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Ice sheet maximum limit of the Vistulian Glaciation in the mid-eastern Chełmno–Dobrzyń Lakeland, northern Poland

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The maximum extent of the Vistulian Glaciation in the mid-eastern Chełmno–Dobrzyń Lakeland fell on the Maximum Phase of the Main Substage (*ca.* 20–18 ka BP). Geomorphologic and sedimentologic record of this phase combines a separate horizon of a lodgement till and associated glaciotectonites, a broad higher level of the Dobrzyń sandur, hills and ridges of end moraines, a push moraine ridge, tunnel valleys, as well as melt-out tills and sands with boulders. The ice sheet maximum limit is marked by a sedimentary scarp to the south of Bryńsk, a morphologic scarp within a higher level of the Dobrzyń sandur to the south of Lidzbark Welski, and a morainic hill to the south-east of Koszelewy. Two glacial lobes became distinct within the ice sheet during the maximum phase: the Bryńsk lobe in the west (unfrozen to the bed, with its ice front in steady-state conditions), and the Lidzbark Welski lobe in the east (with complex thermal conditions). A well-developed subglacial drainage system was active within the Bryńsk ice lobe, with meltwaters runoff along the glacial tunnel valleys of the Lake Bryńsk and the Lake Lidzbark. At the maximum extent, the Lidzbark Welski lobe was in the steady-state conditions, similarly to the Bryńsk lobe, and the higher level of the Dobrzyń sandur was formed to the south of Lidzbark Welski. To the south of Koszelewy, short ice-marginal fans were formed. A minor oscillation of the ice front and development of a push moraine occurred in the western part of the Lidzbark Welski ice lobe.

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INTRODUCTION

So far, the ice sheet maximum limit of the Vistulian Glaciation in the Chełmno–Dobrzyń Lakeland has been frequently based on a general geomorphologic analysis, which was not supported by a more detailed field research. Hence, relatively big discrepancies were perceived (see L. Marks, 1984; W. Wysota, 1992).

Marginal landforms of the ice sheet maximum extent in the study area were commonly accepted to have not been preserved (Fig. 1) due to destruction by outwash waters during deglaciation, or they were covered with glacial deposits in this time (R. Galon, 1957, 1961; R. Galon, L. Roszkówna, 1967; L. Roszko, 1968; R. Galon *et al.*, 1979). These assumptions were found, however, to be only partly correct (W. Niewiarowski, W. Wysota, 1994; W. Wysota, 1992, 1995*a*, 1998).

J. Kondracki (1952) defined the maximum limit of the last ice sheet in the southwestern Mazury Lakeland along the end moraines to the south of the line Lidzbark Welski–Dąbrówno. In his later paper he claimed that this marginal zone was formed during the Poznań Phase of the last glaciation (J. Kondracki, S. Pietkiewicz, 1967). Similar opinions were expressed, among others also by R. Galon (1957, 1961), R. Galon, L. Roszkówna (1967), L. Roszko (1968) and S. Z. Różycki (1972).

M. Liberacki (1961) postulated that a southern limit of the last glaciation was indicated by end moraines to the southwest of Górzno but he did not claimed, however, which phase they were referred to. The maximum limit of the last glaciation was defined relatively well by J. Kotarbiński (1972) who assumed it to be indicated by glacial tunnel valleys and kettles of the Poznań Phase of the Vistulian Glaciation, present on the Dobrzyń sandur in the vicinity of Górzno.

L. Marks (1984, 1988, 1991) was preoccupied too with a subject of the maximum limit of the last glaciation to the east of the presented area. He stated (L. Marks, 1984) a single ice sheet advance only during the Vistulian Glaciation, repre-

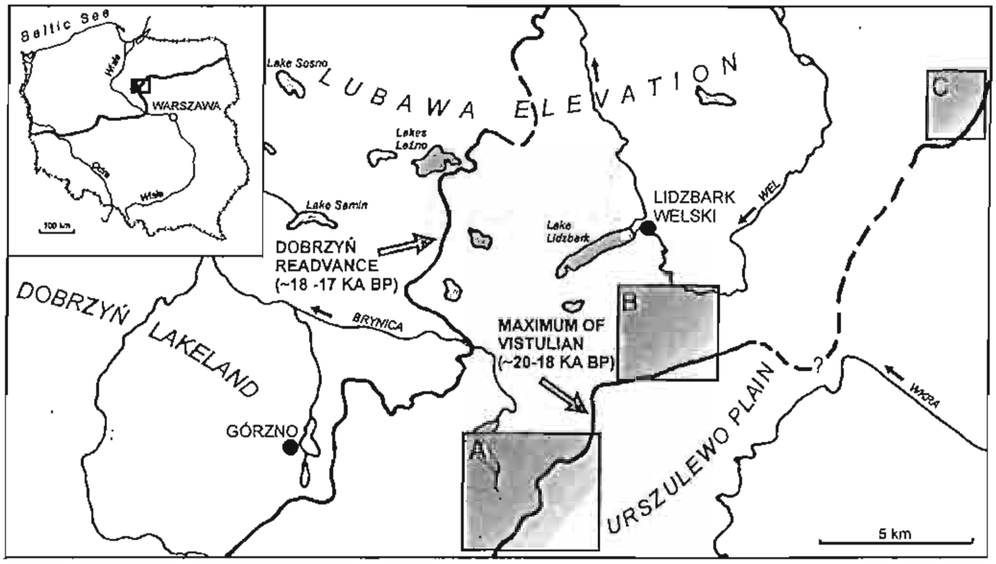


Fig. 1. Test areas: A — Bryńsk, B — Lidzbark Welski, C — Koszelewy

senting the Leszno and the Poznań Phases, and the maximum ice sheet limit to the south of Lidzbark Welski and Dąbrówno. In his later studies L. Marks (1988, 1991) postulated that the maximum limit of the Vistulian Glaciation in this region should not be connected with the Leszno and the Poznań Phases but with the preceding Świecie Substage. This view starts to be more popular (among others S. Lisicki, 1998), yet it is still too sparsely documented.

Geologic, geomorphologic, and sedimentologic research in the mid-eastern Chełmno–Dobrzyń Lakeland, conducted by the author in the last decade, enabled a relatively accurate determination of the limit of the last glaciation in this region (W. Wysota, 1992, 1995*a*, 1998). In this paper the geomorphologic and lithofacies record of glacial processes in the maximum extent zone of the Vistulian Glaciation is presented.

STRATIGRAPHY

Recent research (W. Wysota, 1998) indicated that during the Vistulian Glaciation there were three distinct ice sheet advances in the mid-eastern Chełmno–Dobrzyń Lakeland. The first one occurred during the Świecie Substage (around 60–50 ka BP) and two subsequent ones during the Main Substage, i.e. its maximum phase (around 20–18 ka BP) and the Dobrzyń Subphase (around 18–17 ka BP). All these advances are represented by distinct tills (Fig. 2).

During the Świecie Substage, a sedimentologic record of the ice sheet advance and retreat comprises a distinct basal till, as well as glaciofluvial, glaciolacustrine and gravity flow deposits, and also glaciotectonites (W. Wysota, 1992).

