Geological Quarterly, 2006, **50** (2): 219–228

Record and palaeogeographical implications of Pleistocene periglacial processes in the Drohiczyn Plateau, Podlasie Lowland (Eastern Poland)

Jan DZIERŻEK and Dominik STAŃCZUK

Dzierżek J. and Stańczuk D. (2006) — Record and palaeogeographical implications of Pleistocene periglacial processes in the Drohiczyn Plateau, Podlasie Lowland (Eastern Poland). Geol. Quart., **50** (2): 219–228. Warszawa.

The paper describes 51 ice-wedge casts from Wierzchuca Nagórna village near Drohiczyn town in the Podlasie Lowland in Eastern Poland. The structures are preserved in a till of the Wartanian Glaciation. In the exposure the mean distance between them is 1.7 m; their mean length is 1 m, and their width ranges within 0.2–0.5 m. Most of the structures are typically wedge-shaped, although in some cases less regular pockets or veins are also observed. Some of the casts display a complex origin. They are filled mostly by fine-grained sand, in the lower parts with wind-corroded grains, as well as by sand with gravel from the overlying deposits. Near the ice-wedge casts, traces of frost swelling, uplift and sorting in permafrost conditions, as well as of an active layer are preserved. The thickness of the permafrost active layer, as preserved, is about 0.5–0.7 m. The formation of ice-wedges reflects periglacial conditions during the Vistulian (Weichselian) Glaciation. Three palaeogeographical alternatives are discussed. Probably, the lack of traces of periglacial activity from the Wartanian Glaciation is a result of plateau denudation. The range of this denudation has also been estimated.

Jan Dzierżek and Dominik Stańczuk, Institute of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, e-mail: dzierzek@geo.uw.edu.pl *(received: March 23, 2005; accepted: October 3, 2005).*

Key words: Podlasie Lowland, palaeogeography, Pleistocene, periglacial processes, ice-wedge casts.

INTRODUCTION

Numerous exposures of structures reflecting Pleistocene periglacial processes are known from the Podlasie Lowland, e.g., at Królewski Dwór near Parczew, Augustów near Bielsk Podlaski and Gostchorza (Mojski, 1972). Further exposures were recognized during fieldwork in 2003–2004 within the Drohiczyn Plateau: Wierzchuca Nagórna, Lisowo-Janówek, Putkowice Nagórne and Sytki (Fig. 1). The exposure at Wierzchuca Nagórna, 12 km NNW of Drohiczyn, is exceptional, with 51 ice-wedge casts preserved in a gravel-pit (1 on Fig. 1). The ice-wedge casts reveal different shapes, sizes and types of infill. Due to the low faces of the gravel-pit, the exposure was easily accessible. Well-preserved forms of similar character can also be found in a neighbouring gravel-pit (2 on Fig. 1).

The main goal of this paper is to describe and map this unique exposure of buried periglacial features within its geological and geomorphological context. The measurement of structures and analysis of their shape, size and spatial distribution, together with quartz grain analysis of the sediments filling the ice-wedge casts, were aimed at recognizing the environment of their development. Petrographic analysis of the gravel fraction and TL dating was carried out to estimate the age of the deposits.

This analysis of the periglacial structures on the Drohiczyn Plateau and comparison of these structures with those from other regions, provide new data aiding discussion of the palaeogeography of the Podlasie region.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The exposure in Wierzchuca Nagórna is located on the western part of the Drohiczyn Plateau (Kondracki, 2000), near the distinct margin of the N–S section of the Bug valley (Fig. 1). Just by the gravel-pit lies a smoothly incised valley of an unnamed tributary of the Bug which, with other minor tributaries, forms a system of parallel valleys on the Drohiczyn Plateau. The surface of the study area is generally flat or slightly descends westwards. The topmost part of the gravel-pit lies at 132 m above sea level. The generalized lithological log has been compiled from the section description and a core drilled in the gravel-pit bottom (Fig. 2). Below a humus horizon, silty,

