geomorphological thread was the determination of Late Glacial aeolian processes in the Lake Gościąż catchment based on analyses of fossil soils and dating of aeolian deposits using the OSL method (Kruczkowska *et al*., 2020).

Lake Czechowskie and palaeolake Trzechowskie

Lake Czechowskie is located in north-central Poland on the border of the Tuchola Forest and the Kashubian Lake District, in the immediate forefield of the maximum extent of the Pomeranian phase of the last glaciation (Błaszkiewicz, 2005; Błaszkiewicz *et al*., 2015). The lake fills the bottom of a deep tunnel valley, which cuts through outwash surfaces shaped by ice sheet meltwaters. The formation of the lake was associated with the melting of buried blocks of dead ice in the tunnel valley at the end of the Bølling biozone (Błaszkiewicz, 2005). The lake covers 73 ha and has a maximum depth of 32 m. Lake Czechowskie has bradymictic features with strongly developed thermal stratification.

The annually laminated deposits of Lake Czechowskie were first documented in 2002 (Błaszkiewicz, 2005). In 2012–2018 they were the object of interdisciplinary research within the German–Polish ICLEA project led by A. Brauer and a project financed by the National Science Centre, led by M. Błaszkiewicz. A composite profile (Fig. 3) was compiled from six parallel sediment cores collected at the water depth of 32 m. Its construction was based on varve counting, microlithofacies analyses, AMS ^{14}C dating, tephrochronology and Caesium ^{137}Cs activity measurements.