The ice sheet of the Vistulian Glaciation in the studied area was the most widespread during the Maximum Phase of the Main Substage (Figs. 1 and 2). The marginal zone of the Maximum Phase developed during a long-term standstill of the ice sheet front (with minor fluctuations), probably corresponding both to the Leszno and the Poznań Phases (W. Wysota, 1992; W. Niewiarowski, W. Wysota, 1994). Geomorphologic and sedimentologic record of the Vistulian Glaciation maximum limit comprises the following: (1) a lodgement till and associated glaciotectonites, (2) glacial tunnel valleys, (3) sedimentary scarp and a vast higher level of the Dobrzyń sandur, (4) depositional hills and ridges composed of glaciofluvial series with flow till interbeds, (5) a push moraine, and (6) melt-out sands with boulders, and flow till, sands and silts of kames formed during deglaciation.

During the Dobrzyń Subphase a readvance of the ice sheet was an important event in a deglaciation of this area (Figs. 1 and 2). Associated with this subphase are well-developed ice-marginal and subglacial features, and a distinct lodgement till (W. Niewiarowski *et al.*, 1995; W. Wysota, 1992, 1993, 1994, 1995*b*, 1998).

STUDY AREA

The study area is located in the mid-eastern Chełmno–Dobrzyń Lakeland (Fig. 1). It covers fragments of the Urszulewo Plain in the south, the Dobrzyń Lakeland in the centre and the west, and the Lubawa Elevation in the north and east. The Urszulewo Plain is composed of the vast Dobrzyń sandur with two levels: the higher formed during the Maximum Phase, and the lower corresponding to the Dobrzyń Subphase (W. Wysota, 1992; W. Niewiarowski, W. Wysota, 1994). The Dobrzyń Lakeland and the Lubawa Elevation comprise vast morainic elevations with numerous morainal features, kames and tunnel valleys. The maximum limit of the last ice sheet runs across a southeastern part of the studied area.

The maximum limit of the last ice sheet was examined in three test areas around Bryńsk, Lidzbark Welski and Koszelewy (Fig. 1), in which detailed geomorphologic and sedimentologic studies of the marginal zone were done. A research model was applied, based on analysis of lithofacies and landforms.

The following research methods were used: (1) detailed geomorphologic and geologic mapping in scales 1:25,000 and 1:10,000, (2) lithofacial analysis of the main sedimentary units, (3) palaeocurrents analysis, (4) analysis of glaciotectonic deformations, and (5) till fabric analysis. Special attention was paid to a distribution and lateral contacts of genetic types of landforms and lithofacial associations. Symbols by A. D. Miall (1977, 1978), with some modifications by T. Zieliński (1995), were used to coding the lithofacies.

ICE-MARGINAL LANDFORMS AND DEPOSITS

The maximum limit of the ice sheet of the Vistulian Glaciation is marked on a sedimentary scarp of a higher level of the Dobrzyń sandur to the south of Bryńsk, and the morphologic scarp to the south of Lidzbark Welski. These linear ice-marginal landforms precisely indicate a maximum limit of the ice sheet in this area. To the east of Lidzbark Welski, most ice-marginal features were destroyed by younger meltwater outflow during deglaciation. Rare ice-marginal depositional ridges and hills were retained near Koszelewy.

SEDIMENTARY SCARP AT BRYŃSK

Morphology. To the south and south-east of Bryńsk there is a vast area of the higher level of the Dobrzyń sandur (Fig. 3). It is located at 150.0–157.5 m a.s.l. and gently falls down to the south-east and south. In the north-west a distinct and relatively steep scarp, 5–15 m high, separates the higher outwash level from the lower one at 140.0–147.5 m a.s.l. This edge generally runs northeast-southwest and is curved to the south-east. Elongated pseudo-terraces occur within the sandur scarp and are parallel to it.

The proximal part of the higher level of the Dobrzyń sandur is composed of two vast combined outwash fans. One of them was formed at a mouth of the glacial tunnel valley of the Bryńsk Lake, even at the lower outwash level. This tunnel valley is perpendicular to and directly borders with the scarp of the higher outwash. In the north, the Bryńsk outwash fan occurs at 152–155 m a.s.l. and slightly declines to the south and south-east to 148–150 m a.s.l. To the south of Jamielnik, the Bryńsk outwash fan combines with the Lidzbark Welski outwash fan which rises at a mouth of the tunnel valley of the Lidzbark Lake.

A system of elongated proglacial depressions, formed during a final phase of outwash development is a most characteristic morphologic feature in proximal parts of outwash fans. The main reconstructed palaeochannels on fans are gathered at mouths of glacial tunnel valleys, therefore major meltwater outflows were active just in these very places,

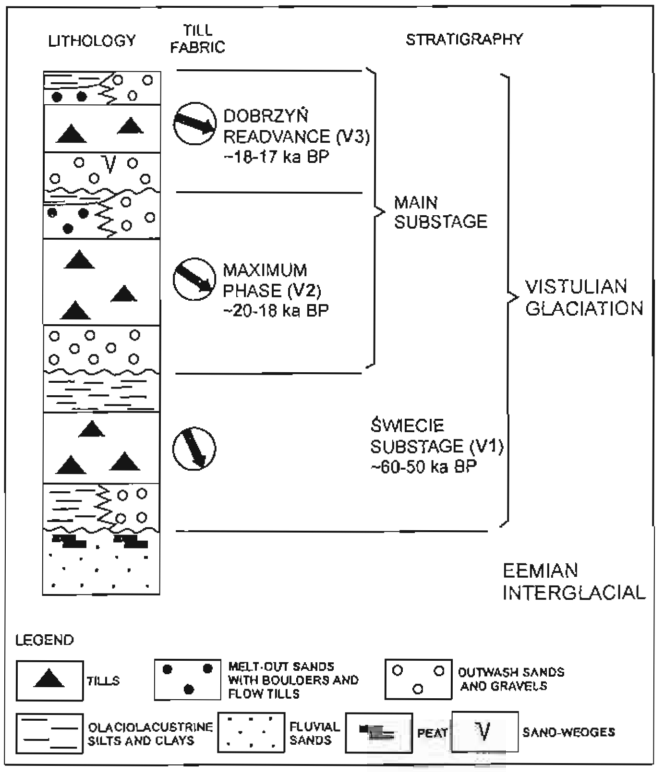


Fig. 2. Synthetic profile of deposits of the Vistulian Glaciation in the mid-eastern Chełmno–Dobrzyń Lakeland