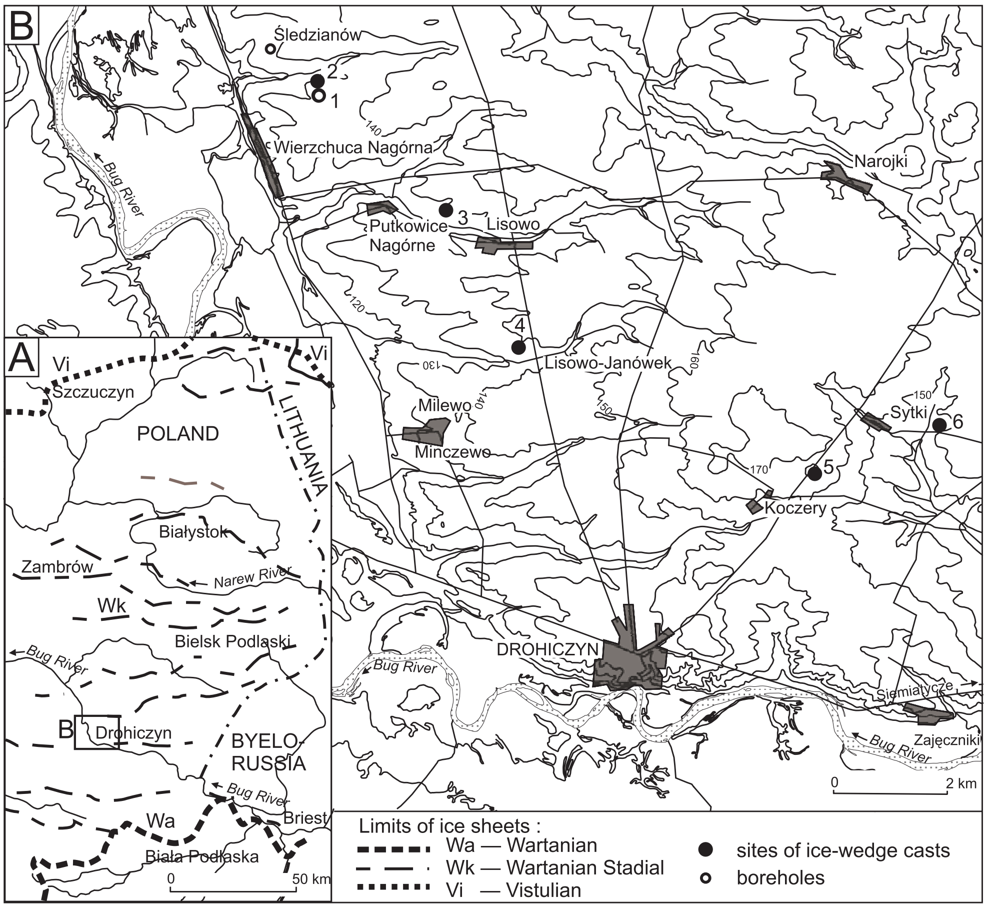

Fig. 1. Location of sites with buried periglacial structures in the Drohiczyn Plateau and limits of ice sheets in eastern Poland, after Marks (2004*a*)

pale yellow, poorly sorted sands with gravel occur. These deposits do not show any distinct sedimentary structures. In the lower part of this bed, horizontal concentrations of gravels are locally present. Greater concentrations of gravel in some parts of the exposure, particularly near the wedge structures, reflects processes of frost segregation in non-uniform soils. The thickness of this bed, which covers the ice-wedge casts, varies between 0.3 and 0.5 m. Below lies brown, sandy till with a high content of gravel. The thickness of till is about 0.5–1.5 m. The till is penetrated by numerous ice-wedge casts, infilled with sandy gravel, in some cases with thin clayey beds. Below lies cross-stratified sand with gravel. This bed continues downwards, reaching up to 4.3 m in thickness (Fig. 2).

The geological setting indicates that the exposed strata may be referred to the Wartanian Glaciation (Nowak, 1971, 1972; Marks, 2004*a*, *b*). The age and succession of deeper-lying strata has been established based on data from the Śledzianów succession, situated about 4 km NW of the gravel-pit studied. Correlation of this succession with the borehole core from the gravel-pit indicates that below the sandy gravel bed lies a succession up to 7.2 m thick consisting of varved clays and silty and clayey sands (J. Nitychoruk, pers. comm.). This succession lies on till from the Odranian (?) Glaciation, the thickness of which reaches about 5 m (Borówko-Dłużakowa, 1973), which is underlain by glaciofluvial sandy gravels several metres thick. Silty deposits with a thin peat layer at the base lie below. The age of this peat has been assigned, based on pollen spectra, to the Mazovian Interglacial (Borówko-Dłużakowa, 1973). These deposits overlie thick till of the Sanian II Glaciation. The lowermost Pleistocene deposits in the study area are represented by fine sandy and silty-clayey deposits, with a total thickness of up to 160 m. At about 35 m below sea level the top of the Miocene succession, which form the basement of the Quaternary deposits.

RESULTS OF PETROGRAPHIC ANALYSIS

Macroscopic petrographic analysis was carried out to compare the gravel fraction from the till, the overlying silty sands and gravels and the ice-wedge infills (of sand and gravel).

For the till, the sample number was 186, for the overlying material it was 73, and for the ice-wedge infills it was 78. The grain size studied was between 2 and 5 cm. The analysis shows a distinct difference between the petrographic composition of the till and the two other deposit types. In the till, sedimentary rocks, mainly limestones and sandstones, prevail. By contrast, the petrographic composition of the overlying and ice-wedge infill material is dominated by crystalline rocks. Moreover, there are no essential differences between the composition of the cover and of the infill deposits. This supports the field interpretation of the exposure and indicates that the gravel of ice-wedge infills originated from the overlying strata. By comparison with the till, the overlying material contains a low percentage of relatively low-density sedimentary rocks. This probably results from erosion of the uppermost part of till and washing out of the least dense rock fragments, particularly limestones, by erosion and denudation (see Manikowska, 1982). The crystalline rocks recognized in the gravel fraction of the till are dominated by granitoid fragments (Prück granite, Cland granite) and porphyries (red Baltic porphyry). The petrographic composition of the till from the Wierzchuca Nagórna exposure is typical of the till of the Wartanian Glaciation (D. Gałązka, pers. comm.).

CHARACTERISTICS OF THE ICE-WEDGE CASTS

DISTRIBUTION, PARAMETERS AND SHAPE

The exposed wall of the gravel-pit has been divided into sections, and the ice-wedge casts have been numbered from 1 to 51, beginning from point A on the eastern wall (Fig. 3). The following parameters of the ice-wedge casts have been measured: length, width of upper part and distance between the casts. Their shape has also been described (type of termination, dip of axis, type of contact with the adjacent sediment). The measurements and field observations show that the casts are closely spaced, from 0.5 to 3.5 m apart, most commonly 1.5–2 m apart, and averaging 1.7 m (Figs. 3 and 4). By dividing the total length of exposed faces by the number of wedge structures we can calculate the ratio of wedge density; the mean wedge spacing (according to Maizels, 1986; method), which is about 3.02. They are best developed in the SE part of the exposure, whereas in the NE part, where the till layer is much thinner, the casts are less numerous and less distinct. Their length typically reaches about 1.0 m (in 27 out of 51 studied), and rarely exceeds 1.2 m. Smaller forms (0.6–0.8 m) are also numerous. The cast width, measured in their upper parts, varies between 0.2 and 0.5 m and in some cases may even exceed 1 m (Fig. 5).