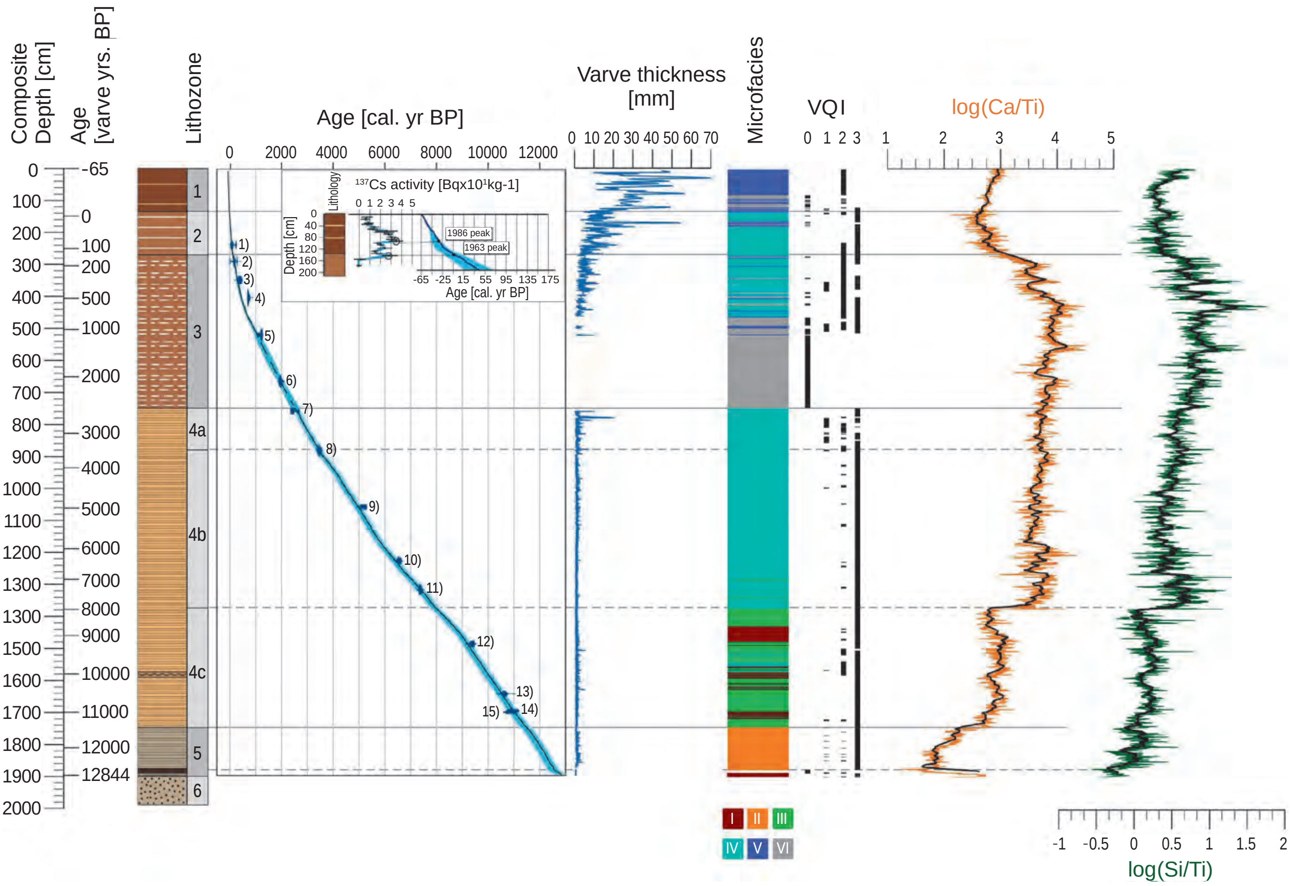

Fig. 2. Age–depth model of the Lake Gościąż composite profile with the sedimentological and geochemical features shown against composite depth in centimetres. Lithological log with lithozones 1 to 6, varve thickness in mm, microfacies types: **I** – calcite-organic varves (type I), **II** – diatom-calcite varves (type II), **III** – calcite-organic varves (type III, a and b), **IV** – calcite-diatom varves (type IV, a and b), **V** – calcite-organic varves (type V), **VI** – homogeneous sediment. Varve Quality Index (VQI), XRF ratios of log(Ca/Ti) and log(Si/Ti), within the Gościąż composite profile. Grey lines mark the lithozone boundaries (modified after Bonk *et al*., 2021)

The combination of these methods including the identification of volcanic glass shards (cryptotephra) from several known volcanic eruptions, including Askja – AD 1875, Askja S and Hässeldalen from Iceland, allowed us to establish a robust age–depth model, even for non-laminated sections within the profile (Fig. 3). Cryptotephra traces constitute a unique tool for correlating distant sediment archives, providing the opportunity to conduct comparative studies of the environmental response in different morphoclimatic zones to global climate change at up to even annual resolution (Wulf *et al.*, 2016).

The composite sedimentary profile from Lake Czechowskie covers the entire Holocene and ranges back to the late Allerød. Several major changes in the course of lacustrine sedimentation were identified, marked by (a): transitions between laminated and non-laminated intervals such as most parts of the Younger Dryas and around 10,500 and 7,300 calibrated years BP, (b): changes in varve microlithofacies around 6,500 and 4,200 cal. BP and (c): a marked increase in varve thickness and greater differentiation within annual couplets from 2–2,800 cal. BP (Fig. 4). Because three levels of Icelandic cryptotephra have been identified (Askja S, Hässeldalen and Askja – AD 1875), the beginning of the Holocene and the last 150 years yielded particularly interesting palaeogeographic interpretation (Ott *et al.*, 2016, 2017). The reliable chronology developed for these deposits, together with that for the Tiefer See, was used to apply the ^{10}Be method for synchronising the Lake Czechowskie sedimentary record with the partly varved record from Lake Tiefer See. This was based on the higher ^{10}Be concentrations during three Holocene grand solar minima (5,500 a BP, Homeric Minimum, Maunder Minimum) (Czymzik *et al.*, 2018). Based on sediment monitoring in Lake Czechowskie, the seasonal sedimentation of calcite

