Biuletyn Peryglacjalny, no. 34, 1995.

STEFAN KOZARSKI*

Poznań

THE PERIGLACIAL IMPACT ON THE DEGLACIATED AREA OF NORTHERN POLAND AFTER 20 KYR BP

Abstract

In the area of the last deglaciation in northern Poland (~20.0–14.5 kyr BP) abundant evidence has been found of the presence of permafrost as well as periglacial deposits and landforms. They are represented by ice-wedge casts, sand-wedge polygons, traces of a former active layer, gelifluction covers, fluvioperiglacial and aeolian deposits, and such landforms as dunes, dry flat-floored valleys and denudation niches on pradolina scarps. The collected material shows that a gradual change of the system took place in northern Poland after ~20 kyr to ~11.8 kyr BP, from a glacial to a periglacial one, characterised by a severe thermal regime and highly arid climatic conditions in the first phase (after 20 kyr to ~14 kyr BP) and an amelioration of climate in the second (after 14 kyr BP to ~10 kyr BP).

INTRODUCTION

The analysis of the terrestial record of environmental changes forms a significant part of research on the termination of the Pleistocene. In the southern Peribalticum the record consists of glacial and periglacial features. It is complemented by aeolian and fluvial features as well as by a palaeobotanical record which are closely related to a periglacial environment. They allow a more precise reconstruction of e.g. the climatic conditions of the deglaciation period and the simultaneous shifting of the periglacial domain into areas abandoned by the last ice sheet.

Particular events and features overlap in various time spans. As a result, they form a continuous record an integrated analysis of which provides deeper insight into the geosystem transformation from a glacial into a periglacial one. An example is the recently published reconstruction of periglacial conditions of the Vistulian in northern Germany carried out by LIEDTKE (1993).

The period of the last *sensu stricto* deglaciation lasted about 5.5 kyr in Poland. Basically, there were no conditions for the existence of vegetation and the accumulation of organic matter in the area abandoned by the ice-sheet. Hence, for the time interval between ~20,000 BP and ~14,000 BP the sedimentological record and cryostratigraphic facts are the principal

* Department of Geomorphology, Quaternary Research Institute Adam Mickiewicz University Science Centre PAS; ul. Wieniawskiego 17/19, 61–713 Poznań, Poland.

source of informaion about changes in the palaeoenvironment and about the contribution of periglacial conditions to them. They will be the main focus of the present paper.

CHRONOLOGY OF DEGLACIATION

The chronology of deglaciation is relevant to periglacial events associated with it, because age estimation of the major ice-sheet positions allows an approximation of the time of permafrost aggradation in extraglacial zones, especially in proximal parts of outwash plains containing syngenetic ice-wedge casts. The age of the major ice-sheet positions during deglaciation, on an uncalibrated radiocarbon scale, can only be estimated indirectly. The first attempt (Kozarski, 1986, 1992) was made on the basis of:

(1) radiocarbon dated organic deposits (Pazdur, Walanus 1979) found under the Vistulian lodgement till in Konin-Maliniec (Stankowska, Stankowski, 1979),

(2) the correlation of Gardno Phase end moraines of the coastal zone with the Low Baltic Stadial (Mörner, *et al.* 1977), and

(3) the calculated mean annual ice-front retreat.

Practically no alterations are necessary for the age estimate of the maximum extent of the ice sheet (the Leszno Phase) at ca. 20,000 BP (Kozarski, 1980, 1981a). New data (Rotnicki, Borówka, 1989) give only a more realistic date of 20,500 ± 500 BP. In turn, a fundamental revision must be made for the Gardno Phase in the coastal zone, so far estimated at 13,200 BP, as a basis for the construction of a time-distance diagram (Kozarski 1986). Taking into consideration the new timing of deglaciation in the Øresund–Kattegat region (Lagerlund, Houmark-Nielsen, 1993) and the distribution of new sites of radiocarbon dated organic deposits in the Polish coastal zone (Rotnicki, Borówka, 1991, 1994; Kramarska, 1993; Kramarska, Uścinowicz, 1992) aged between 14,060 ± 220 BP and 13,800 ± 270 BP, one can accept the age of the Gardno Phase, after Rotnicki and Borówka (1994), at between 14,500 BP and 14,300 BP.

On the basis of the calculated mean ice-front retreat, approximate ages of the remaining major extent lines during deglaciation after 20 kyr BP can be estimated at: the Poznań Phase ca. 18,800 BP the Chodzież readvance ca. 17,700 BP, and the Pomeranian Phase ca. 16,200 BP. These approximate ages have been adopted in the corrected version of the time-distance diagram (Fig. 1). It differs in details of age estimation made for these lines by Rotnicki and Borówka (1994), probably because of a different calculated mean annual ice-front retreat.

By way of a commentary on the above chronology of deglaciation after ca. 20 kyr BP, the following conclusions can be drawn:

(1) The maximum advance of the ice sheet (the Leszno Phase) and the Poznań Phase can still be correlated with climatic deteriorations distinguished with the help of radiocarbon dating by MÖRNER (1981) in the Grande Pile profile.

(2) New studies have shown that general climatic causes of deglaciation are well reflected in the marginal zones of the last ice sheet. It manifests itself in the similarity of radiocarbon dating of cold phases and climatic ameliorations in its western (ALM, 1993) and southern, or Central European, parts (ROTNICKI, BORÓWKA, 1994) as well as in the timing of deglaciation in eastern Denmark, southern Halland and western Skane (LAGERLUND, HOUMARK-NIELSEN, 1993).

(3) There may be complications with the age estimation for the maximum ice-sheet advance (the Leszno Phase), because organic deposits have been found recently in Middle Pomerania radiocarbon dated to 20,280 ± 240 BP (NOWACZYK, personal communication). If further sites of a similar age are found, the maximum ice advance will have to be interpreted as a very rapid surge, or a new basis for the estimation of its age will have to be sought.

(4) Deglaciation chronologies based on an uncalibrated radiocarbon timescale remain relative, because on the calibrated ^{14}C scale (BARD, *et al*,. 1990) before 9.0 kyr BP ^{14}C ages are systematically younger than the U-Th ones. The maximum difference amounts to approximately 3.5 kyr at about 20.0 kyr BP, 1.9 kyr at 17.0 kyr BP, and 1.5 kyr at 10.0 kyr BP (BARD, *et al.*, 1990; table p. 407).

THE PERMAFROST RECORD AND PERIGLACIAL IMPACT ON DEPOSITS

The inventory of periglacial features in northern Poland in the area abandoned by the last ice sheet shows them to be highly diversified. It contains characteristic deformation structures in glacial, glaciofluvial and fluvioperiglacial deposits, as well as specific deposits and landforms which have developed in a periglacial environment (Table I). The frequency of periglacial features, their distribution and indicative value are variable. As a whole, however, they are an abundant record of: (1) periodically variable, very cold and arid to semiarid climatic conditions, (2) the formation of permafrost in the deglaciation area, and (3) intensive wind action and the beginnings of a periglacial denudation system. A selection of them will be discussed, taking into consideration their importance in the reconstruction of the palaeoenvironment in the period from 20.0 to 14.5 kyr BP.

The most important among periglacial structures are ice-wedge casts, sand-wedge polygons and traces of a former active layer. All of them are indicative of the aggradation of permafrost which accompanied deglaciation and gradually spread to areas abandoned by the ice sheet.

Inventory of periglacial phenomena in the deglaciated area of northern Poland

Table I

Indicative of permafrost (+)		Occurence			Frequency
		Geomorphic	Spatial	Lithology	
Structures					
Ice-wedge casts epigenic syngenetic	+	Outwash plains River terraces Alluvial fans	Polygonal pattern	Sands and gravels	Often
Frost cracks epigenic syngenetic		Outwash plains River terraces	Polygonal pattern	Sands and gravels	Often
Sand wedges	+	Till plains	Polygonal pattern	Tills	Often
Reticulate ice-vein network casts	+	Abandonded braided channels	Net-like pattern	Silts and sand	Sporadic
Involutions		Outwash plains River terraces	Cellular patern	Silts, sands and fine gravels	Rare
Soil wedges		Outwash plains River terraces	Polygonal	Sands and gravels	Sporadic
Deposits					
Gelifluction covers		Slopes	Patches	Sands, silts and pebbles	Often
Stratified slope deposits		Slopes	Small patches	Silts and fine sands	Sporadic
Loess massive laminated and banded		End moraines Till plains Outwash plains Slopes	Patches	Loess and fine sands	Local
Aeolian cover sands		Till plains Outwash plains River terraces	Vast patches	Sands	Common
Ventifacts		Till plains Outwash plains River terraces	Random	Sandy surfaces	Very often
Fluvial covers		River terraces	Vast flat patches	Gravels, sands and silts	Common

Landforms					
Oriented icing depressions	+	Proximal parts of outwash plains	Super-imposed on braided drianage patterrn	Sands and gravels, silts	Often
Dry flat-floored valleys		Pradolina and valley scarps		Inicised into sands, gravels, tills etc.	Often
Denudation niches		Pradolina and valley scarps			
Inland dunes		River terraces Outwash plains Till plains	Bow-shaped and parabolic single dunes and dune fields	Sands	Often
River terraces		Pradolinas and valleys	Vast flat surfaces	Sands and gravels	Common

ICE-WEDGE CASTS

Thermal contraction cracks and ice-wedge casts are frequent features on outwash plains and periglacial terraces (Table I, Fig. 1). In all cases under study (Kozarski, 1993) they are of epigenetic or syngenetic nature. Frost wedges form orthogonal or para-orthogonal systems in horizontal section. The distance between these structures, as measured in pits, averages 7 m. There are also polygons, however, whose sizes as measured in aerial photographs attain 20–30 m (Kozarski, 1993, Table I). The length of individual epigenetic and synsedimentary structures, ice-wedge casts and thermal contraction cracks generally varies from a few decimetres to about 1.5 m. Syngenetic ice-wedge casts, in turn, are longer as a rule. While their minimum length also attains a few decimetres, maximum values in multi-level structures exceed 6 m (Kozarski, 1993). Ice-wedge casts have developed in sandy deposits and gravels, and show all the features of secondary filling structures with gravitational microfaults in the host material.

