HYDROLOGICAL CHANGES AFTER THE LAST ICE RETREAT IN NORTHERN POLAND USING RADIOCARBON DATING

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ABSTRACT. A simplified model of hydrological changes during the Late Glacial and Holocene is presented for the northern Polish regions that were ice covered during the Last Glacial. This reconstruction is based on a group of 197 radiocarbon dates from about 120 localities reflecting the sequence of alternating lake transgressions and regressions. The earliest transgressions were related to dead-ice melting (sometimes in 2–3 phases), while the later ones started during more humid phases. However, these were usually followed by regressions, which may have been connected with the formation of new drainage systems and with the overgrowing of shallow lakes by peat bogs.

INTRODUCTION

Reconstructions of climate changes in Poland are based mainly on the dating of samples from sites in southern Poland. The richness of the sedimentation environments in this region has allowed the reconstruction not so much of the thermal fluctuations, but rather of the amount of rainfall and fluctuations in the water cycle over a long period. The reconstructions have included the study and dating of the following records: fluvial sediments (e.g. Starkel 1983; Macklin et al. 2006; Starkel et al. 1996b, 2006); peatbog cores (Michczyńska and Pazdur 2004; Michczyńska et al. 2007); landslides (Margielewski 2006); speleothems (Pazdur et al. 1995; Michczyńska et al. 2007); calcareous tufa (Pazdur et al. 1988, 2002a,b); and debris flows and lake sediments in the Tatra Mountains (Kotarba and Baumgart-Kotarba 1997). The most commonly used proxies were pollen and macrofossil analysis, especially for lake and peatbog environments (e.g. Ralska-Jasiewiczowa 1989; Ralska-Jasiewiczowa and Latałowa 1996; Ralska-Jasiewiczowa et al. 1998b, 2004), as well as Cladocera (Szeroczyńska 1998).

The occurrence of a series of synchronous, alternately wet and dry phases, clearly indicated in the sedimentary archives, has been the subject of many previous studies (e.g. Starkel 1983, 1991, 2002, 2003; Ralska-Jasiewiczowa and Starkel 1988). Recently, these studies, together with those mentioned above, were summarized and a chronostratigraphic subdivision of the Holocene for Polish territory, in calendar years, was proposed (Starkel et al. 2013). Moreover, these records are in accord with fluctuations in the upper limit of forests and advances of glaciers in the Alps (Magny 1993).

Northern Poland (Figure 1) does not have such a diversity of records. Most of the existing records are associated with 2 sedimentation environments: lakes and mires. It is nevertheless worth stressing that numerous papers dealing with climate and environmental reconstructions from the area covered by the last glaciation have been published. These are primarily in the form of extensive paleobotanical data (e.g. Kupryjanowicz 2007; Wacnik 2009; Lauterbach et al. 2011; Gałka and Sznel 2013; Kołaczek et al. 2013), but also increasingly in the form of geochemical and isotopic data, e.g. Apolinarska et al. (2012), Lauterbach et al. (2010), or papers concerning permafrost (Błaszkiewicz 2011; van Loon et al. 2012). The recorded changes show the complexity of the phenomena associated with