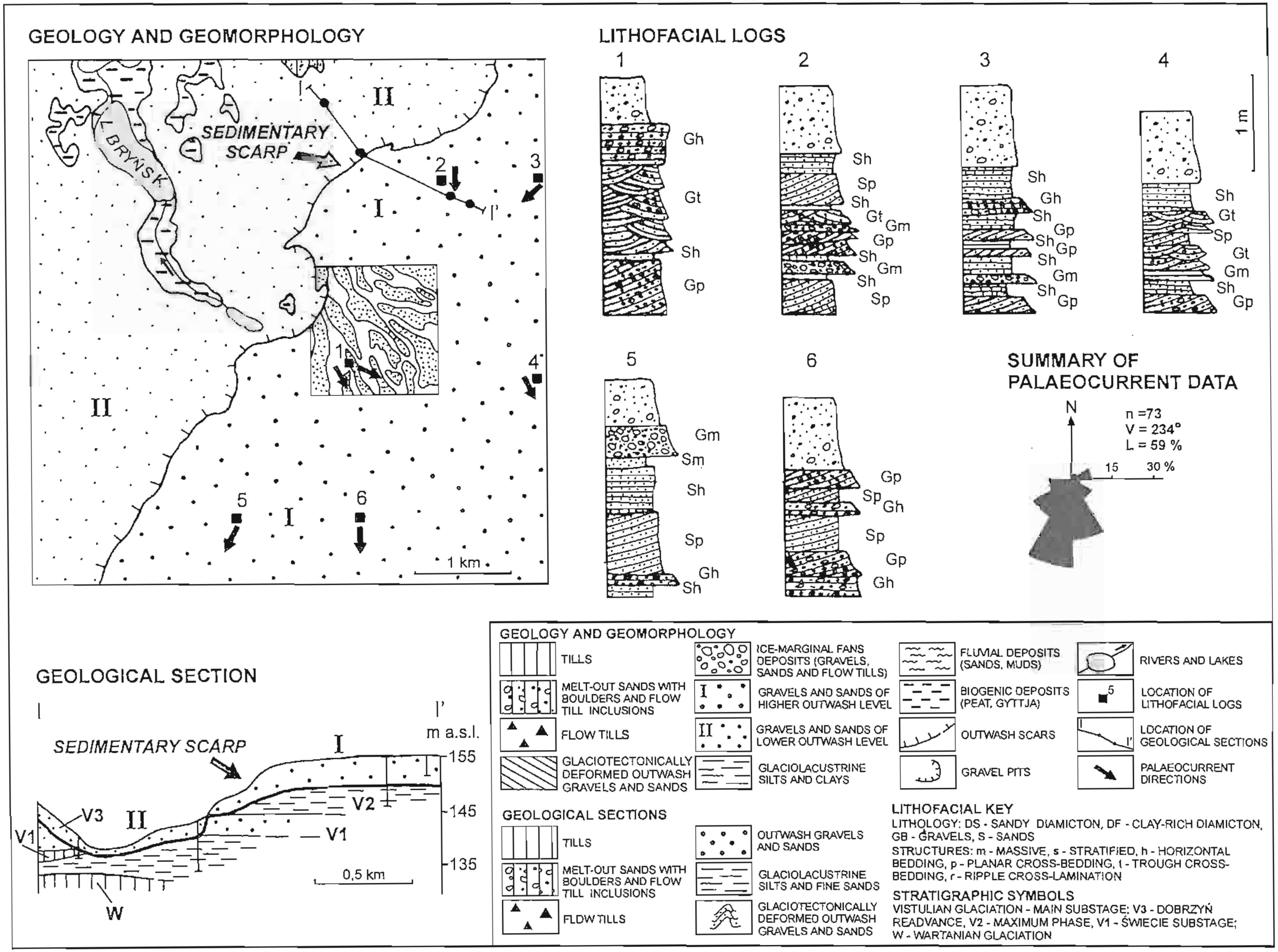
particularly on the Bryńsk fan (Fig. 3). There are two distinct topographical levels, i.e. a lower one with still active main braided channels, and a higher level which was active during floods only. Similar palaeomorphologic features were perceived also within the other Pleistocene sandurs (among others S. Kozarski, 1975, 1977; J. K. Maizels, 1983).

There is a lowered surface of the lower level of the Dobrzyń sandur to the north of the scarp of the higher outwash level. It is located at 140–141 m a.s.l., i.e. about 4–5 m below the primary sandur plain. Its surface is diversified with numerous kettles: some of them are small and relatively deep, and filled with organic deposits. The largest kettle is 700–1300 m long and 300–500 m wide. Longer axes of these depressions are parallel to the scarp of the higher Dobrzyń sandur level.

Sedimentology. A proximal part of the higher Dobrzyń sandur level is composed of fining-up gravelly-sandy series of varying thickness (Fig. 3), about 4–6 m in lower parts of the outwash scarp and 7–10 m at root of the Bryńsk outwash fan. A maximum thickness of outwash deposits was spotted in the northeastern part of the studied sandur (10–13 m).

Below the outwash series there are glaciolacustrine fine-grained sands and silts (Fig. 3). They are associated with the ice sheet advance during the maximum phase. Glaciolacustrine sediments are underlain by glaciofluvial sands and gravels, probably of the Świecie Substage of the Vistulian Glaciation.

At the back of the higher sandur level scarp there are sands with gravels, 2–5 m thick. They constitute a lower part of the lower sandur level. These deposits fill a depression, developed in older deposits of the Vistulian Glaciation.



GEOLOGY AND GEOMORPHOLOGY
L. BRYŃSK
SEDIMENTARY SCARP
I
II
I'
1 km
LITHOFACIAL LOGS
1 2 3 4 5 6
Gh Gt Sh Gp
Sh Sp Sh Gt Gm Gp Sh Gm Sh Sp
Sh Gh Sh Gp Sh Gp Sh Gm Sh Gp
Sh Gt Sp Gt Gm Sh Gp
Gm Sm Sh Sp Gh Sh
Gp Sp Gh Sp Gp Gh
1 m
SUMMARY OF PALAEOCURRENT DATA
N
n =73
V = 234°
L = 59 %
15 30 %
GEOLOGICAL SECTION
SEDIMENTARY SCARP
m a.s.l.
155
145
135
V3 II V2 V1 W
0,5 km
GEOLOGY AND GEOMORPHOLOGY
TILLS
MELT-OUT SANDS WITH BOULDERS AND FLOW TILL INCLUSIONS
FLOW TILLS
GLACIOTECTONICALLY DEFORMED OUTWASH GRAVELS AND SANDS
ICE-MARGINAL FANS DEPOSITS (GRAVELS, SANDS AND FLOW TILLS)
GRAVELS AND SANDS OF HIGHER OUTWASH LEVEL
GRAVELS AND SANDS OF LOWER OUTWASH LEVEL
GLACIOLACUSTRINE SILTS AND CLAYS
FLUVIAL DEPOSITS (SANDS, MUDS)
BIOGENIC DEPOSITS (PEAT, GYTTJA)
OUTWASH SCARS
GRAVEL PITS
RIVERS AND LAKES
LOCATION OF LITHOFACIAL LOGS
LOCATION OF GEOLOGICAL SECTIONS
PALAEOCURRENT DIRECTIONS
GEOLOGICAL SECTIONS
TILLS
MELT-OUT SANDS WITH BOULDERS AND FLOW TILL INCLUSIONS
FLOW TILLS
OUTWASH GRAVELS AND SANDS
GLACIOLACUSTRINE SILTS AND FINE SANDS
GLACIOTECTONICALLY DEFORMED OUTWASH GRAVELS AND SANDS
LITHOFACIAL KEY
LITHOLOGY: DS - SANDY DIAMICTON, DF - CLAY-RICH DIAMICTON, GB - GRAVELS, S - SANDS
STRUCTURES: m - MASSIVE, s - STRATIFIED, h - HORIZONTAL BEDDING, p - PLANAR CROSS-BEDDING, t - TROUGH CROSS-BEDDING, r - RIPPLE CROSS-LAMINATION
STRATIGRAPHIC SYMBOLS
VISTULIAN GLACIATION - MAIN SUBSTAGE: V3 - DOBRZYŃ READVANCE, V2 - MAXIMUM PHASE, V1 - ŚWIECIE SUBSTAGE; W - WARTANIAN GLACIATION

Due to a lack of big exposures in the analysed part of the higher sandur level, which would show sedimentologic formation of the whole outwash series, only a top part of it was carefully examined. It represents a final phase of proglacial deposition.