Synsedimentary thermal contraction cracks and epigenetic ice-wedge casts were found in the proximal parts of outwash plains of all the major ice sheet positions, viz. the Maximum (Leszno) Phase, the Poznań Phase and the Pomeranian Phase (Fig. 1). They are also known from minor marginal deglaciation formations. In one of them the longest syngenetic ice-wedge cast has just been found (Kasprzak, personal communication).

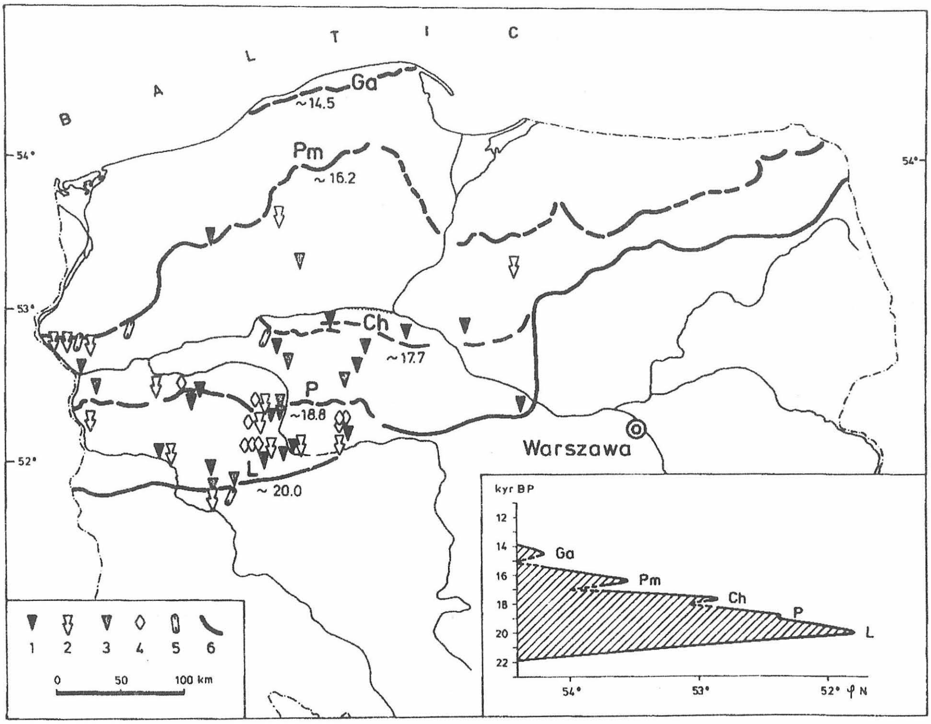

Fig. 1. Distribution of fossil periglacial features indicative of permafrost in the Vistulian deglaciation area of northern Poland

1. epigenetic ice-wedge casts; 2. syngenetic ice-wedge casts; 3. sand-wedge casts; 4. plygonal network systems of sand-wedge and ice-wedge casts; 5. oriented icing depressions; 6. major ice-sheet positions; L – Leszno Phase (ice-sheet maximum), Pz – Poznań Phase; Ch – Chodzież readvance; Pm – Pomeranian Phase; Ga – Gardno Phase. Insert: Time-distance diagram of Vistulian deglaciation in NW Poland

Orthogonal systems in proximal parts of outwash plains have been observed to be covered with allochthonous flow till (Kasprzak, Kozarski, 1984; Kozarski, Kasprzak, 1987), or to be in contact with ridges of ablation end moraines built of large-clast flow tills (Kozarski, 1965, 1978, 1995). This justifies the conclusion that what we deal with here are records of the interaction of glacial and periglacial processes, because permafrost aggradation in the proximal part of an outwash plain also caused the formation of cold-based ice beneath the ice margin. This led to a compressive ice flow, debris transport to the ice surface, and its gravitational flow as allochthonous flow till (Fig. 2).

In fluvial sands and gravels of periglacial terraces and alluvial fans, epigenetic ice-wedge casts and syngenetic thermal contraction cracks predominate (Kozarski, 1971, 1993; Nowaczyk, 1991). Syngenetic ice-wedge casts are less frequent in fluvial covers, but they can attain a length of up to 3.2 m and a width of 0.55 m (Kozarski, 1971). In the material surround-

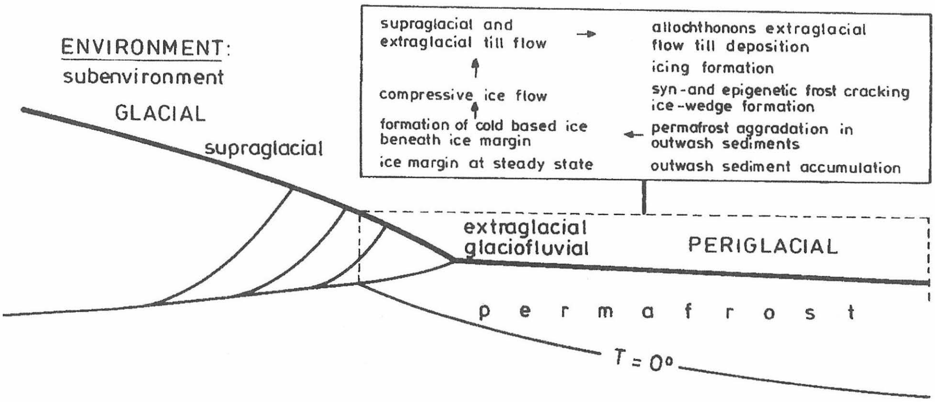

Fig. 2. A model for interrelationships between periglacial and glacial features and processes, related deposits and structures at ice sheet margin steady-state conditions during deglaciation of northern Poland

ing ice-wedge casts numerous gravitational microfaults can be found, and in the axial part, veins of nonsorted deposit penetrating from the former active layer. The gravitational deformations and veins are indicative of the secondary infilling of wedge from above and from the sides during the melting of ground ice.

Ice-wedge casts and ice-vein casts occurring on outwash plains and periglacial terraces are evidence that within these landforms ground ice formation and the aggradation of permafrost took place. That ice formed on the surface of outwash plains in the presence of permafrost is also proved by oriented icing depressions (Fig. 1). They have been found to occur on outwash plains related to all the major positions of the last ice sheet (Kozarski, 1975, 1993).

SAND-WEDGE POLYGONS

So far, sand wedges and sand-wedge polygons have usually been found in west-central Poland and sporadically in Pomerania (Kozarski, 1971, 1974, 1993; Nowaczyk, 1972; Goździk, 1988; Bogdański, Kijowski, 1990). In the first stage of research, they were primarily described as structures analysed in pits, and only exceptionally in horizontal sections (Kozarski, 1971, 1974; Nowaczyk, 1972; Goździk, 1986). In the second stage, sand-wedge polygons in larger areas were detected using aerial photographs; attention was drawn to their geometry (Bogdański, Kijowski, 1990; Kozarski, 1993). It was established that:

(1) sand wedges were fragments of polygonal network systems on till plains, occasionally to be found also in deposits of periglacial terraces,

(2) their pattern was usually tetragonal or at least para-orthogonal (LACHENBRUCH, 1962) to pentagonal, with polygon diameters ranging from 3.95 m to 6.10 m (KOZARSKI, 1993, Table I),

(3) their form varies in vertical sections, starting with a pocket-like structure of 0.5–0.7 m in width which at a depth of 0.3–0.9 m is already developed into a regular wedge ending with a frost crack at the very bottom, and

(4) they are filled up with material showing features of aeolian sands (KOZARSKI, 1993, Tables II and III).

At present, in the third stage of research, more intensive use is made of air-photo techniques to detect sand-wedge polygonal systems in large areas. For this purpose, in June 1992, during a very dry spring season, special flights were made in a belt of 25 km in width and 60 km in length south of Poznań, between the maximum extent of the last ice-sheet and the Poznań Phase. Coloured photographs revealed nine sand-wedge polygonal systems which consist of 66 to 1,123 individual polygons (Table II). In standard panchromatic aerial photographs thermal contraction polygons were also detected on till plains west of Poznań, just before the ice-sheet extent line of the Poznań Phase and behind it (GOGOŁEK, personal communication).

The analysis of polygonal system geometry shows these patterns to have the following specific properties, just as in the cases studied earlier (BOGDAŃSKI, KIJOWSKI, 1990; KOZARSKI, 1993):

(1) tetragonal and pentagonal networks (Fig. 3), and

(2) varying numbers of frost-wedge generations in particular fields; single generations also happen, but most of them are fields with two or three polygon generations (Table II, Fig. 4).

Polygon sizes (Table II) as well as their geological record do not leave any doubt as to the fact that the polygon systems under analysis have formed as a result of thermal contraction.

Two fields of polygon systems, Grabianowo N and Grabianowo S (Table II), have been studied in various intersections in specially made pits. In vertical sections, there are sand wedges occurring in lodgement till with a thin sand cover on top which corresponds to the polygon system. The wedges attain a length of 1.9 m, a width of 0.8 m in the topmost part and 0.2–0.3 m immediately below, and assume a variety of forms. A considerable number of the wedges start at a depth of 0.5 m. Their upper part often has a pocket-like form (Grabianowo N, Table II). Below starts the regular wedge tapering off downwards. However, some wedges show narrowings and very irregular sides. Occasionally, the upper part of a wedge is closed off by the surrounding, slightly sandy till (Grabianowo S, Table II).