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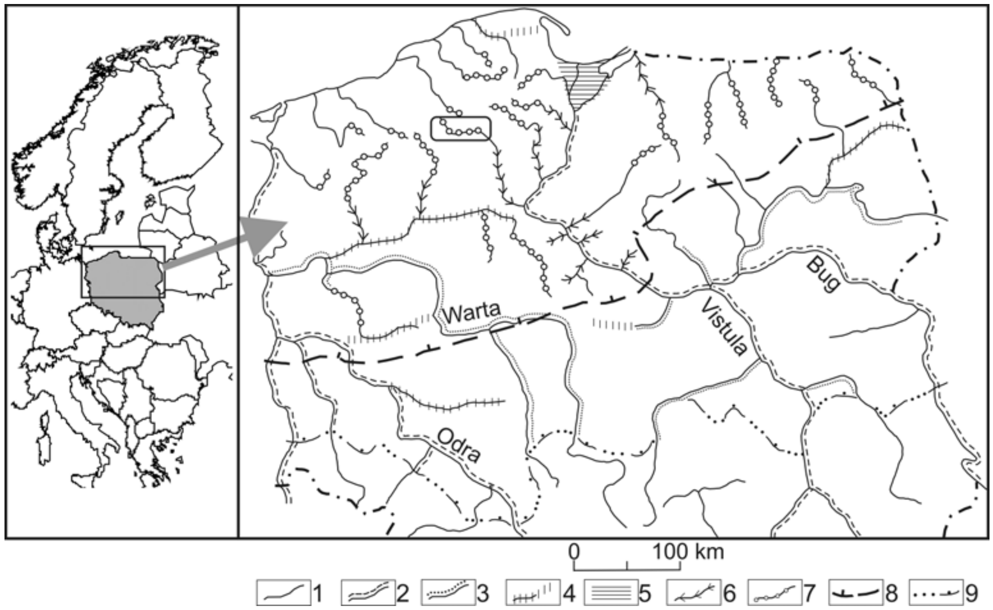

Figure 1 River system and transfluent lakes in the Polish Lowland. There are marked types of valley floor reflecting the Holocene climatic changes (modified after Starkel 2008). The area presented in Figure 2 is marked by the rounded rectangle. 1 – rivers, 2 – valleys of the large transitional rivers, 3 – valleys of other large rivers with developed systems of fills and palaeochannels, 4 – inherited ice-marginal stream ways, 5 – deltaic and coastal plains, 6 – tributary river valleys incised or still not rejuvenated, 7 – system of young river valleys with transfluent lakes, 8 – extent of young postglacial landscape (extent of the ice sheet during the Last Glacial Maximum), 9 – boundary of lowland relief.

the formation of new landscape after the retreat of the Scandinavian ice sheet. Among these phenomena were, initially, dead-ice melting (melting of blocks of ice preserved in the ground), followed by the formation of lakes, with their alternate phases of expansion and recession, which should reflect fluctuations in precipitation. However, in northern Poland, these fluctuations have a more complex history. The formation of a new network of rivers led to the incorporation of lakes into this network, along with their drainage, while they were simultaneously being overgrown from the shore, and gradually filled in.

The dead-ice melting took place in the former systems of subglacial channels with evortional kettle holes, buried channels over outwash plains filled in by ice, or the separated dead-ice blocks in the hilly relief of ice marginal zones. In all these depressions, a short phase of peat formation was followed by the growth of lake basins, which should reflect fluctuations in precipitation and the whole water balance. However, these natural trends displayed several deviations in this young landscape, which led to the raising or lowering of water levels.

The rise in lake level resulted from the filling in of the lake basin by gyttja and other limnic deposits. This was a natural trend during the entire Holocene. Such a lake transgression was combined with surficial overgrowing of the littoral zone by biogenic sediments, and may finally, owing to the rise in evaporation, have resulted in a lowering of the lake level. An additional factor causing a rise in groundwater level in closed depressions, and even the formation of bogs and shallow new lakes, is connected with deforestation, which causes a rapid decline in evapotranspiration. This was documented in Roman times (in Great Poland; Borówko 1990).

On the other hand, the lowering of the water level is a function of the formation of a new drainage system and the gradual inclusion of higher and higher elevated lakes on the morainic plateau. A very good example is that of the elevated ridge of the Pomeranian stage, with rivers draining off transfluent lakes (which are sometimes totally overgrown) and the start of streams from the uppermost lakes in the elevated part of the marginal zone. We may observe both of these on the northern slope of the Pomeranian elevation, e.g. the rivers Słupia, Łupawa (Florek 1991; Florek et al. 1999), and Radunia (Koutaniemi and Rachocki 1981) flowing directly to the Baltic Sea, as well as on the southern slope, towards the Toruń-Eberswalde ice marginal streamway, e.g. the rivers Wierzyca, Wda, and Brda (Błaszkiewicz 1998, 2005; Starkel 2008). An example of a river flowing through numerous transfluent lakes is presented in Figure 2. Only in the watershed zone do there still exist small depressions that were not drained, and these probably reflect fluctuations in rainfall and water budget, similar to those observed in southern Poland.