The variable shape of the structures studied results not only from their intersection with the gravel-pit wall, but most probably reflects variable environmental conditions during their evolution. Therefore the term "wedge" does not necessarily always reflect their shape. Several types of shape have been distinguished. A typical wedge shape occurs in forms nos. 17, 20 (Fig. 6), 23 and 39 (Fig. 3). They are terminated by 1 m long, 0.3 m wide in their upper part (relation between length and width in the upper part is 3:1). They are terminated by a distinct triangle, and the forms are symmetrical along the vertical axis. The second type includes sack-like forms. These are typically 1–1.2 m long, and the width in the topmost part does not change significantly with depth. This shape is represented in forms nos. 8, 15, 19 and 29 (Fig. 3). The next group includes short and wide forms, nos. 1, 2, 9, 10, 11 and 12 (Fig. 3). A separate group includes forms of exceptional sizes. Ice-wedge casts nos. 4, 12, 34 and 48 (Fig. 3) are distinctly larger by comparison with the other casts. They usually have a double termination (Fig. 4). In turn, forms nos. 3, 24, 42, 46 and 47 (Fig. 3) are distinctly smaller than the others.

Regardless of their shape, the axes some casts deviate from the vertical. The best examples of this feature are casts nos. 4, 13, 18, 21, 25, 40, 44, 45 and 48 (Fig. 3).

Forms that are asymmetrical in their upper part have also been noted, e.g., nos. 2, 12, 17, 37, 41, 43, 48 and 51 (Fig. 3). This is probably a result of local palaeoclimatic conditions, i.e. exposure of the cast walls to sunlight or the influence of warm air (Jahn, 1970).

The shapes of ice-wedge casts described and their distribution in the exposure wall suggest unequivocally that they reflect a polygonal network developed on a plateau surface in periglacial conditions (Dylik, 1966; Washburn, 1973; Jahn, 1977). The variable distances between the casts indicate the complex pattern of the polygonal network, and the occurrence of much smaller and shorter forms in the vicinity of larger, longer structures (e.g. 3, 4, 6, 7, 29, 30, 47 and 48 on Fig. 3) may reflect several generations of fractures.

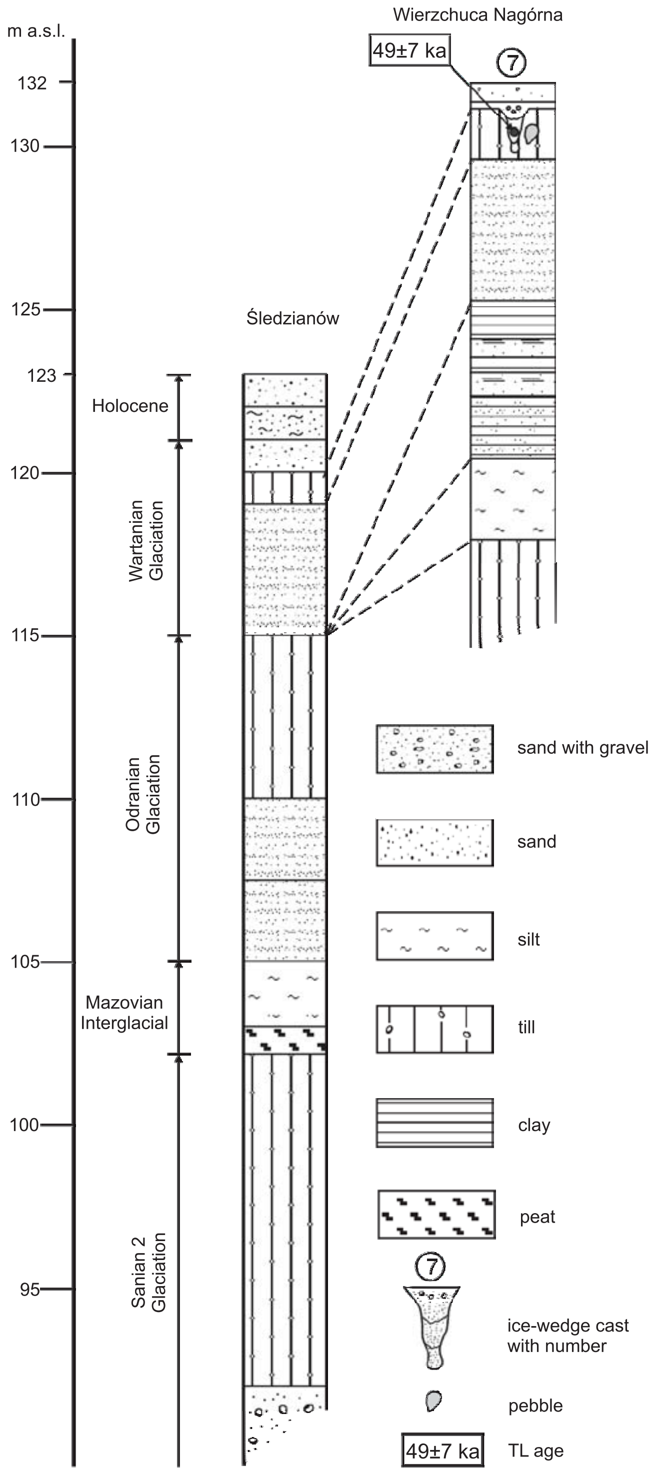

Fig. 2. Stratigraphic logs of the Drohiczyn Plateau at Wierzchuca Nagórna; based on section logging, coring (J. Nitychoruk, pers. comm.) and the Śledzianów borehole (Borówko-Dłużakowa, 1973)

