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Late Quaternary landscape development at the margin of the Pomeranian phase (MIS 2) near Lake Wygonin (Northern Poland)

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A B S T R A C T

In Central Europe, Late Quaternary landscapes experienced multiple phases of geomorphologic activity. In this study, we used a combined geomorphological, pedological, sedimentological and palynological approach to characterize landscape development after the Last Glacial Maximum (LGM) near Lake Wygonin in Northern Poland. The pedostratigraphical findings from soil pits and drillings were extrapolated using ground-penetrating radar (GPR) and electric resistivity tomography (ERT). During the Pomeranian phase, glacial and fluvioglacial processes dominated the landscape near Lake Wygonin. At the end of the glacial period, periglacial processes became relevant and caused the formation of ventifacts and coversands containing coated sand grains. At approximately 15,290–14,800 cal yr BP, a small pond formed in a kettle hole (profile BWI 2). The lacustrine sediments lack eolian sand components and therefore indicate the decline of eolian processes during that time. The increase of *Juniperus* and rock-rose (*Helianthemum*) in the pollen diagram is a prominent marker of the Younger Dryas. At the end of the Younger Dryas, a partial reshaping of the landscape is indicated by abundant charcoal fragments in disturbed lake sediments. No geomorphologic activity since the beginning of the Holocene is documented in the terrestrial and wetland archives. The anthropogenic impact is reflected in the pollen diagram by the occurrence of rye pollen grains (*Secale cereale*) and translocated soil sediments dated to 1560–1410 cal yr BP, proving agricultural use of the immediate vicinity. With the onset of land use, gully incision and the accumulation of colluvial fans reshaped the landscape locally. Since 540–460 cal yr BP, further gully incision in the steep forest tracks has been associated with the intensification of forestry. Outside of the gully catchments, the weakly podzolized Rubic Brunic Arenosols show no features of Holocene soil erosion.

1. Introduction

Late Quaternary landscape dynamics in Central Europe, as in all mid-latitude regions, were primarily controlled by the transition from Pleistocene cold climates to the Holocene warmer climatic conditions, accompanied by the decline of the large ice sheets. The wide range of natural processes (primarily glacial, periglacial, eolian and fluvial) and the interaction with anthropogenic processes (primarily clearing, agriculture and soil erosion) resulted in a complex landscape. The changing climatic conditions determined the character of the main landscape components, i.e., landforms, soils and vegetation. In addition, human impact is another important trigger of landscape change following the beginning of farming in the Neolithic Period.

In the Central European low mountain ranges, periglacial conditions led to the formation of periglacial slope deposits (Semmel and Terhorst, 2010), whereas in the lowlands, eolian processes dominated (Kasse, 2002; Koster, 2005). Due to the gentle relief in the lowlands, solifluction was less significant, and ice wedges and cryoturbation prevailed (Altermann et al., 2008). However, because the processes proceeded partially contemporaneously and because of reciprocal effects, the paleoenvironmental significance of the processes in the landscape development remains vague. The eolian shaping of the landscape in the European lowlands continued from the Late Glacial to the Mid-Atlantic Period, producing different forms and sediments (Kolstrup, 2007; Tolksdorf and Kaiser, 2012). Pedological findings of the so-called Usselo soil and Finow soil suggest that similar conditions for soil development existed in wide areas (Kaiser et al., 2009), but the pedogenic character of these soils has been challenged (Jankowski, 2012). At the transition from the Younger Dryas to the Holocene, the

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vegetation stabilized the landscape. Since 8200 yr BP, changes in the vegetation have been associated with anthropogenic influence (Nielsen et al., 2012). At about 5000 yr BP, Neolithic farmers induced soil erosion in Southern Poland (Szwarczewski, 2009). In the late Holocene, the anthropogenic impact on the landscape caused a considerable increase in the reshaping of the landscape (Dotterweich et al., 2012; Schmidt and Heinrich, 2011; Smolska, 2007; Świtoniak, 2014).

This study aims to improve our knowledge of human–environment interactions since the Late Quaternary by focusing on a geomorphic type locality of the Pomeranian Glacial Stage in the North European Lowlands. The absence of continuous paleoenvironmental archives for the time span from the LGM until today and the sparseness of chronological markers within the existing archives make cross-disciplinary research necessary to connect the different archives. Our study site is situated near the paleolake Trzechowskie, where tephra of the late Allerød Laacher See eruption was recently discovered in lake sediments (Wulf et al., 2013). Therefore, our study site bears the potential to link further archives of that region into a comprehensive paleoenvironmental reconstruction. By applying a combined geomorphological, sedimentological, pedological and palynological approach, this polygenetic archive is evaluated to describe the Late Quaternary landscape development.

2. Materials and methods

2.1. Study area

The study area is located in northern Poland (Fig. 1a) in the northern part of the Tuchola Forest in the Starogard Lake District (Kociewie). This area was entirely covered by the last Weichselian ice sheet. During the retreat of the ice sheet, a distinct ice marginal zone of the Pomeranian Phase developed in this location, which is dated to approximately 16 ka to 17 ka (Marks, 2012), corresponding to the end of the marine isotope stage (MIS) 2 (Lisiecki and Raymo, 2005).