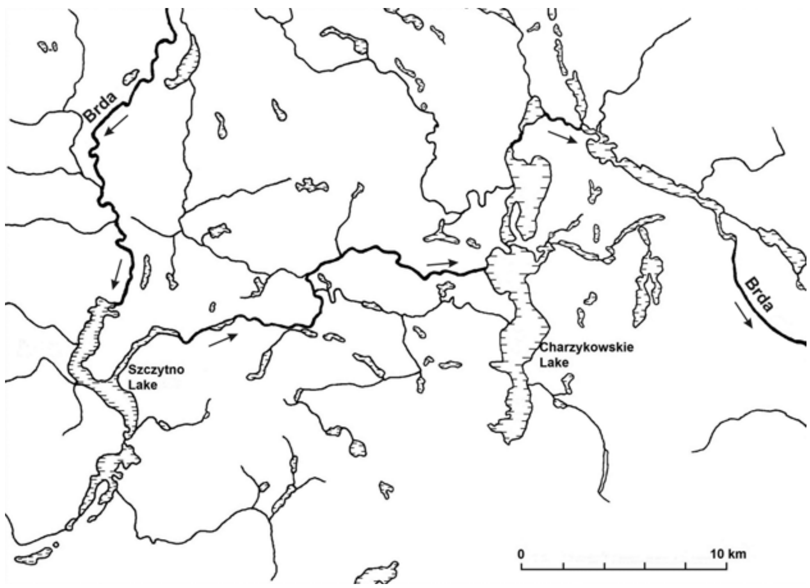

Figure 2 Part of the upper Brda River catchment (Pomeranian Lakeland), with numerous transfluent lakes, as an example of a young river (modified after Starkel 2008). Such a river gradually incorporates dead-ice depressions, subglacial channels with lakes, outwash plains, and the narrow gaps between them. Its presence is critical for the alternating phases of peat formation and lacustrine sedimentation. The phenomena observed in bogs, mires, and the river network depend on each other.

Theoretically, all these factors have been taken into consideration by many authors (e.g. Błaszkiewicz 2005; Starkel 2008; Kaiser et al. 2012), but they still have usually not been sufficiently dated and well illustrated. A unique example is offered by Lake Gościąż and its surrounding depression, which is drained by a small creek, the Ruda. Several dozen borings in the littoral zone, well dated by ^{14}C, and the basic (reference) profile of the deep kettle (with its annually laminated sediment), enabled the reconstruction of the lake-level changes and established the influence of the various factors involved (Starkel et al. 1996a; Ralska-Jasiewiczowa et al. 1998a).

The reconstructed volume of Lake Gościąż, in the Allerød, had reached 8.3×10^6 m^3 after a fall; then, during the next rise, about 9.5–8.5 ka cal BP, Lake Gościąż had been joined to 3 other shallow lakes. After this, there started the gradual drainage of the whole system and overgrowing of all the shallow parts by peat (Starkel et al. 1998a,b). Similar conditions were documented in the Stara Kiszewa post-lake depression, in the Wierzyca Valley, where the higher lacustrine terrace rises to 8–10 m (Błaszkiewicz 1998), as well as in Lake Biskupin (Niewiarowski et al 1995). The latter transgression took place at about 2.5 ka cal BP, which is demonstrated by erosional terrace and calcareous gyttja, covered yet later by peat (Ralska-Jasiewiczowa et al. 1998a). On that occasion, the volume of the lake reached 3.6×10^6 m^3 and the volume of lacustrine deposits may have reached 1.5×10^6 m^3. The present-day volume of Lake Gościąż is only 2×10^6 m^3 and is lower than the volume of the lake sediments (cf. Ralska-Jasiewiczowa et al. 1998a and Figure 3).

