Geologie en Mijnbouw **72**: 143–157, 1993.

Late Plenivistulian deglaciation and the expansion of the periglacial zone in NW Poland

Stefan Kozarski
Quaternary Research Institute, Adam Mickiewicz University, Fredry 10, 61–701 Poznań, Poland

Received 11 February 1992; accepted in revised form 6 July 1993

Key words: cryostructures, oriented icing depressions, permafrost, Late Pleistocene

Abstract

In NW Poland, in the area of the last Scandinavian icesheet, periglacial phenomena occur mostly in outwash plains, till plains and pradolina terraces, and sporadically also in alluvial fans and inland dunes. Some of them contain indications of former permafrost and can be used in palaeoenvironmental reconstructions of the Late Pleistocene deglaciation. They include epigenetic and syngenetic ice-wedge casts, fossil sand-wedge polygons, ice-vein network casts and oriented icing depressions.

The cryostratigraphic record of permafrost indicators and their geomorphic distribution testify to the presence of continuous permafrost or at least vast permafrost patches in the deglaciated area in NW Poland during the Late Plenivistulian and during cold spells of the Late Vistulian.

Introduction

Relatively fresh glacial landforms left behind by the Scandinavian ice sheet are the predominant feature of the Polish-German Lowlands. Due to this, periglacial effects remained largely unnoticed and were not taken into account in older studies on the climate of the Pleistocene termination. In later times, when fossil permafrost phenomena had been found in the region, more attention was given to the periglacial context, though, normally, its relationship to glacial events remained obscure.

It is the objective of this paper to contribute to the knowledge of deglaciation and periglacial features by means of studies on 1) the record of permafrost aggradation in NW Poland, 2) the relationship of glacial and periglacial events during deglaciation and 3) the areal extent and duration of periglacial conditions in the deglaciated zone.

History and basic concepts

In the past five decades, three different models have been proposed for the evolution of the climate in the Polish-German Lowlands. The models are given below and refer to the period that followed the retreat of the last Scandinavian ice-sheet.

1) Rapid change or jump from glacial to temperate climate without conditions suitable for permafrost formation in the deglaciated area (Büdel 1944, Poser 1948, Troll 1948, Büdel 1950).
2) Change from glacial to periglacial climate. After deglaciation, cold periods reappear resulting in a remodelling of glacial landforms due to permafrost conditions. These cold intervals would have occurred near the close of the Late Vistulian (in particular during the Younger Dryas) or during the Pomeranian phase and Late Vistulian stadials (Dücker 1954, Lembke 1954, Dylik 1956, Pierzchalko 1956, Lembke et al. 1970, Liedtke 1981).

3) Change from glacial to periglacial climate. Conditions favouring permafrost development prevailed during the Late Plenivistulian and Late Vistulian stadials or were restricted to cold spells of the Late Vistulian (Kliewe 1968, Kozarski 1971, 1974, Karte 1981, Gozdzik 1986, Karte 1987, Böse 1991).

New data, both published and unpublished, provide support for the third model (Kasprzak & Kozarski 1984, 1989, Bogdanski & Kijowski 1990). These data will be discussed below.

General mode and time of deglaciation

Northwestern Poland is a territory of classical Late Plenivistulian deglaciation landscapes with a large variety of glacial landforms. Prominent ice-margin landscapes which record changes in ice-front position during deglaciation provide a base for the reconstruction of ice-sheet retreat. Two main deglaciation modes have been postulated: 1) retreat of active ice with re-advances and local dead-ice formation (Kozarski 1962, 1965) and 2) zonal ice-sheet wastage with vast stagnant-ice and dead-ice fields (Bartkowski 1967). In all modern studies (Kasprzak & Kozarski 1984, Kozarski & Kasprzak 1987, Kasprzak 1988, Kasprzak & Kozarski 1989) the correctness of the first option could be demonstrated. In this paper it will be confirmed by additional arguments based on the permafrost record that occurs in glacial and glaciofluvial deposits within and between major ice-sheet positions (Fig. 1).

Major and minor ice-sheet positions are manifested by so-called marginal landforms (ablation end moraines, thrust ridges, ice-lobe-contact sedimentary scarps) which resulted from varying ice-front dynamics at different times (Kozarski 1988). Thus, marginal deposits and landforms of the maximum ice-sheet position (Fig. 1, Leszno phase) prove steady-state ice-front conditions with local high-energy conditions that caused pushing (Kasprzak 1985) or thrusting (Kozarski & Kasprzak 1991). In West Poland steady-state conditions dominated during the Poznan and Pomeranian phases (Kozarski 1978, 1981, Kasprzak & Kozarski 1984, Kasprzak 1988, Kasprzak & Kozarksi 1989). On the other hand, high-energy conditions with strong shearing and thrusting by the ice-sheet re-advance were characteristic for the Chodziez subphase (Kozarski 1962, Kozarski & Kasprzak 1987, Kozarski 1988). Detailed analyses of deposits and landforms in different marginal zones (Kasprzak & Kozarski 1984, Kozarski & Kasprzak 1987, Kasprzak 1988) also reveal compressive ice flow under steady-state conditions. Allochthonous flow tills that cover proximal parts of outwash plains associated with ice-lobe scarps (Kasprzak & Kozarski 1989) are the most convincing arguments for such ice-flow conditions.

An inventory of radiocarbon age estimates of major ice-sheet positions shows that: 1) the maximum ice extent, i.e. the Leszno phase, took place ca. 20 ka BP (Kozarski 1980, 1988) or after 20.5 ka BP (Rotnicki & Borówka 1991), 2) the Poznan phase, Chodziez subphase and Pomeranian phase occurred at 18.4, 17.2 and 15.2 ka BP, respectively (Kozarski 1986, 1988) and 3) the Gardno phase in the coastal zone happened at 13.2 ka BP (Kozarski 1986, 1988) or before 13.8 ka BP (Rotnicki & Borówka 1991).

Fossil periglacial phenomena and their distribution

Field observations supplemented with information from aerial photographs showed that a variety of permafrost-dependent periglacial phenomena are present in the study area. Among these are ice-wedge casts, sand wedges, cryotextures and oriented icing depressions which formerly were called oriented kettle holes (Kozarski 1975).

All the phenomena mentioned above reveal regularities in their distribution. Firstly, the ice-wedge casts, both syngenetic and epigenetic, occur in sandy and gravelly deposits of outwash plains and river terraces; two unusual occurrences have been noted also, one in an aeolian sequence (Kozarski et al. 1982), and the other in a sandy fluvial deposit (Nowaczyk 1988). Secondly, the sand wedges are typical of till plains only. Thirdly, the oriented icing depressions appear in proximal to central parts of outwash plains and occasionally in periglacial alluvial fans. The latter case refers to the alluvial fan of

