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Early Holocene hydrology and environments of the Ner River (Poland)

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ABSTRACT

The Ner River valley (central Poland) underwent substantial transformation during the Weichselian–Holocene transition as a result of fluvial processes and climate changes, resulting in the establishment of its present shape in the Holocene. A multiproxy study based on organic deposits from a palaeochannel fill (Lutomiersk–Koziówki) shows that after the channel was cut off during the late glacial termination, it became a shallow oxbow, fed by local springs. In the Boreal period, the oxbow lake was also fed by precipitation and became a telmatic environment overgrown by rush and swamp vegetation. Finally, it was covered by overbank deposits. The first flooding phase (9900–9600 cal. BP) was followed by the accumulation of overbank sediments (after 9500 cal. BP) and flooding increased after ca. 9300–9000 cal. BP. Pollen data provide information on the regional vegetation context for local and regional changes. In the Atlantic period, an increase in both summer and winter temperatures is inferred from the pollen data, corresponding to an expansion of thermophilous deciduous forests. While in general, flooding phases of the Early Holocene are poorly recognised in Eastern Europe, the Lutomiersk–Koziówki site may be considered as one of the reference points for this phenomenon in the region.

Introduction

High climatic variability for the early Holocene in the European temperate zone is documented by numerous detailed multiproxy studies in recent years (e.g. Bond et al., 2001; Hoek and Bos, 2007; Magny et al., 2007; Ortu et al., 2010). This climatic variability resulted in a sequence of rapid palaeoenvironmental changes, as well as phases of intensified geomorphological processes and a clustering of extreme events (Starkel, 2002a, 2002b).

Based on the Greenland Ice Core Chronology 2005 time scale (GICC05) (Rasmussen et al., 2006), three main periods of distinct oscillations in the stable oxygen isotopic record were recognised in Greenland ice-cores by Rasmussen et al. (2007): the Preboreal Oscillation (PBO, between ca. 11,500–11,300 cal yr BP), the 9.3 ka event, and the 8.2 ka event. There was also an isotopic anomaly at 9950 cal yr BP.

In terrestrial record, the PBO and cold event at 9500–9200 cal yr BP have been defined by Björck et al. (1997) and the short event at ca. 10,300 cal yr BP (Boreal oscillation) by Björck et al. (2001). The very distinct 8.2 ka event was recognised for the first time by Alley et al. (1997) and von Grafenstein et al. (1998). Clustering of globally-recorded events during the 8500–8000 cal yr BP interval was noted by Starkel (2002a, 2002b). Dry and cool climatic conditions of the 8.2 ka event in the Northern Hemisphere have been reconstructed as having lasted 150–160.5 years, between 8.3 ka and 8 ka with a peak of cooling taking place 60–69 yr into this interval (Thomas et al., 2007; Baker, 2012). The 8.2 ka event was generally cold and dry, especially in winter, but in North-West Europe (e.g. Scandinavia) it might be characterised by cool and wet summers (Alley and Áugústsdóttir, 2005; Baker, 2012). It caused remarkable changes in plant communities including Central Europe over 180 years (Baker, 2012). According to the reconstructions of Magny and Bégeot (2004) and Magny et al. (2003, 2007), Central Europe experienced wet conditions, but northern (including central Poland) and southern Europe experienced drier conditions during the 8.2 ka event (see also Morrill et al., 2013).

The Preboreal (11,750–10,650 cal yr BP) climatic oscillation is widely recorded in the vegetation history of western and central Europe

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(Welten, 1958; Zoller, 1960; Wijmstra and de Vin, 1971; Iversen, 1973; Behre, 1978; van Geel et al., 1981; Lotter et al., 1992; Ammann et al., 1994; Björck et al., 1997; Haas et al., 1998; Wick, 2000; Bos, 2001; Ralska-Jasiewiczowa et al., 2003; Bohncke and Hoek, 2007; Bos et al., 2007; Stančikaitė et al., 2009; Litt et al., 2009; Turner et al., 2013). Based on palaeoecological data, Haas et al. (1998) defined cold phases in the early Holocene at: 9600–9200 (oscillation CE-1), 8600–8150 (CE-2), and 7550–6900 (CE-3) ^{14}C yr. BP.

Beside the palaeobotanical evidence, early Holocene ecological oscillations have also been recorded by palaeozoological proxies (Coope et al., 1998; Brooks, 2000; Pawłowski, 2010; Kulesza et al., 2012; Brooks and Langdon, 2014). Płóciennik et al. (2011), based on subfossil Chironomidae, identified a cooling phase correlated with the 8.2 ka event in lacustrine deposits from an ancient basin in Central Poland. However, this signal may also be related to local habitat oscillations.

An increase of activity of early Holocene geomorphic processes is recorded in fluvial, lake, aeolian, and slope systems. Notebaert and Verstraeten (2010) emphasize fluvial system stability in the Early Holocene in Europe. In contrast, episodes of increased fluvial activity in that period have been recorded by Starkel et al. (2006) for Poland; Hoffman et al. (2008) and Kaiser et al. (2012) for Germany; Macklin and Lewin (2003), Lewin et al. (2005), Macklin et al. (2005, 2006, 2010) and Macklin et al. (2006) for Great Britain, Spain, and Poland. Evidence of Early Holocene fluvial activity has been found sporadically in mid-Europe (Kalicki, 2006). Fluvial records in Central Poland have not often been recognised until now, and evidence of river activity in that period are very rare — e.g., the Ner River in Łódź (Turkowska, 1990), the Moszczenica River (Kamiński, 1993), the Koło Basin at the Koźmin Las site (Dzieduszyńska et al., 2014; Twardy, 2014; Kittel, 2015) and Grabia River (Pawłowski et al., 2015a).

An increase in aeolian activity in the early Holocene has been described from numerous sites in the Polish Lowland (Wasylikowa, 1964, 2001; Kozarski et al., 1969; Nowaczyk, 1986; Manikowska, 1985, 1995; Kozarski and Nowaczyk, 1991; Kamiński, 1993; Kowalkowski et al., 1999; Jankowski, 2007). Dune reactivation between ca. 10,500 and. 7500 cal yr.BP (with small peak ca. 9000 cal yr. BP) is recorded in Germany by Hilgers (2007).

Slope deposits are also recorded from the early Holocene, and distinct phases of slope process activity have been recognised in Germany at ca. 10,300, 9500 and 8200 cal yr BP, and correlated to climatic oscillations as recorded by Dreibrodt et al. (2010a, 2010b).

Our research focuses on multiproxy palaeoenvironmental studies of the deposits of a large scale palaeochannel found in the mid-Ner River valley at the Lutomiersk–Koziówki site. The limit of both organic and allochthonous inorganic sediments is dated to ca. 9400–9000 cal yr BP. After that the palaeochannel fill was covered by inorganic sediments (sands), mainly of flood, but also partly of slope and aeolian origin.

The aims of the research are: (1) detailed reconstruction of the palaeoecological evolution of the basin and its environment and (2) discussion of distinct environmental changes in the mid-European river valley in the Early Holocene transition, and their correspondence to global, regional and/or local signals.

Regional setting

The Lutomiersk–Koziówki site (51°45′16.3″ N, 19°13′28.6″ E, 152.5 m a.s.l.) is situated in Central Poland in the north-western part of the Łódź region (after Turkowska, 2006) about 10 km west of Łódź on the Łask Plateau (Kondracki, 2002). It is located near Lutomiersk city in the Ner River valley (tributary of the Warta River), in the vicinity of the confluence of the Zalewka (Wrząca) River (Fig. 1).

The site is located within area that was glaciated during the Odranian (Saalian) and the ice sheet was present here for the last time during the Wartanian Cold Stage of the Odranian glaciation during MIS 6 (Marks, 2011). Intense periglacial transformation of the relief, especially in river valleys, took place during the Weichselian glacial period. The area is part of the "European sand belt" (Zeeberg, 1998) characterised by dunes, aeolian cover sands and silts, and fluvial terraces. In the Łódź region two or three terraces are recognised in most river valleys (Turkowska, 1988, 2006). In the Ner River valley, in the immediate surrounding of Lutomiersk, two terraces of Wartanian and Weichselian age are documented (Kittel, 2012a,2012b). The site is situated on a north-western foot slope of the high Weichselian (Vistulian) Ner River terrace (Fig. 1). The terrace is composed of medium- and coarse-grained sands accumulated during the Pleniglacial period of the Weichselian Glaciation. The high terrace was formed in the Late Weichselian as a result of cut-off by a large palaeochannel of the Ner River. The palaeochannel bounded the terrace remnant on the northern and north-western side. The channel was abandoned during the late Weichselian–Holocene transition, as documented by radiocarbon (^{14}C) ages — before 9030 ± 160 BP (MKL-284), i.e. 10,580–9662 cal. BP (2δ range). Then it was filled by organic deposits, and covered with overbank sands and silts in the early Holocene, followed by the late Holocene slope cover (Kittel, 2012a,2012b, 2014) (Fig. 2).

Climatic conditions in the area are highly variable because of the influence of oceanic and continental air masses. The average annual temperature from 1931–1989 in the western part of Łódź (Lodz) was 7.7°C. The mean temperature of the warmest month (July) is 18°C and mean temperature of the coldest month (January) is −3.3°C (Kłysik, 2001). Average annual precipitation from 1951–1989 was 590 mm, but varied between 438 and 937 mm (http://www.tutiempo.net).

The potential natural plant community of the Ner River valley near Lutomiersk is willow-poplar swamp forest (*Salici-Populetum*). The natural vegetation of the local uplands is a rich lime-hornbeam deciduous forest (*Tilio-Carpinetum*) (http://www.igipzpan.pl/Roslinnosc-potencjalna-zgik.html). However, the Ner valley plant communities have been strongly transformed by humans during modern times (Kittel, et al., 2014) and even in prehistoric periods (Mueller-Bieniek et al., 2015).

Materials and methods

Field work

The field work was undertaken in 2009 as part of geoarchaeological studies (Kittel, 2014) during archaeological investigations of the Lutomiersk–Koziówki site 3C (Muzolf, 2012). Three main series of deposits have been recorded: (1) organic deposits of the palaeochannel fill, (2) sandy and silty overbank alluvium interfingering with slope wash deposits, and (3) slope wash deposits with buried soils described in detail by Kittel (2014). During field work, stratigraphic and structural analyses were undertaken and samples and profiles were collected (Fig. 2).