In the analysed outwash series there are predominant medium-scale beds of horizontally bedded, planar cross-bedded and trough cross-bedded sands and gravels (**Gh, Sh, Gp, Sp, Gt**) (Fig. 3). Beds of massive clast-supported gravels (**Gm**), and beds of massive sands (**Sm**) are more rarely represented. Alternate appearance of sand and gravel beds is very characteristic.

The analysed sediments were deposited in the proximal braided channels in varying energetic flow conditions. The alternate sand and gravel beds reflect cyclic changes in proglacial waters (T. Zieliński, 1992, 1993). During floods, deposition concentrated in shallow and broad gravel channels with flat beds and longitudinal bars (lithofacies **Gh, Gm, Gp**). During floods fell, there was a deposition of horizontally laminated sands in shallow channels (lithofacies **Sh**). In deeper channels the lithofacies **Gt** and **Sp** were formed.

A palaeocurrent analysis indicates that meltwaters, which deposited outwash material in a final phase of proximal sandur formation, found their outlet in the sectors SE to SW (Fig. 3).

Former active layer. A strong transformation of the upper part of the outwash series is widely observed in the higher Dobrzyń sandur (J. Kotarbiński, 1971, 1972; W. Wysota, 1992). It is characterised by a complete disappearance of sediment stratification, diversity of grain size, decalcification and enrichment with iron compounds to depth 0.5–1.2 m. Dark rusty-yellowish colour of these sediments is also very characteristic and their lower boundary is relatively sharp. J. Kotarbiński (1971, 1972) called them the structure-less deposits. A similar transformation of the upper part of sediments was spotted in other sandur regions (among others E. Wiśniewski, 1970; M. Bogacki, 1976; S. Kozarski, 1995).

J. Kotarbiński (1971, 1972) assumed that the structure-less deposits evolved in a final phase of the sandur formation due to gravitational flows from the ice sheet snout of water-saturated supraglacial material. Afterwards, these sediments were subjected to transformations under the influence of frost and soil processes.

At present, it is commonly accepted that transformation of the upper part of the sandur series results from bioturbations and frost processes (A. Kowalkowski, 1990; S. Kozarski, 1995). A particularly significant role is attributed to an intensive frost activity in a permafrost zone. A. Kowalkowski (1990) used the term the perstruction zone or the perstruction series. A layer of transformed deposits is, therefore, a meaningful trace of a former active layer. A distinct contact of the structure-less layer and deposits with a primary sedimentary structure is of periglacial origin, and it indicates a previous bottom of the former active layer (S. Kozarski, 1995). It reached to depth 1.2 m in the higher outwash level.

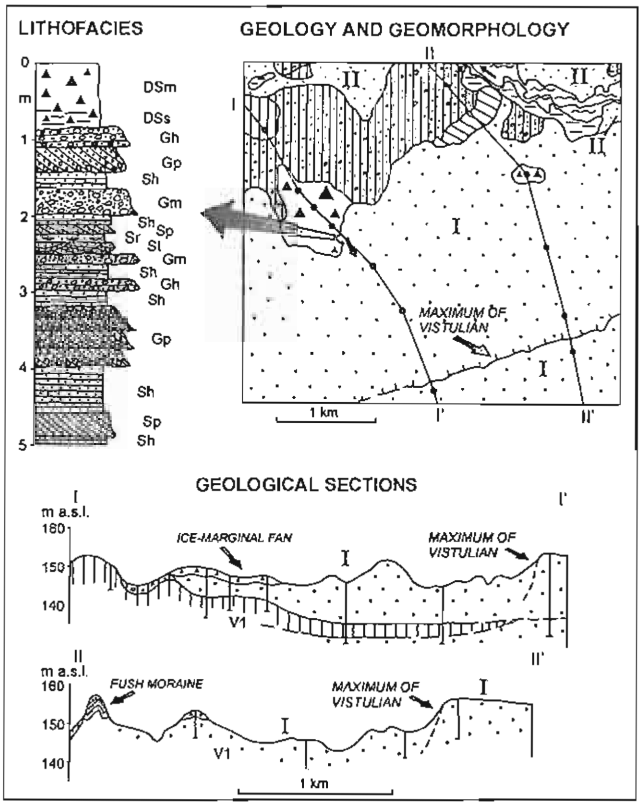


Fig. 4. Ice-marginal features at the ice sheet maximum limit of the Vistulian Glaciation to the south of Lidzbark Welski

Explanations in Fig. 3

Interpretation and model of deposition. A proximal part of the higher level of the Dobrzyń sandur was formed directly in front of the ice sheet in the steady-state conditions. Proglacial deposition took place at a contact with the ice lobe. The Bryńsk sedimentary scarp is a morphologic presentation of such glaciofluvial deposition.

Ice-contact sedimentary scarps exist as characteristic features in some marginal zones of the Pleistocene ice sheets. In Poland they are known from the area occupied by ice sheets of the Middle Polish Glaciations (Saalian) (Z. Michalska, 1959; K. Straszewska, 1969) and the Vistulian Glaciation (T. Bartkowski, 1967; L. Kasprzak, S. Kozarski, 1984, 1989; L. Kasprzak, 1988; S. Kozarski, L. Kasprzak, 1987).

The Bryńsk sedimentary scarp was formed by subglacial meltwaters, main outflows of which occurred at mouths of the glacial tunnel valleys of the Bryńsk Lake and the Lidzbark Lake. Outwash fans occurred at outlets of concentrated and intensively flowing subglacial waters. They culminate in the sedimentary scarp zone and form a system of braided palaeochannels, developed during a final phase. With the undergo-

Fig. 3. Sedimentary scarp at the maximum ice sheet limit of the Vistulian Glaciation at Bryńsk

Small frame in the sketch of geology and geomorphology shows palaeochannels in a proximal part of the Bryńsk outwash fan

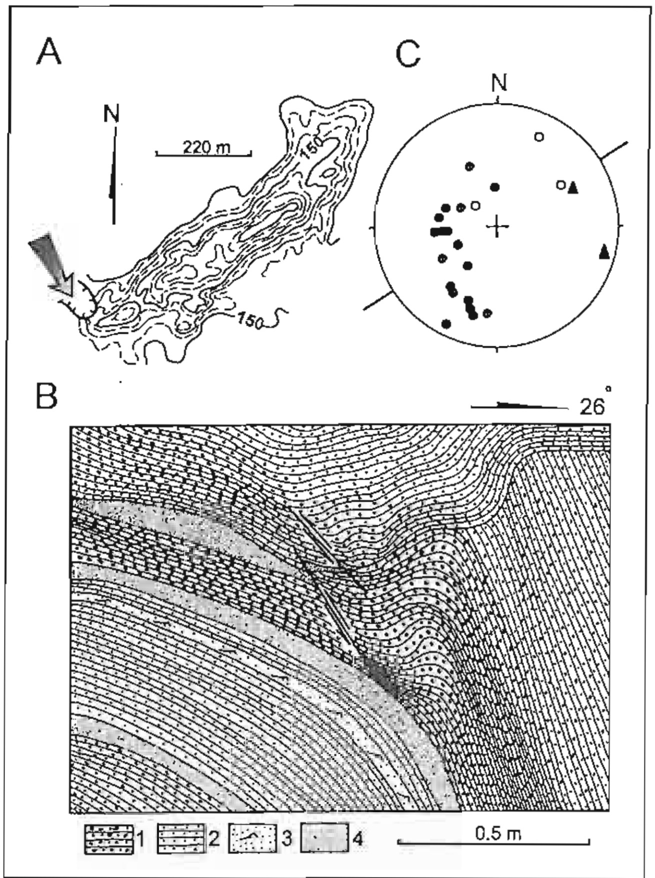


Fig. 5. Push moraine to the south of Lidzbark Welski

A — topography; B — minor folds and reverse faults in a southwestern limb of the overturned fold; C — point diagram with an orientation of deformed outwash layers (black circles), reverse faults (open circles) and axes of minor folds (triangles); lithofacies: 1 — horizontally bedded gravels, 2 — horizontally bedded sands, 3 — ripple-cross laminated fine-grained sands, 4 — massive silts

ing accumulation, proglacial fans combined and created a vast outwash plain.