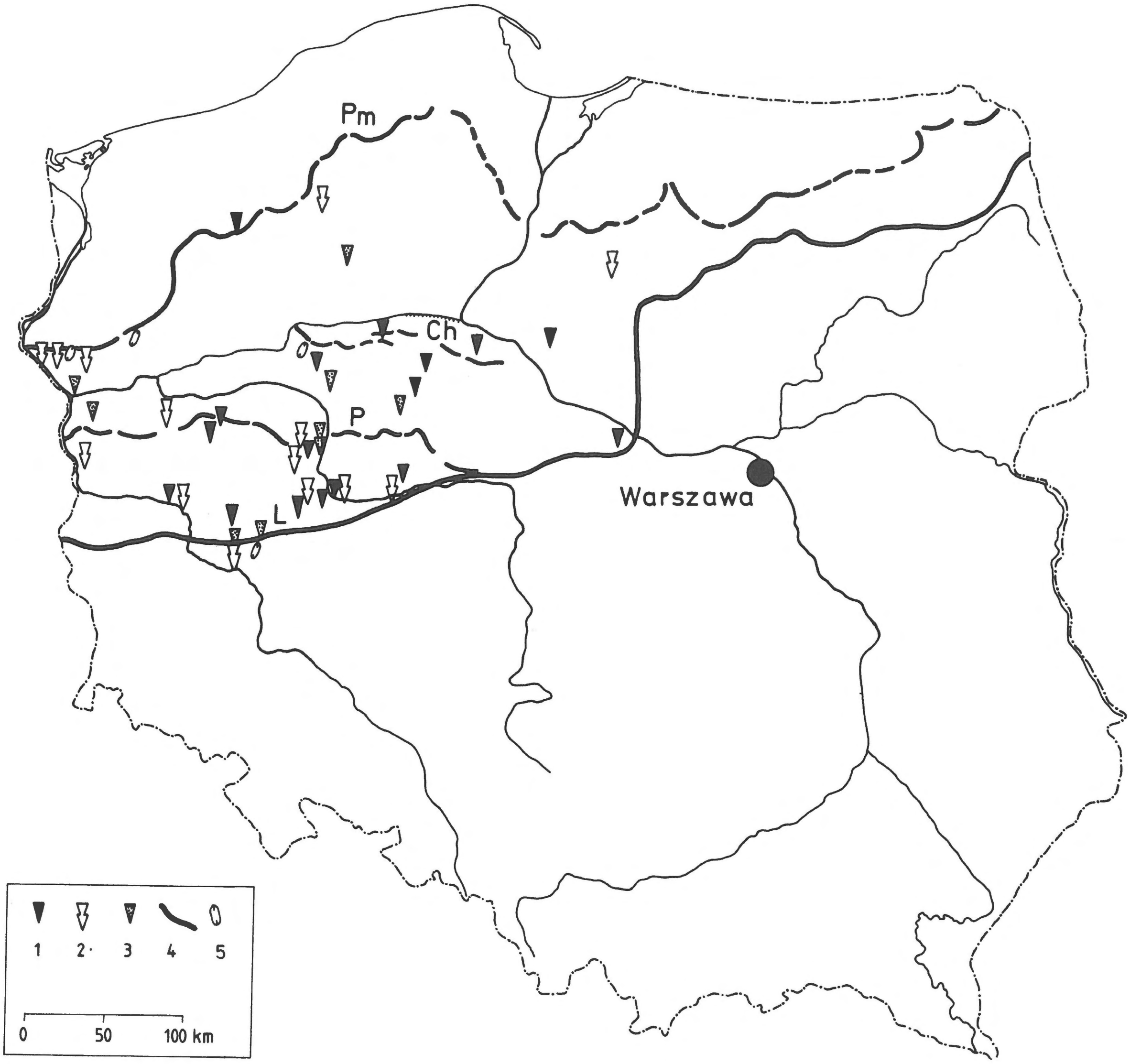

Fig. 1. Distribution of ice-wedge casts, sand wedges and oriented icing depressions in Vistulian of NW Poland (after Kozarski 1991b and unpublished data collected by Kasprzak, Kozarski and Nowaczyk). Legend: 1 – epigenetic ice-wedge casts, 2 – syngenetic ice-wedge casts, 3 – sand wedges, 4 – major ice-sheet margins, 5 – oriented icing depressions; L – Leszno phase, P – Poznań phase, Pm – Pomeranian phase, Ch – Chodziez subphase.

the river Stobber in Eastern Germany (Kozarski 1975).

Permafrost indicators in outwash plains

Syngenetic and epigenetic ice-wedge casts and frost cracks

In NW Poland these structures mostly occur in the sands and gravels of outwash plains. In all studied sequences in proximal parts of outwash plains, syngenetic and epigenetic ice-wedge casts and frost

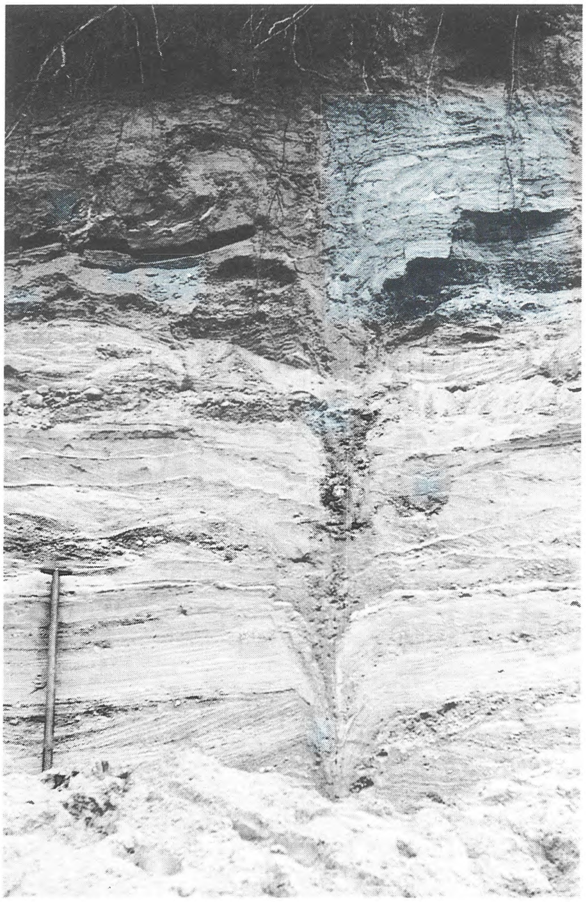

Fig. 2. Zajaczkowo. Syngenetic ice-wedge cast in Vistulian fluvioglacial sand and gravel with distinct traces of former three-level ice-wedge growth (Phot. L. Kasprzak.)

Fig. 3. Zajaczkowo. Vistulian epigenetic ice-wedge cast. In the centre infilling from the previous active layer. On the sides strongly disturbed host material showing its gravitational displacement during ice-wedge decay. (Phot. L. Kasprzak.)

cracks were found (Kozarski 1971, 1975, Kasprzak & Kozarski 1984, 1989, Kasprzak & Nowaczyk, pers. comm.). The syngenetic type is more frequent and convincingly demonstrates permafrost aggradation during glaciofluvial deposition.

The syngenetic ice-wedge casts and frost cracks vary in length from several decimetres to more than six metres, and in width from a few centimetres to more than one metre. They show a distinct multilevel development in the adjacent host material in the form of gravitational faults or wedge-like widenings and occasionally upturned strata in the top-most parts (Fig. 2). The study of structural detail makes clear that during permafrost degradation the ice wedges were replaced by host sediment from the sides and by mixed materials from the overlying active layer (Fig. 3).

Ice-wedge casts form tetragonal systems in horizontal section. Measurements in sand and gravel pits (Kasprzak & Kozarski 1984) show an average distance of 7 m between individual structures. The size of the tetragonal systems seen on aerial photographs (Fig. 4) is 20 to 30 m over relatively large areas (Table 1).

In some cases, the proximal parts of outwash plains with ice-wedge casts are covered with an allochthonous flow-till. This sediment type must have been deposited under compressive ice-flow conditions of the ice-sheet snout.