Two profiles of samples taken every 10 cm were collected from the slope unit and the overbank deposits. Textural and geochemical analyses were conducted on these samples and the charcoal content was examined. The NKZ 3C core contained organic deposits of a palaeochannel fill; this was collected as a monolith into a metal box with dimensions of 50 × 10 × 5 cm. This method preserves the undisturbed structure of sediments. The monolith covers deposits between 170 and 220 cm below surface level. Samples were taken in 1 cm slices at 5 cm intervals (i.e. 172–173 … 217–218 cm) for pollen, diatom and Cladocera analyses and as contiguous 5 cm slice (i.e. 170–175 … 215–220 cm) for plant macrofossils, fossil wood and charcoal, subfossil Chironomidae, and geochemical analyses. According to the stratigraphic depths associated with the sediments in the NKZ 3C core, four samples were collected for radiocarbon dating and one more of selected charcoal from the slope cover. It seems that the excavation was not situated in the deepest part of the palaeochannel. This is currently inaccessible because of strong human alteration of the area in the most recent period.

Accompanying research was conducted at contiguous areas of Lutomiersk–Koziówki. The spatial extent of the studied

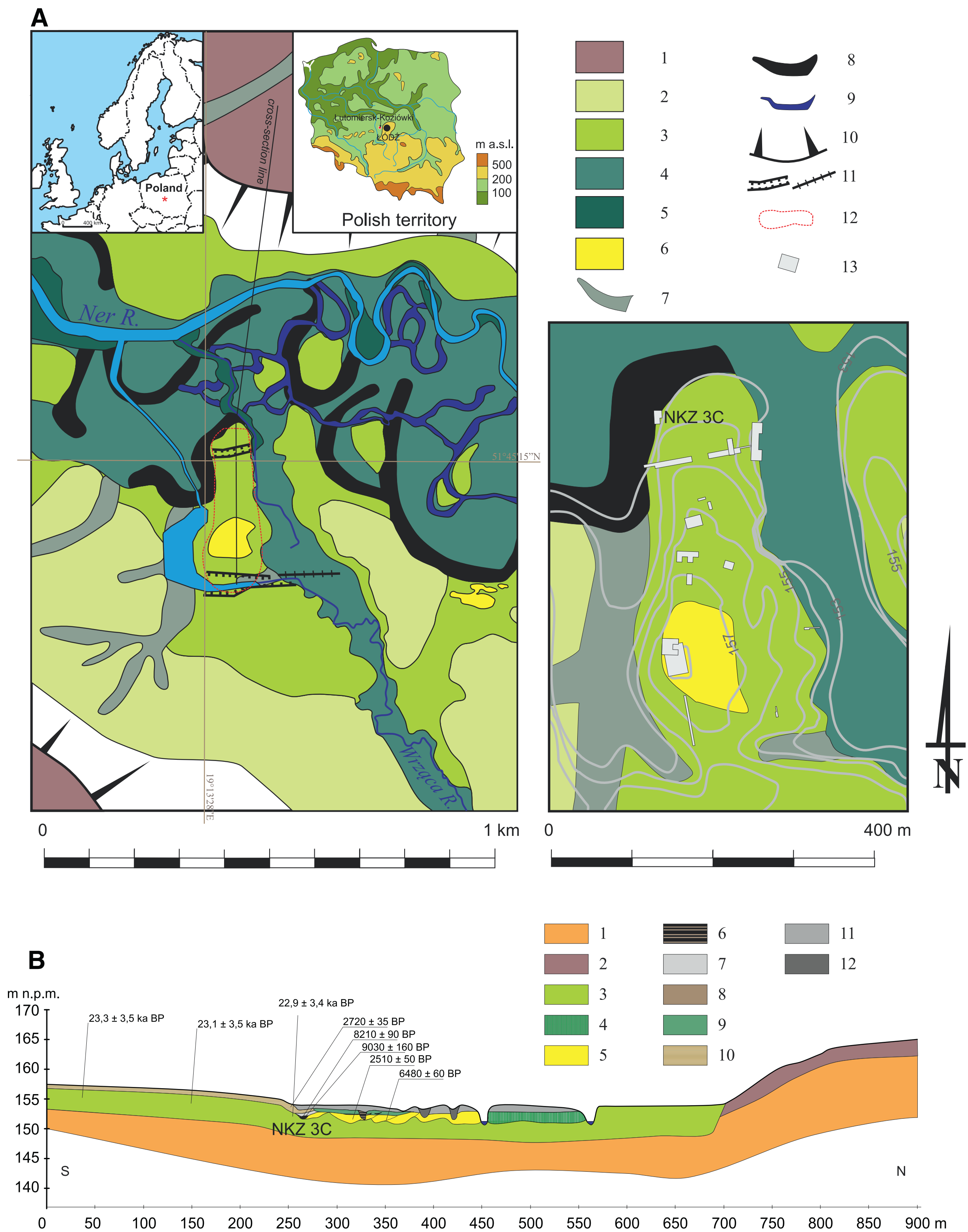

Fig. 1. Location, geology and geomorphology of Lutomiersk-Koziówki site. A. Geomorphologic sketch of the area surrounding the Lutomiersk-Koziówki site. 1 — till plain (Wartanian); 2 — highest terrace (Wartanian termination); 3 — high terrace (Weichselian Pleniglacial, Plenivistulian); 4 — flood plain (Late Weichselian and Holocene); 5 — contemporary flood plain (Late Holocene); 6 — dunes and aeolian sands sheets (Late Weichselian and Early Holocene); 7 — denudational valleys; 8 — large-scale palaeomeanders (Late Weichselian); 9 — small-scale palaeomeanders (Holocene); 10 — valley slops; 11 — anthropogenic cuts and embankments (Late Holocene, Modern Period); 11 — location of archaeological site Lutomiersk-Koziówki no. 3 a–c; 13 — location of archaeological excavations (marked outcrops: NKZ 3C, NKZ 3B and NKZ 3A). B. Cross-section of the Ner River valley in Lutomiersk-Koziówki site: 1 — glacifluvial sands and gravel (Wartanian); 2 — flow till (Wartanian); 3 — fluvial sands with silty laminations of high terrece (Plenivistulian); 4 — fluvial sands with plant detritus and laminations of organic mud (Late Vistulian); 5 — coarse-grained sands with plant detritus and stratifications of organic mud, channel alluvia (Late Vistulian and Holocene); 6 — fluvial sands with organic mud, fillings of palaeochannels (Holocene); 7 — organic mud and sands, overbank alluvia (Early Holocene); 8 — organic mud, overbank alluvia (Late Holocene); 9 — sands with organic mud, overbank alluvia (Late Holocene); 10 — humus sands with artefacts, slope deposits (Late Holocene); 11 — sands with organic mud, overbank alluvia (Late Holocene, Modern Period); 12 — organic mud and sands, overbank alluvia (Late Holocene, Modern Period). Date after Kittel (2012a, 2012b, 2014).

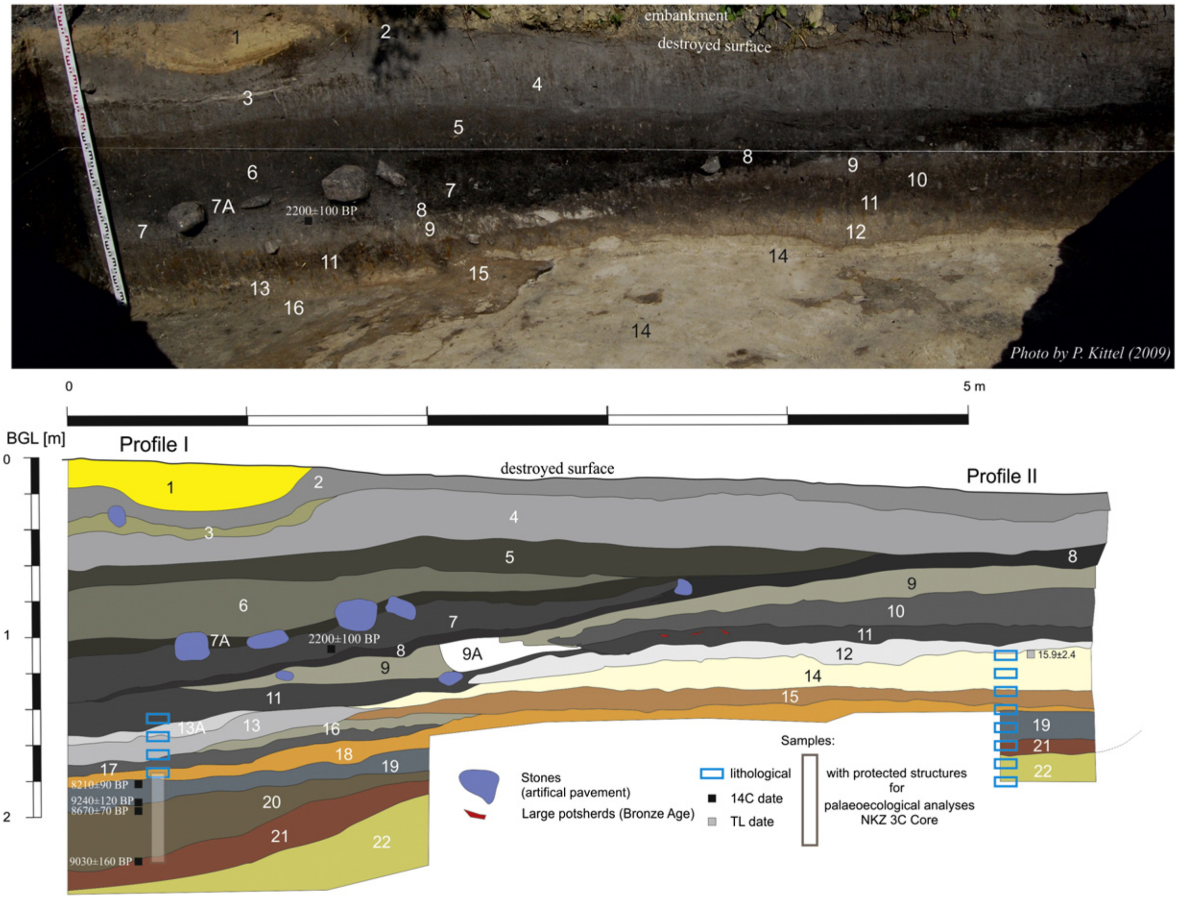

Fig. 2. Lutomiersk-Koziówki site, NKZ 3C. Cross-section of archaeological excavation (after Kittel, 2014). 1 — yellow sands with weakly humic sands lamination, fill of overbank flow channel (Modern Times); 2 — brownish grey humic sands, slope deposits (Modern Times); 3 — sands with organic admixture, fill of overbank flow channel (Modern Times); 4 — brownish grey sands, slope deposits (Medieval Period or Roman Period); 5 — brown humic sands with charcoals, slope deposits (Roman Period); 6 — dark grey humic sands with charcoals, slope deposits (Roman Period); 7A — dark grey humic sands, buried soil horizon (Roman Period); 7 — grey humic sands with charcoals, slope deposits (Pre-Roman Period); 8 — dark grey humic sands with charcoals, buried soil horizon (Early Iron Age); 9 — grey weakly humic sands with charcoals (9A — without organic admixture), slope deposits (Bronze Age); 10 — greyish brown humic sands with charcoals, slope deposits (Bronze Age); 11 — dark grey humic silty sands with charcoals, buried soil horizon (Bronze Age); 12 — grey fine-grained sands and silts laminated, overbank alluvia and slope deposits (Early Holocene); 13 — grey fine-grained sands and silts (13A fine-grained sands) with charcoals, overbank alluvia (Early Holocene); 14 — yellowish grey medium- and coarse-grained sands with silt laminations, overbank aluvia and slope deposits (Early Holocene); 15 — brown medium-grained laminated sands, overbank alluvia (Early Holocene); 16 — grey fine-grained sands, overbank alluvia (Early Holocene); 17 — dark grey mud and fine-grained sands, overbank alluvia (Early Holocene); 18 — greyish brown sands with ironic admixture, overbank alluvia (Early Holocene); 19 — dark grey organic mud with decomposed plant macrofossils admixture, overbank alluvia (Early Holocene, ca. 9.5-9.0 ka BP); 20 — peat of palaeochannel fill (Early Holocene); 21 — organic mud and peat of palaeochannel fill (Early Holocene); 22 — medium- and coarse-grained sands with plant macrofossils admixture, channel alluvia (Late Weichselian).

palaeochannel and examined overbank alluvial deposits was been probed within the surrounding terrain by hand augering.