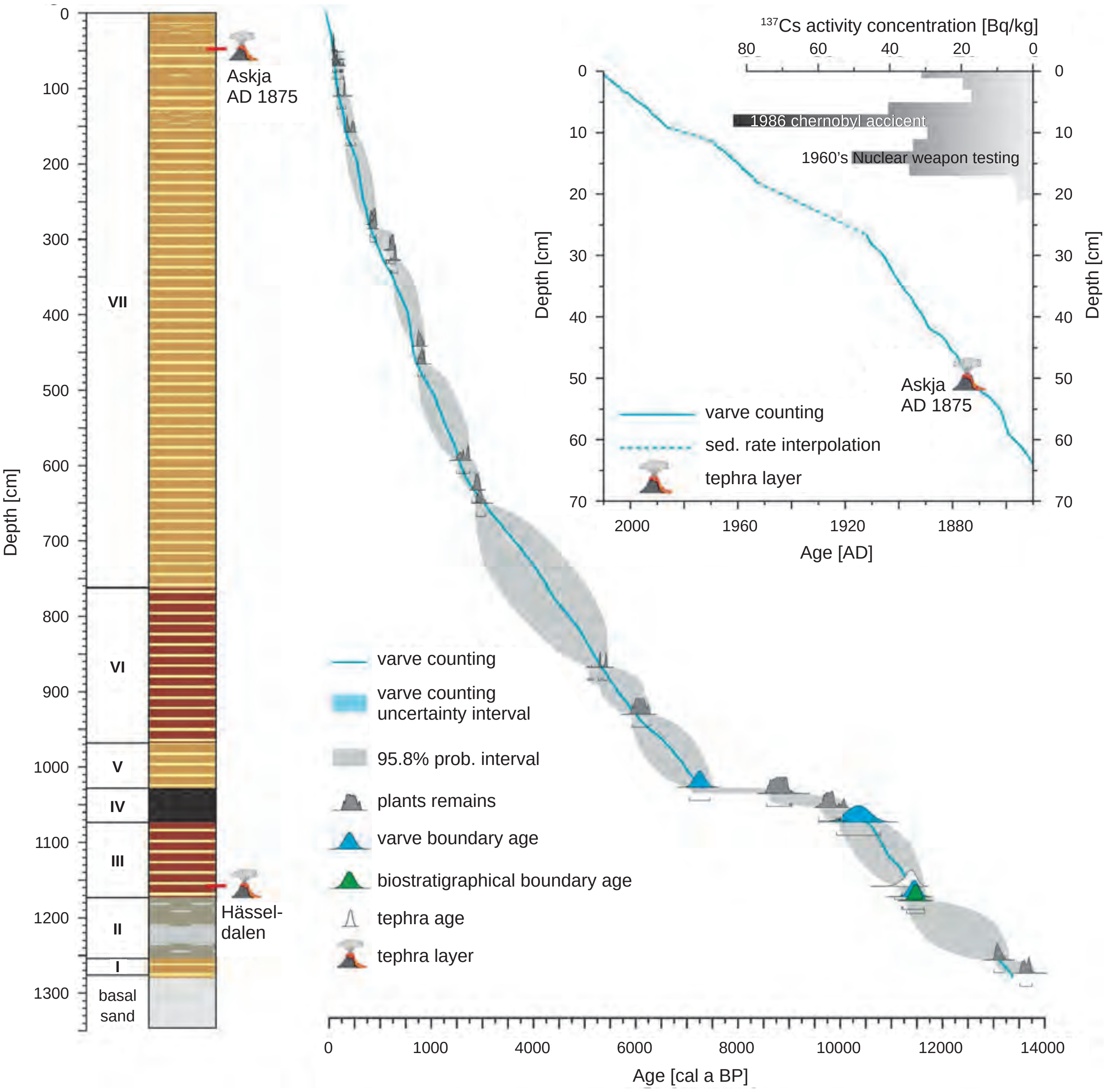

Fig. 3. Age–depth model of the Lake Czechowskie composite profile. Basal sand – fluvioglacial; **I**, **V**, **VII** – calcite varves; **II** – faintly laminated gyttja; **III**, **VI** – calcareous diatomaceous varves; **IV** – homogeneous organic, black gyttja