The most prominent landform in the ice marginal zone of the study area is the Pomeranian contact zone from the glacier and the proglacial sediments (Fig. 1b), running roughly parallel to the Lake Wygonin and further east to the settlement of Okoninki (Błaszkiewicz, 2005). The elevations of the outwash plain reach up to 155 m a.s.l. and gradually decrease towards to 120 m a.s.l. about 12 km to the south. The sedimentation of the outwash plain took place under long and stable depositional conditions. The deposition mostly followed the activity of supraglacial waters, as indicated by the presence of the reduced higher outwash level edge height of approximately 5–20 m at certain locations in the hinterland (Fig. 3i). The morphology of the proximal part of the outwash plain with kames, dead ice and kettle holes is notably diverse, and represents the shaping of the landscape with the melting of the ice sheet after the maximum ice extent. Subsequent to the accumulation of the higher outwash plain, the surface was influenced by a periglacial climate, leading to the development of permafrost, likely of a discontinuous nature (van Loon et al., 2012). Periglacial conditions led to the formation of sandy eolian deposits, and therefore the study site belongs to the northern margin of the European sand belt reaching from the Netherlands to Russia (Kasse, 2002; Zeeberg, 1998). Brunification and, to a lesser extent, podzolization are the prevailing pedogenic processes in the sandy soil substrate in the vicinity of the study area (Bednarek, 1991). According to the classification of IUSS Working Group WRB (2014) Brunic Arenosol is the main soil type in the region (Bednarek, 1991; Jankowski, 2010; Prusinkiewicz et al., 1980).

For characterizing the Late Quaternary landscape development we choose a site with potentially interconnected archives on the northern rim of the Pomeranian outwash plain south of Lake Wygonin (Fig. 1c). We focused on two gully catchments in about 1 km distance (site 1 and site 2). Both sites are characterized by gully erosion, and the respective colluvial fans represent the postglacial landscape development. At site 2, the colluvial fan extends into a small pond situated in a former kettle hole.

2.2. Soil and sediment analysis

To investigate the soils and sediments, soil pits were hand-dug and drillings were performed. The topography along the catena was mapped with a clinometer and measuring tape. Soils were described according to the FAO (2006) and classified following the WRB (IUSS Working Group WRB, 2014). Samples were collected for laboratory analysis from every horizon. Two undisturbed samples were collected in Kubiëna tins for thin section preparation. The thin sections were prepared following Beckmann (1997) and described according to Stoops (2003). Wood taxonomy on the charcoal remains in the thin sections was assigned according to Grosser (2007).

The soil color was determined using a Munsell soil color chart (Munsell, 2009). Due to the high sand content of the soil samples (usually greater than 95%), granulometry was only performed by wet sieving of the sand fraction without any pretreatment. Grain sizes were classified according to FAO (2006). The soil pH was determined potentiometrically at the ratio of 1:5 in deionized H_2O (Schlichting et al., 1996). All samples were tested for calcium carbonate content gasometrical by addition of HCl (Schlichting et al., 1996). The total carbon content of the soil samples was analyzed gas chromatographically on grounded aliquot gas by high-temperature heating with a VARIO EL analyzer. Pedogenic oxides and hydroxides (Fe and Al) were determined by selective extraction with dithionite (Mehra and Jackson, 1958), ammonium oxalate (Schwertmann, 1964) and sodium diphosphate (von Zezschwitz et al., 1973). In the sodium diphosphate extraction, dissolved carbon was additionally analyzed using catalytic oxidation and nondispersive infrared detection with a Shimadzu TOC 5000 instrument. The extracted pedogenic oxides were quantified by inductively coupled plasma atomic emission spectroscopy. The total iron content of the soil samples was measured on grounded aliquots via X-ray fluorescence with a Niton XLT3 analyzer. We differentiated the non-pedogenic-affected iron (Fe_T–Fe_D), the well-formed-crystalline pedonic iron oxides (Fe_D–Fe_O), the amorphous-to-poorly crystalline iron (Fe_o–Fe_P) and the organic-complexed iron oxides (Fe_P) (Schwertmann, 1991).

The ^{14}C dating on charcoal and organic material was carried out via accelerator mass spectrometry in the Poznan Radiocarbon Laboratory. Calibration of the ^{14}C ages into calendar years was performed using OxCal 4.2 (Bronk Ramsey, 2009) in combination with the Intcal13 calibration curve (Reimer et al., 2013).

2.3. Pollen analysis

For pollen analysis, sediment cores were collected with a Więckowski-type corer (Więckowski, 1966) and with an Edelman hand auger (BWIs 2 & 3). The sampling intervals were located 1 cm to 5 cm from the continuous Więckowski core (WYG) and at irregular intervals in the sediment sequences obtained by hand augering. Pollen samples were prepared with a standard procedure and treated with 10% HCl, 10% KOH, 40% HF and Erdtman's acetolysis. Each sample (sample volume = 1 cm^3) was treated with a known number of indicator spores of *Lycopodium* to determine pollen concentration (Stockmarr, 1971). For three sandy samples from BWI 3 (290 cm, 310 cm and 340 cm), 2-cm^3 volumes were taken. At least 500 (between 588 and 1362) pollen grains from trees and shrubs (AP — Arboreal Pollen) were counted for each sample. The pollen sum of AP and NAP (dwarf shrubs and herbs) was used as the basis for calculating the percentage (AP + NAP = 100%). The percentage values of the remaining groups (aquatic, swamp and spore plant as well as non-pollen palynomorphs — NPP) were calculated based on the above-mentioned sum from adding the respective taxa. A Zeiss Axioskop 2 Plus microscope at 400×, 630× and 1000× magnification was used in this process. For counting sporomorphs, the software POLPAL was used for