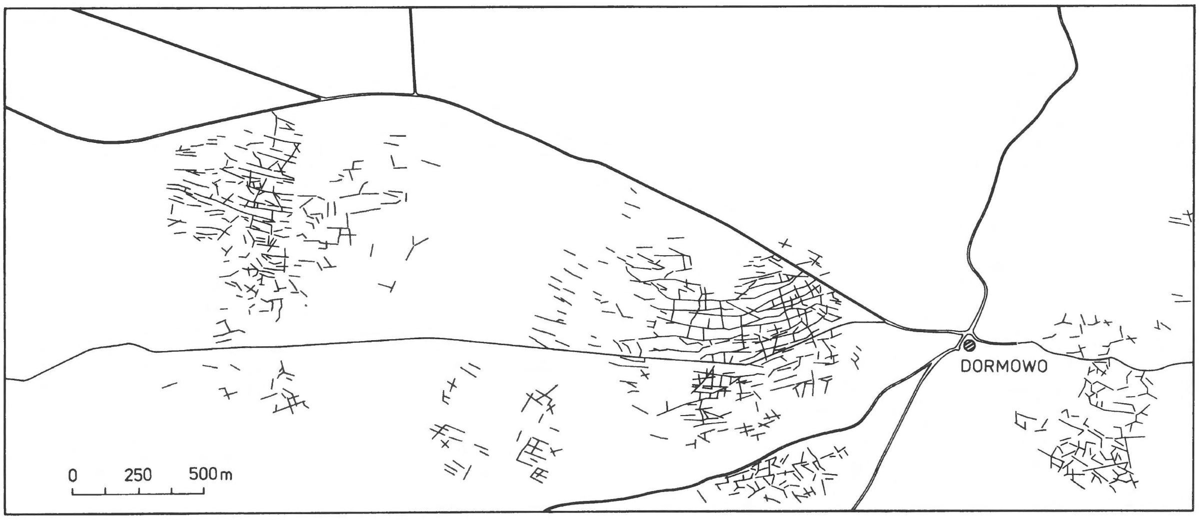

Fig. 4. Dormowo. Tetragonal frost-fissure system drawn after an aerial photograph (source: Pański Przedsiebiorstwo Fotogrametrii, June 9, 1976).

Cryostructures

In NW Poland, cryostructures are a feature of rare occurrence. For the first time they were found in fine-sandy to silty fluvial deposits below a Bølling horizon near Zabinko (Kozarski et al. 1988), where they were developed as 0.25 to 0.75 m-thick horizontally elongated, para-orthogonal networks. The networks are associated with syngenetic frost cracks below and cryoturbations above them, close to the Bølling organic horizon (Kozarski et al. 1988; Fig. 4), and resemble reticulate ice-vein networks described from present-day permafrost regions (Harry 1988).

Such features also appear below a former active layer in glaciofluvial deposits of the Poznan phase outwash plain near Granowo. In a sand and gravel pit, cryostructures are developed as a 1.5 to 2.0 m-thick layer that has a sharp contact with the overlying active layer deposits. Remarkably, the sharp contact coincides with a high (10 to 12%) concentration of $CaCO_3$. The cryostructured layer, as well as the topmost part of the fossil active layer, contain no $CaCO_3$ at all. Such a high calcium carbonate concentration in a Late Plenivistulian cryostructured layer (former permafrost table) seems to be the result of frost-related precipitation under periglacial conditions as discussed by Vogt (1991), since there is no other explanation for the presence of a horizontal $CaCO_3$ concentration in permeable glaciofluvial deposits, be it under cold to cool Late Vistulian or under temperate Holocene climatic conditions.

Table 1. Size and geometry of polygonal systems detected on aerial photographs and/or ground surfaces in NW Poland (sources: Kozarski 1971, 1974, Bogdanski & Kijowski 1990, new unpublished data).

Location	Polygonal area (km^2)	System geometry	Polygon diameter (m)	Deposit
Czarnów	–	pentagonal	5.84	till
Dormowo E	0.30	tetragonal	20–30*	glaciofluvial
Dormowo W	2.50	tetragonal	15.20*	sand and till
Grabianowo	0.10	tetragonal	3.95*	sandy till
Sulejewo	0.13	tetragonal to pentagonal	6.10*	sandy till
Włoszakowice	–	pentagonal	4.80*	till

* Mean value ($\bar{x}$).

Oriented icing depressions

When these Late Plenivistulian periglacial geomorphic features were found for the first time in NW Poland, they were described as 'oriented kettle holes' (Kozarski 1975). In present-day cold climatic conditions such structures were studied in Spitsbergen on the Gåsbreen outwash plain where icings frequently occur (Baranowski 1977, Cegla & Kozarski 1977). They appear also as buried relicts under glaciofluvial deposits on permafrost as well as in front of Pedersenbree (Kozarski 1975, Cegla & Kozarski 1977, Kozarski 1982, Åkerman 1987).

The new term 'oriented icing depressions' used in this paper instead of 'oriented kettle holes', is more informative because it relates to the ice-body that was originally buried under the glaciofluvial deposits.

In NW Poland, oriented icing depressions are present in all outwash plains connected with major ice-margins (Kozarski 1975), including that of the ice-sheet maximum extent (Leszno phase). They are organized along former drainage lines of braided channel patterns. Circular and mostly oval forms, 100 to 250 m in diameter and up to 5 m in depth, predominate over irregular shapes. The former always have long axes oriented parallel to the relevant drainage line.

Observations in Spitsbergen (Kozarski 1975, Cegla & Kozarski 1977) show that all buried icing relicts in glaciofluvial deposits occur on permafrost tables where they can survive for many decades (Kozarski 1982). This is important for a palaeoenvironmental interpretation and allows to use the oriented icing depressions found in NW Poland as indicators of Late Plenivistulian permafrost in the deglaciated area. The diagnostic significance of such depressions is borne out by their common occurrence with syngenetic ice-wedge casts in proximal parts of outwash plains (see Fig. 2).

Sand-wedge polygons in till plains

Contrary to outwash plains, where ice-wedge casts, frost cracks and oriented icing depressions are common, in till plains the only permafrost phenomena are sand wedges developed as polygonal systems. These wedges were observed in vertical sections in till pits and horizontally on the ground surface by boring and digging (Kozarski 1971, Nowaczyk 1972, Kozarski 1974, Goździk 1986). This approach allows the study of sand wedges on a small scale only. Over large areas, fossil polygonal systems are most efficiently mapped by means of aerial photographs (Svensson 1973, 1982a, 1988, Hassenpflug 1988, Bogdański & Kijowski 1990).

Different observation techniques show that in NW Poland sand wedges occur in all till plains between major ice-sheet margins (Fig. 1). Usually they are not found to the north of the Pomeranian ice-margin (Fig. 1). Blume et al. (1979) suggested that this line should be the ultimate northern limit of sand-wedge occurrences. This view, however, seems too extreme as Goździk (1986) demonstrated the sporadical presence of sand wedges and frost cracks in Pomeranian tills in Poland. It means that the Pomeranian ice-sheet margin is very important in palaeoenvironmental terms as in the deglaciated area to the north of it the frequency of sand wedges strongly decreases (Goździk 1986 and Fig. 1). The significance of this limit with respect to origin and distribution of fossil frost fissures has been recognized very early (Dylik & Maarleveld 1967) and is confirmed by new data (Böse 1991).

Geometry

Sand-wedge polygons analysed in smaller and larger areas in NW Poland belong to tetragonal and pentagonal systems. Those previously (Kozarski 1974) and newly observed are mostly pentagonal systems. Polygons detected on aerial phtographs (Bogdański & Kijowski 1990; Fig. 5) are developed in both systems, either clearly tetragonal or at least partly orthogonal (Lachenbruch 1962) to pentagonal (Figs 5, 6). The diameters of sand-wedge polygons are summarized in Table 1. As a rule, polygons are greater in sandy tills. The data corroborate an old observation by Dylik & Maarleveld (1967) that polygons on an average are smaller in tills (< 7 m) and larger in sands (mostly 10 to 20 m).