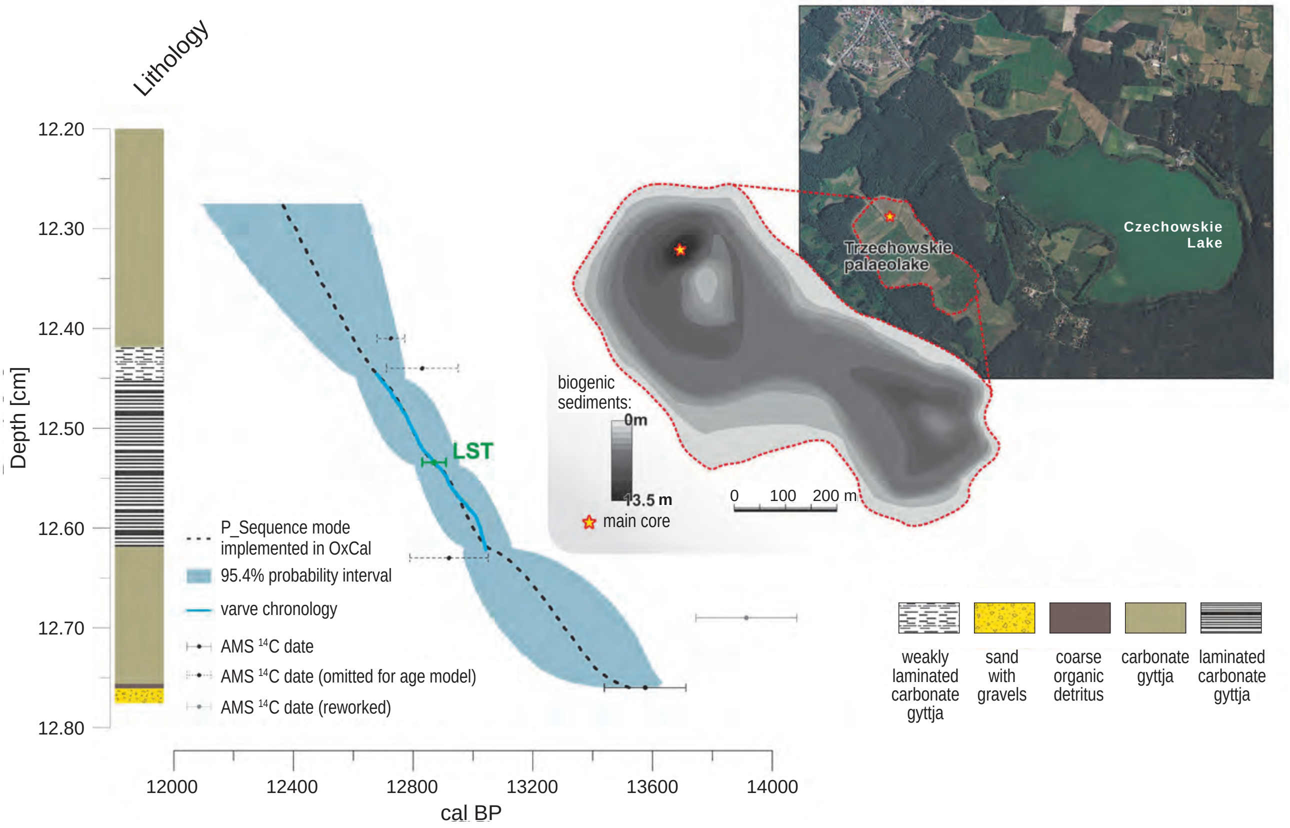

Fig. 4. Location of the palaeolake Trzechowskie, showing the location of the coring site with the thickness of biogenic deposits and the age–depth model for the Trzechowskie Late Glacial sedimentary record. **LST** – Laacher See Tephra (modified after Słowiński *et al.*, 2017)

varves was traced in great detail showing the previously underestimated role of lake internal sediment re-suspension in the autumn and winter seasons (Roeser *et al.*, 2021). Another interesting research thread was the use of the Lake Czechowskie annually laminated deposits to determine how the medieval Via Marchionis road affected the local environment during the transformation from the quasi-natural to the present-day cultural landscape (Słowiński *et al.*, 2021).

The palaeolake Trzechowskie occupies the bottom of a small tunnel valley <2 km south of Lake Czechowskie (Fig. 4). The melting of the dead ice sheet created a depression in which lake sediment accumulation began at 13,450 cal years BP. The high resolution of palaeoecological data (pollen, macrofossils, Cladocera and diatoms) and geochemical data (XRF element scans, TOC, C/N ratios, $\delta^{18}O$ C_{arb}, and $\delta^{13}Corg$ values) in the range of 0.5 to 1 cm sample resolution document the Late Glacial core section with 5–15 years temporal resolution. Based on robust chronology, which includes varve counting, AMS ^{14}C dating and tephrochronology (Fig. 4) we were able to detect by bio- and geochemical proxies how climate change during the late Allerød-Younger Dryas transition affected the reorganization of the postglacial lake system. Our findings demonstrate the potential of annually laminated deposits as a source of information for the consequences of past climate variability on environmental transformation. Our main findings can be presented as follows: a) we observed differential response times between bio-proxies and sedimentary proxies to the cooling associated with the YD: Cladocera and diatoms reacted very rapidly while in sedimentary proxies the change occurred gradually; b) we observed that the biostratigraphical Allerød/Younger Dryas boundary has a lag of about 20 years with respect to the increase of terrigenic detrital flux and bio-proxy response and c) the correlation based on the Laacher See Tephra as an independent chronological tie point of two annually laminated archives, one from the Meerfelder Maar from western Europe and the other from the Trzechowskie palaeolake, revealed that vegetation changes in western Europe occurred about two decades earlier and synchronously with changes in sedimentation (Słowiński *et al.*, 2017; Fig. 5).

Lake Tiefer See

The basin of the Lake Tiefer See (53°35.50' N, 12°31.80' E) was formed within a subglacial channel system during the last glaciation. The lake is oriented north–south, has a surface area of 0.75 km^2 and a maximum depth of 62 m and is connected to Lake Hofsee in the south through a small and shallow channel. The lake is either mono- or dimictic, depending on whether a winter ice cover forms or not. The catchment area (~5.2 km^2) is dominated by glacial till and is presently used for agriculture except for a narrow band along the shoreline composed of stands of large alder, ash, and oak trees (Kienel *et al.*, 2013). Sediments laid down in the last 100 years are annually laminated (varved) (Kienel *et al.*, 2013). These varves consist of three seasonal sublayers formed by (1) a spring diatom bloom, (2) an early summer calcite deposit triggered by the diatom bloom, and (3) an autumn/winter deposition of resuspended littoral sediments caused by wind and wave action (Roeser *et al.*, 2021). Because the lake has no fluvial inflow the contribution of

