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Relationship between morphology and glaciomarginal deposition in the foreland area of the Opava Mountains (S Poland)

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The glaciomarginal zone in front of the Opava Mountains (Eastern Sudetes) shows complex relief. This relief resulted during the Pleistocene in glaciomarginal sedimentation that differed from sedimentation in lowlands. Sedimentological analysis was carried out on deposits of the Odranian Glaciation, when the Scandinavian ice sheet reached its maximum extent in the Eastern Sudetes foreland. Three sites in the foreland of the Opava Mountains, situated in the upper reaches of the Troja River valley, were examined. It appears that the sedimentation was controlled primarily by the relief of the substratum, and changed with the position of the ice front. Glaciomarginal fans of different size formed in the Troja River valley, which was parallel to the ice sheet front. They passed distally into the valley outwash plain, the formation of which was also influenced by mountain rivers, the role of which though changed with time. Occasionally, water flowed from ice-dammed lakes in neighbouring valleys into the Troja River valley.

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INTRODUCTION

The Scandinavian ice sheet reached the foreland of the Sudetes (S Poland) several times during the Pleistocene (Anders, 1939; Jahn, 1960; Walczak, 1966, 1972; Badura *et al*., 1998). The relief of the area controlled the direction of ice sheet advance, and also considerably influenced the sedimentary context and thus the prevailing sedimentation processes. The sedimentary conditions in the foreland of the Opava Mountains (which form part of the Sudetes) are dealt with here. The deposits investigated are located in the Troja River valley, i.e. in the southeastern part of the Głubczyce Plateau (Fig. 1), and were deposited during the Odranian Glaciation. The deposits were examined at three sites in the upper reaches of the valley (Fig. 2). They record deposition in different morphological situations conditioned by the ice sheet front that advanced to its maximum extent.

Research on the glaciogenic deposits of the Głubczyce Plateau was earlier carried out by Jahn (1968). His study concerned the stratigraphy of the deposits and the palaeogeographic evolution of the plateau during the Quaternary. Badura *et al*. (1994, 1996*a*, *b*) carried out geological mapping there.

The close connection between the evolution of the glaciomarginal zone and the bedrock morphology in mountain and foremountain regions has been reported by many researchers (e.g. Walczak, 1957, 1969, 1970, 1972; Jahn, 1960, 1968, 1969; Szponar, 1974, 1986; Szczepankiewicz, 1984). The present study focuses on this connection, with emphasis on sedimentological analysis — an approach not commonly used in the earlier studies. The new research was carried out at several sites in the Sudetic foreland, mostly in a stratigraphic and palaeogeographic context (*cf*. Brodzikowski and Van Loon, 1984; Krzyszkowski 2001; Krzyszkowski and Allen, 2001; Krzyszkowski and Karanter, 2001).

METHODS AND TERMINOLOGY

In the three exposures studied, sedimentary lithofacies were distinguished using Miall's (1978) lithofacies code, modified by Zieliński (1992) (Table 1). In the facies-association code,

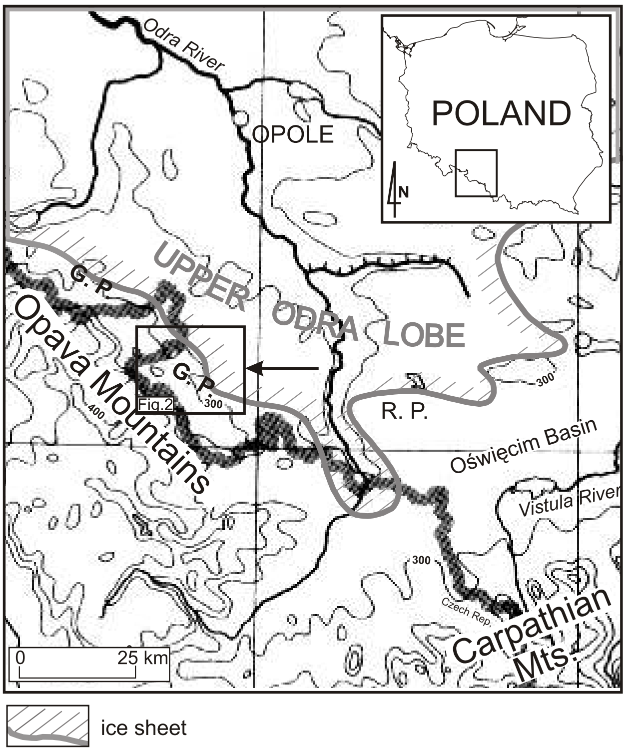


Fig. 1. Extent of the Upper Odra Lobe (solid grey line) and the location of study area