Sedimentological and geochemical analysis

The grain size composition of the inorganic deposits and ash samples remaining after loss on ignition analysis (weight of samples ranged from 5 to 35 g) was determined using the sieve method (Rühle, 1973) and the textural features were evaluated using Folk and Ward (1957) parameters, The relationship between the mean grain size and the sorting index (the so called co-ordinate system) follows Mycielska-Dowgiałło (1995, 2007). Sedimentological analysis is crucial for the recognition of depositional environments and geomorphologic processes responsible for accumulation of deposits, especially sediments with massive structure. Geological analyses were conducted in the Laboratory of the Department of Geomorphology and Palaeogeography, University of Lodz.

Geochemical analysis was carried out every 5 cm of the NKZ 3C core (Fig. 3), comprising ten samples in all. They included identification of: organic matter (loss on ignition method (LOI) in a muffle furnace at a temperature of 550°C), calcium carbonate (volumetric method by means of the Scheibler's apparatus), reaction (potentiometric method – in distilled water), biogenic and terrigenous silica (Bengtsson and Enell, 1986; Borówka, 1992; Heiri et al., 2001; Myślińska, 2001; Kaufhold, 2007; Woszczyk and Szczepaniak, 2008). The ash samples were dissolved (with using HCl, HNO_3 and H_2O_2) in Teflon bombs using a microwave mineraliser. The solution obtained was analysed for concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb, using atomic absorption spectrometry. The proportions of these compounds can be used to classify deposits and to reconstruct environmental change in the sedimentologic basin and in the catchment (Ławacz et al., 1978; Borówka, 1992; Tobolski, 2000; Wojciechowski, 2000; Okupny et al., 2013). Geochemical analyses were conducted in the Laboratory of the Department of Geomorphology and Palaeogeography, University of Lodz, and in the Geochemical Laboratory, University of Szczecin.

Geochronology

Four samples of bulk organic materials collected from walls of outcrops at were dated by the radiocarbon (^{14}C) method in the Laboratory of Absolute Dating in Skała, Poland using the liquid scintillation technique (LST) (see Krąpiec and Walanus, 2011 for details). The OxCal calibration program ver. 4.2.3 (Bronk Ramsey, 2009) was used for the calibration of radiocarbon dates, using atmospheric data from Reimer et al. (2013). Calibrated radiocarbon dates are expressed as cal yr BP (i.e. before 1950 AD) time intervals with a probability of 68.2% and 95.4% (Table 1, Fig. 2, 4). One sample collected from the sand cover was dated by thermoluminescence (TL) methods in the laboratory of the Department of Geomorphology and Quaternary Geology, Pomeranian University in Słupsk, Poland.

Palaeoecological analyses

For pollen analasis, sediment samples of 1 cm^3 were taken at 5 cm intervals and were prepared for microscope analysis following standard palynological methods (Berglund and Ralska-Jasiewiczowa, 1986) including treatment with HF and HCl for removal of inorganic components and carbonates, KOH for removal of organic matter, and acetolysis. One Lycopodium tablet was added to each sample to facilitate the calculation of pollen concentrations. A minimum of 500 AP (arboreal pollen) pollen grains were counted for each sample. Pollen percentages were calculated based on the sum of trees and shrubs (AP) and herbs (NAP, except aquatic and wetland plants). Based on the percentage of taxa, four local pollen assemblages zones (LPAZ) were identified. The pollen diagram was plotted using the TILIA and TILIA GRAPH software package (Grimm, 1987, 1992) (Fig. 5).

A total of 10 samples taken at 5 cm intervals from the NKZ 3C core (Fig. 6) were used for plant macrofossils and charcoal analysis. Samples for plant macrofossil analysis were boiled with KOH to reduce the amount of sediment and remove humic matter, and the material was examined with a microscope. Conservation of plant remains was done with a standard mixture of alcohol, water and glycerine, with addition of thymol. Fragments of plants were then dehydrated in 50% ethyl alcohol. Macrofossils were identified with the use of plant keys, atlases (e.g. Greguss, 1945; Kats et al., 1965; Berggren, 1969; Grosser, 1977; Schweingruber, 1978; Cappers et al., 2006; Velichkevich and Zastawniak, 2006,2008; Schweingruber, et al., 2011), scientific descriptions and publications, a reference collection of modern seeds, fruits, wood and charcoal, and a collection of fossil floras in the Palaeobotanical Museum of the W. Szafer Institute of Botany, Polish Academy of Sciences, in Cracow. Qualitative and quantitative results were presented in diagrams, drawn with use of the POLPAL software (Nalepka and Walanus, 2003).

The extremely low frequency of diatom remains were defined in sediments by M. Lutyńska, Adam Mickiewicz University (personal communication).

For Cladocera analysis, 1 cm^3 of fresh sediment sample was taken at 5 cm intervals from depth interval 173–218 cm (Fig. 7). The samples were processed according to standard procedures (Frey, 1986). The taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska and Sarmaja-Korjonen (2007). The ecological preferences of cladoceran taxa were determined on the basis of the published key after Bjerring et al. (2009).

Chironomid subfossils were analysed at 5 cm resolution. Sample volume ranged between 30 cm^3 and 60 cm^3 (Fig. 8). Chironomid preparation methods followed Brooks et al. (2007). The sediments were passed through a 63 um mesh sieve. As head capsule concentration in the sediments was low, kerosene flotation was used following the methods of Rolland and Larocque (2007). Identification of chironomid head capsules follows mainly keys by Moller Pillot and Klink (2003) and Brooks et al. (2007). Ecological preferences of identified taxa are based mainly on Brooks et al. (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009a, b, 2013).

Results

Geological, sedimentological and geochemical reconstruction

The excavation at the Lutomiersk–Koziówki site allowed the study of a 5.5 m long and 2.3 m high wall exposing a cross-section of palaeochannel fill overlain by overbank and slope wash deposits (Fig. 2). The slope wash deposits have been described in detail in Kittel (2014). The extent of the palaeochannel deposits is documented within a local geological setting (Fig. 1). The overbank cover overlies the palaeochannel fill and occurs within the valley floors of the Ner and Zalewka rivers.

The studied palaeochannel fill consists of about 50 cm thick (between ca. 170/185–230 cm b.g.l.) brownish peat, weakly laminated at its base (Fig. 2: Units 20–21). The top layer of the laminated peat is ^{14}C dated to 9030 ± 160 ^{14}C yr BP (MKL-284), i.e. 10,398–9910 cal yr BP (1δ range) at a depth of 220 cm in the NKZ 3C core (Table 1). The top of palaeochannel fill is dated to 8670 ± 70 ^{14}C yr BP (MKL-287), i.e. 9700–9542 cal yr BP (1δ range) at a depth of 188 cm.

The geochemical analysis of the NKZ 3C profile reflects a three-stage evolution of the oxbow fill. The 1st and 2nd (220–190 cm deep) geochemical zones represent a phase of peat formation (Fig. 3A). The peat unit is characterised by high LOI content (16–43%), biogenic silica (0.7–2.7%) and only a weak admixture of very fine-grained particles of clastic material (generally below 0.16 mm). A small amount of medium-grained sand (particles below 0.25 mm) was found only at 195–190 cm. The pH of the deposits ranged between 4.15 and 4.60 and a small variation in calcium carbonate content was observed: up to 1.66% at 215–210 cm and 1.18% at 195–190 cm (possible shell fragments). In this zone there was a gradual decrease in the concentration of terrigenous silica (up to 55.2%) and Zn (up to 351.7 ug/g) downward through the peat segment. At the same time, there was a weak increase of Na (to 0.23 mg/g), K (to 3.9 mg/g), Ca (to 10.3 mg/g), Mg (to 2.58 mg/g), Fe (to 17.3 mg/g) and Cu (to 35.3 μg/g). This is interpreted as indicating gradually increasing temperature and humidity in the environment, resulting in increasing chemical denudation in the Ner River valley.

The overbank sediments consist of dark grey organic mud with charcoal and fragments of plant detritus (Fig. 2: units 20–21) covered by sands inter-fingering with organic mud (Fig. 2: units 18, 17, 16, 13). The second unit grades into sands up to 50 cm thick on the palaeochannel side (Fig. 2: units 18, 15, 14, 12).

The dark grey organic mud layer reaches up to 15 cm thick. It was dated to 9240 ± 120 ^{14}C yr BP at the bottom (185 cm depth) and to 8210 ± 90 ^{14}C yr BP at the top (170 cm b.g.l.) (Table 1). The older age in the bottom, older than underlying peat (8670 ± 70 ^{14}C yr BP at 188 cm depth), is due to contamination by partly redeposited organic matter within organic mud. The age of deposition of the studied mud unit is defined between 8670 ± 70 ^{14}C yr BP (MKL-287) and ca. 8210 ± 90 ^{14}C yr BP (MKL-286), i.e. between 9500 and 9300/9000 cal yr BP (Fig. 4).

The dark grey organic mud unit is characterised by a high content of organic matter (7.5–18%), biogenic silica (1.3–2.2%) and no content of calcium carbonate, with a pH range 4.5–4.8. A weak admixture of fine-grained clastic particles (below 0.125 mm) is recorded. Within the 3rd zone (190–170 cm depth), together with a large concentration of mineral matter (82–92.5%), lithogenic elements such as Na (0.22–0.25 mg/g), K (3.65–4.33 mg/g), Mg (2.57–3.33 mg/g) and weak decreased content of Ca (0.47–0.87 mg/g) leads to the conclusion that the mud layer was deposited by intense physical processes. The presence of Na, Mg and K in the organic deposits is associated with the silicates and aluminosilicates in the sediments (Woszczyk and Spychalski, 2007; Rydelek, 2011).