A relation between polygonal systems and sedimentary material has been postulated by Lachenbruch (1962). According to this author material homogeneity favours the development of a non-orthogonal system. Inhomogeneity, on the other hand, enhances the formation of orthogonal systems. Such a relationship was not found for the sites discussed in this paper (Table 1), since tetragonal to random orthogonal systems have been found in both glaciofluvial sands and sandy tills (Dormowo, Grabianowo, Sulejewo) as well as in very homogeneous, fine to medium-grained sands (Nowaczyk 1988), while pentagonal, i.e. non-orthogonal systems were observed in inhomogeneous deposits like tills (Czarnów, Wloszakowice).

Sand-wedge infillings

Sand-wedge polygons observed in vertical sections vary in shape. Most of them reveal, close to the ground surface, a 0.5 to 0.7 m-wide pocket-like structure which at a depth of 0.3 to 0.9 m changes into a more or less regular wedge that ends as a crack at the very bottom (Fig. 7). The longest sand wedges found until now in NW Poland are 2.0 to 2.8 m long. The topmost pocket-like sand-wedge widenings developed in former active layers (Ko-

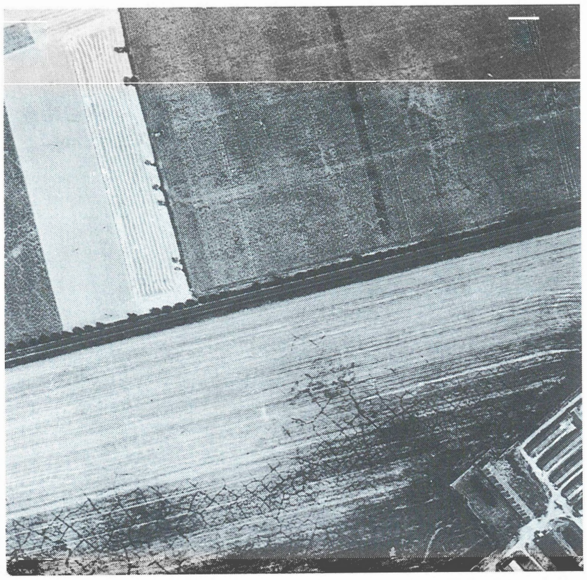

Fig. 5. Grabianowo. Aerial photograph of a tetragonal system of sand-wedge polygons. Note two frost-fissure generations. (Phot. A. Kijowski, July 27, 1983.)

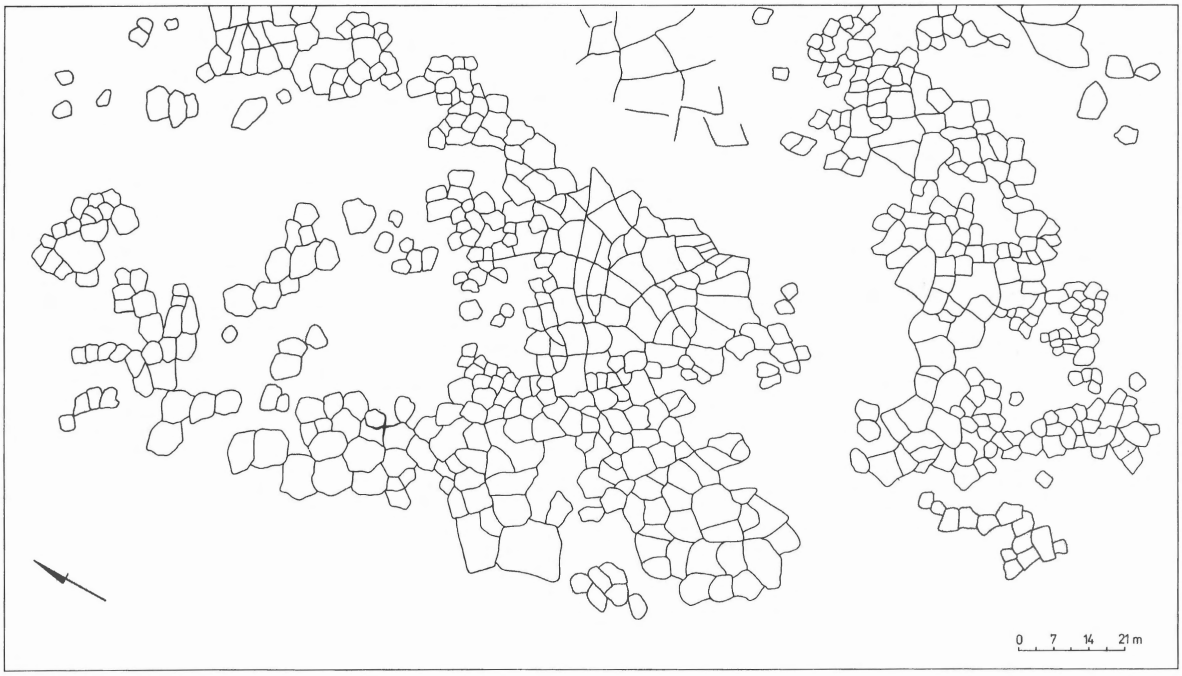

Fig. 6. Sulejewo. Random orthogonal to non-orthogonal sand-wedge systems. (Drawing after aerial photograph by A. Kijowski, June 30, 1983.)

Fig. 7. Kaszczor. Sand wedge in Upper Plenivistulian till (Leszno phase). (Phot. S. Kozarski.)

zarski 1971, 1974). Apart from the shape, this is also proved by the pebble content in the top of the sand-wedge infilling which should be due to material mixing during freezing and subsequent permafrost degradation.

As a rule, the sand wedges are filled with well sorted sands. Among them fine sand prevails (51.0–66.3%), with a significant (22.9–37.0%) medium-sand admixture (Table 2). The mean value ($\bar{x}$ = 58.6%) of the fine sand fraction in sand-wedge infillings is lower than in dune sands ($\bar{x}$ = 71.5%), but histograms of both of them show a very well-pronounced mode (0.125–0.5 mm), represented by mean values ($\bar{x}$) of 88.5% and 94.9%, respectively. This similarity seems to indicate aeolian transport before the sand grains were trapped by open, dry

Table 2. Grain-size distribution of sand-wedge infillings and dune sands in NW Poland (in %).

	Particle size in mm					
	< 0.125	0.125–0.25	0.25–0.5	0.5–0.8	0.8–1.0	> 1.0
Sand wedges						
Czarnów	18.42	37.61	31.28	6.13	2.56	4.0
Grabianowo	21.95	43.35	22.90	4.70	2.50	4.6
Sulejewo	16.25	38.42	33.85	6.36	1.92	3.2
Poznań	30.26	36.07	23.45	6.80	1.62	1.8
Włoszakowice	7.0	44.00	37.00	6.00	2.00	4.0
Dune sands						
Czarnków	5.69	37.67	54.73	1.59	0.2	0.1
Budzyń	7.30	47.60	25.10	4.70	4.1	1.9
Grodzewo	18.70	73.40	7.20	0.40	0.2	0.1
Zabinko	36.60	50.70	11.40	0.80	0.4	0.1
Łaki Pyzdrskie	12.70	70.30	15.30	1.20	0.4	0.1

frost cracks during sand-wedge formation. The process of trapping in narrow elementary cracks is recorded in middle segments of some fossil and modern sand-wedge infillings by a very delicate vertical lamination (cf. Black 1976, Kolstrup 1986, 1987, Harry & Goździk 1988, Dijkmans 1989, Nissen & Mears 1990).

In the discussion about the source of sand infillings another parameter is important too, viz. the quartz grain abrasion index (Kozarski 1971, 1974) which shows that the well-rounded quartz grain content of the sand-wedge infillings differs from that of the host material (Table 3). Such results are also known from the North Polish Plain (Goździk 1986), from the Wyoming Basin, USA (Nissen & Mears 1990) and from Denmark (Kolstrup 1987).

