Periglacial structures within fluvio-aeolian successions of the end of the Last Glaciation – examples from SE Poland and NW Ukraine

PAWEŁ ZIELIŃSKI, ROBERT J. SOKOŁOWSKI, STANISŁAW FEDOROWICZ AND IWAN ZALESKI

The nature of permafrost and related environmental conditions in the Weichselian Late Pleniglacial and Lateglacial are reconstructed based on the assessment of frost structures that are best documented in the Loess Belt and in plateau areas composed of glacial till. Investigations were conducted in the central-eastern part of the European Sand Belt (SE Poland and NW Ukraine) on a fluvio-aeolian sedimentary succession and took into account its chronological context given by luminescence dating. Various generations of periglacial structures found in these deposits indicate not only the development of permafrost (ice-wedge pseudomorphs) and decreased humidity (composite wedge casts) but also the degradation of permafrost (large-scale involutions) and, finally, the establishment of deep seasonal frost (frost cracks). The diversity of structures in the study region appears to result from local conditions rather than increasing continentality of climate towards the east.

Study area and methods

Five representative sites in the central part of the European Sand Belt, in southeastern Poland and northwestern Ukraine (Fig. 1), were examined in the field. They all contain periglacial structures that originated during the LPM, between 300 and 400 km south of the maximum extent of the Last Glacial Maximum (LGM) ice. The sites were selected on the following criteria: (i) a long distance, about 400 km, between the easternmost and westernmost sites, all of which had similar lithology and large-scale morphology, and (ii) small-scale geomorphological diversity among sites located relatively close to one another. All sites are located either within dune fields, on aeolian covers located on Pleistocene-age river terraces, on alluvial fans or within the bottoms of dry valleys.

The Berezno and Bełżeck sites are located on river terraces. The Józefów site is located at the exit of a dry valley into a basin-like depression. The geomorphological position of the Niwiska site is similar, being located at the contact between the exit of a small tributary valley and the highest river terraces of a dry valley into a basin-like depression. The Manevichi site is located on the moraine plateau between the Stır and Stohid rivers. The first four sites are located on well-drained sandy/
silty substratum. The substratum at the Manevichi site is poorly drained, probably also poorly drained in periods of permafrost degradation due to the presence of basal till from the Saalian Glaciation.

Field investigations included the determination of the vertical and spatial range of sediment successions, the identification of lithological characteristics (texture and structure, and the scale and frequency of...
lithofacies) and the documenting of periglacial structures and their lithostratigraphic positions. The dating of the sediment samples was performed using TL (Fedorowicz 2006) and OSL (Molodkov & Bitinas 2006) methods. TL dating was carried out at the University of Gdańsk and OSL dating at the Research Laboratory for Quaternary Geochronology (RLQG) in Tallinn University of Technology. Dating results from the Bereznı and Manevichi sites have been published earlier (Zielinski et al. 2008, 2009). The results from the other sites (Józefów, Niwiska and Bełżec) are presented here for the first time.

Lithological characteristics and age

At all five sites, the sedimentary succession typically consists of three lithofacies complexes (Fig. 2): fluvial sediments change into fluvio-aeolian sediments that are topped with aeolian sediments (Zielinski et al. 2008, 2009). Brief details are outlined below.

Unit 1 is a fluvial complex. Its sandy sediments with medium and large-scale trough cross-bedding (Figs 3D, 4A) usually change into fine-grained sands with ripple lamination in an upward direction and are topped with silty sands with wavy, flaser or horizontal lamination. Sands with medium-scale tabular cross-bedding also occur with limited frequencies, and sands with ripple lamination with very limited frequencies. There are different quantitative relations between the lithofacies at the various study sites. The largest number of channel facies occurs at the Bereznı and Józefów sites.

Unit 2 is a fluviol-aeolian complex basically composed of alternating layers with horizontal bedding or ripple cross-lamination as well as silty sands and silts with wavy or flaser lamination (Figs 3A, 4D). Frequently recorded are sands with translatent stratification (between 10 and 20 cm thick), covering and/or dissected by single troughs, filled with cross-bedded sand that, in some places, changes into ripple cross-laminated sets (the Bereznı, Niwiska and Józefów sites; Fig. 4D).