The upper unit of overbank sediments, i.e. sands inter-fingering with organic mud and sands on the palaeochannel side, were deposited after 8210 ± 90 ^{14}C yr BP, 9432–8999 cal yr BP (2δ range) and before the Early Bronze Age (i.e. before 3800 BP). In the top of the unit, a buried soil (Fig. 2: Unit 11) has been recognised in association with artefacts dated to the mid-Bronze Age (Kittel, 2014).

The overbank deposits are typified by a mean grain-size of 1.21–3.11 (ϕ) (i.e. 0.43–0.12 mm), a sorting index of 0.55–1.65 (i.e. moderately well, moderately and poorly sorted). The percentage of mud (i.e. <0.1 mm; >3.32 ϕ) ranges from 0.20 to 38%. The textural features clearly

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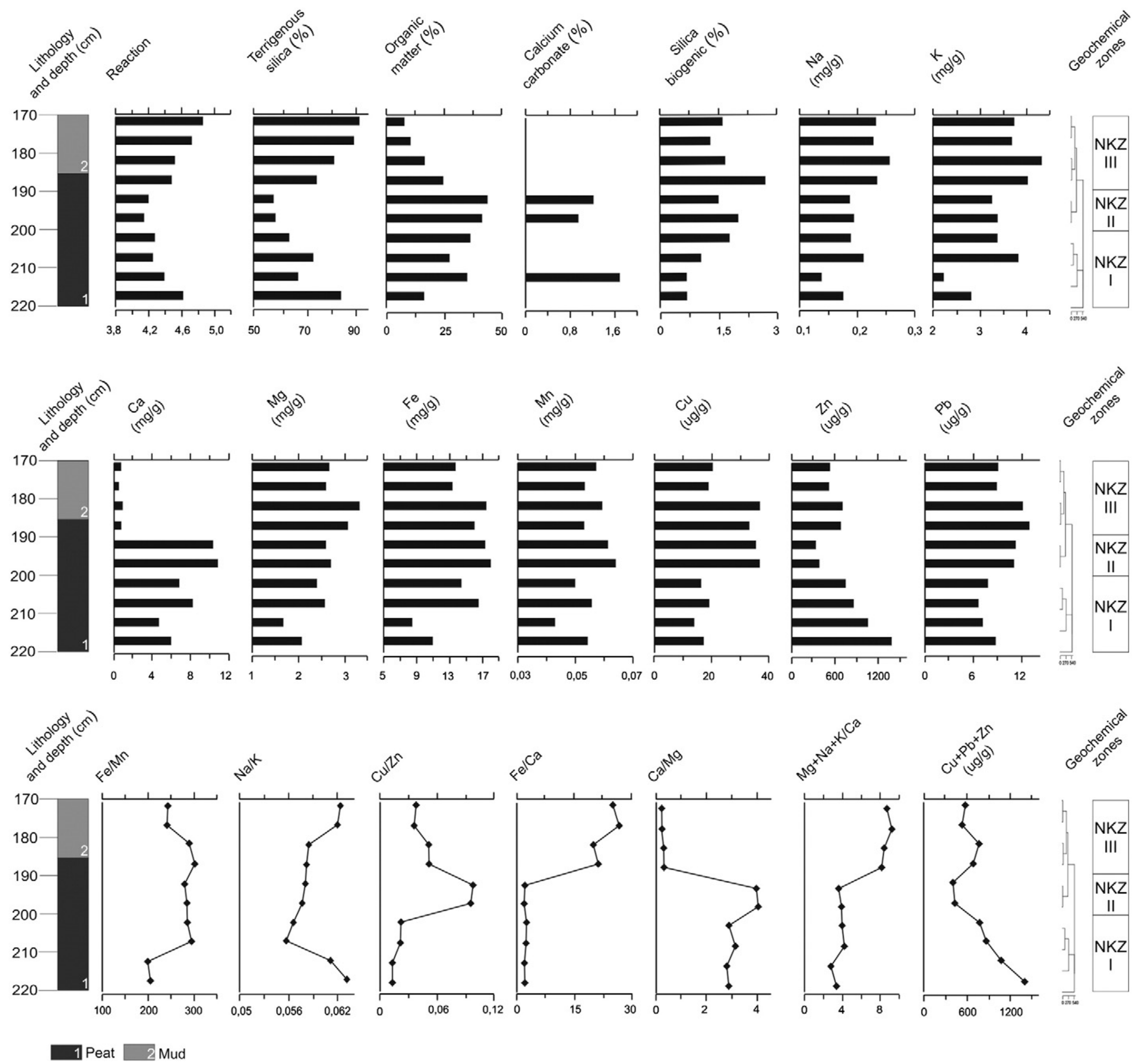

Fig. 3. Results of geochemical analyses of NKZ 3C core at Lutomiersk–Koziówki site.

reveal a differentiation of the overbank deposits from the upper unit of the sediment sequence by silty and sandy laminae. The sandy layers consist mostly of a medium-grained sand fraction (ca. 0.5–0.3 mm). The silty layers are bimodal in grain-size distribution, with higher content of fine-grained sand fraction and clay particles. In addition, the silty laminae consist of an admixture of organic matter (LOI up to 3%) and numerous charcoal fragments. For the upper unit of overbank deposits, the relation between the mean grain size and the sorting index represents the second co-ordinate system after Mycielska-Dowgiałło (1995, 2007), characteristic for overbank alluvia or slope-wash deposits (Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011; Szmańda, 2011). Although the studied deposits satisfy the features of overbank deposits, the medium-grained sands deposited in the marginal part of palaeochannel (Fig. 2: Units. 18, 15, 14, 12) are characterised by higher sorting and very low admixture

Table 1
Results of radiocarbon data of the NKZ 3C core.

	Depth b.g.l. [cm]	Age ^{14}C yr BP	Laboratory No.	Age cal yr BP prob. 68.2%	Age cal yr BP prob. 95.4%	Dated deposits (see Fig. 2)
1.	170	8210 ± 90	MKL-286	9280–9032	9432–8999	top of organic mud (strata 19
2.	185	9240 ± 120	MKL-283	10,549–10,260	10,731–10,196	bottom of organic mud (strata 19)
3.	188	8670 ± 70	MKL-287	9700–9542	9888–9531	top of peat (strata 20)
4.	220	9030 ± 160	MKL-284	10,398–9910	10,580–9662	peat (top of strata 21)

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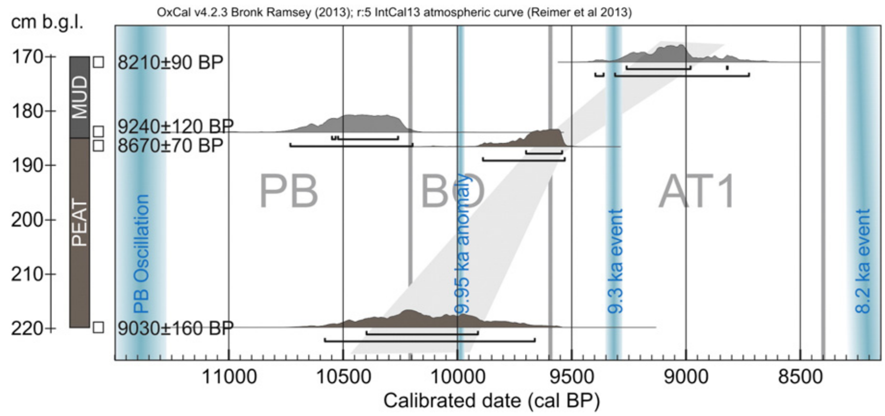

Fig. 4. Results of radiocarbon dating of deposits from NKZ 3C core at Lutomiersk–Koziówki site. Boundaries of the Holocene chronozones after Starkel et al. (2013). Early Holocene climate oscillations after Rasmussen et al. (2007) marked with blue shading.

of the silt fraction. During deposition of these sands, slope wash processes probably played some role on the foot slopes of the terrace remnant. For the studied sand cover, the TL age is 15.9 ± 2.4 ka (GW-1166). The results demonstrate that dated sediments have been only partially bleached, most probably due to a short re-deposition pathway rapid fast accumulation and burial. The features of the deposits in the central part of the palaeochannels are typical for flood basin sediments. The influence of aeolian process during accumulation of overbank alluvia can likewise not be excluded.

Palaeoecological reconstruction — plant communities

Four local biostratigraphic zones (L PAZ) were identified from the simplified pollen diagram (Fig. 5). The zone L PAZ-1 (220 cm) is dominated by *Pinus* (56%) associated with *Betula* and occurrence of *Salix*. The main herbaceous taxa are *Filipendula, Helianthemum*, *Saxifraga*, *Anthemis*-type and *Aster*-type, with little occurrence of steppic taxa (*Artemisia*). The local pollen signal is dominated by Cyperaceae. High NAP percentages indicate the presence of open plant communities with the presence of *Pinus* and *Betula* in wet habitats dominated by sedge rushes. The pollen assemblages indicate vegetation typical of the beginning of the Holocene in this area (Forysiak, et al., 2010).

The second zone (L PAZ-2; 215–210 cm) shows high percentages of *Betula* (80%) with a strong decrease in NAP and local herbaceous plant (Cyperaceae) percentages. Zone L PAZ-3 (205–180 cm) is dominated by *Pinus* with a small occurrence of temperate taxa (*Quercus*, *Ulmus*, *Alnus*) and an increase in NAP (Poaceae, Cyperaceae). Such pollen assemblages can be assigned to the Preboreal period. The biostratigraphic zone L PAZ-4 (175–171 cm) is marked by the development of temperate taxa, especially *Corylus*, *Alnus*, *Quercus*, *Tilia* and *Ulmus*, clearly indicating the Boreal period and perhaps the initial phase of the Atlantic period, however, more data and a longer sequence are needed to test this hypothesis.