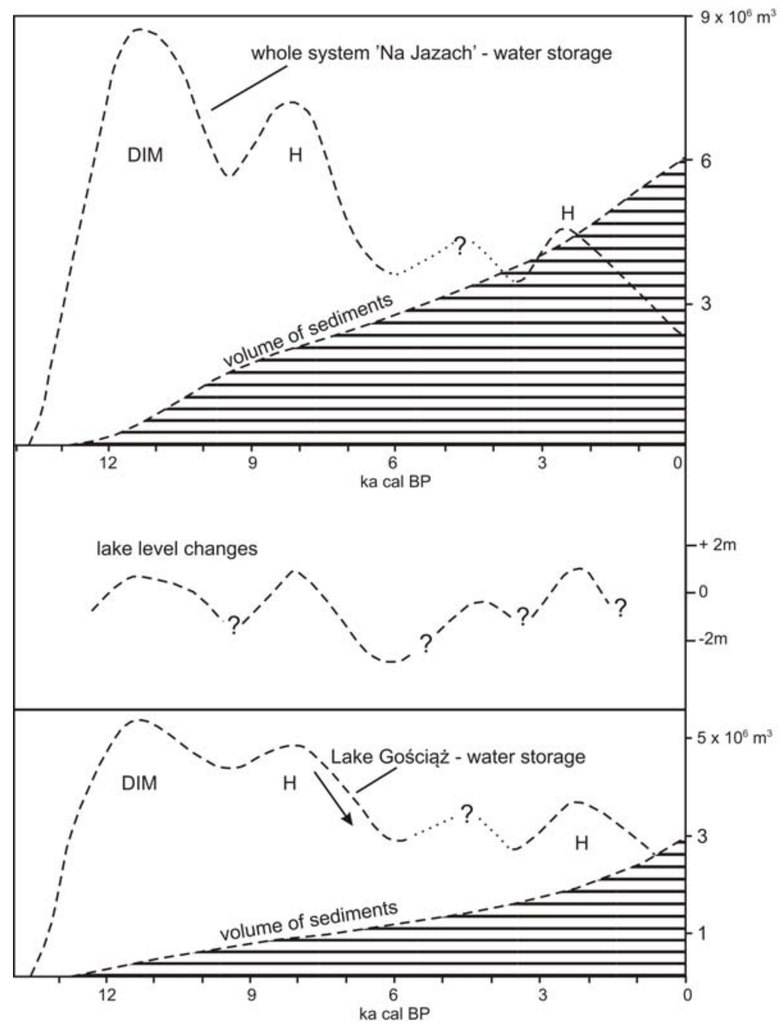

Figure 3 Changes in water storage (volume of lakes) and deposition during last 13,500 cal BP. Above – the whole Na Jazach lake system; below – Lake Gościąż only; center – water-level changes of Lake Gościąż. DIM – dead-ice melting phase; H – humid phase. Arrow indicates drainage through Ruda creek (after Starkel et al. 1998a, redrawn with permission of the W Szafer Institute of Botany, Polish Academy of Sciences).

Taking all these factors into consideration, we can understand why particular lakes within the deglaciation area of the last Scandinavian ice sheet showed different patterns of lake-level changes, depending on local conditions (Starkel 2003). The example of the detailed study of Lake Gościąż shows that, without such investigations, it is not possible to document and separate out the roles of the various factors. Nevertheless, the dating of the sequence of changes, from peat to lacustrine, and back, from gyttja to peat, may demonstrate some regularities in the evolution of lake systems and changes in the hydrological budget.

MATERIALS AND METHODS

The reconstruction of the hydrological changes in the area of the last ice retreat is based on a group of 197 ^{14}C dates. The ages of the transitions from lacustrine sedimentation to peat formation, and from peat formation to the lacustrine stage, as well as the ages of the so-called basal-peat, i.e. the initial organic deposits that formed in the dead-ice depressions, were used as a proxy. The records from 128 lakes and bogs were used. The locations of the sampling sites are presented in Figure 4, together with the extension of the ice sheet during the Last Glacial Maximum. It was decided to use peat samples in the analysis primarily because the dates obtained for the lacustrine sediments may be burdened by a reservoir effect. For this reason, in order to study the transitions from peat formation to the lacustrine stage, dates for the samples collected from the top of the peat layers below the lacustrine sediments were used. To study transitions from the lacustrine sedimentation to peat formation, dates for the samples from the bottom of the peat layers, above the lacustrine sediments (176 dates altogether). Only 19 dates obtained from gyttja, 1 from wood, and 1 from organic matter were used. Most of the dates are recorded in the Gliwice Radiocarbon Laboratory Data Base (RoS; Piotrowska et al. 2004). The remaining dates were taken from a paper by Błaszkiewicz (2011).