Unit 3 is an aeolian complex consisting of sands with high-angle cross-bedding. A significant component is sand with translatent stratification and, to a lesser degree, sand with tabular cross-bedding and trough structure, usually with concordant filling.

The TL/OSL age of Unit 1 was determined at 32.6±4.9–13.0±1.1 ka (Fig. 2; Zielinski et al. 2009). The TL/OSL age of Unit 2 was determined at 27.5±3.8–11.5±1.0 ka (Fig. 2; Zielinski et al. 2008, 2009). Both units thus date from the late Pleniglacial and Lateglacial. The age of Unit 3 was determined at 12.7±1.3–7.2±1.1 ka (Fig. 2; Wojtanowicz 1996; Zielinski et al. 2008, 2009), that is, its deposition occurred in the Lateglacial and at the beginning of the Holocene.

Periglacial structures

Two types of periglacial structures have been identified in the fluvial and fluvo-aeolian deposits (Units 1 and 2) at the study sites: (i) thermal-contraction wedges and (ii) cryoturbations.

Thermal-contraction wedges

Wedge structures and small cracks occur in Unit 1. Structures related to the former existence of ice wedges occur most frequently; the best developed were found at the Bereznı site where the structures are up to 2 m deep, have a maximum width of 0.3 m, and form a distinct horizon (Figs 3B–D, 4A) and a polygonal network (approximating an orthogonal pattern) about 4–6 m in diameter. The wedges have a syngenetic character because their upper part is truncated by successive sets of channel sediments with trough stratification; in these younger sediments further generations of wedges occur (Fig. 3C). They may be similar to those described by Vandenbergh & Kasse (1993) in the Netherlands (same age). Composite wedges were found at the Bereznı site; such wedges are described elsewhere by, for example, Harry & Gozdzik (1988) and Murton (1996). The lower parts of these wedges comprise ice-wedge pseudomorphs with a complex of small normal faults on the walls; their filling consists of the adjacent sediments (Fig. 4A). In the upper part, the wedges contain sand with vertical lamination parallel to its walls, visually distinct from the neighbouring sediments. The third type of crack is represented by small fissures that are between 0.4 and 0.8 m in length and mostly developed in the higher part of Unit 1. At the Bereznı site, they co-occur with cryoturbations (Fig. 4C). They are particularly numerous at the Bełżec site where they form a network (Fig. 3C). They are interpreted as seasonal frost cracks (frost fissures).

At the Bereznı and Józefów sites, vertical platy structures were found in the sediments of Unit 1 (Figs 2, 3A). They form successions between the main ice-wedge pseudomorphs. Along them, layers of sediments are dislocated vertically by a few centimetres. Single structures of this kind are also recorded at Manevichi in Unit 2 sediments.

Cryoturbations

Cryoturbations occur in Unit 1 and 2 (Fig. 2) at all five study sites. The best developed structures were found at the Bereznı site in the top layer of Unit 1. They are composed of medium- and large-scale load casts in three horizons (Fig. 4A–C); brown loams (mainly horizontally laminated) have sunk into fine-grained yellow sands to form finger, drop-like and pocket-like structures, sometimes detached from the layer in which they originated (Fig. 4A, C).
Fig. 2. Sedimentary succession at the study sites, with location of periglacial structures and TL and OSL ages of the deposits (Wojtanowicz 1996; Zelinski et al. 2008, 2009).
At the Niwiska site, deformation features indicate the creep of partially liquefied sandy material. In the proximal part, the deformation has the character of small gravitational faults that change into a system of small antithetic faults.

In Unit 2, cryoturbations take the form of small load casts of fine-grained sediments (Fig. 3A) and water-escape structures. The load casts reach the depth of 0.3 m. Bowl-shaped structures, up to 5 cm high and 10–15 cm wide, are dominant.