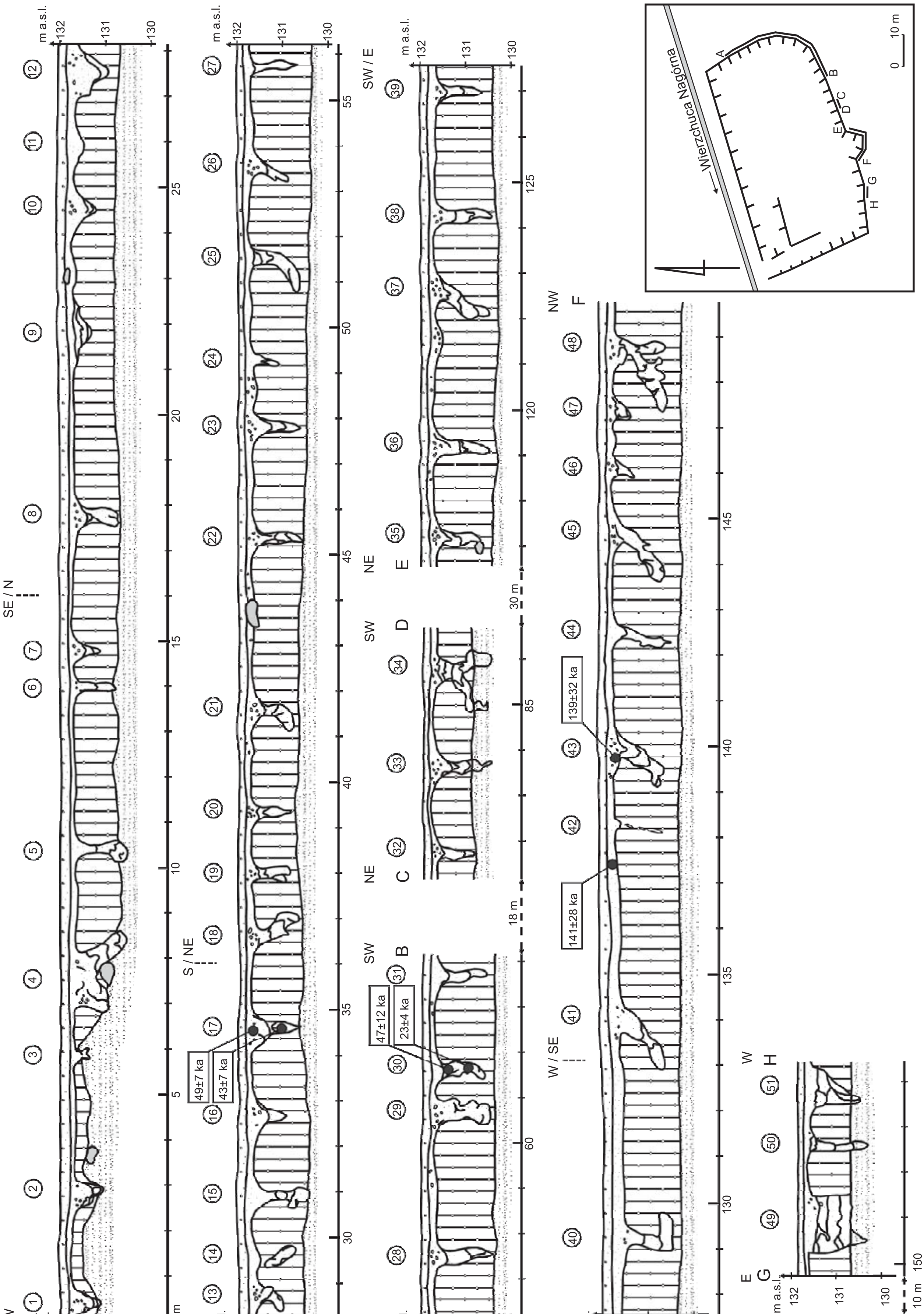

Fig. 3. Geological sections and location of the Wierzchuca Nagórna exposure, with TL ages

Explanations as on Figure 2

HOST SEDIMENTS

In most cases the casts terminate within the glacial till. Only in the NE part of the gravel-pit do they extend through the thin till layer into the underlying sands and gravels. The cast outline is marked by a thin layer of dark brown orstein (Fig. 4). Such a layer in the shape of a widening cast or pocket can also be traced in the sands and gravels below the bottom surface of the till (Fig. 7). However, the structure and lithology of the deposits between the inside and outside of such an orstein pocket remain unchanged. This suggests that the frost processes responsible for the formation of the fractures in the till did not reach down to the underlying sands and gravels. Thus, this type of cast termination is a result of seasonal infiltration of melting waters rich in iron compounds and should be linked with the terminal stage of ice-wedge disintegration. Meltwater reached the still-frozen layer under the till and systematically melted the ground ice (Jahn, 1977). Precipitation of iron compounds took place in the zone of temperature compensation between the water and frozen ground. The width of this zone as well as the irregular shape of the outline indicates the long duration and variable intensity of the thermokarst process.