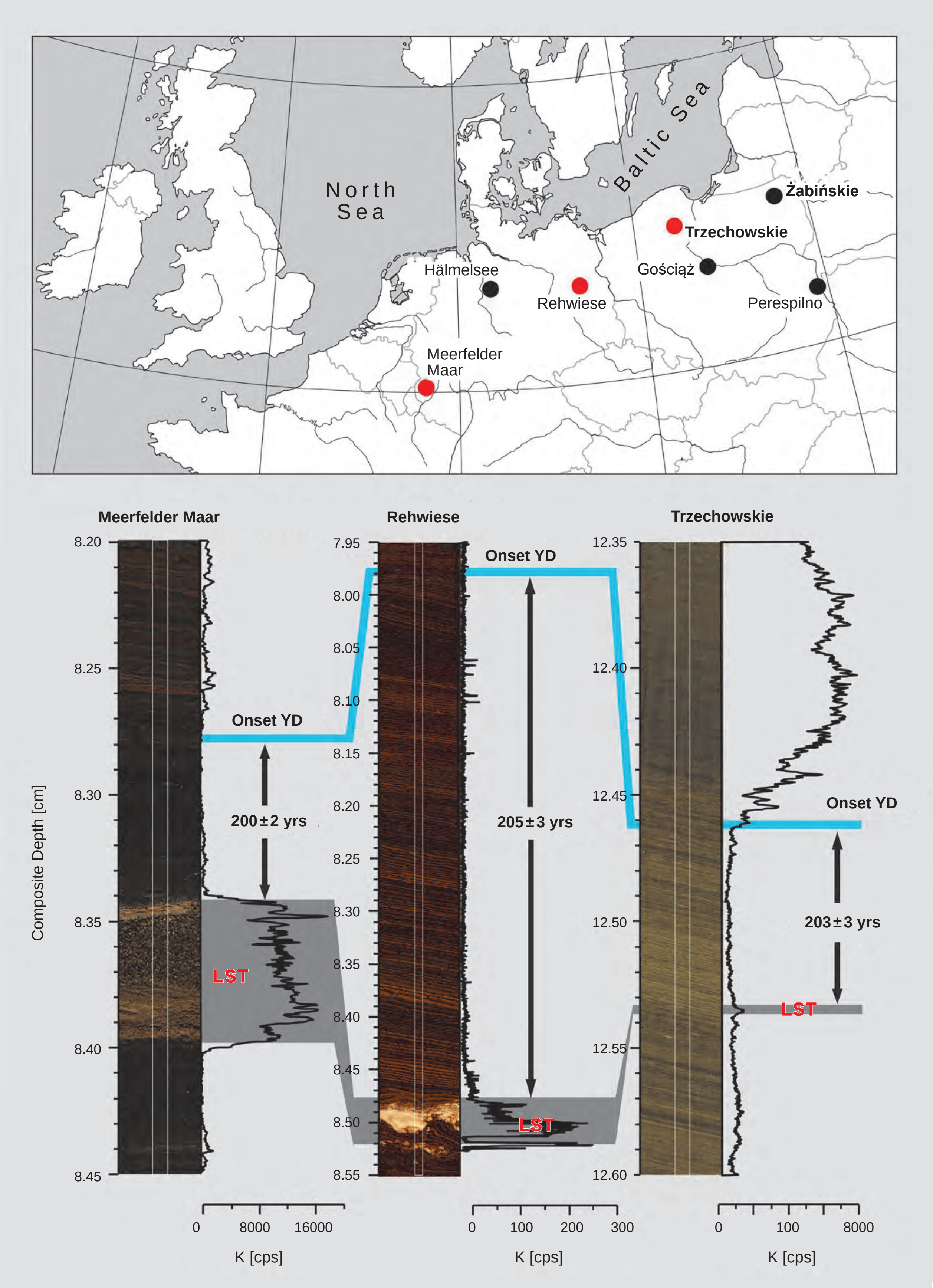

Fig. 5. Comparison of the Allerød/Younger Dryas sequence of the palaeolake Trzechowskie with varved Late Glacial sequences from western Germany (**red dots**) – Lake Meerfelder Maar and northeastern Germany – palaeolake Rehwiese showing the position of the Laacher See Tephra (**LST**) and its temporal relation to the onset of the Younger Dryas (modified after Wulf *et al.*, 2013)

allochthonous sediments from the catchment is negligible. Varve formation and preservation since AD 1924 is favoured by enhanced lake productivity due to modern anthropogenic eutrophication. This modern varve interval is the last of a sequence of recurring varve intervals throughout the Holocene (Dräger *et al.*, 2017; Fig. 6).