Deposits filling the sand wedges belong to the size class of medium and fine sand. At Grabianowo N (Table II) they make up 85-90% of the fill, with fine and very fine sands alone exceeding 50% of the contents of samples under analysis. The sands are medium to well sorted and contain

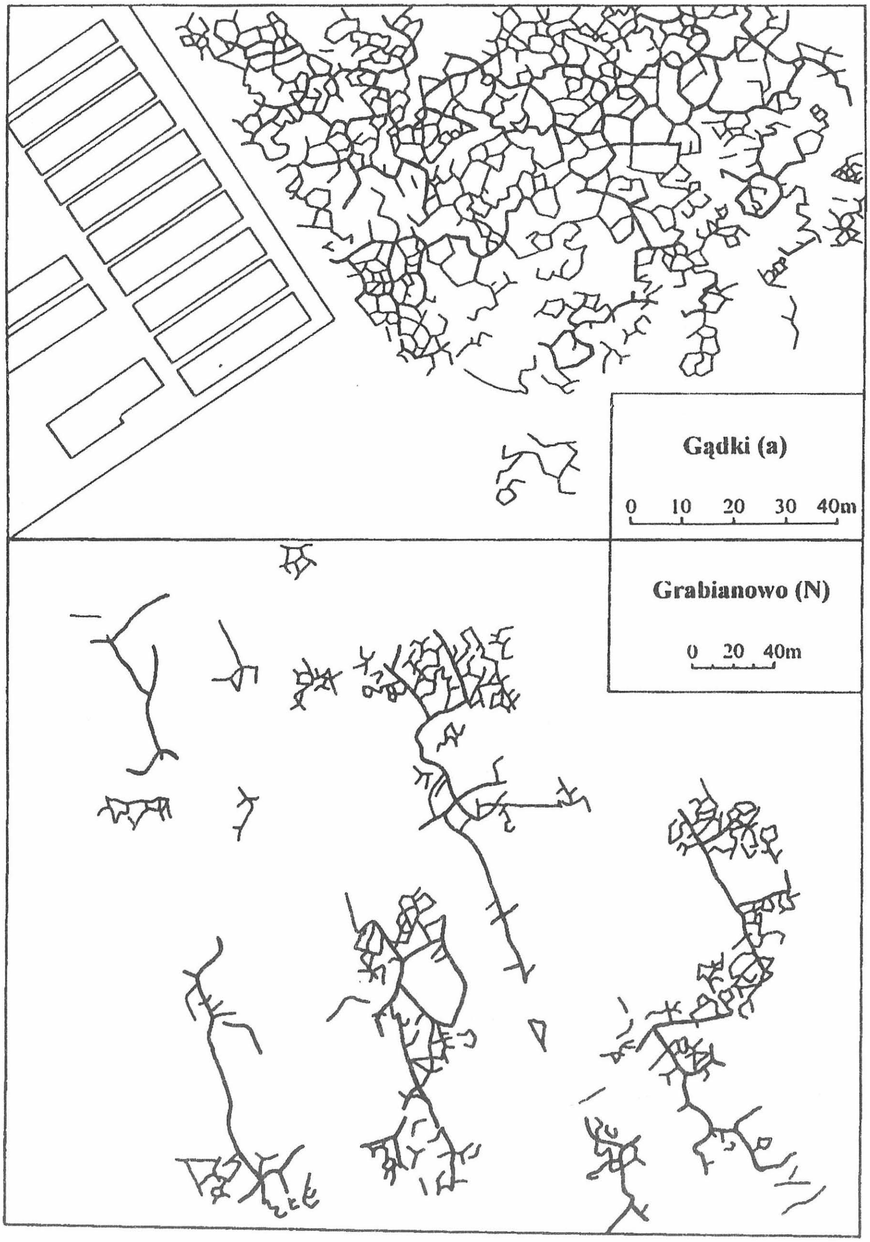

Fig. 3. Examples of sand-wedge polygonal systems in till plains to the south of Poznań

Parameters of polygon-network systems developed in till plains to the south of Poznań

Table II

Location	Number of polygons	Generation	Mean polygon	
			side length (m)	area (m^2)
Dobczyn Książa	121	1	11,2	197,3
		2	7,4	53,9
Gądki (a)	307	1	5,4	23,0
		2	4,3	11,2
		3	3,3	6,2
Gądki (b)	207	1	6,3	33,5
		2	4,2	10,0
Gorzyczki	1 123	1	11,2	111,1
		2	7,7	33,9
Grabianowo N	66	1	10,6	201,6
		2	6,2	37,1
Grabianowo S	505	1	17,2	297,0
		2	5,5	17,5
Pigłowice (a)	108	1	13,6	252,4
		2	8,7	66,4
Pigłowice (b)	192	1	12,7	202,5
		2	8,5	67,1
Srocko	311	1	13,9	113,8
		2	6,5	18,4
Winnagóra	137	1	14,1	309,5
		2	6,3	63,6

27.9% of well rounded quartz grains of the size class 0.8–1.0 mm. Similar results have been obtained for the wedges at Grabianowo S, where medium and fine sands constitute 71%, and very fine sands an additional 15%. They are medium sorted and also contain a lot (28.5%) of well rounded quartz grains 0.8-1.0 mm in size.

A comparison of the above parameters of sands filling the wedges with the parameters of ablation sands covering the till of the plain on which the polygonal networks of sites Grabianowo N and S are found, shows the latter to be worse sorted and have a lower content of medium and fine sands (5–24%) and a lower content of well rounded quartz grains 0.8–1.0 mm in diameter. On the other hand, the parameters of the filling sands are similar to those of dune sands. This corroborates the regularity discovered earlier in northwestern Poland, that the sand filling sand wedges come from aeolian transport which supplied material to open frost cracks and was responsible for the fossilisation of the wedges (KOZARSKI, 1971, 1974, 1993). A further argument for the share of aeolian processes in the

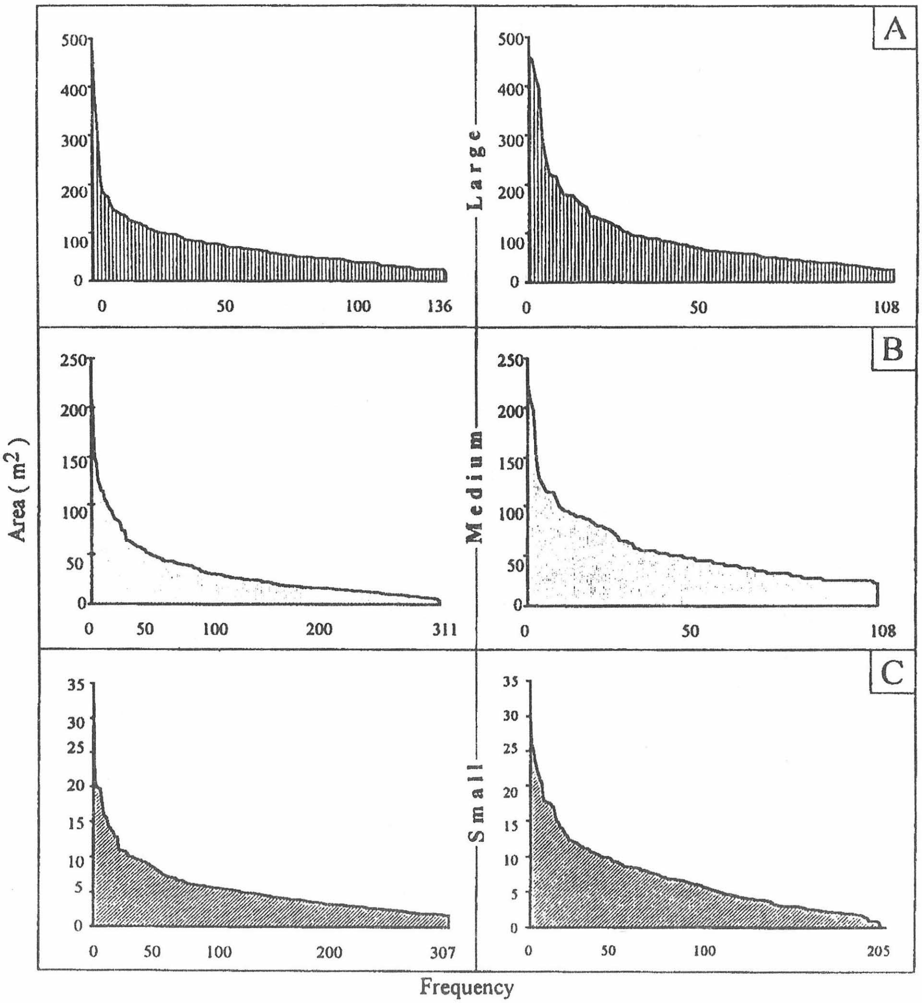

Fig. 4. Size variation of polygon area at selected sites distributed in till plains to the south of Poznań.

A – large-size polygons – sites Winnagóra and Pigłowice (a); B – medium-size polygons – sites Srocko and Dobczyn Książa; C – small-size polygons – sites Gądki (a) and Gądki (b) deflation of cover sands is the presence of ventifacts on the surface of polygonal blocks at site Grabianowo N 25% of clasts 2–16 cm in size have been found to bear clear traces of aeolian polishing, and some of them have distinct facets or multifacets and small-scale flutings. Multifacets show the ventifacts to have been changing positions, which indicates intensive deflation as well as bareness of the surface and much dryness during the formation and fossilisation of sand-wedge polygons.

Sand wedges rarely occur in fluvial deposits. They have been found in a 42-m Odra terrace near Słubice (Kłysz, 1969) and in a bifurcation terrace of the Warsaw-Berlin Pradolina near Mosina. The length of these structures varies between 0.6 m and 1.8 m, and their width amounts to 0.2–0.3 m. Part of them show features of syngenetic development with characteristic widenings at the levels of sedimentary breaks. Epigenetic sand wedges, in turn, are straight in shape and form a least-length group.

THE ACTIVE LAYER AND SOIL WEDGES

A common feature of the deglaciation area in northern Poland is a radical transformation of the topmost parts of sequences. It manifests itself as a total disappearance of stratification of fluvial and glaciofluvial deposits, a heterogeneous grain-size composition, and strong decalcification down to an average depth of 0.5 m to 1.2 m. It is assumed that this transformation is an effect of bioturbation, but to an even greater extent of frost action (Kowalkowski, 1990). The frost action involved is not so much present-day winter action as the periglacial frost action during the late Pleni-Vistulian. That is why Kowalkowski (1990) uses the term "perstruction zone" or "perstruction series" to describe this structureless layer.