Fig. 4. Fragment C–D of the exposure wall at Wierzchuca Nagórna, with the double termination of ice-wedge cast no. 34 and the dome-like shape of the till between casts

Fig. 5. 1-m wide ice-wedge cast no. 49 with features of secondary infilling: bent (orsteined) clayey layers and coarse material

Analysis of the deposits adjacent to the ice-wedge cast showed a distinct change in the structure of the till near the cast walls, where a system of "ascending" joints is present (Fig. 6), revealing the dynamics of the frost processes. These processes, of frost heaving, ascension and segregation are reflected in the domal shape of the till fragments between the casts (Fig. 4), and in the vertical orientation of the long axes of pebbles in the till (Fig. 8). These phenomena are most distinct in the regions of dense polygonal network within permafrost at the boundary with the live ice of the wedge (Jahn, 1970, 1977). The preservation of frost structures in the till, contrasting with the overlying structureless layer may allow evaluation of the depth of seasonal thawing. Alternatively, the preservation of such a pattern may suggest fast fossilization of the wedges; thus, replacement of ice with deposit took place in the wedges when the neighbouring till was still frozen.

INFILLS

The infills of the ice-wedge casts are represented mainly by sand with a small admixture of gravel, as well as thin (2–3 cm), concave down clay layers. An increased content of pebbles can be observed in the wider parts of the ice-wedge casts, with their long axes semi-parallel to the cast walls. Both the macroscopic

Fig. 6. Ice-wedge cast no. 20 showing lower part of the cast with primary infilling, upper with secondary infilling; note swelling of till in the upper part of the till

Fig. 7. Ice-wedge cast no. 50, with "thermokarst" pocket within the sub-till sands and gravels and the boundary of the infill; note the distinct asymmetry of the upper part of the structure

Fig. 8. Ice-wedge cast no. 27, showing vertical orientation of pebbles in the till and the concentration of coarse material at the till surface

features of the deposits as well as the results of petrographic analysis suggest that the main source of the material infilling the casts was the surface layer. The distinct contrast between the ice-wedge cast and the till suggests that the till was still frozen during the filling of the ice-wedge cast. The concave structure of the infill suggests secondary filling of the wedges and the curvature of the clay layers indicates rapid melting (Jahn, 1977).

Forms, in which the lowermost, sharply ending part is filled with fine-grained sand without distinct melt-out structures are also present (Fig. 6). Most probably this is a record of the initial stage of frost fracture development, with a primary infill, where later an ice-wedge was formed. The upper part of these ice-wedge casts already bears melt-out structures.

In order to confirm this observation, analysis of quartz grain rounding, carried out for samples collected from three depths was performed for one of the casts (Markiewicz, 2004). The analysis was carried out using the Cailleux method as modified by Mycielska-Dowgiałło and Woronko (1998). The composition of two grain-size fractions — 0.5–0.8 and 0.8–1.0 mm — were analysed for about 200 grains from each sample (Table 1).

Table 1

Composition of quartz grains types in ice-wedge cast no. 35

Grains type	Lower part		Middle part		Upper part	
	∅ 0.5–0.8mm	∅ 0.8–1.0mm	∅ 0.5–0.8mm	∅ 0.8–1.0mm	∅ 0.5–0.8mm	∅ 0.8–1.0mm
	[%]					
NU	16	5	3	1	10	4
RM	23	24	16	22	16	30
EL	0	0	1	4	1	1
EM/RM	56	59	74	64	64	60
EM/EL	4	8	5	7	7	3
C	1	4	1	2	2	2

NU — angular grains, RM — rounded frosted grains, EL — polished grains, EM/RM — transitional frosted grains, EM/EL — transitional polished grains, C — fractured grains

The quartz grains in all three samples are very similar to each other (Table 1). The lower sample clearly suggests the modification of quartz grain surfaces in periglacial conditions due to wind reworking and frost fracturing, as is shown by the larger content of rounded matt grains (24%), the highest content of non-reworked grains (16%) and the absence of polished grains. These features are typical of periglacial structures with a primary infill and probably indicate a complex development of the ice-wedge cast (Goździk, 1970, 1982; Jahn, 1977; Murton *et al*., 2000). Deposits in the middle part of the infill include a higher content of transitional polished grains, with matt-surfaced corners (64–74%), and a low (but the highest in the profile: 4%), content of rounded polished grains. Angular grains comprise only 1–3%. This indicates that the climate probably became relatively milder during infilling of the ice-wedge (Goździk, 1982). A higher content of angular grains, and a high content of grains with wind reworking of coarser grains (30%) in the upper part of the infill, indicates the return of severe periglacial conditions.

Although preliminary, the quartz grain surface analysis suggests that the ice-wedge cast development took place in several stages, supporting conclusions drawn from fieldwork.

THICKNESS OF THE ACTIVE PERMAFROST LAYER

The shape of the ice wedge-cast and the character of the host sediments can be used to estimate the depth of seasonal thawing. According to Jahn, (1970) the wider, often asymmetrical, upper part of the wedge represents the active layer of permafrost, the lower, narrow, sharply ending part being formed in the permafrost zone. Multiple freeze-thaw processes in the active layer have disrupted primary sedimentary structures and resulted in the formation of frost-sorted ground. We, thus, estimate that the thickness of the active permafrost layer at Wierzchuca Nagórna was rather small: about 50–60 cm. The seasonal thawing affected only the surficial layer, which commonly contains a larger concentration of gravels. This is also reflected in the frost segregation processes. In some places seasonal thawing reached about 70 cm, marked by the location of the bottom of the asymmetrical, upper part of the wedge casts (Figs. 6 and 7). Additional evidence for the shallow location of permafrost includes: the well-preserved primary sedimentary structures in the sands and gravels below the till layer; the planar base of the till, located about 2 m below the surface; the fracture system in the till adjacent to the cast walls (Fig. 6); and the vertical orientation of the long axes of pebbles in the upper part of the till layer.