The varved sedimentary intervals are characterized by higher organic carbon contents and more positive δ^{13}C values of the organic matter, both indicating anoxic deep-water conditions that favour varve preservation. In contrast, non-varved sedimentary intervals show lower organic carbon contents and more negative δ^{13}C values of the organic matter, indicating predominantly oxic deep-water conditions. Consequently, the alternation of varved and non-varved sedimentation likely is related to centennial-scale variations in water circulation and mixing (Dräger *et al.*, 2019). Lake-level reconstructions revealed an overall amplitude of fluctuations of about 10 m during the Holocene, with the highest fluctuations during the Early and Late Holocene. Centennial to decadal-scale fluctuations are superimposed on the general trend of increasing water level with lowest stands during the Early Holocene (Theuer-kauf *et al.*, 2021). It is assumed that land cover changes in the lake catchment contributed to the observed lake

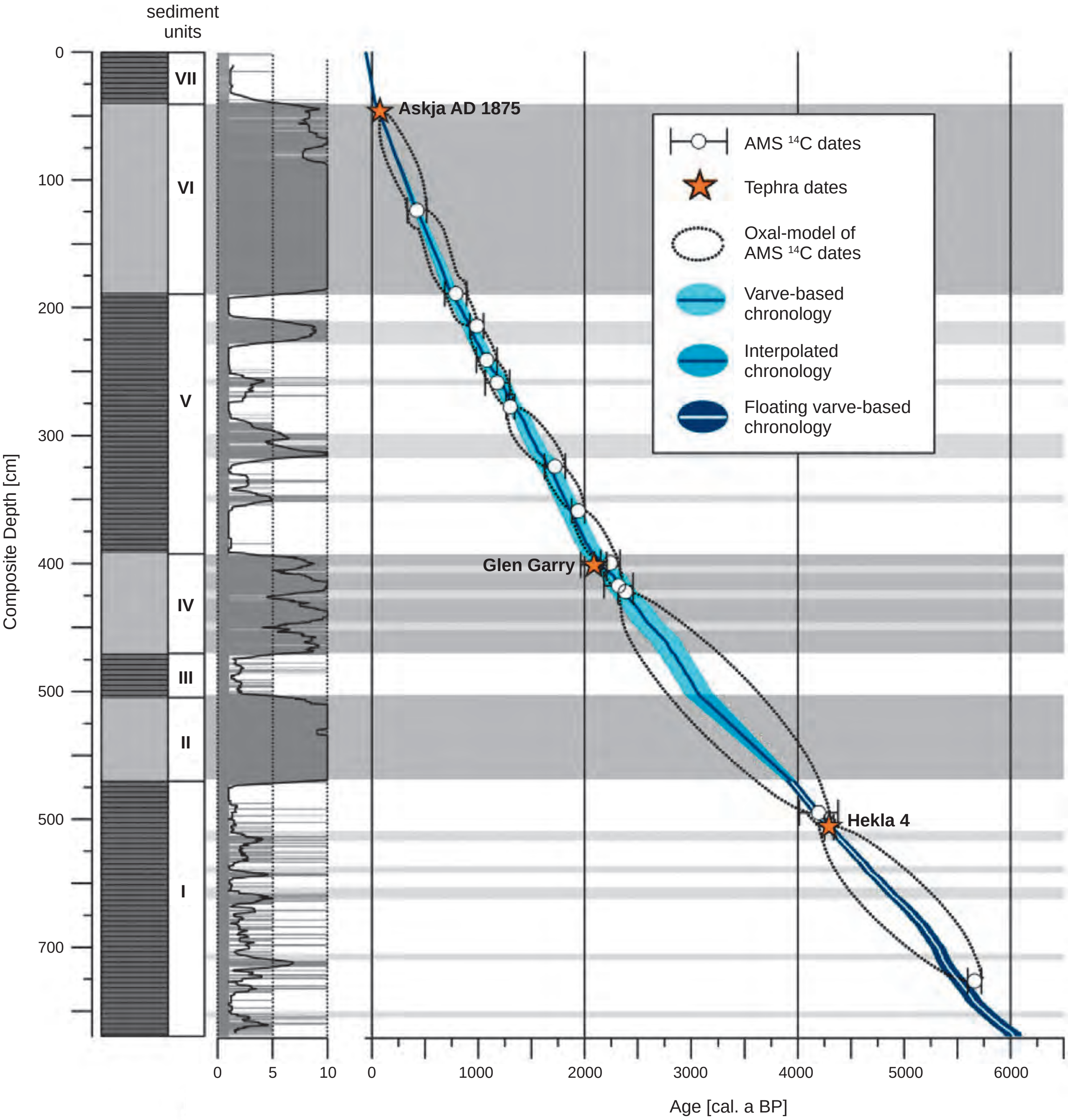

Fig. 6. Age–depth model of the Lake Tiefer See composite profile. Units **I**, **III**, **V**, **VII** – annually laminated gyttja; units **II**, **IV**, **VI** – homogeneous gyttja (modified after Dräger *et al.*, 2016)

level variations because the large amplitudes are difficult to explain as driven by climate change alone.