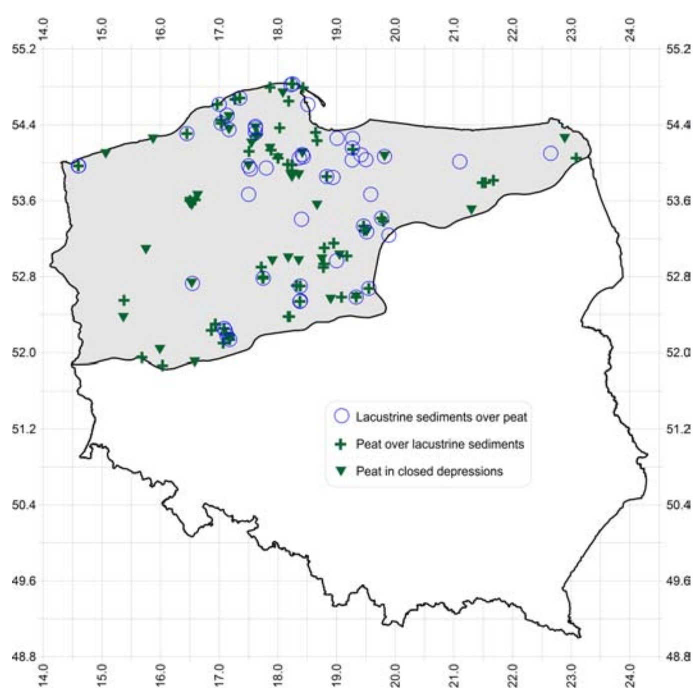

Figure 4 Locations of analyzed sampling sites within the range of the Last Glacial Maximum extent. Samples were collected from 128 lakes and bogs.

An analysis of the frequency distribution of transition dates can be helpful in assessing regional hydrological changes. A rather obvious rule was applied here: if data are collected from many places, the signs in common are then increased, and the signs concerning local changes (or connected with random dates) are smoothed. As a result, if there is any common sign in the chosen group, we can expect peaks in the frequency distribution of the dates. The use of summed probability curves of ^{14}C dates is widespread in paleoclimatic studies, as well as in archaeology. They have been used for the analysis of sea-level changes (e.g. Geyh 1980), fluvial activity (e.g. Macklin et al. 2006; Starkel et al. 2006; Hoffmann et al. 2008), environmental changes (Michczyńska et al. 2007), chronostratigraphic reconstruction (Michczyńska and Hajdas 2010; Starkel et al. 2013), and in numerous archaeological papers as a proxy record of human occupation (Williams 2012 and references therein). The limitations of the method have been discussed in a number of studies (Michczyńska and Pazdur 2004; Michczyński and Michczyńska 2006; Michczyńska et al. 2007; Surovell et al. 2009).

To study the chronological order of the appearance of lakes and the peat formation processes on a calendar timescale, probability density functions (PDFs) were constructed by summing up the probability distributions for particular dates. These PDFs were constructed using the Sum option in the OxCal program (Bronk Ramsey 2009) and the IntCal09 calibration curve (Reimer et al. 2009).

RESULTS AND DISCUSSION

The results of this study are presented in Figure 5. A PDF curve for the ^{14}C ages obtained from the peat formed above the lacustrine sediments is shown in Figure 5a (78 ^{14}C dates). In addition, in the same figure, the total PDF curve is presented for peat formed on top of the lacustrine sediments, and for the bottommost peat in closed dead-ice depressions (137 ^{14}C dates altogether). In the lower panel (Figure 5b), a PDF curve for the lacustrine sediments deposited on top of the peat layer is shown (60 ^{14}C dates). Even though the amount of data is relatively modest, the probability density functions (PDFs) of ^{14}C dates from northern Poland enable the identification of hydrological changes during the past 15,000 yr.