Such a thin active layer indicates a severe climate. Based on the density of relic wedge casts preserved in river sediments (about 27 per km) Maizels (1986) suggested that during Younger Dryas times, the temperature in eastern Scotland was comparable with that prevailing today in Alaska and Arctic Canada, where a mean annual temperature of –7°C to –10°C has been recorded and where the permafrost is over 360 m thick. The mean wedge spacing at Wierzchuca Nagórna was found to be 10 times greater than that observed by Maizels. Even taking into account the fact that till is more susceptible to frost processes than alluvial sands and gravels, low temperature conditions seem to be the main reason for such a density of ice-wedge casts on the Drohiczyn Plateau.

AGE OF ICE WEDGES

Most of the buried periglacial structures described from the Polish Lowlands were formed during the last glaciation. Examples of older structures are mostly within the loesses of southern Poland (Maruszczak, 1995*a*, *b*; 1998). Based on the distribution of periglacial structures, the ranges of permafrost during several recessive stages of the last ice sheet (Kozarski, 1995*a*, *b*) and the permafrost character (Goździk, 1995) have been reconstructed. According to Kozarski (1995*b*), in NW Poland the expansion of the periglacial area to the N following deglaciation continued from about 20 to 11.8 ka.

As mentioned above, the tills in which the ice-wedges of Wierzchuca Nagórna developed are from the Wartanian Glaciation. The overlying sands and gravels have been modified by frost processes (obliterated sedimentary structures, traces of segregation) and partly infill the ice-wedge casts. These pro-

Table 2

TL ages of sediments at Wierzchuca Nagórna

Depth [m]	Number of samples	Nr. lab. Lub-	Annual doze Dr [Gy/ka]	Absorbed doze ED [Gy]	TL age [ka]
1.0	WN 1	4273	1.285±0.15	30±4	23±4
0.6	WN 2	4274	2.135±0.19	101±25	47±12
1.0	WN 3	4275	1.219±0.16	52±6	43±7
0.6	WN 4	4276	1.263±0.14	62±6	49±7
0.3	WN 5	4277	1.720±0.19	239±49	139±32
0.3	WN 6	4278	1.966±0.18	278±48	141±28

cesses must have taken place after deposition: either during the following recessive stadials of the Wartanian Glaciation; or during the Vistulian Glaciation.

In order to constrain their stratigraphy, 6 samples collected from the fine-grained sand infilling ice-wedges nos. 17 and 30 of Figure 3 (2 samples each) and from the overlying sand (2 samples) in the vicinity of ice-wedges 17 and 30 (Fig. 3) have been TL-dated. The dating was carried out by J. Kusiak in the Maria Curie-Skłodowska University laboratory. Although the results (Table 2) do not determine the ultimate age of the sediments (Bluszcz, 2000), they supplied useful data for palaeogeographic interpretation. The oldest dates were obtained from the overlying sands, and indicated the terminal part of the Wartanian Glaciation: 141±28 ka (Lub-4278) and 139±32 (Lub-4277). In turn, the dates obtained from the sands infilling the ice-wedges may be referred to the Vistulian, and, notably, indicate at least two stages of cooler climatic conditions. Dates of 49±7 ka (Lub-4276), 47±12 ka (Lub-4274) and 43±7 ka (Lub-4275) correlate with a global climatic cooling documented in North Atlantic sediments and Greenland ice as Heinrich event H5 (Bond *et al*., 1992, 1993). By contrast, the date of 23±4 ka (Lub-4273) indicates the cooling during the maximum of the last glaciation (Heinrich event H2).

Thus, the geological setting, sedimentary features and TL dates suggest that the Wierzchuca Nagórna ice-wedge casts were formed during the Vistulian Glaciation, and their development and filling took place in several phases. During cooler climate periods (*ca*. 43–49 and 23 ka), "whitening" and partial eolisation of quartz grains occurring on the surface, and later filling the ice-wedge casts, took place.

The inverted of the ages in ice-wedge cast no. 30 (Fig. 3) may indicate deeper ice-wedge formation, and thus more severe climatic conditions, just before the maximum of the Vistulian Glaciation by comparison with the earlier cool period. According to Maruszczak (1995*a*), during the Vistulian Glaciation the Podlasie Lowland was located within periglacial tundra of the sub-Arctic zone, with much more continental features of the climate than during the previous glacial cycle. During the maximal stadial of the last glaciation, the permafrost was continuous in character, and occurred sporadically until the first part of Younger Dryas time (Goździk, 1995).

SIGNIFICANCE OF THE WIERZCHUCA NAGÓRNA SITE FOR THE PALAEOGEOGRAPHY OF PODLASIE

Palaeogeomorphological implications linking the ice-wedges at Wierzchuca Nagórna with the Vistulian periglacial zone are, however, considerable and raise questions as to why no traces of older, Wartanian, periglacial processes are preserved. To consider this problem, at least three alternatives may be discussed:

— during the Wartanian Glaciation there were no conditions favourable for the development of periglacial structures in the study area;

— periglacial structures were formed during the Wartanian Glaciation, but were not preserved;

— periglacial structures from the Vistulian Glaciation were developed exactly in the places of older structures.