Another fact indicates an activity of subglacial waters in development of the sedimentary scarp, namely there are neither ablation nor gravity flow deposits in a top of the outwash series (L. Kasprzak, S. Kozarski, 1989). A presence of glacial tunnel valleys at contact with the scarp of the higher outwash level indicates that a marginal part of the stationary ice sheet had a warm basal regime during a glaciofluvial deposition.

In a final phase of the sedimentary scarp development, the outwash was partly deposited at a stagnant ice sheet front. This process is indicated by pseudo-terraces with gravitational deformations in their deposits.

ICE-MARGINAL LANDFORMS TO THE SOUTH OF LIDZBARK WELSKI

Morphology. In a distance of about 2 km to the south of Lidzbark Welski there is a ridge at 159.6 m. a.s.l. (Figs. 4 and 5). It is 5–10 m high, 800 m long and 250–500 m wide. The ridge axis is curved to the south-east and runs SW–NE. This feature has an asymmetric cross-section, with its distal (southeastern) slope steeper than the proximal (northwestern) one. On the northern side of the ridge there is a weakly developed glacial tunnel valley. To the north of the tunnel valley there is a morainic plain at 153–155 m a.s.l. It is mostly composed of glacial sands with boulders and flow till inserts, 1–1.5 m thick. They are underlain by a basal till or glaciofluvial sediments (Fig. 4).

The higher level of the Dobrzyń sandur spreads to the south of the ridge. Directly in the neighbourhood of the ridge the outwash surface occurs at 152–160 m a.s.l., and is very diversified. In a distance of 2–2.5 km to the south of the ridge, the higher level of the Dobrzyń sandur is rather a flat plain. It is located at 153–160 m a.s.l. and slopes south-easterly. The scarp, 5–10 m high, separates this plain from the outwash with a more diversified morphology.

To the south of Lidzbark Welski, this ridge was classified among the ice-marginal landforms of the Kujawy Subphase (at present, the Dobrzyń Subphase) of the last glaciation (J. Kotarbiński, 1972; R. Galon *et al.*, 1979). The outwash in their foreland was also associated with this subphase. J. Kotarbiński (1972) classified the moraine ridge, located to the south of Lidzbark Welski, as a thrust end moraine. He also distinguished hummocks of depositional end moraines close to this ridge in the surroundings of Jamielnik. However, this fact has not been proved by studies of the author (W. Wysota, 1992).

Sedimentology of a proximal part of the sandur. A proximal part of the higher level of the Dobrzyń sandur to the south of Lidzbark Welski is composed of sandy-gravel deposits (Fig. 4), just like in the Bryńsk area. A thickness of the outwash series is diversified, to 4–10 m to the south-east of Jamielnik and over 10 m further to the south.

Sedimentary features of the proximal part of the outwash were studied at Jamielnik (Fig. 4). The outwash deposits are overlain there by a sandy diamicton, 0.5–1 m thick, which is stratified at the bottom. Medium- and small-scale horizontally bedded sands and gravels (lithofacies **Sh** and **Gh**) and medium-scale planar cross-bedded sands and gravel (lithofacies **Sp** and **Gp**) predominate in the underlying outwash deposits (over 4 m). In the top there are also middle-scale beds of massive clast-supported gravel (**Gm**). Single thin trough cross-bedded and ripple cross-laminated sands (**St**, **Sr**) were distinguished. An alternate coexistence of sands and gravel draws attention. Small deformations of deposits: normal faults and small folds were also detected. The layers dip southwards at an angle of 4–7°. Palaeocurrents indicate the meltwater outflow to the south-east.

The analysed outwash series at Jamielnik represents deposits of a proximal part of the vast ice-marginal alluvial fan which is predominated by channel flows (T. Zieliński, 1992, 1993). During the short-term ablation floods, in conditions of high-energy flows, a bed deposition of gravel sheets and longitudinal bars predominated (lithofacies **Gh, Gm, Gp**). At a lower flow in the channels, there was mainly a deposition of sandy lithofacies. In shallow channels with a flat bed, the horizontally laminated sands were deposited (**Sh**), whereas in deeper channels the transverse bars were formed (**Sp**). After the outwash deposition had been completed, subaerial cohesive flows of supraglacial tills took place. They covered a proximal part of the fan. Gravitational disturbances in the outwash layers indicate that deposition took place in a supraglacial environment.

Structure of a push moraine. An internal structure of the push moraine ridge was examined in an exposure in its western part (Fig. 5). This moraine is composed of glaciotectonically disturbed, coarsening upwards outwash deposits, 10 m thick. In the lower part, they are horizontally bedded and cross-bedded sands (lithofacies **Sh, St** and **Sr**). In the upper part both horizontally and massive sandy gravel were distinguished (**Gh, Gm**). Lithofacial features indicate their deposition in a proximal part of the outwash in the rising energy of flow.

A meso-scale structure of the overturned fold constitutes the main element of internal composition of the ridge (Pl. I, Fig. 1). Secondary structures of minor drag folds and discontinuous deformations of the reverse faults type and subhorizontal shear planes were stated (Fig. 5; Pl. I, Fig. 2). The fold axis is SW–NE oriented and therefore, complies with the axis of the ridge (Fig. 5).

The deformed layers are non-conformably overlain by sandy-gravel diamicton with boulders and interbeddings of clay-rich diamicton, 0.5–1.8 m thick. It was formed due to subaerial cohesive flows of supraglacial tills (D. E. Lawson, 1979, 1981; M. Rappol, 1983; T. Zieliński, 1992; T. Zieliński, A. J. van Loon, 1996).

The structural analysis of the fold speaks for a flexural folding (W. Jaroszewski, 1980). The arrangement of stresses in the fold was related to the activity of horizontal forces, perpendicular to the ridge axis. The axis of the greatest principal stress δ_1 was parallel to the compression axis and hence, perpendicular to the fold axis. Minor drag folds indicate approximate coincidence of axial elements against the main fold. They are typical for syn-kinematic structures with respect to this fold and they were formed as a result of stresses, coming directly from the activity of folding forces. In a further phase, the flexure folding was accompanied by development of reverse faults and subhorizontal shear planes, which were also the results of stresses, related directly to the folding forces.

The fold structure was formed by a horizontal push of the ice sheet front. During a horizontal compression, the greatest principal stress δ_1 was perpendicular or diagonal to the axial surface of the fold, hence in the NW–SE direction.