The first 4 maxima of the curve in Figure 5a (marked by numbers 1–4 on the curve for 137 ^{14}C dates) represent the dating of material from the bottommost peat sections in the closed dead-ice depressions, and they prove the existence of peat formation processes at the end of the Late Glacial and beginning of the Holocene. The dates obtained from the lowermost peat layers covering the lacustrine sediments indicate a lowering of the lake level. A very rapid change to lowering only 1–3 centuries after the maximum rise may not be explained only by a drop in precipitation. In the opinion of the authors, it resulted from inclusion of lakes into the drainage system or by the overgrowth of lakes.

The first and third maxima on the PDF curve for lacustrine sedimentation on top of peat (marked by numbers in Figure 5b), observed at 14,500–13,500, 11,300–10,500 cal BP, result from dead-ice melting. The first appearance of the lake reservoirs dated to the Allerød, recorded in a number of paleoenvironmental publications (e.g. Lake Gościąż [Ralska-Jasiewiczowa 1989], Lake Biskupin [Niewiarowski et al. 1995], Lake Mikołajki [Pawlikowski et al. 1982], Lake Skrzynka [Apolinarska et al. 2012], the Osonki site [Nalepka 2005; Nowaczyk 2008], Eastern Pomeranian [Błaszkiewicz 2011; van Loon et al. 2012]), indicates the melting of dead-ice blocks. The younger maximum, at 11,300–10,500 cal BP, from the beginning of the Holocene, was clearly delayed by 200–300 yr in comparison with the climate change at the YD/PB transition. It should be seen as linked to the gradual warming of the deeper layers of the ground.