Development of the lacustrine basin at the site was divided into three stages, distinguished on the basis of composition of plant macrofossils (Fig. 6). The initial zone, L MAZ-1 (220–205 cm), is dominated by the remains of trees and shrubs, mainly birch (*Betula sect*. Albae and, at the base, *Betula nana*), common pine (*Pinus sylvestris*), alder (*Alnus* sp.) and willow (*Salix* sp.). Based on pollen analysis, the beginning of sedimentation in the basin may correlate with the beginning of the Holocene. The dominant sedges, particularly *Carex rostrata*, were accompanied by *Scheuchzeria palustris*, *Scirpus sylvaticus*, and the aquatic *Lemna trisulca*. Zone L MAZ-2 (205–185 cm) shows a strong decrease in the frequency of tree and shrub remains. Only the basal part of this zone includes infrequent wood fragments of *Alnus* sp., nutlets of *Betula sect*. Albae, seeds and charcoal of *Pinus sylvestris*, and wood fragments of *Salix* sp. Eutrophic habitats were still overgrown by *Urtica dioica*; *Stachys palustris* appeared as well. Nutlets of *Carex rostrata* were less abundant, though still present. Remains of *C. elata* and *C. vesicaria*, most likely originating from littoral tall sedge swamp, were observed as well. Apart from a single fruit of *Potamogeton rutilus*, the base of this zone is devoid of macrofossils of other aquatic plants. Therefore, the examined site seems to have been a rather shallow and small depression, initially filled with water and afterwards, ca. 8670 ± 70 ^{14}C yr BP (ca. 9700–9500 cal yr BP), covered by a peat bog. Zone L MAZ-3 (185–170 cm), corresponding to pollen assemblage zone L PAZ-4 (Fig. 9), assigned to the Boreal period, does not include any identifiable plant macrofossils. However, as pollen analysis showed the presence of *Sphagnum*, it may be assumed that infilling of the basin with peat continued until the beginning of the Atlantic period. In the NKZ 3C core, charcoal accumulation was minimal and remains of uncharred wood were also rather sparse. Fragments of alder and birch branches were most frequently determined.

Palaeoclimatic reconstruction

Estimates of climatic parameters were obtained through the Modern Analogues Technique "MAT" developed by Guiot (1990), as previously

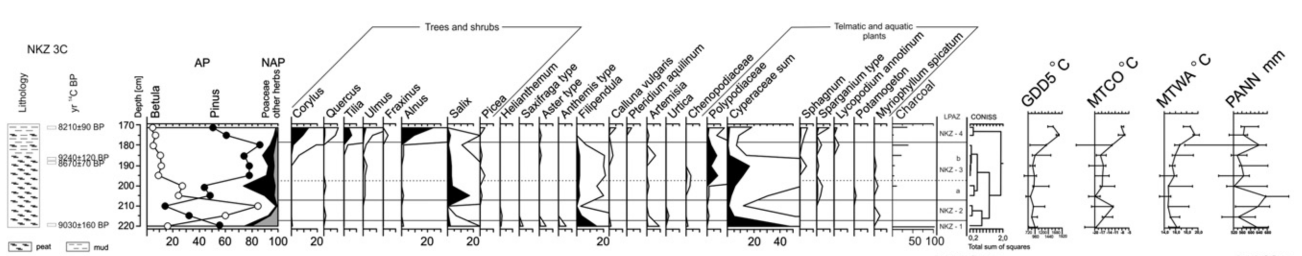

Fig. 5. Percentage pollen diagram with selected taxa of trees and herbs, total sum diagram of charcoals, estimates of climatic parameters (MET) and absolute data of deposits from NKZ 3C core at Lutomiersk–Koziówki site. Climatic reconstructions as follows: GDD5 — pollen-inferred sum of growing degree days above 5°C, MTCO — mean temperature of the coldest month, MTWA — mean temperature of the warmest month, PANN — annual precipitation.

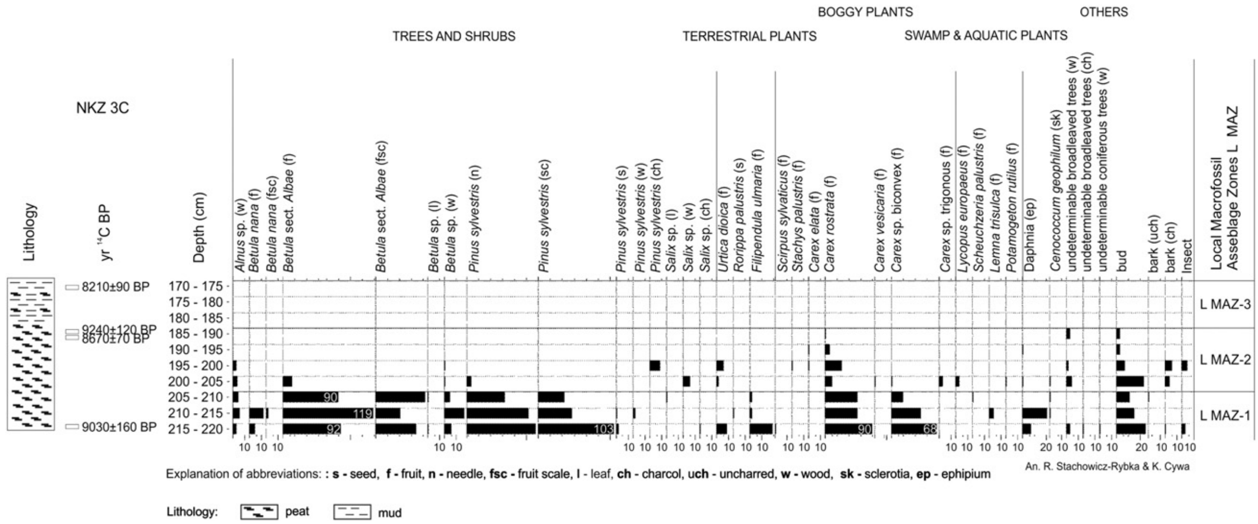

Fig. 6. Plant macrofossil diagram from NKZ 3C core at Lutomiersk–Koziówki site.

applied to late glacial and Holocene terrestrial pollen records (e.g. Peyron et al., 2005, 2013; Feurdean et al., 2014; Joannin et al., 2012; Kühl et al., 2010). This method, based on comparisons of past pollen assemblages to modern pollen assemblages, is tested here from palaeochannel pollen assemblages. Quantitative climate reconstructions were performed for the mean temperature of the coldest month (MTCO), the mean temperature of the warmest month (MTWA), and annual precipitation (PANN). More details on the validation procedure and on the statistic reliability are given in Peyron et al. (2011). For clarity, the error bars estimates calculated with the MAT are plotted (Fig. 5). We test here this approach on palaeochannel pollen data to see whether this method is able to provide reliable results from these types of sediments.

Our attempt to infer climate values from pollen data of the Ner River valley record shows two distinct periods of temperature change: cold conditions prior to around 9500 cal. BP, followed by a period with cool/warm conditions (Fig. 5, 9). Cold conditions both in winter and summer characterize the NKZ 3C core record during the Preboreal period, with temperatures around −15°C in winter and 15–16°C in summer. Subsequent pollen-inferred temperature increases were inferred from 9500 cal. BP, reaching a maximum (+10°C in winter, +4°C in summer compared to the Preboreal period). The precipitation signal is less clear, with values fluctuating around the modern mean value of 600 mm.

Palaeoecological reconstruction — invertebrate communities

Seven littoral, mostly macrophyte/sediment-associated species of Cladocera were found in the depth interval 218–188 cm (Fig. 7). The first Cladocera occurred at a depth of 218 cm. Up to a depth of 208 cm, habitat conditions favoured the development of this aquatic group, comprising six species. The presence of these taxa suggests the existence of a small, shallow oxbow with macrophytes, but the abundance of sediment-associated taxa most likely suggests a variable supply of mineral matter to the basin. Above a depth of 203 cm, the aquatic conditions deteriorated, and only one species was found: *Chydorus sphaericus*, a water flea with a wide ecological tolerance. These remains were not abundant (ca. 160 individuals/cm^3). Between 198 and 188 cm depths the aquatic habitat conditions slightly improved, as shown by the presence of four species: *Alona affinis*, *Alona guttata*, *Ch. sphaericus*, and periodically *Eurycercus lamellatus*. No cladoceran remains were found in the depth intervals of 188–173 cm.

Analysis of Chironomidae remains (Fig. 8) indicates fully aquatic conditions in the bottom section of the NKZ 3C profile (220–205 cm). The assemblages reveal high taxonomic diversity, as more than 40 morphotypes were recorded in five samples containing midge subfossils. Abundance and species richness were highest in samples from 220–215 cm core depth. Assemblage composition suggests high energy conditions. The diverse assemblage including reophile taxa, is not typical of a swampy pool, and provides a strong hint that high energy hydrological conditions might wash allochthonic taxa into the oxbow (Smith and Howard, 2004). Contrary to the hypothesis of local flooding, presence of rheophile species may be interpreted as groundwater or spring inflow to the oxbow. Many of the morphotypes from these layers (*Krenopelopia*, *Eurycnemus crassipes*, *Parametriocnemus*–*Paraphaenocladius*, *Tvetenia bavarica*-type, *Micropsectra contracta*-type, *Rheotanytarsus*) are reported today from seepages and in small streams (Brooks, et al., 2007; Vallenduuk and Moller Pillot, 2007; Moller Pillot, 2009b, 2013). Part of the morphospecies is associated with thermophilous, nutrient-rich environments. Midge abundance and taxonomic diversity decreased in samples from 210–205 cm. The increase in dominance of *Chironomus plumosus*-type is characteristic of stagnant and eutrophic waters. Few taxa associated with small flowing waters were found in above 210 cm (*Thienemannimyia*-type, *Eurycnemus crassipes*, *Tvetenia bavarica*-type). Above 205 cm core depth only a singular head capsule was found.

Results of ordination analysis

To estimate major changes in geochemical composition and the other proxy assemblages along the stratigraphic gradient, Principal Component Analysis (PCA) and Detrended Correspondence Analysis (DCA) were implemented with CANOCO 4.5 (ter Braak and Šmilauer, 2002). Prior to PCA, geochemical data were centred and standardised. DCA was used to explore patterns in the distribution of the taxa and was run with detrending by segments, non-linear rescaling, and down-weighting of rare species. Palynomorph percentage and plant macrofossil count values were square-root transformed. Chironomidae and Cladocera percentage data were not transformed. Statistical parameters of DCA and PCA for each proxy are shown in Table 2 and Fig. 9.