Occasionally, sand wedges have been found in dunes (Stankowski 1963, Kozarski et al. 1982). The aeolian source of its infilling is unquestionable because no other material is available. The best-shaped sand wedges in dunes were studied in Sokolowo Budzyńskie (Kozarski et al. 1982): they are only up to 1 m long and 0.04 to 0.2 m wide. The contact of the wedges with the laminated dune sand is distinct because the infilling consists of structureless sand. In the investigated Late Vistulian and Holocene dune sequence, the sand wedges appear in the lower dune sand deposited during the Older Dryas; they are covered with a radiocarbon-dated Allerød soil (Gd-375: 11 400 ± 320 BP; Kozarski et al. 1982).

Epigenetic and syngenetic ice-wedge casts in fluvial deposits

Previous studies (Kozarski 1971, 1974) and recent research show that both epigenetic and syngenetic ice-wedge casts are less common in fluvial deposits of river terraces than in glaciofluvial deposits of outwash plains. These casts are developed as 1.2 to 3.2 m-long structures of secondary infilling associated in many sequences with frost cracks spread over various sedimentary units. Syngenetic ice-wedge casts are longer and their shape reveals a multi-level growth in gradually accumulated fluvio-periglacial sands and gravels.

Table 3. Well-rounded quartz-grain (∅ 0.8–1.0 mm) content (%) in till and sand-wedge infillings in NW Poland (sources: Kozarski 1971, Nowaczyk 1972, new unpublished data).

Location	Till	Sand-wedge infilling
Czarnów	7.9	17.5–19.0 $\bar{x}$ = 18.0
Poznań	7.0	8.0–12.0 $\bar{x}$ = 9.0
Włoszakowice	7.9	16.7–20.7 $\bar{x}$ = 18.4

Ice-wedge casts of both types contain in their upper part a strongly mixed infilling from above whereas on the sides a zone of gravitational disturbance is manifested by small faults and flexures in the adjacent host material. The multi-level, faulted host material of syngenetic ice-wedge casts is usually widest in its uppermost part. This suggests that the final stage of ice-wedge growth was the most efficient because of 1) the ceased fluvial accumulation and 2) the longest period of frost cracking of the permafrost which aggraded during deposition. To the latter suggestion contribute also the wide uppermost parts of epigenetic ice-wedge casts found on river terraces. Altogether, they give information about the stabilization of the former valley floor before a new phase of vertical incision and terrace formation.

Epigenetic and syngenetic ice-wedge casts occur in terraces of different age. The oldest syngenetic ice-wedge casts were found in the Poznan-phase terrace of the Warsaw-Berlin pradolina (Nowaczyk 1988). The younger ones are known from the Pomeranian terrace and from the Late Vistulian terrace system; they formed during the Oldest Dryas and Older Dryas in the Warsaw-Berlin and Toruń-Eberswalde pradolinas, including the Odra river and Warta river-gap valleys between them.

Chronostratigraphy of periglacial phenomena and palaeoenvironmental implications

The relative age and chronostratigraphy of permafrost-diagnostic periglacial features are summarized in Table 4. As a comment to this table it must be stressed that: 1) the beginning of Late Plenivistulian permafrost aggradation coincided with the formation of outwash plains in the foreland of the ice-sheet when it had reached its greatest extent, 2) the permafrost aggradation in the last deglaciation area was continuous until the Oldest Dryas, 3) permafrost presumably survived the Bølling climatic amelioration, at least on abandoned valley floors (Kozarski 1991), 4) after 12 ka BP evidence exists only for Older Dryas formation of epigenetic ice-wedge casts and sand wedges, 5) up to now cold-climate thermal contraction cracking features from the Younger Dryas have not been found in NW Poland; this is a puzzling problem, since usually the Younger Dryas is considered as a cold spell of rather intensive thermal-contraction cracking, formation of the

Table 4. Chronostratigraphy and geomorphic occurrence of Late Plenivistulian and Late Vistulian permafrost indicators in NW Poland.

Chronostratigraphy	14C age ka BP	Structures	Geomorphic occurrence	Landforms
Late Vistulian				
Younger Dryas	10			
Allerød	11			
Oldest Dryas	11.8	Epigenetic ice-wedge casts and sand wedges	Alluvial fans and dunes	
Bølling	12			
Oldest Dryas	13	Epigenetic and syngenetic ice-wedge casts, frost cracks, cryostructures	River terraces and alluvial fans	
Late Plenivistulian				
Pomeranian phase	15.2	Epigenetic and syngenetic ice-wedge casts, frost cracks	Outwash plains and river terraces	
		Sand wedges	Till plains	Oriented icing
Chodziez subphase	17.2	Epigenetic ice-wedge casts	River terraces	depressions in outwash
Poznań phase	18.4	Epigenetic and syngenetic ice-wedge casts, frost cracks, cryostructures	Outwash plains and river terraces	plains
		Sand wedges	Till plains	
Leszno phase (= ice sheet max.)	20	Epigenetic and syngenetic ice-wedge casts, frost cracks	Outwash plains	

youngest polygonal ice-wedge cast systems in Scandinavia and widespread occurrence of frost fissures between the Rhine and Elbe (Svensson 1973, Maarleveld 1976, Svensson 1982b, 1988, 1990, Böse 1991).

The existence of polygonal ice-wedge and sand-wedge systems in areas of up to 2.5 km^2 or more, their distribution among various landforms, and the long time (ca. 7000 years) of permafrost aggradation, suggest a continuous permafrost formation or, at least, vast permafrost patches to the south of the Pomeranian ice-sheet margin. This is supported by the observation (Bogdański & Kijowski 1990) that on aerial photographs (Fig. 5) the random orthogonal sand-wedge polygons reveal two distinct frost fissure systems with variable size. According to the theory of Lachenbruch (1962) these systems did not form simultaneously. Following the theory of Dostovalov (1960) they belong to different generations. It must be added, however, that the younger, smaller frost-fissure generation represents climatic deterioration, since to account for inner cracking of polygonal blocks (Lachenbruch 1962) and increase of horizontal thermal stress at the ground surface is necessary. Additional evidence for extensive permafrost is provided by the frequent occurrence of secondary, smaller frost fissures in ice-wedge cast polygonal systems of the first order studied in several fluvioglacial and fluvioperiglacial sequences (e.g. Kozarski 1971, 1974, Kasprzak & Kozarski 1984, Kasprzak, pers. comm.).

The still growing number of newly found sites with permafrost-diagnostic features, their wide geomorphic distribution and the long time of permafrost aggradation suggest a continuous permafrost in NW Poland gradually expanding within the last deglaciation area during the Late Plenivistulian and Late Vistulian to the south of the Pomeranian ice-sheet margins, i.e. in the period between ca. 20 ka and 13 ka BP. To the north of this line a discontinuous permafrost probably developed. The latter type is recorded by a strongly decreased number of sand wedges and/or frost fissures with primary sand infilling (Goździk 1986), as well as by local occurrence of sand wedges (Kozarski et al. 1982, Nowaczyk 1988) in Late Vistulian deposits without any relationship to the ice-sheet margin. Cryostructures, syngenetic ice-wedge casts and frost cracks in permeable deposits (fine gravels and sands), immediately beneath lacustrine sediments of Bølling age, also suggest that permafrost, at least locally, survived this interstadial warming (Kozarski 1991). Otherwise it would be difficult to explain the persistence of a shallow lake on unconsolidated sediments at a low ground water level.