It has been shown earlier (Kozarski, 1971) that in the case of sand wedges with pocket-like structures in their upper parts, this zone of the topmost transformation of deposits is a trace of a fossil active layer. This suggestion can be backed by new arguments found in glaciofluvial and fluvial deposits of west-central Poland. They include:

(1) Reticulate ice-vein network casts (Kozarski, 1993), which at sites under investigation (Żabinko, Granowo) sharply separate the layer with cryoturbations from underlying river deposits (Kozarski, *et al.*, 1988; Kozarski, 1991), or the transformed layer with soil wedges from glaciofluvial sands.

(2) Soil wedges of varying forms and vertically laminated sand infillings. Soil wedges end sharply at the level of reticulate ice-vein network casts (Fig. 5).

(3) $CaCO_3$ concentration immediately above the reticulate ice-vein network casts (Fig. 6).

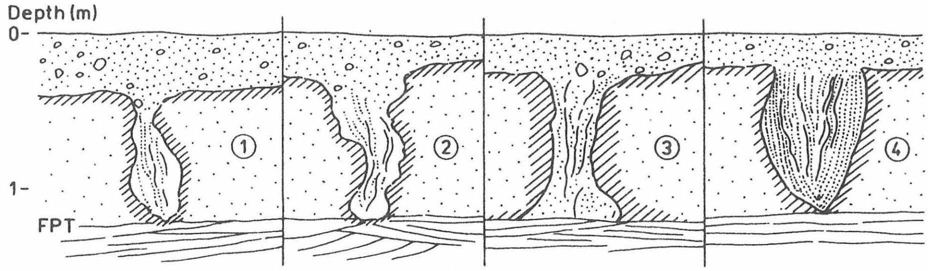

Fig. 5. Variation of soil-wedge forms; site Granowo, west-central Poland
FPT – former permafrost table; 1 and 2. irregular pocket-like forms with traces of infilling vertical lamination; 3. anvil-like form with traces of infilling vertical lamination and elementary frost cracks; 4. leaf-like form with distinct infilling vertical lamination and elementary frost cracks

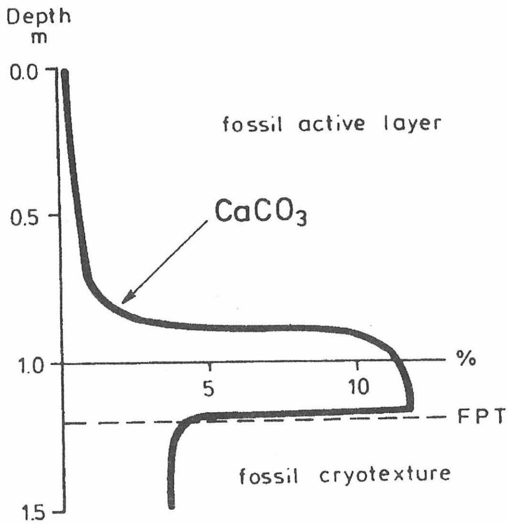

Fig. 6. Curve showing $CaCO_3$ concetration above the level of reticulante ice-vein network casts; site Granowo, west-central Poland. FPT - former permafrost table

Taken together, and considering the fact that these arguments concern permeable deposits, they are convincing evidence of a former active layer about 1.2 m thick at sites under study. Especially significant is the well marked border of $CaCO_3$ concentration, also known occasionally from pedological works (KOWALKOWSKI, 1990), which is indicative of very effective carbonate transport in the cold periglacial environment. In the absence of very distinct cryostructures in present-day permeable deposits, the very presence of the level of high $CaCO_3$ concentration is of palaeoenvironmental significance. It shows that the sharp separation of this level from the underlying deposits with a perfectly preserved primary sedimentary structure is of periglacial origin and defines the bottom of the active layer.

At sites where ice-wedge casts occur, determination of the active layer and its thickness is easier, because as a rule the border between the topmost structureless layer and the pseudomorph is well marked. Moreover, upturned layers of the host deposit occurring close to the upper parts of ice-wedge casts can be an additional criterion.

In the case of sand wedges with pocket-like widenings in their upper parts, the fossil active layer is separated from the former permafrost table by the lower part of the pocket, which is simultaneously the beginning of a sharply pointed wedge (Kozarski, 1971, 1974). This criterion has also proved useful at other sites in west-central Poland (Górska, *et al.*, 1992; Kozarski, 1993).

Sporadically, frost-heave features can occur in the topmost parts of late Pleni-Vistulian deposits. They are known, e.g., from northeastern Poland (Churska, 1976) and have the shape of symmetrical or slightly inclining folds covered with sheet-wash deposits. In the latter ice wedges have developed whose pseudomorphs reach frost-heave structures, the record of the former active layer.

THE GEOMOPHIC RECORD OF PERIGLACIAL CONDITIONS

In the area of the last deglaciation there are complexes of landforms which have developed in periglacial conditions (Table I). They differ in spatial distribution and importance for the periglacial environment reconstruction. Among them, only oriented icing depressions can be treated as indicative of the existence of permafrost (Kozarski, 1975, 1993). Indirect evidence is supplied by fluvioperiglacial terraces with syngenetic ice-wedge casts. The remaining landforms (Table I), especially denudation niches and dry flat-floored valleys, have the status of probable indicators of permafrost existing during their formation (Kozarski, 1971; Sinkiewicz, 1989). Inland dunes contain no evidence of perennially frozen ground, with one exception (Kozarski, et al., 1982).

ORIENTED ICING DEPRESSIONS

In proximal parts of many outwash plains associated with all the major positions of the last ice-sheet, closed ellipsoidal landforms have been found which are arranged along former drainage lines (Kozarski, 1975, 1993).

Apart from the elongated shape and distinct orientation, these landforms show the following features:

(1) A depth of 2–5 m, and the length of the a-axes of 100–350 m.

(2) They are dry when their depth does not exceed the thickness of the outwash, and contain water when their bottoms reach the till underlying this deposit.

(3) Some of them contain dry peat and gyttja, pollen-dated to the close of the Younger Dryas and the beginning of the Holocene, and gravitationally disturbed, banded mineral deposits at the bottom.

(4) Sandy or sandy-gravelly host deposits are structureless, and gelifluction covers appear on the slopes.

A comparison of the mode of occurrence of these landforms and some of their properties (KOZARSKI, 1975) with present-day Spitsbergen icings on permafrost and their sedimentary and geomorphic effects (CEGŁA, KOZARSKI, 1977) has allowed them to be interpreted as landforms left by icings. The icings, as proved by synsedimentary frost cracks and syngenetic ice-wedge casts in the proximal parts of outwash plains of NW Poland, developed in the presence of permafrost. Thus, in the palaeogeographical interpretation of deglaciation conditions during the late Pleni-Vistulian, oriented icing depressions can be treated as the only indicator of permafrost among periglacial landforms.

DENUDATION NICHES

Denudation niches are frequently met landforms in the scarp zones of pradolinas, valleys and tunnel valleys as well as on the slopes of end moraines. Their location does not show any lithological preference, as they can be found both on slopes with till and with glaciofluvial sands and gravels (CHURSKA, 1966, 1976; KOZARSKI, 1971; SINKIEWICZ, 1989). The length of niches on the slopes of the Toruń–Eberswalde Pradolina and the Drwęca valley (CHURSKA, 1966, 1976; KOZARSKI 1971) as well as in the Kuyavian Lakeland (SINKIEWICZ, 1989) usually does not exceed 500 m, averaging between 40–60 m and/or 100–400 m. Their maximum gradient equals 17–18° and the minimum one at the outlets, 2–5°. The niches are generally shallow, 2–8 m, and have asymmetric slopes inclining 9–13° (the N slope) and 7–11° (the S slope).

The bottoms and slopes of niches are covered with sheet-wash and gelifluction deposits. CHURSKA (1976) found that in some niches the thickness of periglacial deposits attains up to 4 m. In cross-sections studied, in such situations the primary shapes of the niches, of greater depths, can be observed.

The denudation niches on scarps of the western part of the Toruń–Eberswalde Pradolina (the Gorzów Basin) contain as a standard: (1) periglacial deposits in the axial parts, represented by rhythmically stratified sheet-wash deposits, and (2) gelifluction deposits in the middle and lower parts of slopes (KOZARSKI 1971). This is similar to the findings in the eastern scarp of the pradolina and the Drwęca valley (CHURSKA 1966, 1976). Sheet-wash deposits are the primary ones which were later disturbed by gelifluction. This justifies the conclusion that the principal process which has shaped the niches was sheet wash (KOZARSKI, 1971). However, reverse sequences can also be found in the Kuyavian Lakeland (SINKIEWICZ 1989), which may have resulted from differences in the time of niche formation. Sheet wash is also the process favoured by GOŁĘBIEWSKI (1981). In his estimate of the denudation rate in the upper Radunia catchment in East Pomerania, he asserts that sheet wash constituted 68% of mechanical denudation during the Late Vistulian.

Outside denudation niches, sheet-wash deposits including rhythmically stratified ones can only be find sporadically (KOZARSKI, 1958; MARUSZCZAK, 1960). In turn, gelifluction covers (KOZARSKI, 1971) can be observed on slopes quite frequently. They take on a variety of forms, from covers of an amorphic structure to ones with folds and gelifluction lobes (KOZARSKI, 1971; SINKIEWICZ, 1989). This is also the picture emerging from as yet unpublished data from sites distributed throughout northwestern Poland.

Sheet-wash processes have also left their marks on till plains and end-moraine slopes (SINKIEWICZ, 1989). Recently, clayey and silty or silty and sandy deposits have been found on the bottoms of numerous closed depressions of West Pomerania below organic ones (JUVIGNÉ, KOZARSKI, NOWACZYK, unpublished data). They are a record of the first phase of the filling up of kettle holes with mineral deposits. In one of them (Warnowo, Wolin Island) a 0.5-m thick clay-silt layer with pollen of Tertiary plants has been found under Bølling deposits. This is clear evidence of denudation and the redeposition of Tertiary pollen, first incorporated into Pleistocene deposits through glaciotectonic disturbances of the substratum and then washed out from tills. Bottom mineral deposits from the Younger Dryas in kettle holes of northwestern Poland have recently been described by BORÓWKA (1992); they are indicative of intensive processes of mechanical denudation on till plains spanning the Pleistocene/Holocene border.