Sedimentary interpretation and palaeoenvironmental implications

**Unit 1**

The sediments of Unit 1 were formed by a braided river. The trough cross-bedding (representing 3D dunes) was formed in the thalweg zone by strong water flow in turbulent cells during seasonal flooding. Their transition to ripple lamination can be interpreted as a record of drop in velocity and shallowing of the channel. This occurred as a result of deposition after the flood wave. The finest lithofacies (Fw) was formed as a result of water stagnation on the floodplain.

A gradual decrease in the size of the particular lithofacies and their decreasing grain size can be interpreted as a result of decreasing discharge under increasingly dry cold-climate conditions (Kasse et al. 2003; Vandenberghe 2003). The presence of cold (periglacial) climatic conditions is attested by the well-developed wedge structures that formed on the exposed parts of the mid-channel bars (Berezno and Niwiska sites) and floodplains. The wedges and veins have been buried by material from the sides (Fig. 3B–D). A composite wedge with primary sandy infilling was preserved only at the Berezno site. In this case, the prevalence of ice wedges can be better explained by their morphological position in the braidplain.

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Fig. 3. Photographs of fluvial and fluvio-aerial deposits with periglacial structures. A. Józefów site; large-scale (∼50 cm) involutions (black arrows) and vertical platy structures (white arrows) in fluvial deposits (Unit 1). B. Józefów site; lower part of syngenetic ice-wedge cast (black arrow) and frost fissure (white arrow) in the top layer of fluvial deposits (Unit 1). C. Bełże site; syngenetic frost cracks (white arrow). D. Niwiska site; fluvial deposits (Unit 1) with frost fissure (white arrow) and lower parts of ice-wedge casts (black arrow). This figure is available in colour at http://www.boreas.dk.
Fig. 4. Photographs of fluvial and fluvio-aolian deposits with periglacial structures. A. Berezno site; fluvial deposits (Unit 1). Large-scale involutions at the top of Unit 1 (white arrow) and composite wedge (black arrow). B. Large-scale involution (black arrow) and palaeosol (white arrow) at the top of Unit 1. C. Small-scaled involutions (white arrow) at the top of Unit 1. frost crack (black arrow) and deflation pavement (grey arrow). D. Manevichi site; frost crack (black arrow) in fluvio-aolian deposits (Unit 2). This figure is available in colour at http://www.boreas.dk.
The development of cryoturbations can be explained by the saturated nature of thawing sandy sediments overlying an impermeable substratum. Structures from the Berezno site could be classified as pocket-like structures (type 4 according to Vandenberghe 1988, 2007). As permafrost degraded, the upper (silty) sediments sank (Vandenberghe 1988, 1992). After the cryoturbations developed, frost cracks were formed (Fig. 4C). Structures of similar age and origin were described by Superson et al. (2010) nearby the Niwiska site.

Unit 2

Silty–sandy rhythmtes of Unit 2 indicate alternating fluvial and aeolian accumulation resulting from seasonal discharge regimes followed by aeolian accumulation on wet surfaces (Good & Bryant 1985; Schwan 1986, 1987). Dry and windy winter conditions would have favoured aeolian deposition, while the spring thaw, summer rain and the inhibition of infiltration by permafrost would have been conducive to spring and early summer discharge and the subsequent redeposition of aeolian material later in the summer (Böhncke et al. 1995; Kasse 1997; Mol 1997; Huisink 2001; Van Huissteden & Kasse 2001; Kasse 2002; Kasse et al. 2007).

The time frame obtained for Unit 2 (27.5–11.5 ka, Fig. 2) indicates the non-synchronous character of deposition. The differences in the onset of the fluvio-aeolian complex deposition were controlled by the geomorphological conditions. Typically, deposition would have begun earlier at sites located in small or dry valleys; this can be explained by smaller discharges in small catchments resulting in a clear predominance of aeolian processes over fluvial ones.

Lowered precipitation resulted in the decrease of discharge in the smaller river systems and the dominance of aeolian deposits reworked by fluvial processes.

Unit 3

The presence of high-angle inclined bedding of the deposits of Unit 3 at the Józefów and Niwiska sites indicates deposition within the lee (distal) slope of transverse dunes (cf. McKee 1966; Sharp 1966; Hunter 1977). The sands constitute the entire dune succession indicating that the dunes were laterally migrating dunes.