DISCUSSION

Lake formation

The development of the lakes studied was associated with the melting of buried blocks of dead ice in tunnel valleys, which in the young-glacial areas of the Central European Lowland was closely related to the degradation of permafrost together with thermokarst processes (Błaszkiewicz, 2011; Błaszkiewicz *et al.*, 2015). The course of melting of dead ice blocks was determined, alongside global climate changes in the Late Glacial, by local factors – mainly the relation of the tunnel valleys filled with dead ice blocks to the hydrographic network. Hence, the lakes in young-glacial areas did not form synchronously. In terms of the onset time of lake sedimentation, three generations of lakes are distinguished: Pre-Bølling lakes, lakes of the Bølling–Allerød interval, and lakes that formed only early in the Holocene (Błaszkiewicz, 2005, 2011; Błaszkiewicz *et al.*, 2015; Słowiński *et al.*, 2015). Generally, for all lakes described in this publication, the beginning of lacustrine sedimentation took place in the Allerød.

Climate of the Allerød and Younger Dryas

Varve formation in the lakes studied commenced in the late Allerød. Analyses of Chironomidae from sediment cores of Lake Gościąż indicate that average July temperatures ranged from 16 to 17°C (Müller *et al.*, 2021; Płóciennik *et al.*, 2022), which is consistent with reconstructions based on analyses of pollen and plant macrofossils (Goslar *et al.*, 1998; Ralska-Jasiewiczowa *et al.*, 1998). Generally, very stable environmental conditions prevailed at that time in all the lakes studied with only weak water circulation and low bioproduction. These conditions were related to the lack of significant erosion in the catchments and low nutrient supply to the lakes. Similar conclusions based on the analysis of lake deposits have been drawn also for other lakes in central Europe (Brauer *et al.*, 1999).

The transition from the relatively warm climatic conditions during the Allerød to the cold Younger Dryas was abrupt, lasting not >50–100 years (Müller *et al.*, 2021; Płóciennik *et al.*, 2022). The precise tephrochronological correlation of the palaeolake Trzechowskie sedimentary record with those from Meerfelder Maar in the Eifel region (Brauer *et al.*, 1999; Brauer *et al.*, 2008) and the palaeolake Rehwiese in northeastern Germany (Neugebauer *et al.*, 2012; Wulf *et al.*, 2013) allowed the detection of slightly varying environmental responses around these sites at the beginning of the Younger Dryas cooling (Słowiński *et al.*, 2017). The first environmental response of the palaeolake Trzechowskie to the Younger Dryas cooling was related to increased erosion in the catchment area. Changes in the catchment and lake biota of the palaeolake Trzechowskie occurred only with a several-decades delay relative to the environmental response in the Meerfelder Maar catchment (Fig. 5). These temporal differences in environmental responses to the Younger Dryas cooling were most likely related to the differences in degree of climate continentality (Słowiński *et al.*, 2017).

The course of climate change during the Younger Dryas is best recorded in the annually laminated deposits of Lake Gościąż (Goslar *et al.*, 1995; Goslar *et al.*, 2000; Műller *et al.*, 2021; Płóciennik *et al.*, 2022). The Allerød/Younger Dryas boundary in this sedimentary record is dated at 12,620 +133/–231 cal. a BP and the Younger Dryas/Preboreal boundary at 11,470 +126/–206 cal. a BP, while the duration of the Younger Dryas was more precisely determined at 1149 +14/–22 years (Müller *et al.*, 2021; Bonk *et al.*, 2021). The first half of the Younger Dryas was colder than the second, while the annual cycle was characterized by relatively mild, short summers with average July temperatures ~14°C and very long and severe winters, with average temperatures in the coldest month around –20°C (Müller *et al.*, 2021). It is generally accepted that the mean annual air temperatures decreased rapidly by at least 5°C relative to the end of the Allerød (Goslar *et al.*, 1998; Kuc *et al.*, 1998). The consequence of such profound climate changes was the inhibition of the degradation of permafrost and also the melting of buried blocks of dead ice that survived the warming of the Bølling–Allerød interval (Błaszkiewicz, 2011; Błaszkiewicz *et al.*, 2015; Słowiński *et al.*, 2015). In some areas of Poland, partial aggradation of permafrost in the Younger Dryas has been recorded in the youngest cryogenic structures (Błaszkiewicz, 2011; Van Loon *et al.*, 2012; Petera-Zganiacz, Dzieduszyńska, 2017).