The first alternative requires the assumption that, after the deposition of the glacial deposits of the Wartanian Glaciation, permafrost did not develop in the study area. In this case, deglaciation of the ice sheet was not followed by development of a periglacial zone and its migration together with the ice-sheet front. Thus, it would take place according to a different scheme (regional stagnation?) than that (frontal type) suggested for the last ice sheet in NW Poland by Kozarski (1995*b*). This is not supported by the palaeogeographic maps of the Podlasie area, on which numerous moraines (Fig. 1) mark the limits of successive recessive phases of the Wartanian Glaciation (Marks, 2004*a*, *b*; Terpiłowski and Dobrowolski, 2004; Wojtanowicz, 2004). Besides, many Eemian Interglacial sites in the area indicate that severe, tundra-type climatic conditions prevailed in the initial stages of the accumulation of lake deposits, that is, those potentially favouring the development of periglacial phenomena (Albrycht *et al*., 1997). It might be considered that the destruction of the surface part of the till (plateau denudation) began in the terminal part of the Wartanian Glaciation, in periglacial conditions.

In turn, the second alternative requires finding the reason for not preserving the ice-wedges from the Wartanian Glaciation. One such reason could be extensive denudation of the plateau surface. The vertical extent of this would reflect reduction of the lithological column by at least the ice-wedge length, that is, by more than *ca*. 1.2 m. This is supported by the flat, peneplained surface of this part of the Drohiczyn Plateau, the character of the top of the glacial till observed in the gravel-pit walls, as well as by its small (reduced) thickness. The sands and gravels occurring directly at the surface in the study area derive mainly from the destruction of till. Because the Vistulian ice-wedge casts are so well preserved, it may thus be concluded that the main part of plateau denudation took place earlier (terminal part of the Wartanian Glaciation and Eemian Interglacial?).

The third alternative, involving the inheritance of periglacial forms, is difficult to discuss at present. It requires finding evidence that the complex structure of some ice-wedge casts a results from multiple ages of glaciation.

Among these alternatives, the second one, according to which periglacial forms from Wierzchuca Nagórna were developed during the last glaciation on the earlier denuded surface of a plateau from the Wartanian Glaciation, seems to best fit the observations.

Overall, analysis of the ice-wedge casts at Wierzchuca Nagórna has illuminated a number of aspects of the changing palaeogeography of the study area during the Pleistocene.

CONCLUSIONS

A remarkable record of periglacial processes, in the form of densely spaced ice-wedge casts of different size and shape, reflecting a polygonal network on a flat plateau surface, has been recognized at Wierzchuca Nagórna. Most probably this network developed in several (more than one) phases. Results of frost processes are also visible in the local accumulation of coarse sediments in the surficial horizons, thickness changes of glacial till near the casts and the vertical orientation of pebbles in the topmost part of the till.

The fill of the ice-wedge casts is typically secondary in origin; however, the lowermost parts of some structures include fine-grained sand with evidence of wind reworking. Fossilization of the ice-wedge casts took place rapidly, albeit in several places.

The thickness of the active layer of permafrost was 0.5–0.7 cm. The high density of the ice-wedge casts, as well as the small thickness of the active layer, indicates severe climatic conditions during their development.

The formation of the ice-wedges should be linked with the periglacial zone of the Vistulian Glaciation. TL dates from the sand fills of the ice-wedges can be correlated with cool phases of the maximal (LGM) and pre-maximal stage of the last glaciation.

In the interval between the deposition of the Wartanian till and initiation of ice-wedge development, extensive denudation of the plateau surface took place, reflected in reduction of the sediment succession by at least 1.2 m.

The results obtained should encourage further studies of the Drohiczyn Plateau, to reconstruct the ice-wedge network pattern in detail, to further constrain their age and to analyse the infilling sediment in more detail.

Acknowledgements. The authors would like to express their gratitude to Dr. J. Nitychoruk for access to unpublished geological data; Dr. D. Gałązka for help with interpreting the results of petrographic analysis; A. Kiełbratowska, M. Krajcarz and M. Nowacka for fieldwork and laboratory assistance. The study was financed by Institute of Geology (University of Warsaw) individual grant BW 1642/1.

REFERENCES

ALBRYCHT A., BIŃKA K., BRZEZINA R., DYJOR K., NITYCHORUK J. and PAWŁOWSKAJA I. (1997) — Uwagi o nowych stanowiskach interglacjalnych na tle stratygrafii młodszego czwartorzędu południowego Podlasia. Prz. Geol., **45** (6): 629–633.

BOND G., BROECKER W., JOHNSEN S., McMANUS J., LABEYRIE L., JOUZEL J. and BONANI G. (1993) — Correlations between climate records from North Atlantic sediments and Greenland ice. Nature, **365** (9): 143–147.

BOND G., HEINRICH H., BROECKER W., LABEYRIE L., McMANUS J., ANDREWS J., HUON S., JANTSCHIK R., CLASEN S., SIMET C., TEDESCO K., KLAS M., BONANI G. and IVY S. (1992) — Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. Nature, **360** (19): 245–249.

BORÓWKO-DŁUŻAKOWA Z. (1973) — Wyniki analizy pyłkowej profilu ze Śledzianowa (ark. Drohiczyn). Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

BLUSZCZ A. (2000) — Luminescence dating of Quaternary sediments — theory, limitations, interpretation problems (in Polish with English summary). Zesz. Nauk. PŚl., Mat.-Fiz. Geochron., **86**.