All the different biotic proxy data reveal a similar trend on the first DCA axes, from high values in the Boreal period, to low values in the Boreal-Atlantic periods transition (Fig. 9). This signal follows the general trends of the hydrological reconstruction. The existence of a groundwater-fed pond in the L PAZ 1/L MAZ 1 zone is associated with an abundance of aquatic invertebrates such as Cladocera and

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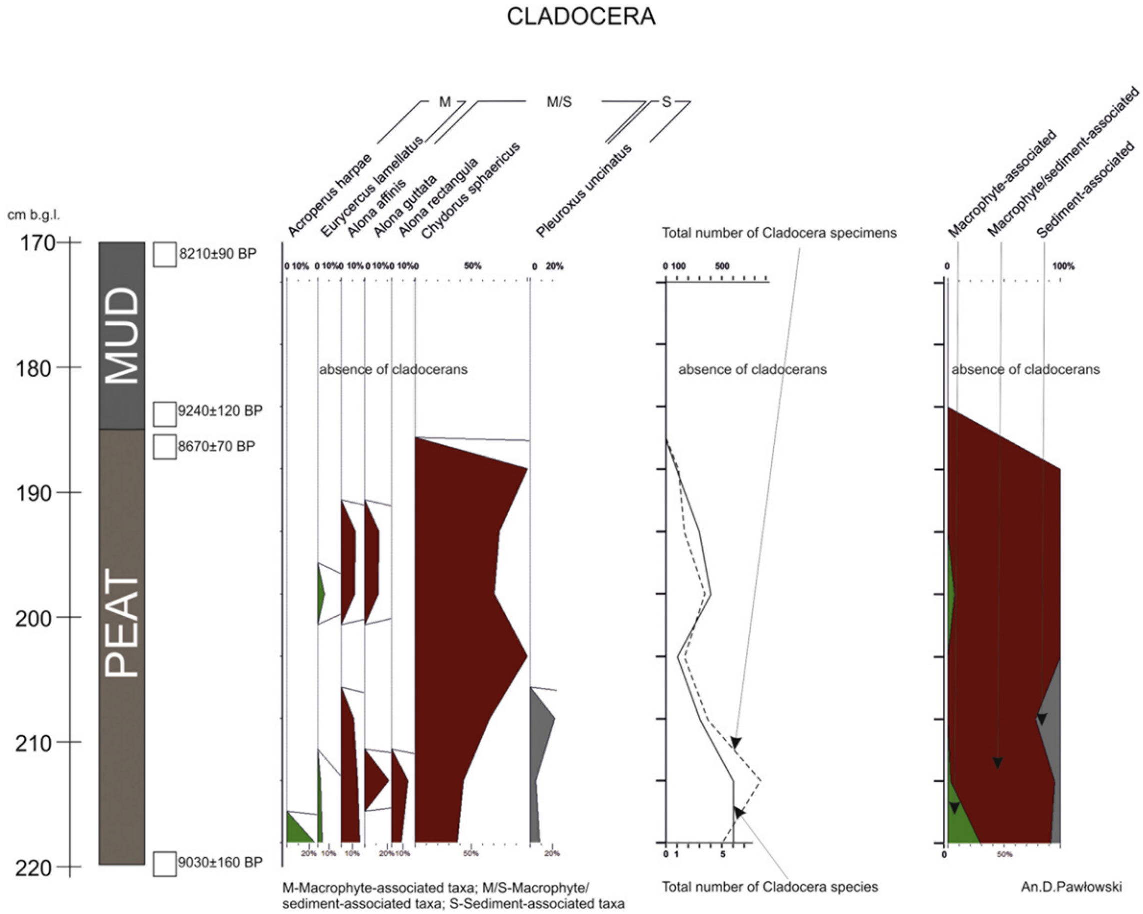

Fig. 7. Percentage Cladocera diagram from the NKZ 3C core at Lutomiersk–Koziówki site.

Chironomidae, and the appearance of aquatic plants. The conditions became progressively telmatic and fully terrestrial to the top of sequence, as reflected in a decrease of DCA values. The second PCA axis of the geochemical signal and the second DCA axis of palynomorphs show an increasing trend towards the top of the sequence. This might be associated with climate warming in the late Boreal period.

Discussion

Development of the oxbow basin

The studied sediment basin developed within a large-scale palaeochannel after its cut-off during the Younger Dryas–Holocene transition (Fig. 10), as shown in other parts of the Ner River valley

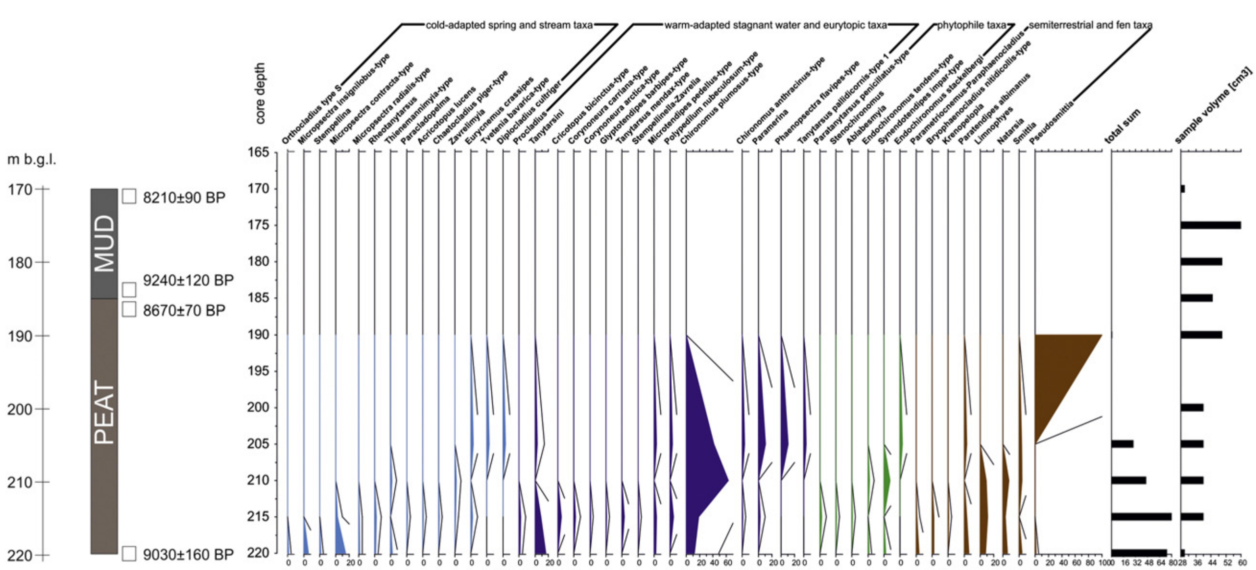

Fig. 8. Percentage Chironomidae diagram from the NKZ 3C core at Lutomiersk–Koziówki site.

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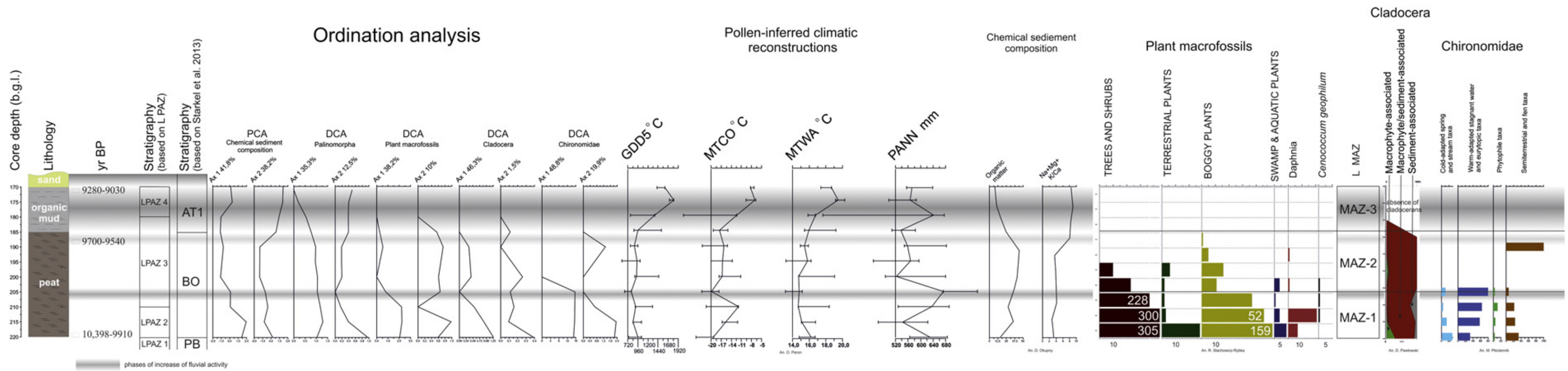

Fig. 9. Comparison of research results in the NKZ 3C core.

Table 2
PCA and DCA ordination analysis parameters (eigenvalues, gradient lengths, cumulative percentage variance of species data, sum of all eigenvalues).

PCA	Axes	1	2	3	4	Total variance
Geochemical composition	Eigenvalues:	0.418	0.381	0.084	0.059	1.000
	Cumulative percentage variance of species data:	41.8	80.0	88.4	94.3	
	Sum of all eigenvalues					1.000
DCA	Axes	1	2	3	4	Total inertia
Palinomorpha	Eigenvalues:	0.191	0.067	0.023	0.008	0.540
	Lengths of gradient:	1.285	0.946	0.618	0.783	
	Cumulative percentage variance of species data:	35.3	47.8	52.0	53.6	
	Sum of all eigenvalues					0.540
DCA	Axes	1	2	3	4	Total inertia
Plant macrofossils	Eigenvalues:	0.402	0.105	0.002	0.001	1.054
	Lengths of gradient:	2.236	0.979	1.037	1.037	
	Cumulative percentage variance of species data:	38.2	48.2	48.3	48.4	
	Sum of all eigenvalues					1.054
DCA	Axes	1	2	3	4	Total inertia
Cladocera	Eigenvalues:	0.291	0.009	0.000	0.000	0.627
	Lengths of gradient:	1.197	0.381	0.000	0.000	
	Cumulative percentage variance of species data:	46.3	47.8	0.0	0.0	
	Sum of all eigenvalues					0.627
DCA	Axes	1	2	3	4	Total inertia
Chironomidae	Eigenvalues:	0.984	0.401	0.122	0.000	2.015
	Lengths of gradient:	15.606	1.947	1.549	0.000	
	Cumulative percentage variance of species data:	48.8	68.7	74.7	0.0	
	Sum of all eigenvalues					2.015

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(Turkowska, 1990; Kittel, 2012a,2012b, 2014). An erosional phase of rivers and abandonment of large-scale palaeomeanders at the beginning of Holocene has been recorded widely in Europe (see: Starkel, 1983, 2002a, 2002b; Starkel and Gębica, 1995; Turkowska, 1995; Lewin et al., 2005; Kasse et al., 2005; Starkel et al., 2006; Kalicki, 2006; Kaiser et al., 2012; Turner et al., 2013).