The data concerning the internal structure of the ridge to the south of Lidzbark Welski indicate that it constitutes a push end moraine. Similar landforms were frequently described from the contemporaneously glaciated regions (among others L. A. Bayrock, 1967; M. Kalin, 1971; R. J. Price, 1973; J. Rabassa *et al.*, 1979; J. Krüger, 1985, G. S. Boulton, 1986; F. A. Eybergen, 1987; D. G. Croot, 1988), and also from the regions of the Pleistocene glaciations (among others E. Drozdowski, 1981, 1987; M. Pasierbski, 1984; F. M. van der Wateren, 1985, 1987; L. Kasprzak, 1985, 1988; J. K. Hart, 1990, 1996; P. Kłysz, 1990).

Model of formation. The analysis of ice-marginal landforms and deposits to the south of Lidzbark Welski indicates that the push moraine does not determine the maximum limit

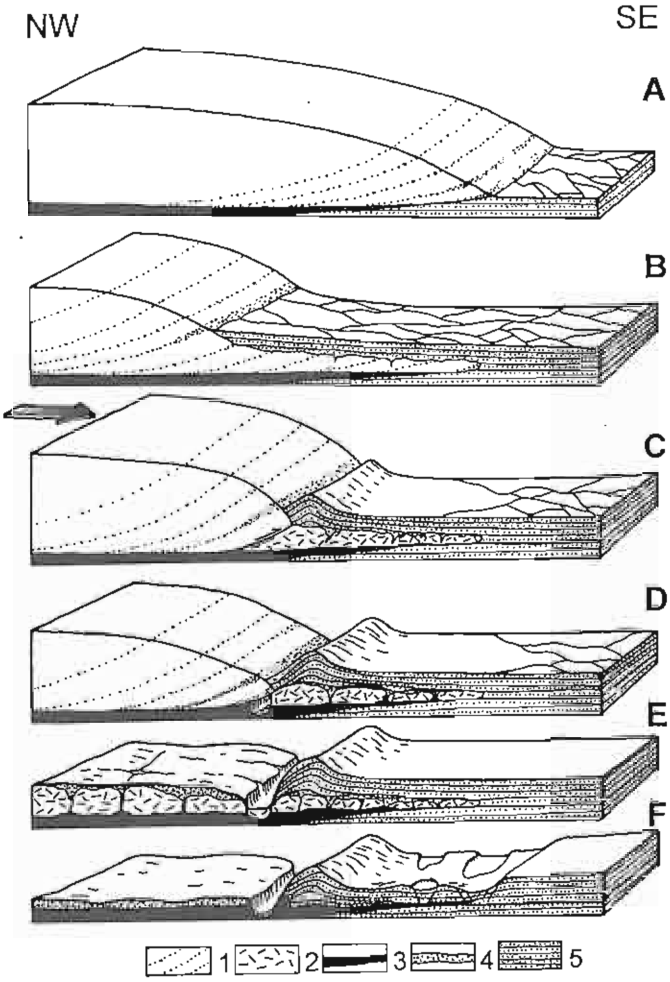


Fig. 6. The model of development of ice-marginal features during a maximum ice sheet limit of the Vistulian Glaciation to the south of Lidzbark Welski (explanations in the text)

1 — active ice, 2 — stagnant ice, 3 — basal till, 4 — supraglacial till, 5 — outwash

of the ice sheet, but of a minor oscillation during a retreat. The maximum extent is defined by the morphologic scarp, about 2–2.5 km further to the south within the higher level of the Dobrzyń sandur, and separates a diversified surface of the outwash from a flat outwash plain.

The acquired results allowed for a reconstruction of subsequent formation stages of the ice-marginal zone at the maximum ice sheet limit of the Vistulian Glaciation to the south of Lidzbark Welski (Fig. 6).

A. During the first stage, a stabilisation of the ice front took place. It was 4 km to the south of Lidzbark Welski. The ice front remained in steady-state conditions. A proximal part of the higher level of the Dobrzyń sandur was formed. Proglacial waters flew to the south and south-east.

B. As a result of a negative ice sheet balance its marginal part, probably frozen to the bed, was subjected to stagnation. The active ice sheet front was about 3–4 km to the north. It could be presumably stabilised at a contact of temperate

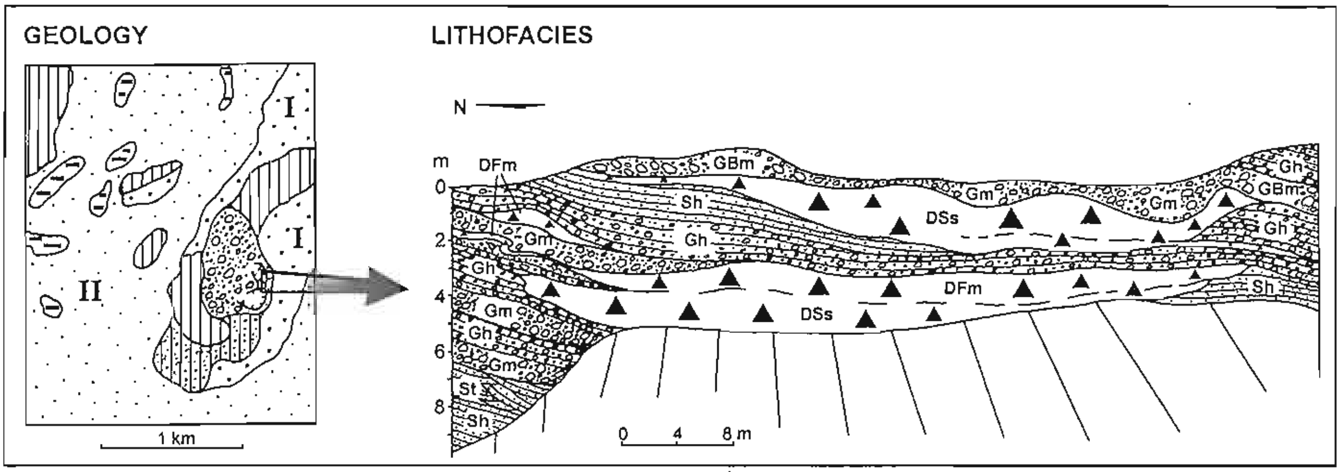


Fig. 7. Depositional end moraine at the maximum ice sheet limit of the Vistulian Glaciation to the south-east of Koszelewy

Explanations in Fig. 3

(active) and cold (stagnant) ice. Outwash deposits were accumulated on a stagnant ice in the ice sheet foreland.

C. As a result of positive changes in the ice body balance, there was an ice sheet oscillation. A push of the ice sheet front resulted in development of proglacial glaciotectonic deformations, and continuous disturbances came first. They were a main fold and congruent minor drag folds. Increasing horizontal stress, after exceeding threshold values, resulted in development of discontinuous deformations, i.e. reverse faults and subhorizontal shear planes. Due to a horizontal compression the outwash deposits, ahead of the advancing ice sheet front, were disturbed (W. Jaroszewski, 1980; J. S. Aber, 1982; L. Kasprzak, 1985; D. G. Croot, 1987; J. K. Hart, 1990). The push moraine ridge constitutes a morphologic feature of the advancing ice sheet front. The advancing ice front stopped at this terrain obstacle.

On the basis of the collected geologic materials, it is hard to define a mechanism that initiated a development of proglacial glaciotectonic deformations. They are assumed to have been related to development of a strong compression zone and increasing stresses at the border of the active (temperate) and a stagnant (frozen to the bed) ice. Released compression stresses caused the advance of the ice sheet front, probably of a surge type, and a development of proglacial glaciotectonic deformations.