G. P. — Głubczyce Plateau, R. P. — Rybnik Plateau

Table 1

Lithofacies code symbols used in this study

Grain-size codes	
G	gravel
GS	sandy gravel
SG	gravelly sand
S	sand
D	diamicton
Codes for sedimentary structure	
m	massive structure
h	horizontal stratification
r	ripple coss-lamination
l	low-angle cross-stratification
p	planar cross-stratification
t	trough cross-stratification

the main lithofacies with lower frequency of occurrence have been placed between brackets. A two fold or, in some complicated cases, three fold division of depositional units has been used, with a distinction of lithofacies, facies associations and series. Three classes of thickness are used: thin units (up to 6 cm), intermediate units (6 to 30 cm) and thick units (more than 30 cm). The various symbols used in the diagrams are explained in Figure 3.

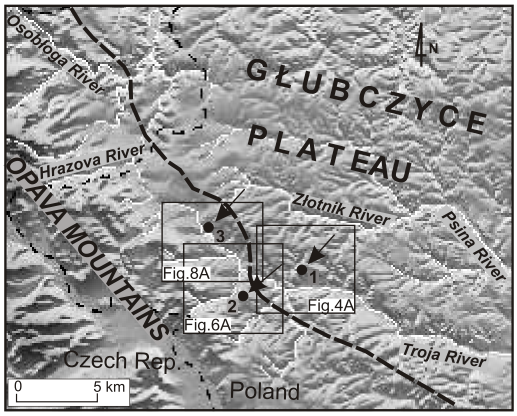


Fig. 2. Relief of the southern part of Głubczyce Plateau and location of the sites

1 — Włodzienin site, 2 — Lewice site, 3 — Zopowy site (heavy dashed line shows approximate position of ice sheet margin during its maximum extent)

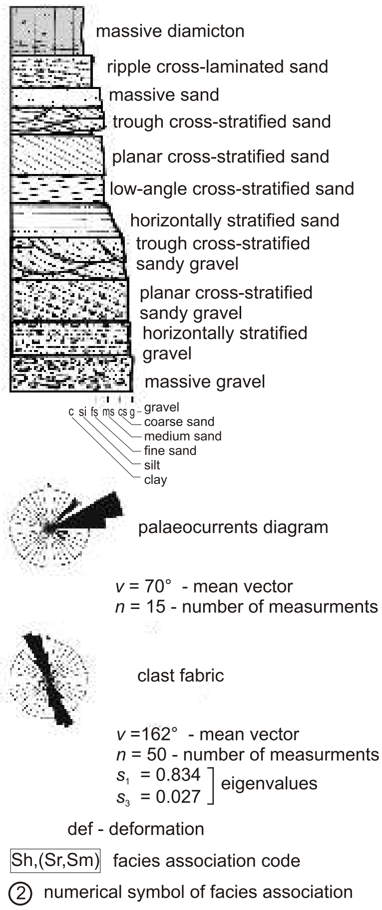


Fig. 3. Symbols used in Figures 4B, 6B and 8B

REGIONAL SETTING

The Opava Mountains are a small part of the eastern Sudetes (Fig. 1), composed of Carboniferous rocks. The higher parts are situated 500–900 m a.s.l., whereas the marginal parts have an elevation of 400–500 m a.s.l., passing NE-wards into the Głubczyce Plateau, which is composed mainly of Late Miocene strata that are overlain by Pleistocene deposits. The Głubczyce Plateau was ice-covered during the Sanian and Odranian glaciations (Środoń, 1957; Lewandowski, 1988; Badura *et al*., 1996*a*). The deposits of the Odranian Glaciation are sometimes exposed, but commonly occur under a loess cover of Vistulian age (Badura *et al*., 1994). The incised surface of the plateau descends towards the N-NE from 280–300 m a.s.l. to 220–240 m a.s.l.

The Osobłoga River that flows from the mountains divides the Głubczyce Plateau into two parts. The present study was carried out on the SE part of the plateau (Fig. 2). The Troja and Psina rivers jointly form a small river system running parallel to the mountain range. The axes of their valleys run to the SE (Fig. 2), towards the Odra River valley. During the Odranian Glaciation, these two rivers flowed probably within one wide valley, which only in its upper section was divided into two depressions, separated by a hill composed of Carboniferous rocks. In the opinion of Jahn (1968), this valley was a zone of SE-directed glaciomarginal drainage parallel to the ice front.