DRY FLAT-FLOORED VALLEYS

Dry flat-floored valleys are landforms frequently occurring in scarp zones of pradolinas, big valleys and subglacial tunnels; less often outwash plains (Table I). They were examined in three main areas: (1) between Gdynia and Reda on the Bay of Gdańsk (MARSZ, 1964), as well as in the Radunia catchment (GOŁĘBIEWSKI, 1981), (2) along the eastern section of the Toruń–Eberswalde Pradolina and the Drwęca valley (CHURSKA, 1966, 1976), and (3) along the western scarp of the Toruń-Eberswalde Pradolina and the lower Odra valley (Kozarski, 1971). The length of these landforms ranges from 2 km to 7 km, with the longest valleys found in the first area, where differences in height are also the biggest, and the shortest ones in the scarp zone of the Drwęca valley, 1–2 km. There are also variations in the width of the valleys, from 200 m to 500 m, and their depth, from 20 m to 60 m with relation to the local erosion base. Those flat-floored valleys which have underwent multi-stage development and have terrace systems are longer and deeper. Slope gradients differ from area to area and within the valleys themselves. The steepest gradients have been recorded in the first area, up to 45°, with an average of 22°–26° and a minimum of 6°–9°. In the first and second areas, there is a marked asymmetry in the inclination of slopes: SW and S slopes have gradients of 5°–6° or 6°/16°–18°/2°–6° in the upper, middle and lower sections, respectively, and NE and N slopes, 13°–15° or 12°/18°–27°/2°–4°.

The features that the dry flat-floored valleys of all the areas share include:

(1) niche-like or multiniche-like head parts and small-scale denudation niches on slopes,

(2) gelifluction and sheet-wash deposits on slopes,

(3) thermal-contraction structures in terrace deposits, and

(4) fluvial deposits of braided streams with stone pavements on their floors.

Sporadically, small and shallow closed depressions can be found within these valleys which presumably contained buried icings. Some flat-floored valleys are superposed with relation to subglacial tunnel valleys and cut across them. This is indicative of the tunnel valleys being filled with dead-ice bodies during the valley formation. Dead ice was protected against fast melting by permafrost. The evidence of its aggradation during valley development is the occurrence of syngenetic and epigenetic ice-wedge casts and frost cracks in terrace deposits of the flat-floored valleys. Of no little significance for the reconstruction of conditions under which these valleys formed is the fact that some of them were cut in highly permeable deposits, viz. sands and gravels. In periglacial conditions, such deposits must have been made impermeable by permafrost.

The period of the emergence and development of flat-floored valleys must have been a rather brief one. By geomorphological (Kozarski, 1971) and palaeobotanical arguments (Churska, 1966), their formation took place mainly before the Allerød, over a time span between the period immediately following the Pomeranian Phase and the Younger Dryas inclusive. Marsz (1964) prefers the Older Dryas as the period of the formation of flat-floored valleys, the Allerød as the stage of deep erosion, and the Younger Dryas as the time of their slopes covering with gelifluction deposits, but he does not provide any convincing evidence in favour of his suggestion. SINKIEWICZ (1989), in turn, has found the pre-Pomeranian period to be the most efficient, but periglacial denudation processes were active until the late Vistulian inclusive. It was then, before the Allerød melting of buried dead ice, that the last niches are supposed to have formed. However, GOŁĘBIEWSKI (1981) has shown, on well dated examples, that intensive sheet wash took place in the Younger Dryas, and less frequently in the Older Dryas.

AEOLIAN PHENOMENA

The area abandoned by the last ice-sheet is characterised by an abundance of highly diversified aeolian features: ventifacts, loess patches, aeolian cover sands, and inland dunes. All of them have a periglacial context and supply very important information about environmental conditions during deglaciation and the termination of the Pleistocene.

VENTIFACTS

Wind-polished pebbles in the area of the last deglaciation in northern Poland have not been the object of intensive and systematic investigation so far. The only special study has been made by KUBIŚ (1978) in the region of Konin, on both sides of the maximum limit line of the last ice-sheet. The study has shown that: (1) the number of ventifacts in the area of the last glaciation is 10.9% smaller than south of the ice-sheet maximum, and (2) in the latter area, there are deflation pavements under aeolian cover sands, which are absent from the former area. Sporadically, ventifacts have also been found in the area of the last glaciation on eskers (BORÓWKA, 1975), outwash plains and periglacial terraces (STANKOWSKI, 1963a, b; NOWACZYK, 1976; KOZARSKI, NOWACZYK, 1991b).

Recently, the study of the occurrence and distribution of ventifacts in the area of the last glaciation in west-central Poland has been conducted in a systematic way, and produced new and very important results (ANTCZAK-GÓRKA, 1994). The statistical procedures applied made it possible to attain a high confidence level of results in a comparative analysis of 141 sites (test areas 10 x 10 m each): (1) on till plains of equal ages, (2) on outwash plains of different ages, (3) on till plains and outwash plains of equal ages, (4) on pradolina terraces of different ages, and (5) on the surface of lithologically varying slopes. The test areas were located immediately to the south of the last ice-sheet maximum extent line, in the hinterland of this line, in the foreland of the Poznań Phase extent line, and north of it (the western part of the Warta–Noteć Interfluve).

Varying population of ventifacts (in %) vs. total amount of erratics analysed on the surface of test sites distributed on till plains, outwash plains and pradolina terraces

Table III

Location	Number of erratics	Vetifacts	Ventifacts with well shaped edge(s)
Till plains			
Foreland of ice-sheet maximum	2 571	49,6	41,2
Hinterland of ice-sheet maximum	2 213	42,1	38,6
Foreland of Poznań phase	2 147	36,3	29,1
Hinterland of Poznań phase	1 915	32,8	21,9
Outwash plains			
Foreland of ice-sheet maximum	1 994	50,2	44,7
Hinterland of ice-sheet maximum	1 701	42,6	38,0
Foreland of Poznań phase	1 628	35,9	30,1
Hinterland of Poznań phase	1 691	33,8	22,3
Pradolinas			
Głogów – Baruth	1 140	47,1	42,8
Warsaw –Berlin	2 331	35,1	30,2
Toruń – Eberswalde	2 617	37,1	21,6

Source: data contained in ANTCZAK-GÓRKA (1994)

The present investigations of the distribution of ventifacts in the area of the last glaciation lead to a few general conclusions, some of which follow from the data included in Table III:

(1) There is a marked difference, 7.5% to 12.0%, in the proportion of ventifact populations in the total number of erratics found on the surface, between the areas immediately south and north of the ice-sheet maximum limit. These results corroborate the earlier opinion of KUBIŚ (1978) based on the study of a smaller area and a smaller population of erratics.

(2) Ventifacts occurring south of the ice-sheet maximum limit are more mature and display well curved edges more frequently.

(3) The number of ventifacts decreases northwards. This is a function of time, on the one hand, because in areas deglaciated later also aeolian processes started to work later. On the other hand, however, this phenomenon is also a result of change in climatic conditions, of the polar desert of the Late Pleni-Vistulian turning into the shrub tundra and park tundra at the beginning of the Late Vistulian. The growing density of vegetation hampered corrasive wind action.

(4) Aeolian processes were widespread and occurred both on till plains with their covers of ablation sands redeposited by the wind, and on outwash plains and terraces of pradolinas.

The palaeoenvironmental meaning of ventifacts is obvious, because they are another important factor, besides sand-wedge polygons, indicating the aridity of the Late Pleni-Vistulian climate, especially during ice-margin steady states when very cold conditions prevailed, with permafrost aggradation and intensive thermal contraction.

LOESS PATCHES

Yet another indication of the dry climate prevailing at the end of the Pleni-Vistulian and the beginning of the Late Vistulian is the occurrence of periglacial loess patches in the proximal parts of outwash plains, end-moraine ridges and till plains of the Pomeranian Phase of south-western Pomerania (KOZARSKI, NOWACZYK, 1991a, b). They have formed in three lithofacies: massive loess, laminated and/or cryptolaminated loess, and loess colluvium, as ISSMER (1994) has confirmed in her recent research.

The cold, periglacial origin of loess on deposits of the Pomeranian Phase results, among other things, from the lack of mollusc remnants in their covers (KOZARSKI, NOWACZYK, 1992), thermal contraction cracks found in them at various depths, and the recently discovered (ISSMER, 1994) association of flow till and cryptolaminated loess covers. The flow tills derived from melting ice bodies from ice-cored moraines (KOZARSKI, 1978, 1981b) on the slopes of which loess was deposited.

DUNES

Dunes occurring in the area of the last glaciation are as a rule considered outside the periglacial context (e.g. STANKOWSKI, 1963; ROSZKO, 1968; KOZARSKI, 1986; NOWACZYK, 1986). It is only occasionally that periglacial structures found in dunes are listed (STANKOWSKI, 1963; KOZARSKI *et al.* 1982), or that dunes are shown as relating to the periglacial environment (KOZARSKI, 1990), also in a negative sense (Böse 1991) as indicators of dryness without permafrost.

It has been proved, however, that dunes formed in northern Poland primarily in the Older and Younger Dryas (NOWACZYK, 1986; KOZARSKI, NOWACZYK, 1991b). It is also known from studies of dunes (KOZARSKI, *et al.*, 1982) and alluvial fans (NOWACZYK, 1991) that permafrost was then present in west-central Poland (KOZARSKI, 1993). Since dune formation was geomorphologically most effective in the Older Dryas (NOWACZYK, 1986), it is fair to believe that on the one hand, dunes are indicators of dryness, as claimed by Böse (1991), but on the other, the presence of permafrost in that period justifies their treatment as a geomorphic component of the periglacial environment. At that time huge dune fields and their smaller groups developed in northern Poland, covered with new portions of aeolian sands in the Younger Dryas (NOWACZYK, 1986). Starting from the south, they are known primarily from the Warsaw–Berlin Pradolina, the Toruń–Eberswalde Pradolina, and some outwash plain surfaces and till plains covered with sand.

Dunes are accompanied by aeolian cover sands, which also occur alone (NOWACZYK, 1976). Like the dunes, cold aeolian cover sands formed in the Older Dryas (KOZARSKI, *et al.*, 1969; BORÓWKA, *et al.*, 1986). Unfortunately, no sequences have been found so far in which aeolian cover sands would be associated with thermal contraction structures indicating the presence of permafrost during the Older Dryas at the sites studied.