D. In this stage the ice sheet front was stable and in the steady-state conditions. During summer ablation the supraglacial tills kept creeping down to cover slopes of the push moraine. At the contact of the ice sheet front and the push moraine, a small ice-marginal tunnel valley was developed. It drained off meltwaters to a proximal part of the outwash. The formation of the tunnel valley indicates a warm basal regime of the ice sheet margin in this stage.

E. It is a stage of the ice sheet retreat. Stagnant and dead ice remained at the back of the push moraine, being conserved with supraglacial material.

F. This stage is predominated by melting of the buried dead ice. Pitted outwash was formed in foreland of the push moraine. A morphologic scarp emerged between the pitted outwash and the primary outwash level. It indicates the maximum limit of the ice sheet.

DEPOSITIONAL END MORAINE TO THE SOUTH-EAST OF KOSZELEWY

Morphology. Ice-marginal landforms related to the maximum ice sheet limit of the Vistulian Glaciation to the east of Lidzbark Welski were destroyed to a greater amount by younger outwash outlets. One of the few relic forms is the end moraine to the south-east of Koszelewy (Fig. 7), located in a morainic plateau, mainly composed of a till, and the higher outwash level composed of sands and gravel. The hill is oval, 10–15 m high, and its surface is uneven. Its internal structure was examined in an exposure.

Sedimentology. The morainic hill is composed mainly of coarse gravel with interbeddings of diamicton, 8–12 m thick (Fig. 7). Glaciofluvial deposits are mainly represented by massive coarse gravel (**Gm**), massive clast-supported coarse gravel with boulders (**GBm**) and horizontally bedded coarse gravel (**Gh**). Occasionally there are planar cross-bedded and horizontally bedded coarse-grained sands (**St, Sh**). Gravel beds are interbedded with thin layers of stratified sandy diamicton (**DSs**) and massive clay-rich diamicton (**DFm**) to 3 m thick (Fig. 7; Pl. II). Characteristic interfingering of gravel and diamicton occurred (Fig. 7). The diamicton contains several sedimentary deformations, comprising small folds, pseudonodules or slumps. Intraclasts of clay-rich diamicton were common in the horizontally bedded coarse gravel. Glaciofluvial and diamicton beds are gently dipping (8–10°) to the south-east.

Interpretation. The analysed deposits form a proximal part of the short ice-marginal fan. The lithofacies **Gm, GBm** and **Gh** result mainly from deposition of high-energy sheet flows during floods. Accessory lithofacies **St** and **Sh** were accumulated in channels during falling floods. Diamicton

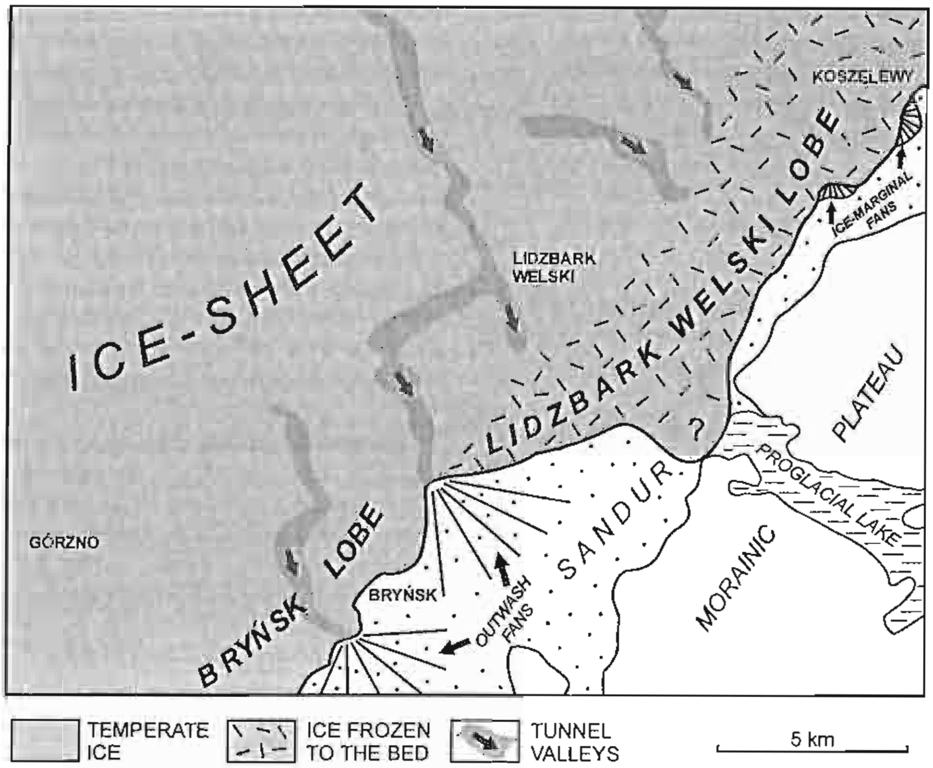


Fig. 8. Ice sheet dynamics during the maximum limit of the Vistulian Glaciation in the mid-eastern Chełmno–Dobrzyń Lakeland

beds were deposited in gravity flows of supraglacial tills during less intensive ablation (D. E. Lawson, 1979, 1981; T. Zieliński, 1992; T. Zieliński, A. J. van Loon, 1996). Flow tills mantled a fan surface with a relatively continuous cover. Locally, they were redeposited by weak currents and slumps. During floods they were occasionally completely eroded.

Similar ice-marginal landforms have been widely described in the areas of the Pleistocene continental glaciations (among others T. Bartkowski, 1967; G. S. Fraser, J. C. Cobb, 1982; H. Ruszczyńska-Szenajch, 1982; L. Kasprzak, S. Kozarski, 1984; S. Kozarski, L. Kasprzak, 1987; S Kozarski, 1990; T. Zieliński, 1992; T. Zieliński, A. J. van Loon, 1996; R. Dobracki, D. Krzyszkowski, 1997).

DYNAMICS OF THE ICE SHEET MARGIN

During the Maximum Phase of the Vistulian Glaciation in the mid-eastern part of the Chełmno–Dobrzyń Lakeland, two relatively distinct lobes occurred in a marginal part of the ice sheet, i.e. the Bryńsk lobe in the west and the Lidzbark Welski lobe in the east (Fig. 8).

A distinct sedimentary scarp was formed at the contact with the Bryńsk ice sheet lobe. It indicates the steady-state conditions of the ice sheet front (L. Kasprzak, S. Kozarski, 1984; S. Kozarski, L. Kasprzak, 1987; L. Kasprzak, 1988; W. Wysota, 1992, 1995*a*), being the evidence of a stable balance of the ice body. A marginal temperate zone of the ice sheet had a well-developed subglacial channelled meltwater system, composed of two main glacial tunnel valleys, i.e. of the lakes Bryńsk and Lidzbark (Fig. 8).