In palaeoenvironmental reconstructions of Plenivistulian periglacial regions, mean annual air temperatures (MAAT), mean temperature of the coldest month (T_c) and mean annual precipitation (MAP) usually are estimated on the basis of permafrost-diagnostic structures such as ice-wedge casts and sand wedges. Less attention has been paid to mean annual ground temperatures (MAGT), which at the depth of no annual change must have been below – 5° C or below – 2° C, and to rapid drops in temperature generating thermal contraction cracking of permafrost (Romanovskii 1973, Black 1976, Washburn 1979/80). In estimates, the environmental conditions of ice-wedge growth and sand-wedge formation in modern permafrost regions are taken as analogues. For this reason MAAT should have been less than – 4° C or – 8° C during ice-wedge growth in polygonal systems and less than – 12° C or – 20° C during sand-wedge development, T_c of the order of – 18 to – 20° C or below and MAP over 50 to 500 mm in areas with ice-wedges or less than 100 mm in areas with sand wedges (Maarleveld 1976, Karte 1979, Washburn 1979/80, Karte 1981, 1983, Kolstrup 1986).

However, Harry & Goździk (1988, p. 53) are of the opinion that '. . . the relationship between mean annual air or ground temperature and active wedge growth remains uncertain' because data from Alaska, North Canada and Siberia show a wide range of mean annual air and ground temperatures below 0° C at which these features grow. This opinion has been confirmed by Burn (1990) after detailed studies of ice-wedge development near Mayo, Yukon Territory, Canada. Therefore one has to be cautious in estimating mean annual air and ground palaeotemperatures for Late Plenivistulian permafrost regions.

In spite of the uncertainty in MAAT and MAGT estimates the existing data allow to infer the approximate thermal conditions generating ice-wedge growth and sand-wedge formation in polygonal systems. Regions in which such processes have been active for long periods have the following thermal characteristics:

1. The MAAT and MAGT must have been at least – 1° C to – 2° C.
2. The air-ground temperature gradients of the period (early winter) of thermal contraction must have been very high, and cooling at low temperatures rapid. This follows both from theoretical studies and present-day observations that have revealed ground cracking at abrupt temperature decreases from – 24° C to – 43° C in 18 hours (Lachenbruch 1962, Dylik & Maarleveld 1976).
3. In polygonal systems that consist of several frost-fissure generations, temperature gradients as well as severity of climate must have increased during development.

With slight variations in intensity, the above thermal conditions must have existed in the periglacial domain of NW Poland during the timespan from 20 to 13.2 ka BP.

In periglacial palaeoenvironmental research, sand wedges are used not only for palaeotemperature reconstruction but also for inferences on edaphic conditions, ground surface instability, continentality of climate and mean annual precipitation (Kozarski 1971, 1974, Karte 1979, 1981, 1983, Kolstrup 1986, Böse 1991). Most appropriate for NW Poland seem to be inferences on ground surface instability and snow cover. Kozarski (1986) made reference to the lack of organic sediments in the deglaciation area of the North Polish Plain from ca. 20 to 14.5 ka BP. With regard to the palaeoenvironmental conditions during this time, this implies that the ground surface was free of vegetation and easily affected by geomorphic processes including wind transport of sand grains which were subsequently trapped by open frost cracks. On lodgement till surfaces where most of the sand wedges were found, wind transport may have been particularly efficient in winter conditions because of sublimation on bare surfaces. Yet, the snow cover must have been thin or blown away during thermal contraction permafrost cracking, since it is well known (Lachenbruch 1962) that by growing thickness of winter snow the maximum winter cooling rates at the top of permafrost decrease. Decisive is, of course, rapid cooling which generates deep frost cracking.

It is difficult to conclude about climate continentality and its changes in local and, especially, in regional terms during sand-wedge formation because: 1) the precise age of sand wedges in relation to ice-wedge casts remains unknown, and 2) the limited number of rather poorly dated sand wedges and ice-wedge casts in the North European Plain does not provide a sufficient basis for large-scale comparisons in time and space.

Conclusions

The cryostratigraphic record in NW Poland provides evidence for a great variety of periglacial phenomena which indicate permafrost formation and aggradation during the last deglaciation period. Geomorphic and stratigraphic distribution of thermal contraction features seem to testify to the existence of continuous permafrost to the south of the Pomeranian ice-sheet margin. Permafrost developed in this deglaciated area during the Late Plenivistulian and during cold spells of the Late Vistulian. Because of the drastic decrease in permafrost-diagnostic structures, it must be assumed that in the Late Vistulian deglaciation-area north of the Pomeranian ice-sheet margin, the permafrost was discontinuous only. This may have been due to the shorter time that was available for its development.

During deglaciation, from the ice-sheet maximum to the Pomeranian phase, major and minor ice-margin standstills coincided with periods of permafrost aggradation which are recorded in the first place by syngenetic ice-wedge casts and frost cracks in proximal parts of outwash plains. Permafrost aggradation at the ice-sheet margin was a very essential process in the formation and preservation of buried icing relicts, and in the generation of compressive ice flow at the ice-sheet front. Allochthonous flow tills either covering proximal parts of the outwash plains or interfingering with fluvioglacial deposits are convincing arguments for a steady-state flow of the ice.

Epigenetic development of sand-wedge polygons on till plains shows that these depositional landforms became ice-free at an early stage of deglaciation. The processes of deglaciation were mostly frontal and along with sand-wedge polygon formation, they contradict the assumption that wastage of the last ice-sheet should have been of the areal type.

In spite of a general change in climate which in North Poland resulted in ice-sheet recession, conditions during deglaciation were still severe as permafrost developed in deglaciated areas. Thus, there was no climatic jump after the ice-sheet maximum such as postulated in older models involving areal ice-sheet wastage but rather a gradual change of climate from glacial to periglacial. The latter type of climate can be characterized by MAATs and MAGTs estimated at – 1 to – 2° C, by a low coldest-month mean temperature (T_c) and particularly by abrupt temperature drops in early winter and high air-ground temperature gradients at low temperature ranges.

As yet, there are no convincing permafrost-related data available for a serious discussion on continentality of climate in the expanding late Late Plenivistulian periglacial realm. Sand wedges on till plains, often used in such discussions, are not a good argument for dry climatic conditions until the age relationship between the sand wedges and ice-wedge casts has been established. If both types of wedge structure originated at the same time, then sand wedges on till plains may inform us only about local ground-moisture conditions during frost-fissure development, i.e. about the lack of free water, existing in the active layer on fluvioglacial and fluvioperiglacial deposits, and causing the ice-wedges to grow in the top of the permafrost.

Acknowledgements

This study was sponsored by the State Committee for Scientific Research, grant no. 6 0318 91 01. I am grateful to Prof. B. Nowaczyk and Dr. L. Kasprzak for providing unpublished data on periglacial features. I am also indebted to Professor J. Rose (London) for terminological discussion and to Dr. A. Kijowski for valuable discussions and for photographs of sandwedge polygonal systems in Grabianowo and Sulejewo. To Mgr. W. Rosik thanks are due for the drawing of Figs 4 and 6 and to Mrs. B. Gruszecka for typing the manuscript.