FLUVIAL EVENTS

It has been mentioned earlier (p. 77) that some of the syngenetic ice-wedge casts and frost cracks of north-western Poland were found in terraces (KOZARSKI, 1971, 1974, 1993; KŁYSZ, 1969; ANTCZAK, 1986; KOZARSKI, *et al.*, 1988; VANDENBERGHE, *et al.*, 1994). It is of prime importance for the determination of periglacial conditions under which rivers operated in the Late Pleni-Vistulian and the Late Vistulian, the Older Dryas inclusive. An additional argument can be the finding of a permafrost block buried in braided-river sediments from the Oldest Dryas (ANTCZAK, 1986). This finding is the only fact bearing out the hypothesis formulated earlier by JAHN (1975) that pradolinas were shaped by thermoerosion.

The periglacial conditions, first of a polar desert, then, in the Late Vistulian, of the park tundra (KOZARSKI, 1980, 1981), were conducive in cold spells to strong lateral erosion and the accumulation of sandy-gravelly covers (KOZARSKI, 1962, 1965, 1988) by braided streams (KOZARSKI, 1965; ANTCZAK, 1986; KOZARSKI, *et al.*, 1988). What best confirms their geomorphic effectiveness in lateral erosion is the width/depth ratio in pradolinas. In the case of the Toruń–Eberswalde Pradolina in its Polish section, the ratio is 1,000 : 3 (KOZARSKI, 1965).

With plant recolonisation in the Late Vistulian, runoff conditions and sediment yield to streams started to change. The result was a change in river channel patterns from braided to curved multichannel or meandering at a large scale in the valleys of big rivers (KOZARSKI, 1983, 1991a, b), with a transitional phase at the start of the Bølling (VANDENBERGHE, *et al.*, 1994). In north Pomerania the process of the transformation of river channels in the Late Vistulian was simpler. The change from a braided channel to a meandering one took place without the transitional phase and without large-scale meanders (FLOREK, 1991; KOZARSKI, 1991b).

The phases of strong lateral erosion and accumulation alternated with those of the vertical cutting of rivers in pradolinas to the depth of 5–14 m

(Kozarski, 1962, 1988). Phases when the cutting prevailed have been correlated with those of interstadial climatic amelioration. The cutting was especially effective in the Allerød, with its intensive melting of dead ice (Kozarski, 1963; Niewiarowski, 1993; Andrzejewski, 1994) and possibly severe degradation, if not total disappearance, of permafrost, because so far no evidence has been found in northern Poland of the existence of permafrost in the Younger Dryas (Kozarski, 1993).

DISCUSSION AND CONCLUSIONS

Systematic research on traces of periglacial environment in northern Poland has added new data to earlier findings (Kozarski, 1971, 1974, 1993), primarily new evidence of:

(1) permafrost aggradation during deglaciation in the period from <20.0 kyr BP to 14.5 kyr BP, and then to 11.8 kyr BP, i.e. until the Older Dryas inclusive,

(2) high gradients between air and ground temperatures, especially during the Poznań Phase, and

(3) extreme aridity of climate during deglaciation.

These data have been collected owing to intense large-area studies using remote-sensing techniques (new aerial photographs taken during special flights), and to the use of a big number of test surfaces when analysing features on the ground surface.

The first and second groups of data embrace sand-wedge polygons with primary filling, which have not been known so far, in such numbers and partly also in such sizes, either from Polish studies (Goździk, 1986; Kozarski, 1971, 1974, 1993; Bogdański, Kijowski, 1990) or from German ones (Böse, 1991, 1992; Liedtke, 1993). Sand-wedge casts have the quality of being the indicators of, simultaneously: (a) intensive thermal contraction cracking of the permafrost table, (b) high gradients between air and ground temperatures, mainly at the beginning of winter, and (c) a very arid continental climate. The last indicator function is specially stressed by French (1976), Kolstrup (1986), Karte (1979, 1983), Böse (1991), and Vandenberghe and Pissart (1993). The last two authors are also of the opinion that sand wedges are only indicative of aridity, because this is what induces their development. It is worth remembering, however, that their status as indicators of permafrost is also of no little significance (Kolstrup, 1993). French (1976) asserts that the palaeoclimatic relevance of sand wedges is similar to that of ice wedges, since they are genetically the same (thermal contraction cracking). What is more, they are evidence of extremely low winter temperatures, because their host deposits contain very little ground ice and have relatively low linear contraction ratios. In our examples, especially important are the sizes of individual polygons and the areas of their network systems, which cannot have formed solely due to aridity (Table II).

In the third group, there are ventifacts as an additional, significant indicator of the dryness of climate during deglaciation. They are evidence of intensive deflation and effective transport of sand grains in saltation, which were widespread and of long duration (Table IV). It is known that one of the factors facilitating the formation of ventifacts is the absence or scarcity of vegetation (GREELEY, IVERSEN, 1985). This means that we have to assume the conditions of a polar desert for our area, which also follows from the fact that the deglaciation period is not documented in northern Poland by any sites with organic deposits of radiocarbon ages < 20.0 kyr BP 14.5 kyr BP (KOZARSKI, 1986). However, the process of limited ventifact formation was still at work in the semiarid conditions of the Late Vistulian, because the youngest ventifacts come from the Older Dryas (KOZARSKI, NOWACZYK, 1991b).

In the discussion about the presence of permafrost in the area of Vistulian deglaciation, the recurrent problem is its mode of occurrence (KOZARSKI, 1971, 1974, 1993; LIEDTKE, 1993). For LIEDTKE (1993), the basic dilemma is whether permafrost was continuous, discontinuous or episodic, or whether it took on a long-lasting periodical or a deep seasonal form. He also is not sure if permafrost disappeared altogether in particular climate ameliorations, or if it survived in the substratum. For the last deglaciation area in northern Poland, continuous permafrost is advocated (KOZARSKI, 1971, 1993) because of age differences among its indicators and their distribution within various landforms and deposits. The new data presented in this article supply further arguments in favour of this opinion. The most important of them is the finding of large areas of sand-wedge polygonal network systems, which require very cold climatic conditions. These conditions must have intensified over long time spells which allowed the development of polygonal networks of second- or even third-generation thermal contraction cracks (Table II). That permafrost persisted until the beginning of the Late Vistulian is indicated by a shallow pond preserved on a sand-gravelly terrace surface which had survived the Bølling amelioration of climate. If permafrost had disappeared then, the existence of the pond on such permeable deposits would not have been possible (KOZARSKI, *et al.*, 1988; KOZARSKI, 1991a).

Analysis of data on the existence and impact of the periglacial environment on the deglaciation area in northern Poland, both those published so far and those newly found and presented above, leads to some fundamental conclusions summarised in Table IV.

(1) The process of deglaciation was accompanied by a northward expansion of the periglacial domain. The ice-sheet retreated mainly frontally,

Environmental changes in northern Poland after 20 kyr – 10 kyr BP

Table IV

^{14}C ka BP	GLACIAL PERIGLACIAL	Geomorphic processes	Vegetation	Climate
		Lateral erosion & fluvial accumulation Sheet-wash & gelifluction	Park tundra	July temp. ~10°C Semi-arid cold
	YOUNGER DRYAS	Dune sand accumulation		
→11				
	Permafrost degradation ALLERØD	Vertical cutting	Pine/birch Woodland Birch/pine	July temp. ~17°C
	OLDER DRYAS Frost cracking	Sheet-wash & gelifluction Dune sand accumulation		MAAT ~ –1°C Semi-arid cold
→12				
	BØLLING Permafrost survival	Vertical cutting & Large-scale meandering	First forest patches	July temp. ~15°C
→13			Park tundra	
	OLDEST DRYAS Permafrost aggradation Frost cracking	Sheet-wash & gelifluction Lateral erosion & fluvial accumulation	Shrub tundra	MAAT ~ –1°C Dry cold
→14				
	KAMION	Vertical cutting		
	Ice-sheet retreat GARDNO Phase	Glacial & glacio-fluvial accumulation		Dry cold
→15		Deflation & patchy loess accumulation (local)		
		Vertical cutting	POLAR DESERT	
	Ice-sheet retreat			
→16				
	POMERANIAN Phase Permafrost aggradation Frost cracking Icings formation	Glacial & glacio-fluvial accumulation Lateral erosion & fluvial accumulation		MAAT ~ –1(–2)°C High air-ground temp. gradients
	DEGLACIATION OF NORTHERN POLAND			

		DEGLACIATION OF NORTHERN POLAND	Deflation & ventifacts	ARCTIC DESERT	Dry cold
→17	Ice-sheet retreat				
			Sheet-wash Vertical cutting		
	CHODZIEŻ Readvance Permafrost aggradation		Glacial & glacio-fluvial accumulation		Dry cold
→18	Icings formation				
	Ice-sheet retreat		Deflation & ventifacts		
	POZNAŃ Phase		Glacial & glacio-fluvial accumulation		MAAT ~ -12°C →-20°C
→19	Permafrost aggradation Frost cracking Icings formation		Very strong defla-tion & ventifacts		Very high air/ /ground temp. gradients MAGT ~ -2°C MAP ~100 mm
→20	Ice-sheet retreat LESZNO Phase (Ice-sheet maximum)		Glacial & glacio-fluvial accumulation		Very dry and cold

exposing vast areas of till plains to the action of very low temperatures and high temperature gradients. Such conditions prevailed already during the Poznań Phase, around 18,800 BP. Böse (1992) has come to a similar conclusion on the basis of her observations in eastern Germany.

(2) The permafrost that formed then had a continuous character, and the severe climatic conditions and high temperature gradients facilitated the development of vast sand-wedge polygons with primary filling.

(3) Conditions favourable to permafrost aggradation persisted until the Older Dryas inclusive. Permafrost could have disappeared totally only in the Allerød.

(4) The first stage of deglaciation was characterised by a climate that was not only cold, but also very dry, as indicated by sand-wedge polygons that developed then, and by big ventifact populations occurring also on the surfaces of polygon blocks. They form a so-called desert pavement (Vandenberghe, Pissart, 1993). The high aridity of climate lasted till the beginning of the Oldest Dryas, when loess patches developed on Pomeranian Phase deposits in the absence of vegetation.