In comparison with the Bryńsk ice lobe, the Lidzbark Welski ice lobe had a more diversified dynamics in its western part. They were due to changes in ice sheet balance and probably, thermal conditions of the ice sheet margin. During the maximum limit, the Lidzbark Welski lobe — similarly to the Bryńsk lobe — was in steady-state conditions. At that time, the higher level of the Dobrzyń sandur was formed to the south of Lidzbark Welski. To the south of Koszelewy, deposition of short ice-marginal fans occurred. They were predominated by a coarse glaciofluvial deposition and subaerial gravity flows of supraglacial tills, and a marginal zone of the ice sheet was probably frozen to its bed (Fig. 8). This phase was followed by a stagnation of the Lidzbark Welski ice lobe. Subsequently, a renewed small advance of the ice sheet front in the western part of the lobe occurred. The push moraine ridge was formed to the south of Lidzbark Welski as a result of proglacial glaciotectonics.

There was a permafrost in the ice sheet foreland at its maximum extent during the Vistulian Glaciation. A significant transformation of the upper part of the higher outwash deposits resulted from freezing processes in the active layer.

After the maximum phase, the ice sheet retreat was reflected by its stagnation, which gradually lost contact with the active ice and was subjected to ablation. A stagnant ice sheet zone, 4–7 km wide, comprised the compact ice areas directly at the back of the Bryńsk and Lidzbark Welski ice lobes, which were subjected to a slow ablation. In the other areas with a more widespread disintegration of the ice body, there are common crevasses, presumably developed at the contact between a stagnant and an active ice.

RECAPITULATION

1. The maximum ice sheet limit of the Vistulian Glaciation in the mid-eastern part of the Chełmno–Dobrzyń Lakeland occurred during the Maximum Phase of the Main Substage (*ca.* 20–18 ka BP).

2. A record of the Vistulian Glaciation maximum limit comprises a separate lodgement till and associated glacioteetonites, a vast higher level of the Dobrzyń sandur, depositional hills and ridges, tunnel valleys, and melt-out deposits and kame landforms formed during deglaciation.

3. The maximum limit of the ice sheet is precisely indicated by the sedimentary scarp to the south of Bryńsk, the morphologic scarp within the higher level of the Dobrzyń sandur to the south of Lidzbark Welski and the depositional end moraine to the south-east of Koszelewy.

4. There were two lobes in a marginal zone of the ice sheet, i.e. in the west the Bryńsk lobe (unfrozen to the bed) in steady-state conditions, and in the east the Lidzbark Welski lobe with complex thermal conditions and more diversified dynamics. A well-developed meltwater subglacial drainage system occurred within the Bryńsk ice sheet lobe. It was based on subglacial drainage of meltwaters along the glacial tunnel valleys of the lakes Bryńsk and Lidzbark. A minor oscillation of the ice front and a development of a push moraine took place in the western part of the Lidzbark Welski ice sheet lobe.

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MAKSYMALNY ZASIĘG LĄDOLODU ZLODOWACENIA WISŁY W ŚRODKOWO-WSCHODNIEJ CZĘŚCI POJEZIERZA CHEŁMIŃSKO-DOBRZYŃSKIEGO

Streszczenie

Szczegółowe badania geologiczne, geomorfologiczne i sedymentologiczne, prowadzone przez autora w ostatnich dziesięciu latach w środkowo-wschodniej części Pojezierza Chełmińsko-Dobrzyńskiego (fig. 1), umożliwiły stosunkowo dokładne poznanie maksymalnego zasięgu ostatniego zlodowacenia na tym terenie. Miał on miejsce podczas fazy maksymalnej stadiału głównego, tj. około 20–18 ka BP (fig. 2). Zapis geomorfologiczny i

sedymentologiczny tej fazy obejmuje oddzielny pokład gliny bazalnej z nałożenia i stowarzyszone z nią glacjotektonity, rozległą równinę wyższego poziomu sandru dobrzyńskiego, wzgórza i wały moren czołowych akumulacyjnych, wał moreny pchnięcia, rynny subglacjalne, a także gliny i piaski z wytopienia z głazami.

Maksimum zasięgu ostatniego lądolodu analizowano w trzech obszarach testowych: Bryńsk, Lidzbark Welski oraz Koszelewy (fig. 1). W ich obrębie prowadzono szczegółowe badania geomorfologiczne i sedymentologiczne strefy marginalnej.

W rejonie Bryńska maksymalny zasięg zlodowacenia wisły wyznacza skarpa sedymentacyjna wyższego poziomu sandrowego (fig. 3). Powstała ona na kontakcie z lobem lodowcowym Bryńska, w warunkach stałej równowagi dynamicznej czoła lądolodu. Brzeżna część lądolodu cechowała się ciepłym reżimem bazalnym i miała dobrze rozwinięty system drenażu subglacjalnego (fig. 8).

W rejonie Lidzbarka Welskiego maksymalny zasięg lądolodu wyznacza wyraźna krawędź morfologiczna w obrębie wyższego poziomu sandrowego (fig. 4). Na zapleczu tej krawędzi występuje wał moreny pchniętej (fig. 5; tabl. I). Formy marginalne związane z maksymalnym zasięgiem zlodowacenia wisły na wschód od Lidzbarka Welskiego zostały w znacznym stopniu zniszczone przez młodsze odpływy sandrowe. Jedną z nielicznych zachowanych form jest wzgórze akumulacyjnej moreny czołowej na SE od Koszelew (fig. 7; tabl. II).

Kształtowanie strefy marginalnej w rejonie Lidzbarka Welskiego i Koszelew związane było z lobem lodowcowym Lidzbarka Welskiego o złożonym reżimie termicznym i zróżnicowanej dynamice (fig. 8). Podczas maksimum zasięgu formował się wyższy poziom sandru dobrzyńskiego na S od Lidzbarka Welskiego, a na S od Koszelew zachodziła sedymentacja krótkich stożków glacjomarginalnych. Brzeżna część lądolodu była prawdopodobnie przymarznięta do podłoża. Po krótkotrwałej stagnacji, w zachodniej części tego lobu doszło do niewielkiej oscylacji czoła lądolodu (fig. 6). W wyniku glacitektoniki proglacjalnej powstał wał moreny pchnięcia na S od Lidzbarka Welskiego.

Podczas maksimum zasięgu lądolodu zlodowacenia wisły na jego przedpolu istniała wieloletnia zmarzlina. W wyniku procesów mrozowych w warstwie czynnej doszło do znacznego przeobrażenia stropowej części (około 1,2 m) osadów wyższego poziomu sandrowego.

Recesja lądolodu fazy maksymalnej postępowała na drodze stagnacji mas lodowych, które stopniowo traciły kontakt z lodem żywym (aktywnym) i podlegały wyłącznie ablacji

EXPLANATIONS OF PLATES

PLATE I

Figs. 1, 2. Glaciotectonic deformations in a push moraine ridge, south of Lidzbark Welski

Fig. 1 — southwestern limb of an overturned fold, approximately 10 m top to bottom; Fig. 2 — subhorizontal shear planes, scale division 0.5 m

PLATE II

Figs. 1, 2. Diamicton beds in a depositional end moraine, south-east of Koszelewy

Fig. 1 — massive clay-rich diamicton, underlain by horizontally bedded sands with gravel, scale division 0.5 m; Fig. 2 — stratified sandy diamicton with small slumps, scale division 0.5 m

Fig. 1

Fig. 2

Wojciech WYSOTA — Ice sheet maximum limit of the Vistulian Glaciation in the mid-eastern Chełmno–Dobrzyń Lakeland, northern Poland

Fig. 1

Fig. 2

Wojciech WYSOTA — Ice sheet maximum limit of the Vistulian Glaciation in the mid-eastern Chełmno-Dobrzyń Lakeland, northern Poland