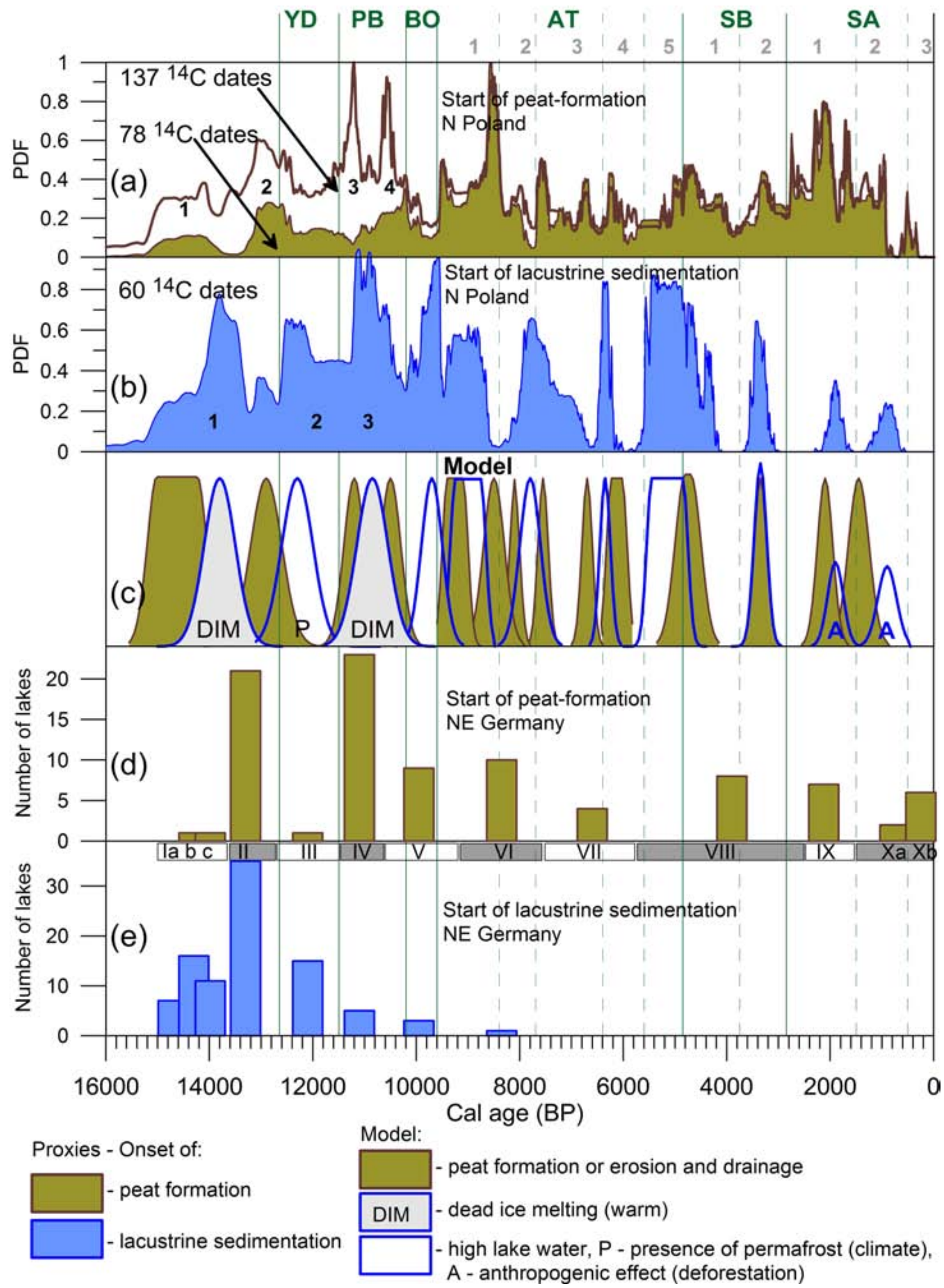

Figure 5 (a) Probability density function (PDF) obtained for peat samples above the lacustrine sediments, i.e. 78 ^{14}C dates. On the same graph is presented the total PDF for 137 ^{14}C dates representing the start of peat formation (78 dates for peat above lacustrine sediments and 59 dates for the bottommost peat in closed dead-ice depressions); (b) PDF for dates of transition from peat formation into lacustrine sedimentation (60 dates); (c) simplified model of hydrological changes in N Poland; (d) start of peat formation in NE Germany (modified after Kaiser et al. 2012); (e) start of lacustrine sedimentation in NE Germany (modified after Kaiser et al. 2012); The number of lakes was been determined for particular palynozones. The timing of the palynozones is marked by the line between (d) and (e). The chronozone boundaries proposed by Starkel et al. (2013) are indicated by vertical lines.

The middle maximum (12,600–11,800) from the Younger Dryas (YD) may be connected with the frozen ground. The appearance of shallow water reservoirs above the peat in the YD are connected not so much with the humid phase, but may be explained by the appearance of periodic permafrost in depressions. This is confirmed by contemporary observations: namely, the appearance of shallow water bodies in depressions, while the ground is still frozen after a cold winter. The presence of frozen ground during the YD is evidenced in periglacial structures throughout the central European lowland (e.g. Kozarski 1986, 1993; Vandenberghe 2006). The start of lacustrine sedimentation has been noted for the whole YD, but it seems to have been more intensive during the first half of the YD. It is interesting that the first phase of the YD was humid in the Netherlands (cf. Hoek and Bohncke 2002), but the authors did draw conclusions that are too far-reaching. It is difficult to compare both regions, as the Netherlands was not ice-covered during the LGM and was under the strong influence of the Atlantic Ocean.

The next 2 “lacustrine” peaks (from 9700 ± 200 and 9000 ± 400 cal BP) correlate well with the high humidity phase, 9500–8500 cal BP, registered in various litho-facies of sediments throughout Poland (Starkel 1999; Starkel et al. 2006, 2013). This phase resulted in an increase in the number and depth of lakes. This wet period was followed by the expansion of peat formation, which overgrew the lakes, and was probably also due to their drainage during their incorporation into river network systems (Koutaniemi and Rachocki 1981).