Palaeoclimatic conditions

Certain periglacial structures may indicate the climatic conditions under which they formed. For example, the ice-wedge structures at the Berezno and Niwiska sites can be regarded as representative of MAAT lower than −4 or −5°C and MAGT lower than −2°C (Harry & Gozdzik 1988; Vandenberghe 1988; Van Huissteden et al. 2003; French 2007). Given the dominance of relatively coarse-grained (sandy) sediments, it can be assumed that temperatures closer to −8°C may have occurred. The repeated upward extension of ice-wedge pseudomorphs by sand-wedge casts can be regarded as an indicator of a fall in the mean annual precipitation (MAP) to about 100 mm a⁻¹ and intensified activity of aeolian processes (Huijzer & Isarin 1997).

The OSL dating indicates that thermal-contraction cracking began some time after c. 30–28 ka (Fig. 2). The extreme cold-climate conditions probably occurred c. 22–16 ka, as recorded in the development of composite wedges (Figs 2 and 5). At the end of that period, c. 16–14 ka, the climate became slightly milder, and large-scale involutions developed at the top of Unit 1 as a result of permafrost degradation, similar to the case in the Netherlands (Vandenberghe 1988, 1992). During deposition of Unit 3, the climate remained cool, as manifested by the seasonal frost cracks in this unit.

A decrease in annual precipitation resulted gradually in decreased fluvial activity, replaced by greater aeolian activity on the braidplains. For example, at the Berezno site, the top layer of Unit 1 is characterized by a deflation pavement that seems to occur over the entire extent of the European Sand Belt, the ‘Beuningen desert pavement’ dated around 17–16 ka (Bateman & Van Huissteden 1999; Kasse et al. 2007). The absence of such a distinct horizon at the other sites may reflect wetter local conditions and/or an absence of coarse material.

Discussion

The stratigraphic position of the fluvio-aeolian sedimentary succession has been often determined in the western and central part of the European Sand Belt (e.g. Böhncke et al. 1995; Mol 1997; Kasse 2002; Kasse et al. 2007; Zieliński et al. 2009, 2011). According to those studies, braided river sediments were deposited during the Late Pleniglacial. These rivers became inactive because their channels changed into meandering channels, and this generally occurred at the start of the Bölling interval (Kozarski et al. 1988; Böhncke et al. 1995; Huisink 2000; Vandenberghe 2003). The time frame (32.6–13.0 ka, Fig. 2) determined for the fluvial complex (Unit 1) at the sites studied confirms that age.

The aeolian deposition and fluvial reworking of Unit 2 are characteristic of the accumulation of Older Coversand I that occurred also in the Late Pleniglacial (e.g. Böhncke et al. 1995; Mol 1997; Kasse 2002; Kasse et al. 2007). The deposition of the dune complex (Unit 3) occurred in the Lateglacial and early Holocene (12.7–7.2 ka, Figs 2 and 5). The time frames obtained are consistent with the age of aeolian deposition in the European Sand Belt (Gozdzik 1991; Kozarski & Nowaczyk 1991; Böhncke et al. 1995; Wojtanowicz 1996; Mol 1997; Kasse 2002; Kasse et al. 2007).
However, many authors place the beginning of aeolian deposition in present-day Poland before the Bölling interstadial (Gozdzik 1991; Kozarski & Nowaczyk 1991; Wojtanowicz 1996).

Ice-wedge pseudomorphs and sand-wedge casts are widely interpreted as clear proof of continuous permafrost conditions (Péwé 1966; Gozdzik 1973; French 2007). Their formation requires a considerable fall in temperature (by at least 15°C (Plug & Werner 2002; Van Vliet-Lanoë et al. 2004)). Thus, it can be suggested that the fluvial sedimentation of Unit 1 was accompanied by the aggradation of permafrost on floodplains (Vandenberghe & Kasse 1993). In autumn and winter, the exposed floodplain surface was deeply frozen and vertical platy structures, caused by ice segregation, developed (Mol et al. 1993).