The ice sheet invaded the study area from the NE. The exact position of the maximum extent of the ice sheet in this part of the Głubczyce Plateau is unknown, because end moraines are absent and borehole data are ambiguous. It is, however, more or less accepted that the ice sheet reached the slopes of the Opava Mountains (Badura *et al*., 1996*a*, *b*).

DESCRIPTION AND INTERPRETATION OF THE SITES INVESTIGATED

The three sites under study are situated in the upper reaches of the Troja River valley, several kilometres apart from each other (Fig. 2). The deposits examined represent slightly different stages of glaciomarginal deposition of the final phase of the maximum ice sheet advance.

WŁODZIENIN SITE

The Włodzienin site is situated at the watershed between the valleys of the Troja and Psina rivers, on the valley side of a small left-bank tributary of the Troja River (Fig. 4A).

LITHOFACIES CHARACTERISTICS

The gravelly-sandy and sandy deposits in this exposure, with a till on top, constitute six facies associations (Fig. 4B). Glaciogenic deposits are covered by thin bed of loess. The total exposed thickness is about 12 m.

The lowermost facies association (1) — GSp, GSt, (Gh, Sh, Sp) — consists of fine-grained gravel and sandy gravel forming thick units with planar cross-stratification (GSp) (Fig. 4B). Thick gravelly and gravelly-sandy lithofacies with trough cross-stratification (GSt) are also common. Units of horizontally stratified gravels (Gh) are less frequent. Sandy lithofacies with horizontal stratification (Sh) and planar cross-stratification (Sp) also occur, but are of secondary importance. The orientation of the cross-bedding indicates palaeocurrents that flowed towards the ESE (Fig. 4B). Gravels are dominated by quartz clasts (about 40%). Carboniferous sandstones constitute 28%. Crystalline rocks, including both Scandinavian and Sudetes material, constitute about 10%.

Facies association (2) — Sh, (Sr, Sm) — is composed of fine-grained sand, mostly with horizontal lamination (Sh) (Fig. 4B). Thin (3–6 cm) interlayers of sand with ripple cross-lamination (Sr) and massive sand (Sm) occur sporadically.

Facies association (3) — St — consists of a coset of extremely large trough structures with thicknesses reaching 1–1.5 m and widths of about 20–25 m (Fig. 4B). It is composed of coarse- and medium-grained sands, sometimes with an admixture of fine-grained gravels. The thickness and width of this lithofacies decrease laterally (to 50–70 cm and 4–6 m, respectively). The axes of the thick trough structures have an ESE–WNW orientation.

The thin facies association (4) — GSp — which is found on top of facies association (3), contains several beds of sandy gravel with planar cross-stratification and thicknesses of 20–40 cm (Fig. 4B). This association is characterized by dip directions of cross-strata almost opposite to those measured in the under- and overlying deposits. They indicate northwards — running palaeocurrents (Fig. 4B).

Facies association (5) — Sp, (Sh, St, Sr) — is dominated by lithofacies of fine- to coarse-grained intermediate sand layers with planar cross-stratification (Sp). Intermediate units of sand with horizontal stratification (Sh), trough cross-stratification (St) or ripple stratification (Sr) are less frequent. The cross-stratification indicates that palaeocurrents flowed towards the S-SW (Fig. 4B).

The sandy deposits are overlain by a sandy-silty diamicton Dm (6) about 5–6 m thick (Fig. 4B). Its basal contact is sharp. A thin layer (15–25 cm) of grey, stratified diamicton is present in the lower part. It is overlain by 2.5–3 m of brown, massive diamicton, in which locally a system of small oblique fractures and sets of shear planes, mostly of P and R type, is present, oriented in NE–SW. The fabric shows a strongly preferred orientation of clasts (Fig. 4B). The massive diamicton is capped by a layer of light brown diamicton about 3 m thick. This strongly weathered deposit is usually massive, but locally has a laminated structure. Intercalations of gravel and sand-rich diamicton, with chaotic orientation of clasts, are found at several places in the exposure.