Climate in the Holocene

Holocene climatic changes are clearly attenuated compared to those during the transition from glacial to interglacial conditions. The last major climatic shift thus occurred at the transition from the Younger Dryas to the Holocene when summer temperatures increased markedly to >14.6°C in the period 11,500–11,495 cal. a BP to >17°C in the period 11,470–11,475 cal. a BP and ~18°C in the period 11,445–11,450 cal. a BP. In turn, annual precipitation at the beginning of the Holocene was 400–500 mm (Müller *et al.*, 2021; Płóciennik *et al.*, 2022). The annually laminated lake deposits record several short, climate oscillations, although these were not of the same amplitude as the Younger Dryas cooling. Commonly known multi-decadal Holocene fluctuations are the Preboreal oscillation and the oscillations at around 8.2 and 4.2 ka cal. BP. These short climatic changes often are difficult to detect in sedimentary records (Björck *et al.*, 1996). Indications for the Preboreal oscillation were reported from the deposits of Lake Czechowskie and supported by two cryptotephra finds (Hässeldalen and Askja-S Tephras), (Fig. 4). However, the oscillation is reflected only in sediment geochemistry changes as a drier and cooler period, lasting 178 ±3 varve years (Ott *et al.*, 2016). The Preboreal oscillation is more clearly recorded in the laminated deposits of the nearby Lake Jelonek in the Tuchola Forest. Its first part, dated 11,450–11,300 cal. a BP, was also characterized by a continental climate (colder and drier), while the second one, lasting between 11,300 and 11,150 cal. a BP, was more humid (Kramkowski *et al.*, 2023). The Preboreal oscillation and the oscillation around 8.2 ka cal. BP have been recognized mainly in pollen, Cladocera and isotope records in several sites in northern Poland (Wacnik, 2009; Lauterbach *et al.*, 2011; Fiłoc *et al.*, 2016) but not in the records studied from the lakes Czechowskie and Tiefer See. In the Lake Czechowskie deposits, a transition from calcite to diatomaceous-calcite varves is observed at 4.2 ka cal. BP, while the Homeric Minimum around ~2.8 ka cal BP is marked by a distinct thickening and greater internal compositional differentiation of varves. Similar lithofacies changes were also recorded in the Late Holocene deposits of Lake Gościąż, but from the beginning of the Homeric Minimum the varves are very poorly preserved, likely due to increased redeposition. The preservation of varves in Lake Gościąż improves again with the onset of the Little Ice Age, which may be related to changes in mixing and bioproduction induced by a longer persistence of ice cover (Bonk *et al.*, 2021). The deposits from Tiefer See do not show a clear change at 4.2 ka cal. BP but at the onset of the Homeric Minimum one of the laminated intervals ended.

CONCLUSIONS

In general, the amplitudes of Late Glacial climatic shifts such as the Younger Dryas cold period were much more pronounced than short-term Holocene oscillations. Consequently, the transition from the Younger Dryas to the Holocene is distinctly reflected in inferred sedimentation processes and in all proxy data analysed in the lake records along a west–east transect in the Southern Baltic Lowlands. In this region, a stable environment with dense vegetation had developed early in the Holocene and was only disrupted in the Late Holocene by anthropogenic activity. Therefore, the lake environments were largely resilient to the lower-amplitude Holocene climatic variability. Consequently, the response of the lake records studied to climate changes is only weak and some of the known fluctuations are not recorded at all. Dating uncertainties can be excluded as explanation for the differences between the lake records because the independently dated varve records are precisely correlated based on tephrochronology (Wulf *et al.*, 2016) and ^{10}Be analyses (Czymzik *et al.*, 2018). Although the sedimentary response in these lakes to centennial and decadal fluctuations is neither uniform nor synchronous due to regional climatic differences and local effects of the lake basins, all the lake records reveal a long-term trend throughout the Holocene mainly expressed by increasing sedimentation rates and, in some cases, by a greater complexity of varve structures. This trend might be related to the long-term changes in insolation with increasing winter and decreasing summer insolation. The particular value of these varved lake records is their potential to record local environmental responses both to global climate changes and to anthropogenic activity. This information is crucial to develop effective adaptation measures to the expected future climate changes.

Acknowledgements. We would like to thank the reviewers L. Marks and A. Börner for their very valuable comments and suggestions, which helped us to improve the quality of this paper.

This study is a contribution to the project no. 2019/34/E/ST10/00275 funded by the National Science Centre.

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The work was received by the editorial office on 20.12.2024
Accepted for printing on 13.01.2025

View of Teide in the Canary Islands archipelago. Photo by S. Wołkowicz