DYLIK J. (1966) — Problems of ice-wedge structures and frost-fissure polygons. Biul. Perygl., **15**: 241–291.

GOŹDZIK J. (1970) — Geneza szczelin zmarzlinowych w regionie łódzkim, w świetle analizy ich wypełnień. Acta Geogr. Lodz., **24**: 181–196.

GOŹDZIK J. (1973) — Origin and stratigraphical position of periglacial structures in Middle Poland. Acta Geogr. Lodz., **31**.

GOŹDZIK J. (1995) — Permafrost evolution and its impact on deposition conditions between 20 and 10 ka BP in Poland. Biul. Perygl., **34**: 54–72.

GOŹDZIK J. (1982) — Zmienność kształtu i cech powierzchni ziarn kwarcowych w osadach z odkrywki bełchatowskiej. In: Czwartorzęd rejonu Bełchatowa, I Sympozjum: 164–168. Inst. Geol. Wrocław-Warszawa.

JAHN A. (1970) — Zagadnienia strefy peryglacjalnej. PWN. Warszawa.

JAHN A. (1977) — Structures connected with ice wedges in Pleistocene deposits. Stud. Geol. Polon., **52**: 177–194.

KONDRACKI J. (2000) — Geografia Polski. Mezoregiony fizyczno-geograficzne. PWN. Warszawa.

KOZARSKI S. (1995*a*) — Deglaciation of Northwestern Poland: environmental conditions and geosystem transformation (~20 ka ÷10 ka BP) (in Polish with English summary). Dok. Geogr. IGiPZ PAN, **1**.

KOZARSKI S. (1995*b*) — The periglacial impact on the deglaciated area of northern Poland after 20 kyr BP. Biul. Perygl., **34**: 73–102.

MAIZELS J. K. (1986) — Frequency of relic frostfissure structures and prediction of polygon pattern: a quantitative approach. Biul. Perygl., **30**: 67–89.

MANIKOWSKA B. (1982) — Upfreezing of stones in boulder clay of Central and North Poland. Biul. Perygl., **29**: 87–115.

MARKIEWICZ R. (2004) — Ekspertyza w sprawie obtoczenia ziarn kwarcu w wypełnieniu klina lodowego w Wierzchucy Nagórnej. Inst. Geol. Podst. Uniw. Warszawa.

MARKS L. (2004*a*) — Zasięgi zlodowaceń plejstoceńskich na obszarze Wschodniej Polski i Zachodniej Białorusi. Mat. XI Konf. Strat. Plejstocenu Polski, Supraśl: 8–10.

MARKS L. (2004*b*) — Ice-sheet limit of the Warta Glaciation in Poland (in Polish with English summary). In: Warta Glaciation in Poland (eds. M. Harasimiuk and S. Terpiłowski): 27–35. UMCS Press. Lublin.

MARUSZCZAK H. (1995*a*) — Glacial cycles of loess accumulation in Poland during the last 400 ka and global rhythms of paleogeographical events. Ann. UMCS, **B 50**: 127–156.

MARUSZCZAK H. (1995*b*) — The penultimate glacial cycle of the loesses accumulation in Poland and the global rhythm of the paleogeographical events (in Polish with English summary). Prz. Geogr., **67** (3–4): 249–257.

MARUSZCZAK H. (1998) — Interpretation problems of macroscopic cryogenic structures in loess deposits (in Polish with English summary). In: Sedimentological and Postsedimentological Structure in Quaternary Sediment and their Value for Interpretation (ed. E. Mycielska-Dowgiałło): 136–150. WGiSR UW. Warszawa.

MOJSKI J. E. (1972) — Nizina Podlaska. In: Geomorfologia Polski, **2**, Niż Polski. (ed. R. Galon): 318–362. PWN. Warszawa.

MURTON J. B., WORSLEY and GOŹDZIK J. (2000) — Sand veins and wedges in cold aeolian environments. Quatern. Sc. Rev., **19**: 899–922.

MYCIELSKA-DOWGIAŁŁO E. and WORONKO B. (1998) — Rounding and frosting analysis of quartz grains of sand fraction, and its interpretative value (in Polish with English summary). Prz. Geol., **46** (12): 1275–1281.

MARKS L. (2004*a*) — Zasięgi zlodowaceń plejstoceńskich na obszarze Wschodniej Polski i Zachodniej Białorusi. Mat. XI Konf. Strat. Plejstocenu Polski, Supraśl

NOWAK J. (1972) — Przeglądowa Mapa Geologiczna Polski (A) 1:200 000, ark. Siedlce. Inst. Geol. Warszawa.

TERPIŁOWSKI S. and DOBROWOLSKI R. (2004) — Role of valley morphology in the development of accumulation moraines of the Bug lobe during the Warta Glaciation in Mielnik environs (Drohiczyn High Plain) (in Polish with English summary). In: Warta Glaciation in Poland (eds. M. Harasimiuk and S. Terpiłowski): 153–161. UMCS Press. Lublin.

WASHBURN A. (1973) — Periglacial processes and environments. Edward Arnold. London.

WOJTANOWICZ J. (2004) — Warta Glaciation in Poland: position and stratigraphic division (in Polish with English summary). In: Warta Glaciation in Poland (eds. M. Harasimiuk and S. Terpiłowski): 13–25. UMCS Press. Lublin.