(5) The area of the last deglaciation abounds in periglacial landforms of denudational, fluvial and aeolian origin that have developed on the glacial relief. Taking into consideration the evidence of permafrost existence as well as periglacial deposits and landforms occurring in the study area,

it must be assumed that in the period between < 20.0 kyr BP and 11.8 kyr BP the geosystem changed from a glacial into a periglacial one. This transformation signified terrestrial conditions of the Central-European termination of the Pleistocene, and rather than having a threshold nature, it was a gradual change of a still cold environment. The proof of a climatic amelioration, starting with the close of the Oldest Dryas through the Bølling and then the Allerød, was plant recolonisation and the development of shrubland followed by the park tundra, and most importantly, woodland (Kozarski 1981, 1991c).

Translated by Maria Kawińska

References

Alm, T., 1993 – Øvre Aeråsvatn – palynostratigraphy of a 22,000 to 10,000 BP lacustrine record on Andøya, northern Norway. *Boreas*, 22; p. 171–188.

Andrzejewski, L., 1994 – Ewolucja systemu fluwialnego doliny dolnej Wisły w późnym vistulianie i holocenie na podstawie wybranych dolin jej dopływów. Toruń.

Antczak, B., 1986 – Transformacja układu koryta i zanik bifurkacji Warty. Uniw. im. A. Mickiewicza, ser. *Geografia*, 35. Poznań.

Antczak-Górka, B., 1994 – Analiza przestrzenna i gęstość występowania eologliptolitów na obszarach testowych Polski środkowozachodniej (unpublished report; res. project no. 6 0318 91 01), Poznań.

Bard, E., Hamelin, B., Fairbanks, R. G., Zindler, A., 1990 – Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*, 345; p. 405–410.

Bogdański, P., Kijowski, A., 1990 – Photointerpretation of geometry of Vistulian ice-wedge polygons: the Grabianowo and Sulejewo sites, south of Poznań. *Quaestiones Geographicae*, 12 (1985/1986); p. 39–52.

Borówka, R. K., 1975 – Oz skocko-wągrowiecki. *Badania Fizjogr. nad Polską Zach.*, 27, ser. A. Geogr. Fiz.; p. 7–38.

Borówka, R., 1992 – Przebieg i rozmiary denudacji w obrębie śródwysoczyznowych basenów sedymentacyjnych podczas późnego vistulianu i holocenu. Uniw. im. A. Mic- kiewicza, ser. *Geografia*, 54. Poznań.

Borówka, R.K., Gonera, P., Kostrzewski, A., Nowaczyk, B., 1986 – Stratigraphy of eolian deposits in Wolin and the surrounding area, North-West Poland. *Boreas*, 15; p. 301–309.

Böse, M., 1991 – A palaeoclimatic interpretation of frost-wedge casts and aeolian sand deposits in the lowlands between Rhine and Vistula in the Upper Pleniglacial and Late Glacial. *Ztschr. f. Geomorph.*, N. F., Suppl.-Bd., 90; p. 15–28.

Böse, M., 1992 – Late Peistocene sand wedge formation in the hinterland of the Brandenburg stade. *Sveriges Geol. Undersökning*, Ser. Ca; p. 59–63.

Cegła, J., Kozarski, S., 1977 – Sedimentary and geomorphological consequences of the occurrence of naled sheets on the outwash plain of the Gås Glacier, Sörkappland, Spitsbergen. Acta Univ. Wratislaviensis, 387. Results of investigations of the Polish Scientific Spitsbergen Expeditions 1970–1974, 2; p. 63–84.

CHURSKA, Z., 1966 – Późnoglacjalne formy denudacyjne na zboczach pradoliny Noteci–Warty i doliny Drwęcy. *Studia Soc. Sci. Torunensis*, vol. VI, Sec. C. Toruń.

CHURSKA, Z., 1976 – Osady stokowe jako zapis etapów rozwoju stoku doliny Drwęcy w Nowym Mieście Lubawskim. *In*: Problemy geografii fizycznej (ed. W. NIEWIAROWSKI). PWN Warszawa–Toruń–Poznań; p. 23–43.

FLOREK, W., 1991 – Postglacjalny rozwój dolin rzek środkowej części północnego skłonu Pomorza. Wyższa Szkoła Pedagogiczna, Słupsk.

FRENCH, H. M., 1976 – The Periglacial Environment. Longman, London, New York.

GOŁĘBIEWSKI, R., 1981 – Kierunki i intensywność denudacji na obszarze zlewni Raduni w późnym würmie i holocenie. *Zesz. Nauk. Uniw. Gdańskiego*, Rozprawy i monografie, 26. Gdańsk.

GOŹDZIK, J., 1986 – Structures de fentes remplissage primaire sableux du Vistulien en Pologne et leur importance paleogégraphique. *Biul. Peryglacjalny*, 31; p. 71–105.

GÓRSKA, M., KASPRZAK, L., KOZARSKI, S., 1992 – Vistulian maximum glaciotectonite and sand wedges. Site Włoszakowice. International Symposium "Last Ice Sheet Dynamics and Deglaciation in the North European Plain" (Poznań/Berlin, 4–9 May), Exursion–Guide, M. BÖSE, L. KASPRZAK, S. KOZARSKI (eds); p. 16–21.

GREELEY, R., IVERSEN, J.D., 1985 – Wind as a Geological Agent on Earth, Mars, Venus and Titan. Cambridge University Press. Cambridge.

ISSMER, K., 1995 – Analiza litofacjalna i litostratygrafia osadów lessowych w strefie kontaktu z osadami glacjalnymi fazy pomorskiej ostatniego zlodowacenia w Starym Objezierzu, Pomorze Zachodnie. *Badania Fizjogr. nad Polską Zach.*, 46, A. Geogr. Fiz.; p. 63–84.

JAHN, A., 1975 – Problems of the Periglacial Zone. PWN, Warszawa.

KARTE, J., 1979 – Räumliche Abgrenzung und regionale Differenzierung des Periglaziärs. *Bochumer Geogr. Arb.*, 5, F. Schöningh, Paderborn.

KARTE, J., 1983 – Periglacial phenomena and their significance as climatic and edaphic indicators. *Geogr. Journ.*, 7; p. 329–340.

KASPRZAK, L., KOZARSKI, S., 1984 – Analiza facjalna osadów strefy marginalnej fazy poznańskiej ostatniego zlodowacenia w środkowej Wielkopolsce. Uniw. A. Mickiewicza, ser. *Geografia* 29. Poznań.

KŁYSZ, P., 1969 – Cechy geologiczne i morfologiczne 42 m terasy w słubickim przełomie Odry. *Badania Fizjogr. nad Polską Zach.*, 23, ser. A. Geogr. Fiz.; p. 93–112.

KOLSTRUP, E., 1986 – Reappraisal of the Upper Weichselian periglacial environment from Danish frost-wedge casts. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 56; p. 237–249.

KOLSTRUP, E., 1993 – Complex frost wedge casts as indicators of ice age environmental change. *Würzburger Geogr. Arb.*, 87; p. 269–282.

KOWALKOWSKI, A., 1990 – Evolution of Holocene soils in Poland. *Quaestiones Geographicae* 11/12; p. 93–120.

KOZARSKI, S., 1958 – Warstwowane osady stokowe w okolicy Chodzieży. *Biul. Peryglacjalny*, 6; p. 137–144.

KOZARSKI, S., 1962 – Wydmy w pradolinie Noteci koło Czarnkowa. *Badania Fizjogr. nad Polską Zach.*, 9; p. 37–60.

KOZARSKI, S., 1963 – O późnoglacjalnym zaniku martwego lodu w Wielkopolsce zachodniej. *Badania Fizjogr. nad Polską Zach.*, 11; p. 51–60.

KOZARSKI, S., 1965 – Zagadnienie drogi odpływu wód pradolinnych z zachodniej części pradoliny Noteci–Warty. *Pozn. Tow. Przyj. Nauk, Wydz. Mat.–Przyr., Prace Kom. Geogr.–Geol.*, 5. Poznań.

KOZARSKI, S., 1971 – Ślady działalności późnowürmskich procesów peryglacjalnych w regionie dolnej Odry i dolnej Warty. *Badania Fizjogr. nad Polską Zach.*, 24, ser. A. Geogr. Fiz.; p. 97–177.

KOZARSKI, S., 1974 – Evidences of Late–Würm Permafrost Occurrence in North–West Poland. *Quaestiones Geographicae*, 1; p. 65–86.

KOZARSKI, S., 1975 – Oriented kettle holes in outwash plains. *Quaestiones Geographicae*, 2; p 99–112.

KOZARSKI, S., 1978 – Lithologie und Genese der Endmoränen im Gebiet der skandinavischen Vereisungen. *Schriftenreihe f. Geologische Wiss.* 9,. Akademie–Verlag Berlin; p. 179–200.

KOZARSKI, S., 1980 – An outline of Vistulian stratigraphy and chronology of the Great Poland Lowland. *Quatern. Studies in Poland*, 2; p. 21–35.

KOZARSKI, S., 1981a – Stratygrafia i chronologia Vistulianu Niziny Wielkopolskiej. PAN Oddz. w Poznaniu, *Geografia*, 6. PWN Warszawa.

KOZARSKI, S., 1981b – Ablation end moraines in western Pomerania, NW Poland. *Geogr. Annaler*, 63; p. 169–174.

KOZARSKI, S., 1983 – River channel adjustment to climatic change in west central Poland. *In*: Background to Palaeohydrology. A perspective. (K. J. GREGORY, ED.). Chichester; p. 355– –374.

KOZARSKI, S. 1986. Skale czasu a rytm zdarzeń geomorfologicznych vistulianu na Niżu Polskim. *Czas. Geogr.*, 57; p. 247–270.