References

Åkerman, J. 1987 Periglacial forms of Svalbard: a review. In: J. Boardman (ed.): Periglacial Processes and Landforms in Britain and Ireland – Cambridge Univ. Press, Cambridge: 9–25

Baranowski, S. 1977 Naled type of ice in front of some Spitsbergen glaciers – Acta Univ. Wratislaviensis 387, Spitsbergen Expeditions II: 85–89

Bartkowski, T. 1967 Deglacjacja strefowa deglacjacją normalną na obszarach nizowych, na wybranych przykladach z Polski zachodniej (Zusammenfassung: Zonaler Eisabbau – ein 'normaler' Eisabbau des Tieflandsgebietes, erlautert an Beispielen aus West- und Nordpolen) – Badania Fizjograficzne nad Polską Zachodnią, Ser. A. Geogr. fiz.: 7–34

Black, R.F. 1976 Periglacial features indicative of permafrost: ice and soil wedges – Quat. Res. 6: 3–26

Blume, H.-P., R. Hoffmann & H.-J. Pachur 1979 Periglaziäre Steinring- und Frostkeilbildungen norddeutscher Parabraunerden – Zeitschr. f. Geomorph. N.F., Supplementband 33: 257–265

Bogdanski, P. & A. Kijowski 1990 Photointerpretation of geometry of Vistulian ice-wedge polygons: the Grabianowo and Sulejewo sites, south of Poznan – Quaestiones Geographicae 11/12 (1985/1986): 39–52

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 – Zeitschr. f. Geomorph. N.F. Suppl.-Bd. 90: 15–28

Büdel, J. 1944 Die morphologischen Wirkungen des Eiszeitklimas im gletscherfreien Gebiet – Geol. Rundsch. 34 (7/8): 482–519

Büdel, J. 1950 Die Klimazonen des Eiszeitalters – Eisz. u. Gegenw. 1: 16–26

Burn, C.R. 1990 Implications for palaeoenvironmental reconstruction of recent ice-wedge development at Mayo, Yukon territory – Permafrost and Periglacial Processes 1 (1): 3–14

Cegla, J. & S. Kozarski 1977 Sedimentary and geomorphological consequences of the occurrence of naled sheets of the outwash plain of the Gas Glacier, Sorkappland, Spitsbergen – Acta Univ. Wratislaviensis 387, Spitsbergen Expeditions II: 63–84

Dijkmans, J.W.A. 1989 Frost wedges in an aeolian sand sheet near Søndre Strømfjord, W. Greenland and their palaeoenvironmental implications – Zeitschr. f. Geomorph. N.F. 33 (3): 339–353

Dostovalov, B.N. 1960 Zakonomernosti razvitya tetragonalnyh system ledyanyh i gruntovyh zil. In: K.K. Markov & A.I. Popov (eds): Periglatsyalnye yavlenya na territori SSSR lzd – Moskovskovo Univ., Moskva: 37–65

Dücker, A. 1954 Die Periglazial-Erscheinungen im holsteinischen Pleistozän – Göttinger Geogr. Abh. 16 (Studien über Periglazial-Erscheinungen in Mitteleuropa, Teil III Studien aus dem Norddeutschen Tiefland): 5–54

Dylik, J. 1956 Coup d'oeil sur la Pologne periglaciaire – Biul. Perygl. 4: 185–238

Dylik, J. & G.C. Maarleveld 1967 Frost cracks, frost fissures and related polygons – Meded. Geol. Sticht. N.S. 18: 7–21

Gozdzik, J. 1986 Structures de fentes à remplissage primaire sableux du Vistulien en Pologne et leur importance paléogéographique – Biul. Perygl. 31: 71–105

Harry, D.G. 1988 Ground ice and permafrost. In: M.J. Clark (ed.): Advances in Periglacial Geomorphology – J. Wiley & Sons, Chichester: 113–149

Harry, D.G. & J. Gozdzik 1988 Ice-wedges: growth, thaw transformation, and palaeoenvironmental significance – Journ. Quat. Sci. 3 (1): 39–55

Hassenpflug, W. 1988 Polygonmuster auf der Schleswiger Geest – Geogr. Rundschau 40 (5): 27–32

Karte, J. 1979 Räumliche Abgrenzung und regionale Differenzierung des Periglaziärs – Bochumer Geogr. Arb. 5: 211 pp

Karte, J. 1981 Zur Rekonstruktion des weichselhochglazialen Dauerfrostbodens im westlichen Mitteleuropa – Bochumer Geogr. Arb. 40: 59–71

Karte, J. 1983 Periglacial phenomena and their significance as climatic and edaphic indicators – GeoJournal 7 (4): 329–340

Karte, J. 1987 Pleistocene periglacial conditions and geomorphology in north central Europe. In: J. Boardman (ed.): Periglacial Processes and Landforms in Britain and Ireland – Cambridge Univ. Press, Cambridge: 67–75

Kasprzak, L. 1985 A model of push moraine development in the marginal zone of the Leszno phase, west central Poland – Quaternary Stud. in Poland 6: 23–54

Kasprzak, L. 1988 Dyferencjacja mechanizmow formowania stref marginalnych faz leszczynskiej i poznanskiej ostatniego zlodowacenia na Nizinie Wielkoplskiej (Summary: Mechanism differentiation in the formation of marginal zones, Leszno and Poznan phases of the last glaciation, Great Poland Lowland) – Dokumentacja Geograficzna 5–6, Inst. Geogr. i Przestrz. Zagosp. PAN, Wroclaw-Warszawa, 159 pp

Kasprzak, L. & S. Kozarski 1984 Analiza facjalna osadow strefy marginalnej fazy poznanskiej ostatniego zlodowacenia w środkowej Wielkoplsce (Summary: Facies analysis of marginal zone deposits produced by the Poznań phase of the last glaciation in Middle Great Poland) – Univ. A. Mickiewicza, Wyd. Nauk., Geografia 29, 54 pp

Kasprzak, L. & S. Kozarski 1989 Ice-lobe contact sedimentary scarps in marginal zones of the major Vistulian ice-sheet positions, West Central Poland – Quaestiones Geographicae, Spec. Iss. 2: 69–81

Kliewe, H. 1968 Periglazialphänomene im Spätglazialgebiet der Weichselvereisung – Przegląd Geograficzny 40 (2): 351–362

Kolstrup, E. 1980 Climate and stratigraphy in northwestern Europe between 30,000 B.P. and 13,000 B.P. with special reference to The Netherlands – Meded. Rijks Geol. Dienst 32-15: 181–253

Kolstrup, E. 1986 Reappraisal of the Upper Weichselian periglacial environment from Danish frost wedge casts – Palaeogeogr., Palaeoclimatol., Palaeoecol. 56: 237–249

Kolstrup, E. 1987 Frost wedge casts in western Jutland and their possible implications for European periglacial research – Zeitschr. f. Geomorph. N.F. 31 (4): 449–461

Kozarski, S. 1962 Recesja ostatniego ladolodu z północnej części Wysoczyzny Gnieznieńskiej a ksztaltowanie sie pradoliny Noteci Warty (Summary: Recession of last ice sheet from northern part of Gniezno Pleistocene Plateau and formation of the ice-marginal valley of the rivers Notec-Warta) – Prace Komisji Geogr.-Geol. 2 (3), Pozn. Tow. Przyj. Nauk, Poznan, 154 pp

Kozarski, S. 1965 Zagadnienie drogi odplywu wod pradolinnych z zachodniej częsci pradoliny Noteci-Warty (Summary: The problem of outflow way of pradolina waters from the west part of NotecWarta pradolina) – Prace Komisji Geogr.-Geol. 5 (1), Pozn. Tow. Przyj. Nauk, Poznan, 98 pp

Kozarski, S. 1971 Slady dzialalnosci poznowürmskich procesow peryglacjalnych w regionie dolnej Odry i dolnej Warty (Summary: Traces of the activity of Late Würm periglacial processes in the Lower Odra and Lower Warta region) – Badania Fizjograficzne nad Polską Zachodnią 24, Ser. A. Geogr. fiz.: 97–177

Kozarski, S. 1974 Evidences of Late Würm permafrost occurrence in north-west Poland – Quaestiones Geographicae I: 65–86