Deposition in the investigated oxbow basin began shortly after isolation from the main Ner River channel. Biogenic accumulation then began, leading to peat formation. Before ca. 9700 cal yr BP, the rate of the peat accumulation was most probably stable and no traces of depositional hiatuses have been recorded. Palaeoecological analyses indicate the presence of a very shallow oxbow basin and partly telmatic conditions. The Cladocera record from NKZ 3C core contains only littoral, mostly macrophyte/sediment-associated taxa, which are common in European small lakes and ponds (Bjerring et al., 2009). However, in the development of this oxbow, variable hydrological conditions are suggested by the periodic coexistence of limnic and telmatic aquatic invertebrates with chironomid species associated with seepages and small streams (Fig. 8). This interpretation is supported by variable values of geochemical components at depths from 220-185 cm (Fig. 3, 9). The relatively large concentrations of organic matter and high Fe/Mn ratios (mean 264.2) indicate reducing conditions and low-intensity mechanical denudation in the catchment (mean Na + K + Mg/Ca ratio is 4.25). This, in turn, may have been the result of long-term oxygen deficiency in the water (Mackereth, 1966; Borówka, 2007). The input of spring water to the oxbow was significant during the first stage of the basin development, as shown by the Chironomidae record at depths of 220–205 cm, i.e., between ca. 10,500–9700 cal yr BP. The hypothesis of spring inflow to the oxbow is supported by increased Ca (mean 7.77%) derived from groundwater. The hypothesis that high energy flow episodes at 215 cm and 205–200 cm depth happened is supported by studies on beetle assemblages from fluvial deposits in Trent River basin (Great Britain). Smith and Howard (2004) found that subfossil beetle assemblages which are characterized by high species diversity, presence of reophile and other allochthonic taxa indicate high energy deposits. These conditions probably also favored the presence of cladocerans during this time. The geological structure of the terrace limited by the palaeochannel is suitable for spring inflows due to the fact that fine, poorly-permeable sediments are covered with easily-drained sands and gravel. In the lower part of the geochemical zone NZK 1, the highest Zn content is observed, likely as a result of bioaccumulation of this element. The increase in Zn content could have been associated with the appearance of birch (Fortescue, 1980; Reimann et al., 2007).

We interpret a flood episode at depths of 208–203 cm, dated to ca. 10,000 cal yr BP. This is supported by the decrease of taxonomic aquatic invertebrate diversity, an increase of sediment-associated cladocerans, appearance of a few chironomid taxa associated with small flowing waters, by the pollen-inferred precipitation maxima and by an increase in lithogenic elements, especially K and Na, as well as terrigenous silica, in this interval (Fig. 10). Similar situations were also interpreted from palaeo-oxbows and other small water bodies on floodplains situated in the valleys of the Ner, Widawka, Rawka and Grabia rivers (Pawłowski, 2012; Pawłowski et al., 2012, 2015a, 2015b).

Above 205 cm, midge larvae of chironomid disappear from the sediment, indicating a decrease in aquatic habitat availability. On the other hand, a slight increase of cladoceran diversity at depths from 198–193 cm (ca. 9900–9600 cal yr BP) might reflect a temporary increase in groundwater supply in the valley due to inundation of flood waters and probably, of rainwater. This is partly supported by high Ca concentrations — the highest values in the whole section, caused by groundwater supply. In addition to the Ca/Mg ratio, increased Pb content (between 11.9–12.9 μg/g) and the low pH imply that atmospheric deposition has been the main source of the elements for this peat profile during its accumulation. The evidence of flooding is defined by a small admixture of medium-grained sand and increasing reduced-oxidized conditions (based on Cu/Zn ratios) in the organic deposits at 190–185 cm, dated between 9850 and 9550 cal. BP.

More intense overbank deposition is indicated by the dark grey organic mud layer (185–170 cm). These sediments accumulated after ca. 9700–9500 cal yr BP and before 8210 ± 90 ^{14}C yr BP, i.e. 9300–9000 cal yr BP. The flooding, supported by high precipitation estimates at 180 cm depth (Fig. 9), resulted in redeposition of older organic matter (such as charcoal), probably partly of slope wash and aeolian deposits. In this interval, the highest content of terrigenous silica, lithogenic elements (Na + K + Mg/Ca mean 8.87) are found. We ascribe this to increased rates of catchment erosion, which may also have been the cause of the spuriously old radiocarbon age for the bottom of the layer (9240 ± 120 ^{14}C yr BP at 185 cm b.g.l.). The increase of fluvial activity is considered to be a phase of overbank deposition of medium-grained sands interfingering with organic mud deposited after 9300–9000 cal yr BP.

The main phase of development of the oxbow basin includes the period ca. 10,300–9500 cal yr BP. Between 9900 and 9600 ca yr BP, flooding influences are interpreted from the organic deposits of the palaeochannel fill. Shortly after ca. 9500 cal yr BP, the marked flood episode indicated by an accumulation of organic mud concluded the accumulation of the palaeochannel fill (Fig. 10).

Palaeoeclimatic context of the oxbow development

During the Preboreal period, birch-pine forests were already an important part of the landscape of Central Europe. In less shaded areas of higher humidity, *Betula nana*, *Filipendula ulmaria* and *Rorippa palustris* also occurred. Habitats of higher eutrophication supported *Urtica dioica*. At the beginning of the Holocene, increased warmth and humidity in the study region enabled a local rapid expansion of communities such as low and transitional peat bogs.

The vegetation cover interpreted from the palaeobotanical data is similar to changes recorded in other pollen diagrams from western and central Europe (e.g. Bohncke and Hoek, 2007; Bos et al., 2007) and Poland (Ralska-Jasiewiczowa and van Geel, 1998). The inferred vegetation changes fit well with changes in pollen spectra observed for the same time period in the lacustrine deposits at Woryty near Olsztyn (northeast Poland) and the Lake Gościąż (Starkel et al., 1998; Ralska-Jasiewiczowa et al., 2003). It is of note that the onset of *Corylus* is recorded at these two sites around 10,500 cal yr BP as in most central European pollen diagrams (Giesecke et al., 2011) whereas it appears around 9500 in the NKZ 3C profile. This disparity may be due to dating uncertainties, especially at Lake Gościąż (Kilian et al., 2002).

The early Holocene was generally a time of precipitation and temperature increases in Central Europe. However, in the Polish lowlands the temperature rise was lower and less pronounced than in western and southern Europe (Pawłowski et al., 2015c). Summer temperatures generally reached 1–1.5°C higher values then today about 9000–8000 cal yr BP in most of Europe (Morrill et al., 2013; Feurdean et al., 2014). The pronounced summer and winter temperature shift is visible in L PAZ 4 (Figs. 5, 9). Summer temperature gradients in northwest Europe inferred from chironomid assemblages indicate that by 11 ka, temperatures rose in Central Poland by about 2–3°C above those inferred for the Younger Dryas interval, increasing an additional 2°C by 8000 cal yr BP, reaching their highest values at 10,000–9500 and 8000 cal yr BP (Brooks and Langdon, 2014). This amelioration allowed for deciduous forest expansion in the region. Nevertheless, climate warming caused water levels to decrease in river valleys, Polish lakes and peatlands in the Early Holocene, in comparison to the Late Glacial/Holocene transition (Feurdean et al., 2014; Pawłowski et al., 2015c). Significant, brief cooling episodes have been inferred in North-Central Europe at 10,500 and 9000 cal. BP (Brooks and Langdon, 2014).

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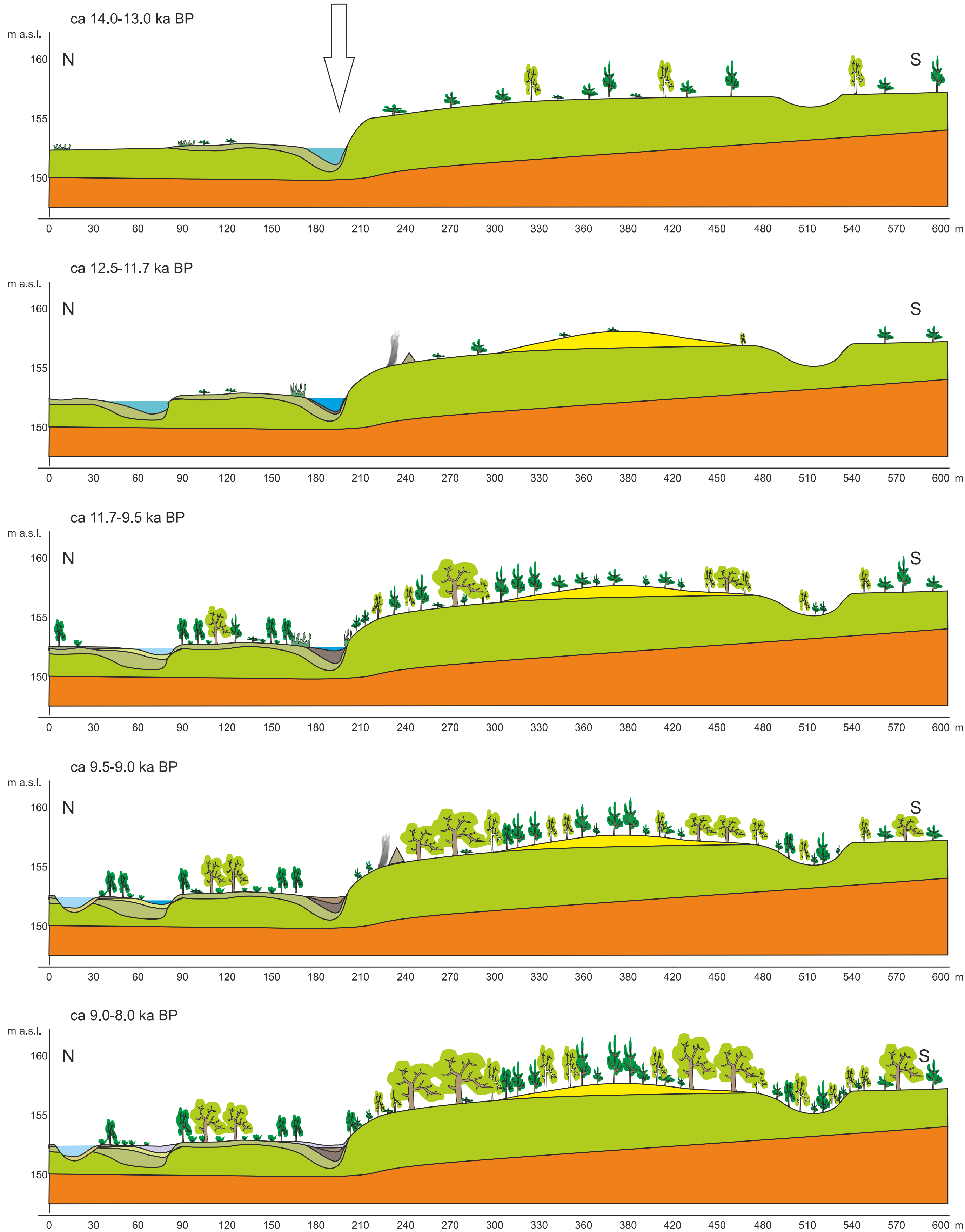

Fig. 10. Phases of the Early Holocene natural environment evolution of the Ner River valley at Lutomiersk–Koziówki site (the arrow shows the NKZ 3C core location).

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A distinct lake level transgression in Poland has been recorded for about 9600–8400 cal yr BP (Starkel et al., 1998, 2013). Wojciechowski (2000) recorded a dry Preboreal period phase (ca. 11,300–10,800 and 10,600–10,200 cal yr BP and a wet Boreal period phase ca. 10,200–9400 cal. BP for Kórnik-Zaniemyśl Lakes (Western Poland). Based on the results of peat research in Eastern Poland, Żurek et al. (2002) interpreted wet periods at ca. 10,400–9700, 9500–8800 cal yr BP. In north-eastern Germany, low lake levels associated with a Holocene minimum water table are recognised for the Early Holocene (Preboreal and Boreal period) (Kaiser et al., 2012) or directly at the Preboreal–Boreal transition (Turner et al., 2013).