It is worth stressing that, as indicated above, the oldest periods of lacustrine sedimentation are in general accord with the periods of lacustrine sedimentation near Lake Gościąż (Pazdur et al. 1994). The beginning of lacustrine sedimentation in this area has been established as having been several centuries before 11,440 ± 300 ^{14}C BP, which, on the calendar scale, corresponds to several centuries before 13,700–12,900 cal BP. The next lacustrine sedimentation was noted as having been between 8200 and 7000 ^{14}C BP, which, on the calendar scale, corresponds to 9500–7700 cal BP (cf. Figure 3). The low precision of the calendar ages for these periods was due to the need for reservoir effect corrections (2000 ± 120 yr having been assumed; for details, see Pazdur et al. 1994).

The next few phases of lake transgression correspond to the humid periods 7800 ± 200, 6350 ± 100, 5150 ± 400, and 3350 ± 120 cal BP. The Subatlantic period was a time when the overgrowth of lakes was common. Some individual dates from Figure 5b indicate elevated water levels, well documented as humid phase in Lake Gościąż about 2500 cal BP (see Figure 3). The younger 2 peaks are probably due to anthropogenic effects. Deforestation and agriculture might have led to a reduction in evapotranspiration and to the emergence of new reservoirs (cf. Borówko 1990).

This appears to be a pattern. Lake transgression is observed as a result of the humid phase (or dead-ice melting); next, after a short delay (of 100–300 yr), the recession of lakes and expansion of peat is usually recorded. The latter has its source in the drainage of lakes (Koutaniemi and Rachocki 1981; Starkel 2008) and their being overgrown (Iversen 1958; Birks 1986). In particular cases, it is difficult to separate these 2 processes, but both have been documented by the authors for several lake systems (e.g. in Lake Gościąż; see previous section).

The alternating processes observed—the onset of lacustrine sedimentation (Figure 5b) and the onset of peat formation (Figure 5a)—are simplified and summarized in Figure 5c (Model). Each of these phases is presented as a Gaussian-type peak (though some of the peaks are flat-topped). The lacustrine phases were the result of climate change. Two of them are the result of warming and dead-ice melting depressions (peaks with the letters DIM in Figure 5c), 1 is the result of permafrost (the peak with the letter P in Figure 5c), and the rest are the result of humid conditions. Environmental changes after 4000 cal BP were under the influence of human activity, and the last 2 lacustrine phases were the effect of deforestation (peaks with the letter A in Figure 5c). Deforestation results in a rise of the groundwater table and the appearance of shallow lakes in the depressions. "Peat phases" are the result of the overgrowth of lakes, frequently combined with an incorporation of lakes into the river network. These 2 processes are not distinguished in Figure 5c.

Hydrological changes in northern Poland were compared with analogous changes in northeastern Germany. Information about the onsets of lacustrine sedimentation and onsets of peat formation from NE German regions that were also ice-covered during the Last Glacial has recently been presented by Kaiser et al. (2012). The general accord of the lacustrine sedimentation and peat formation phases is visible (see Figure 5d–e). A more detailed comparison is not possible, because the results for NE Germany were presented only for particular palynozones, without providing detailed information about calendar age or discussion about the genesis of the recorded phases.

SUMMARY

The authors selected 197 ^{14}C dates from the area of the last ice sheet deglaciation in northern Poland. Samples from the lowermost parts of the peat profiles on top of lacustrine sediments or mineral fractions, as well as samples from the uppermost parts of the peat profiles directly under lacustrine sediments, were taken for analysis. PDFs of the ^{14}C dates were built to establish the sequence of events. There is a clearly visible anti-correlation of the curves from Figures 5a and 5b. The observed sequences of events allowed the building of a simplified model of environmental changes (Figure 5c). Each "lacustrine phase" was followed by a "peat formation phase." The expansion of peat appeared, as was usual, 100–300 yr after the lake transgression, and was connected with the incision of a river channel and the drainage of lakes. The general consistency between the hydrological changes recorded in both the Polish and German young postglacial areas was presented.

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