Kozarski, S. 1975 Oriented kettle holes in outwash plains – Quaestiones Geographicae 2: 99–112

Kozarski, S. 1978 Lithologie und Genese der Endmoränen im Gebiet der skandinavischen Vereisungen – Schriftenreihe f. Geol. Wissensch. 9: 179–200

Kozarski, S. 1980 An outline of Vistulian stratigraphy and chronology of the Great Poland Lowland – Quaternary Studies in Poland 2: 21–35

Kozarski, S. 1981 Ablation end moraines in western Pomerania, NW Poland – Geogr. Ann. 63A (3–4): 169–174

Kozarski, S. 1982 The genetic variety of ice cores in the marginal forms of some Spitsbergen glaciers, Hornsund Region – Acta Univ. Wratislavensis 525, Spitsbergen Expeditions: 153–164

Kozarski, S. 1986 Skale czasu a rytm zdarzen geomorfologicznych vistulianu na Nizu Polskim (Summary: Time scales and the rhythm of Vistulian geomorphic events in the Polish Lowland) – Czasopismo Geograficzne 57 (2): 247–270

Kozarski, S. 1988 Time and dynamics of the last Scandinavian ice-sheet retreat from northwestern Poland – Geographia Polonica 55: 91–101

Kozarski, S. 1991a Warta – A case study of a lowland river. In: L. Starkel, K.L. Gregory & J. Thornes (eds): Temperate Palaeohydrology – John Wiley & Sons Ltd., Chichester: 189–215

Kozarski, S. 1991b Palaeogeografia Polski w vistulianie. In: L. Starkel (ed.): Geografia Polski, srodowisko przyrodnicze – Wyd. Nauk. PWN, Warszawa: 80–105

Kozarski, S. & L. Kasprzak 1987 Facies analysis and depositional models of Vistulian ice-marginal features in northwestern Poland. In: V. Gardiner (ed.): International Geomorphology 1986 Part II – J. Wiley & Sons Ltd., Chichester: 693–710

Kozarski, S. & L. Kasprzak 1992 Glacidynamometamorfoza osadów nieskonsolidowanych w makro- i mezoglacitektonitach Niziny Wielkopolskiej. (Summary: Dislocation glaciometamorphism of unlithified deposits in macro- and mesoglaciotectonites of the Great Poland Lowland) – Przegląd Geograficzny 49 (1–2): 95–119

Kozarski, S., A. Mocek, B. Nowaczyk & K. Tobolski 1982 Etapy i warunki rozwoju wydm w Budzyniu kolo Chodziezy w swietle analizy radioweglowej, paleobotanicznej i pedologicznej (Summary: Development stages and conditions of the dune at Budzyn near Chodziez in the light of radiocarbon, palaeobotanical and pedologic analyses) – Roczniki Gleboznawcze 23 (3–4): 159–174

Kozarski, S., P. Gonera & B. Antczak 1988 Valley floor development and palaeohydrological changes: the Late Vistulian and Holocene history of the Warta river (Poland). In: G. Lang & Ch. Schlüchter (eds): Lake, Mire and River Environments – A.A. Balkema, Rotterdam: 185–203

Krygowski, B. 1964 Graniformametria mechaniczna, teoria, zastosowanie (Zusammenfassung: Die mechanische Graniformametrie, Theorie, Anwendung) – Prace Komisji Geogr.-Geol. 2 (4) Pozn. Tow. Przyj. Nauk, Poznan, 112 pp

Lachenbruch, A.H. 1962 Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost – Geol. Soc. America Special Papers 70, New York, 69 pp

Lembke, H. 1954 Die Periglazial-Erscheinungen im Jungmoränengebiet westlich des Oder-Bruchs bei Freienwalde – Göttinger Geogr. Abh. 16 (Studien über Periglazial-Erscheinungen in Mitteleuropa, Teil III Studien aus dem Norddeutschen Tiefland): 55–96

Lembke, H., G. Altermann, G. Markuse & B. Nitz 1970 Die periglaziäre Fazies im Alt- und Jungmoränengebiet nördlich des Lössgürtels – Peterm. Mitteil. Erght. 274: 213–268

Liedtke, H. 1981 Die nordischen Vereisungen in Mitteleuropa, Forschungen zur deutschen Landeskunde 204, 2. erweiterte Auflage, Trier, 397 pp

Maarleveld, G.C. 1976 Periglacial phenomena and the mean annual temperature during the Last Glacial time in the Netherlands – Biul. Perygl. 26: 57–78

Nissen, T.C. & B. Mears Jr 1990 Late Pleistocene ice-wedge casts and sand-wedge relics in the Wyoming Basins, USA – Permafrost and Periglacial Processes 1 (3–4): 201–219

Nowaczyk, B. 1972 Cechy granulometryczne osadow wypelniajacych struktury wielobokow szczelin mrozowych z pierwotnym wypelnieniem mineralnym w Poznaniu-Grunwaldzie (Summary: Granulometric features of sediments filling structures of sand-wedge polygons of frost cracks in Poznan-Grunwald) – Badania Fizjograficzne nad Polską Zachodnią 25, Ser. A Geogr. fiz.: 113–132

Nowaczyk, B. 1988 Wiek i warunki sedymentacji stozkow naplywowych w zachodniej części pradoliny Warszawsko-Berlinskiej. In: A. Kostrzewski (ed.): Geneza, litologia i stratygrafia utworow czwartorzedowych, Univ im. A. Mickiewicza, Ser. Geografia 50: 153–178

Pierzchalko, L. 1956 Periglacial phenomena in northern Poland – Biul. Perygl. 4: 415–427

Poser, H. 1948 Boden und Klimaverhältnisse in Mittel- und West-Europa während der Würmeiszeit – Erdkunde 2 (1–3): 53–68

Romanovskij, N.N. 1973 Regularities in the formation of frost-fissures and development of frost-fissure polygons – Biul. Perygl. 23: 237–277

Rotnicki, K. & R.K. Borowka 1991 Dating of the last Scandinavian ice sheet in the Polish Plain. In: Abstracts XIII Intern. INQUA Congress 2–9 Aug. 1991, Beijing, China: 309 pp

Stankowski, W. 1963 Rzezba eoliczna Polski polnocno-zachodniej na podstawie wybranych obszarow (Summary: Eolian relief of Northwest Poland on the ground of chosen regions) – Prace Komisji Geogr.-Geol. 4 (I), Pozn. Tow. Przyj. Nauk, Poznan, 147 pp

Svensson, H. 1973 Distribution and chronology of relict polygon patterns on the Laholm Plain, the Swedish west coast – Geogr. Ann. Ser. A 55 (3–4): 159–175

Svensson, H. 1982a The use of aerial photographs and remote sensing techniques in research of fossil periglacial features – Biul. Perygl. 29: 129–138

Svensson, H. 1982b A low-lying polygon locality on the Laholm plain, Swedish west coast – Geol. Forenin. Stockholm Forhandl. 104: 69–73

Svensson, H. 1988 Ice-wedge casts and relict polygonal patterns in Scandinavia – Journ. Quat. Sci. 3 (1): 57–67

Svensson, H. 1990 Relict periglacial structures, occurrences, age and development in different matrices on a coastal plain of southwestern Sweden – Geogr. Ann. 72A (1): 79–91

Troll, C. 1948 Der subnivale oder periglaziale Zyklus der Denudation – Erdkunde 2 (1–3): 1–21

Vogt, T. 1990 Cryogenic physico-chemical precipitations: iron, silica, carbonate – Permafrost and Periglacial Processes 1 (3–4): 283–293

Washburn, A.L. 1979/80 Permafrost features as evidence of climatic change – Earth Sci. Rev. 15: 327–402