Flooding phases

The first increase of flooding in the Ner River valley has been interpreted by the admixture of medium-grained sand within organic deposits of palaeochannel fill, dated to ca. 9900–9600 cal yr BP. The beginning of accumulation of overbank sediments (dark grey organic mud with sand) is dated to the period shortly after ca. 9500 cal yr BP and the increase of flooding (sand cover deposition) is dated to the period after ca. 9300–9000 cal yr BP. The accumulation of overbank alluvia finished the filling of palaeochannel.

The main phase of increased fluvial activity and deposition of overbank alluvium in the Ner River valley in Lutomiersk took place during a phase of accentuated river activity, resulting in the cut-off of numerous channels in the upper part of the valley (Turkowska, 1988, 1990). Radiocarbon dates of organic deposits from point bars and fills of subfossil channels in the Łódź section of the valley range from 12,950 ± 390 ^{14}C yr BP (16,117–14,836 cal yr BP) to 8180 ± 220 ^{14}C yr BP (9443–8786 cal yr BP) (Turkowska, 1988, 1995). The youngest date documents the most probable period (as *terminus post quem*) of fluvial activity increase. The older dates are the result of redeposition of older organic deposits, e.g., tree trunks, cones.

The recognised phases of increase of fluvial activity, especially after ca. 9300–9000 cal yr BP, may be synchronous with increasing moisture and rising lake levels and/or with flooding phases recorded in Poland and elsewhere in Europe (Table 3). In upper Wisł (Vistula) basin, increased fluvial activity in the period 9500–8500 cal yr BP was recorded by Kalicki (1991) and Starkel (Starkel and Gębica, 1995; Starkel et al., 1996). The main phases of accumulation of overbank sediments in upper Wisła River valley occurred at 9800–9600 and 8800–8000^{14}C yr BP (Kalicki, 1991). Similarly, in Grabia River valley significant period of water-level increase (and flooding phase) occurred ca. 9500–9200 cal yr BP (Pawłowski et al., 2015a).

Based on the age of various facies of terrestrial sediments, Starkel et al. (2006, 2013) distinguished Early Holocene flooding phases in Poland at 11,300–10,300, 9700–9400, 8600–8400 cal yr BP, with distinct, sharp peaks at 11,200–11,100, 9600–9500, 8400 cal yr BP. A decline in flood activity in the Polish lowlands is widely interpreted for the period between 11,200–10,700 cal yr BP. They summarise the subsequent phases of environmental change and fluvial activity in Poland as follows: from 11,500–10,200 cal yr BP there was a high frequency and abundance of palaeochannels; from10,200–9600 there was a decline of fluvial activity; from 9600–8400 there was a humid phase with a distinct rise in alluviation, lake levels increased, and there was a phase of extreme events; from 8400–7700 cal yr BP conditions were warm and drier.

In Germany, periods of higher geomorphic (especially fluvial and slope) activity took place at ca 9000 and 8200 cal yr BP. The increase in fluvial activity was significant between 13,500–10,000 cal yr BP with the small peak ca. 11,000 cal yr BP. The narrow peak in geomorphic (especially slope wash deposits) activity can be correlated with the Preboreal Oscillation and 8200 cal yr BP event (Hoffmann et al., 2008).

Phases of increased fluvial activity occurred during cool and humid climate periods (Starkel, 1983; Starkel et al., 1996), corresponding with phases of lake level increases interpreted by Magny et al. (2003) and to the North Atlantic IRD events published by Haas et al. (1998) (see: Macklin and Lewin, 2003; Macklin et al., 2005, 2006, 2010; Starkel et al., 2006, 2013). In light of the information on major flooding episodes in Poland and the rest of Europe, and European climatic changes during the Early Holocene, we may correlate the recorded flooding events in the Ner River valley in Lutomiersk-Koziówki (Table 4). The 3rd phase (after ca. 9300–9000 cal yr BP) is the main Early Holocene flood phase in the Ner River and it may by correlated with climatic oscillations during the 8.2 ka event (Fig. 10).

Slope and aeolian sediments associated with overbank deposit accumulation

Slope wash deposits and aeolian processes may have been involved in the formation of the Early Holocene sandy cover (after ca. 9300–

Table 3
The flooding phases recorded in central European river valleys (data in cal yr BP).

Chronostratigraphic phases	PB (11,500–10,200)	BO (10,200–9600)	AT1 (9600–8400)	AT2 (8400–7700)	After: Starkel et al., 2013
River valley:					
Ner (central Poland)		ca. 9900–9700	ca. 9500–9300/9000	after 9300–9000	this paper
Warta (Koło Basin, Poland)	after 11,500–11,000				Dzieduszyńska et al., 2014; Twardy, 2014; Kittel, 2015
upper Wisła (southern Poland)	after: 11,229–10,744; 11,200–10,793; 11,068–10,301	after: 10,177–9737	after: 9031–8637	after: 8994–8726	Kalicki, 2006 and references within
Wisłoka (southern Poland)			ca. 9500–8500		Niedziałkowska et al., 1977; Alexandrowicz et al., 1981
Czarna Nida (eastern Poland)	from 11,187–10,884 to 8405–8364				Krupa, 2013
Belnianka (eastern Poland)	11,200–10,700				Ludwikowska-Kędzia, 2000
Wetter (eastern Germany)		10,194–9922; 9662–9542; 9665–9482			Houben, 2003 and references within
Dnieper (Belarus)		10,196–9709			Kalicki, 2006 and references within
Western Dvina (Belarus)		9857–9440	9736–9025; 9396–9038		Kalicki, 2006 and references within
Łuczosa (Belarus)				8328–8170	Kalicki, 2006 and references within
Niemen (Belarus)			9666–9491		Kalicki, 2006 and references within
Drut (Belarus)			9008–8770; 8537–8401		Kalicki et al., 2008

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Table 4
Correlation of flooding events in the Ner River valley at Lutomiersk–Koziówki site with European natural environmental changes (data in cal yr BP).

Flooding events in the Ner River		Flooding phases in Poland after Starkel et al. (2006, 2013)	Flooding phases in Europe after Macklin et al. (2006)	Early Holocene cold events after Rasmussen et al. (2007)	Cold event after Alley et al. (1997)	Cold phases after Haas et al. (1998)	Bond events after Bond et al. (2001)	Cooling episodes after Mertens et al. (2009)	Episodes of higher lake level after Magny (2004)	Neoglacial events after Matthews and Dresser (2008)
Chronology	Record									
ca. 9900–9700	Fine-sand deposition within the organic unit	9700–9400		9.95 ka BP anomaly					14 10,300–10,000	Erdalen Event 10,400–9600
ca. 9500–9300/9000	overbank organic mud deposition	9700–9400 (9600–9500 peak)	9530	9.3 ka BP event		CE-1 9600–9200	6 9400		13 9550–9150	
After 9300–9000	Overbank deposition of laminated organic mud and sand	8600–8400 (8400 peak)	8400	8.2 ka BP event (8300–8140)	8.2 ka BP	CE-2 8600–8150	5b ca. 8200	8 84,400	12 8300–8050	Finse Event 8400–7650

9000 cal. yr BP) at the Lutomiersk Koziówki site. Intensity of slope processes increased during the last glacial termination, but also during the Early Holocene (e.g. Borówka, 1992; Leopold and Völkel, 2007; Dreibrodt et al., 2010a). The large peak of slope process activity in Germany at 7000 BC (9000 cal yr BP) is recognised as an effect of climate impact (Hoffmann et al., 2008). The Early Holocene phases of slope instability have been connected with palaeofire during climate oscillations (ca. 11,100, 10,300, 9500 and 8200 cal yr BP) (Dreibrodt et al., 2010a). Grant et al. (2014) underline the coincidence of burning events with warmer and drier climate periods of the Holocene and an increase in summer moisture deficit.

In the Łódź region, phases of intensification of aeolian processes and deposition of thin sandy cover on slopes of older late glacial dunes are recorded in the Preboreal and Boreal periods (Wasylikowa, 1964, 2001; Manikowska, 1985, 1995). The example of very intense aeolian activity in the Boreal period is associated with processes resulting from the formation of 2 m high dune in the Moszczenica River valley floor, as described by Kamiński (1993). The dune-covered palaeochannel fill dates back to 8740 ± 190 ^{14}C yr (10,128–9543 cal yr BP). The favourable conditions of the Lutomiersk Koziówki site area for an activation of aeolian processes was confirmed for younger periods (Kittel, 2012a, 2014).

Conclusions

The multi-disciplinary studies of palaeochannel fill and overbank deposits at the Lutomiersk Koziówki site allow the recognition of palaeoenvironmental evolution of an oxbow basin.

Each proxy contributes different aspects to the general reconstruction of palaeochannel history. The invertebrate and plant macrofossil analysis provides insights into habitat heterogeneity and to the somewhat complicated hydrological history of the site. This is often the situation in shallow valley stagnant waters, as their moisture sources vary from groundwater seepage to precipitation and episodic floods. This unstable situation easily and rapidly transforms local fens into oxbows and vice versa. The pollen-inferred reconstructions of the coldest and warmest month mean temperature is one of the few Early Holocene climatic reconstructions from Poland, but these results must be treated with caution and need to be validated by other proxies and other lake or peat sequences. Palaeoenvironmental investigations provide a general overview of the river valley history, from oxbow basin emergence in the Late Glacial/Holocene transition through paludification of the pool in the Boreal period, followed by the final overbank alluvial deposition in the Early Atlantic period.

Sedimentological analysis indicated three flooding phases which may be linked to climatic oscillations of the Early Holocene. These oscillations are much better recognised in Western Europe, while in the eastern part of the continent there are fewer reference sites. The state of preservation of Early Holocene deposits in river valleys is usually poor. Our research, in contrast to other studies from Central and Eastern Europe, clearly indicates Early Holocene overbank alluvia in a second-order stream valley.

The studied small basin responded to both global changes and local natural factors. Traces of Mesolithic camp sites were uncovered at Lutomiersk Koziówki site (Papiernik and Płaza, 2012), but the human impact of small hunting-gathered communities seems to have been insignificant (Fig. 10) and no record of early human land-use change has been found during geoarchaeological research (Kittel, 2012a). The record of global change impacts on the evolution of the study basin is clear. It appears to be the result of high climatic variability, ushering in a series of natural environmental changes during the Early Holocene. The pronounced global climatic influences therefore affected the evolution of natural environment components at the site most considerably, followed by local factors, until ca. 8000 cal. BP.

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