KOZARSKI, S., 1990 – Pleni- and Late Vistulian Aeolian Phenomena in Poland: New Occurrences, Palaeoenvironmental and Stratigraphic Interpretations. *Acta Geogr. Geolog. Meteorol. Debrecina*, 26/27; p. 31–45

KOZARSKI, S., 1991a – Warta – A Case Study of a Lowland River. *In*: (L. STARKEL, K. J. GREGORY and J. THORNES, eds) – Temperate Palaeohydrology. Chichester; p. 189– –215.

KOZARSKI, S., 1991b – Spätglazial–holozäne Klimaschwankungen und ihr Einfluss auf Veränderungen der Gerinnebettmuster mitteleuropäischer Flüsse. Jhrb. deutsch. Akad. Naturf. Leopoldina (Halle/Saale) Leopoldina (R. 3), 36; p. 153–159.

KOZARSKI. S., 1991c – Paleogeografia Polski w vistulianie. *In*: (L. STARKEL, ed.) Geografia Polski, środowisko przyrodnicze. PWN, Warszawa; p. 80–105.

KOZARSKI, S., 1992 – Eine auf der Radiokarbonmethode basierende Abschätzung der Rückzugschronologie des Inlandeises in Nordpolen. *In*: (K. BILLWITZ, K.–D.JÄGER, W. JANKE, Hrsg.) Jungquartäre Landschaftsräume. Aktuellen Forschungen zwischen Atlantik und Tienschan. Springer–Verlag; p. 16–22.

KOZARSKI, S., 1993 – Late Vistulian deglaciation and the expansion of the periglacial zone in NW Poland. *Geol. en Mijnbouw*, 72; p. 143–157.

KOZARSKI, S., 1995 – Large–clast flow tills in end moraines of southern Pomerania, NW Poland. *In*: J. EHLERS, S. KOZARSKI, P. L. GIBBARD (eds), Glacial deposits in North East Europe. A. A. BALKEMA, Rotterdam, Brookfield: p. 301–307.

KOZARSKI. S., GONERA. P., ANTCZAK., B., 1988 – Valley floor development and paleohydrological changes: The Late Vistulian and Holocene history of the Warta River (Poland). *In*: Lake, Mire and River Environments during the last 15,000 years (G. LANG and CH. SCHLCHTER, Eds). Proceedings of the INQUA/IGCP 158 Meeting on the Palaeohydrological Changes during the last 15,000 years (Bern, June 1985). Rotterdam, Brookfield; p. 185–203.

KOZARSKI, S., KASPRZAK, L., 1987 – Facies analysis and depositional models of Vistulian ice-marginal features in northwestern Poland. *In*: V. GARDINER (ed.) International Geomorphology 1986 Part II. Chichester; p. 693–710.

KOZARSKI, S., MOCEK, A., NOWACZYK, B., TOBOLSKI, K., 1982 – Etapy i warunki rozwoju wydm w Budzyniu koło Chodzieży w świetle analizy radiowęglowej, paleobotanicznej i pedologicznej. *Roczniki Glebozn.*, 33; p. 159–174.

KOZARSKI, S., NOWACZYK, B., 1991a – Late Quaternary Climate and Human Impact on Aeolian Processes in Poland. *Ztschr. f. Geomorph.*, N. F., Suppl.-Bd., 83; p. 29–37.

KOZARSKI, S., NOWACZYK, B., 1991b – Lithofacies variation and chronostratigraphy of Late Vistulian and Holocene aeolian phenomena in northwestern Poland. *Ztschr. f. Geomorph.*, N. F. Suppl.-Bd., 90; p. 107–122.

KOZARSKI, S., NOWACZYK. B., 1992 – Późnowistuliańskie i holoceńskie zjawiska eoliczne w regionie dolnej Odry i dolnej Warty. *In*: T. SZCZYPEK (ed.) Wybrane zagadnienia geomorfologii eolicznej. Sosnowiec; p. 37–105.

KOZARSKI, S., NOWACZYK, B., ROTNICKI, K., TOBOLSKI, K., 1969 – The eolian phenomena in West-Central Poland with special reference to the chronology of phases of eolian activity. *Geographia Polonica*, 17; p. 231–248.

KRAMARSKA, R., 1993 – Odra Bank – New Geological Data. *In*: Third Marine Geological Conference – The Baltic. Polish Geological Institute, Branch of Marine Geology, Sopot; 76.

KRAMARSKA, R., UŚCINOWICZ, S., 1992 – Osady lądowe z południowego Bałtyku datowane ^{14}C. *In*: W. FLOREK (ed.) Konferencja Geologia Środkowego Pobrzeża i Południowego Bałtyku, Streszczenia wystąpień i przewodnik wycieczki, Słupsk; p. 47–48

KUBIŚ, W., 1978 – Próba wykorzystania graniaków jako prawdopodobnego wyznacznika północnego zasięgu strefy peryglacjalnej w pełni Würmu między Turkiem i Koninem. *Badania Fizjogr. nad Polską Zach.*, 31., ser. A. Geogr. Fiz.; p. 103–126.

LACHENBRUCH, A. H., 1962 – Mechanics of Thermal Contraction Cracks and Ice- Wedge Polygons in Permafrost. *Geol. Soc. America*, Special Papers, 70; p. New York.

LAGERLUND, E., HOUMARK-NIELSEN, M., 1993 – Timing and pattern of the last deglaciation in the Kattegat region, southwest Scandinavia. *Boreas*, 22; p. 337–347.

LIEDTKE, H., 1993 – Phasen periglaziärgeomorphologischer Prägung während der Weichselkaltzeit im nordischen Tiefland. *Ztschr. f. Geomorph.*, N. F. Suppl.-Bd., 93; p. 69–94.

MARSZ, A., 1964 – O rozcięciach erozyjnych krawędzi pradoliny kaszubskiej mię- dzy Gdynią a Redą. *Badania Fizjogr. nad Polską Zach.*, 13; p. 113–154.

MARUSZCZAK, H., 1960 – Peryglacjalne utwory pokrywowe na obszarze Wzgórz Szeskich. *Biul. Peryglacjalny*, 7; p. 19–33.

MÖRNER, N.A., 1981 – Weichselian chronostratigraphy and correlations. *Boreas*, 10; p. 463–470.

MÖRNER, N.A., FLODEN, T., BESKOW, B., ELHAMMER A., HAXNER, H., 1977 – Late Weichselian deglaciation of the Baltic. *Baltica*, 6; p. 33–51.

NIEWIAROWSKI, W., 1993 – Geneza i ewolucja rynny żnińskiej w okresie pełnego i późnego vistulianu. *Acta Univ. N. Copernici, Geogr.*, 25; p. 3–30.

NOWACZYK, B., 1972 – Cechy granulometryczne osadów wypełniających struktury wieloboków szczelin mrozowych z pierwotnym wypełnieniem mineralnym w Poznaniu-Grunwaldzie. *Badania Fizjogr. nad Polską Zach.*, 25, ser. A. Geogr. Fiz.; p. 113–132.

NOWACZYK, B., 1976 – Aeolian Cover Sands in Central-West Poland. *Quaestiones Geographicae*, 3; p. 57–77.

NOWACZYK, B., 1986 – Wiek wydm, ich cechy granulometryczne i strukturalne a schemat cyrkulacji atmosferycznej w Polsce w późnym vistulianie i holocenie. Wyd. Nauk. UAM, ser. *Geografia*, 28, Poznań.

NOWACZYK, B., 1991 – Wiek i warunki sedymentacji stożków napływowych w zachodniej części Pradoliny Warszawsko–Berlińskiej. *In*: A. KOSTRZEWSKI (ed.) Geneza, litologia i stratygrafia utworów czwartorzędowych. Wyd. Nauk. UAM, ser. *Geografia*, 50, Poznań; p. 153–178.

PAZDUR, M., WALANUS, A., 1979 – The Konin–Maliniec site: Age assesment by radiocarbon method. Symposium on Vistulian Stratigraphy, Poland 1979, Guide-book of excursion, Warszawa.

ROSZKO, L., 1968 – Z historii rozwoju doliny dolnej Wisły. *Folia Quaternaria*, 29; p. 97–108.

ROTNICKI, K., BORÓWKA, R. K., 1989 – Osady górnego plenivistulianu w dolinie dolnej Prosny pod Macewem a wiek maksymalnego zasięgu ostatniego zlodowacenia podczas fazy leszczyńskiej. *Badania Fizjogr. nad Polską Zach.*, 40, ser. A. Geogr. Fiz.; p. 5–20.

ROTNICKI, K., BORÓWKA, R. K., 1991 – Dating of the last Scandinavian ice sheet in the Polish plain. Abstracts, INQUA XIII International Congress, Beijing, China; p. 309.

ROTNICKI, K., BORÓWKA, R. K., 1994 – Stratigraphy, palaeogeography and dating of the North Polish Stage in the Gardno–Łeba Coastal Plain. *In*: K. ROTNICKI (ed.) Changes of the Polish Coastal Zone. A. Mickiewicz University, Poznań; p. 84–88.

SINKIEWICZ, M., 1989 – Zmiany rzeźby terenu Pojezierza Kujawskiego pod wpływem procesów stokowych. *Studia Soc. Sci.*, 9, sec. C. *Geogr. et Geol.* Toruń.

STANKOWSKA, A., STANKOWSKI, W., 1979 – The Vistulian till covering stagnant water sediments with organic sediments. Symposium on Vistulian Stratigraphy, Poland 1979, Guide-book of excursion. Warszawa.

STANKOWSKI, W., 1963a – Rzeźba eoliczna Polski północno-zachodniej na podstawie wybranych obszarów. *Pozn. Tow. Przyj. Nauk, Prace Kom. Geogr.–Geol.*, 4. Poznań.

STANKOWSKI, W., 1963b – Deflatiation relief of the western part of the Warta–Noteć interfluve. *Report of the VIth INQUA Congress, Warsaw 1961*, vol. III, Łódź; p. 337–339.

VANDENBERGHE, J., KASSE, C., BOHNCKE, S., KOZARSKI, S., 1994 – Climate-related river activity at the Weichselian–Holocene transition: a comparative study of the Warta and Maas rivers. *Terra Nova*, 6; p. 476–485.

VANDENBERGHE, J., PISSART, A., 1993 – Permafrost changes in Europe during the Last Glacial. *Permafrost and Periglacial Processes*, 4: p. 121–135.