The upward extension of ice-wedge pseudomorphs by sand-wedge casts reflects at least local drying climatic conditions (Ghysels & Heyse 2006). However, the repetition of this pattern at two sites (Fig. 2) suggests that it may have resulted from changes of a regional character. It can be argued that, as the climate became increasingly drier, there was a corresponding decrease in the amount of segregated ice that formed in the sandy deposits. At the same time, the reduction of vegetation on the upper terraces and some parts of floodplains increased the mobilization of aeolian material into open cracks. The result was the cessation of typical fluvial sedimentation and the beginning of aeolian deposition. The fluvi-aeolian deposits of Unit 2 accumulated. The more limited development of periglacial structures within these successions resulted both from the extremely dry climate and the shorter duration of sedimentation. Their deposition records the driest part of the Pleniglacial and the disappearance of normal (rhythmic) fluvial sedimentation in smaller river systems.

Load casts, well-developed at several sites, record the degradation of near-surface permafrost just before the formation of the desert pavement, that is, just before 17 ka by analogy with the age of the ‘Beuningen desert pavement’ (Vandenberghe 1988, 1992). The relatively small depth of the load casts seems to indicate a seasonally thawing layer rather than a deeper degradation of permafrost (Vandenberghe 1992, 2007). The development of the small cryoturbations in Unit 2 probably occurred as the result of the seasonal cycle of freeze-thaw of the ground (Schwan 1986, 1987). Water-escape structures probably formed due to the liquefied material being displaced by the ground surface freezing up (Van Huissteden et al. 2000; Kasse et al. 2007).

Conclusions

The five sites indicate that permafrost was widespread in the region of northwestern Ukraine and southeastern Poland between 28 and 18 ka. Its maximum spatial extent probably coincided with the cold-climate permafrost maximum (LPM) towards the end of this period. Permafrost-related structures suggest that continuous permafrost formed in river valleys and lowlands. Similar conditions existed elsewhere in Poland (e.g. on
the terraces of the Wisłoka valley; Superson et al. 2010), and analogous structures can be found in the loess areas of Poland and Ukraine (Morozowa & Nechaev 1997; Jary 2009; Jary & Ciszek 2013) and in formerly ice-covered areas of the LGM (Sokolowski 2007; Wysota et al. 2007).

Permafrost aggradation occurred on the exposed parts of floodplains and mid-channel bars. Unlike fine-grained sediments, sandy sediments do not preserve frost fissures very well. Hence, relatively narrow syngenetic ice-wedge pseudomorphs are observed in the fluvial sandy deposits studied here. At the same time, wetter conditions on the floodplain and adjacent terraces favoured the development of ice-wedges rather than sand wedges. On the adjacent till-covered plateaus sand wedges dominated (Kozarski 1993; Sokolowski 2007).

The development of permafrost-related phenomena in Unit 1 sediments at all five study sites does not show any distinct variation in the west-to-east direction. It seems that the differences are determined by local factors such as land relief, sediment texture or hydrologic regime during deposition. However, in order to prove the increasing continental character of the cold climate in eastern Europe during the Late Weichselian, and to eliminate the impact of local factors, a greater number of sites, more widespread along the east–west axis, has to be investigated. In addition, other palaeoclimatic proxies such as palaeosols may be more suitable to determine a shift in continentality.

Finally, the resemblance of the morphological–sedimentological–palaeoclimatic evolution in the Late Pleniglacial between the study area and the western part of the Sand Belt should be stressed. Braided rivers were typical in (continuous) permafrost conditions during the LPM; towards the end of the LPM and at the time of permafrost degradation their runoff decreased while aeolian activity (deposition and deflation) increased.

Acknowledgement. – Investigations at the Niwiska, Józefów, Berezno and Manevichi study sites were supported by Grant N N 306 197639 from the Polish Ministry of Science and Higher Education. The study in Belzec site was financed by the Grant of Vice-Rector for Science and International Cooperation, UMCS. We would also like to thank the reviewers (Else Kolstrup and Ole Humlum) and guest editors of this volume (Hugh French and Jef Vandenberghe) for their valuable comments which helped to improve this article.

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