INTERPRETATION OF THE SEDIMENTARY ENVIRONMENT AND PALAEOGEOGRAPHY

The deposits of facies association (1) were formed by a temporarily high-energy braided river with various types of channel-bed relief. The thick lithofacies GSp indicates a moderately deep channel dominated by transverse bars with distinct progradational fronts accreting during floods (*cf*. Smith 1971; Miall 1977, 1996; Cant 1978). The gravelly lithofacies with trough cross-stratification (GSt) formed in the thalwegs, where the current velocity was the highest. Under conditions of high-energy discharge, the channel bed was eroded, and the resulting troughs were filled with gravel when flow competence decreased (*cf*. Siegenthaler and Huggenberger, 1993; Slater, 1993). Gravel sheets were deposited from critical and super-

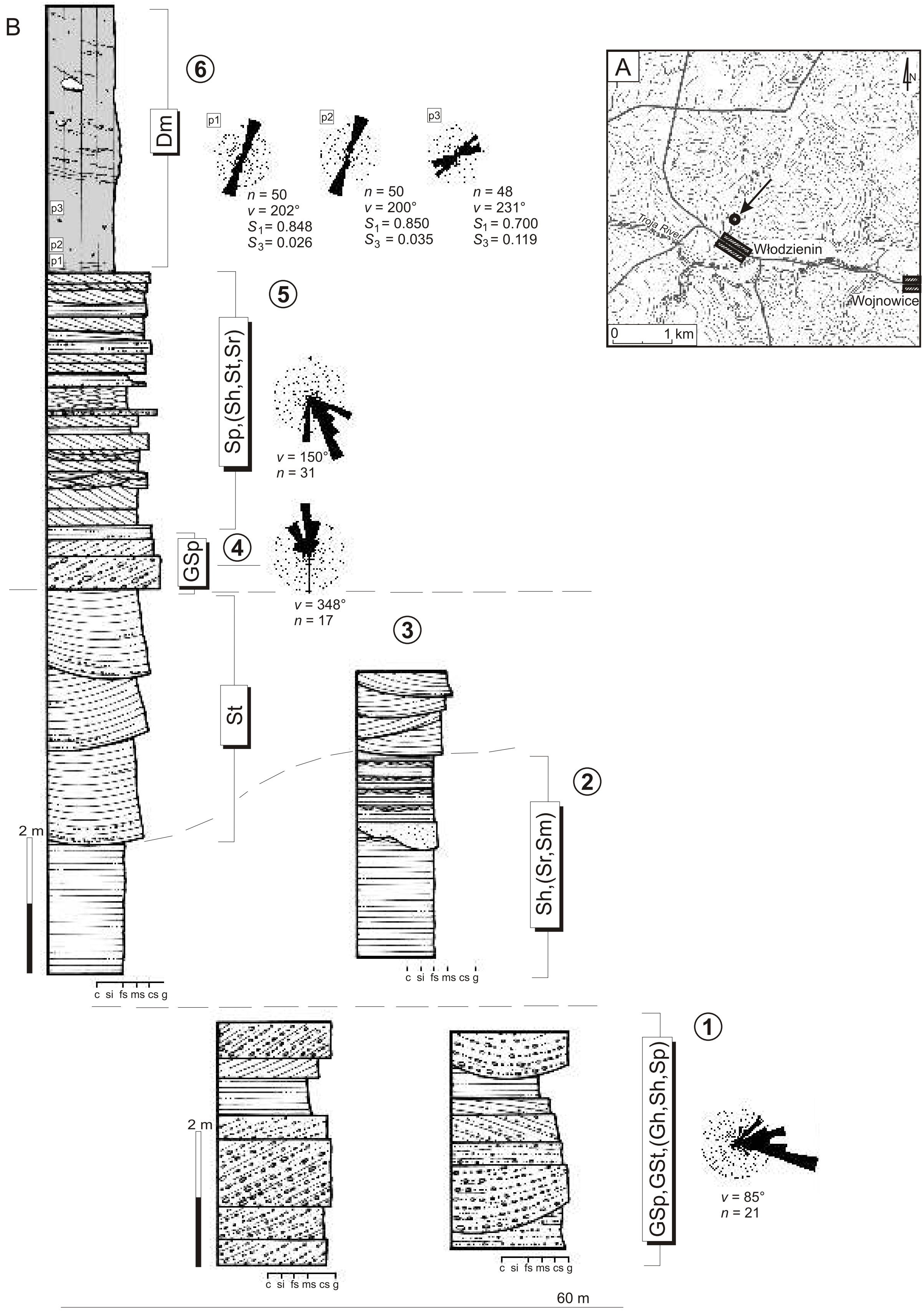


Fig. 4. A — topography of the study area with the Włodzienin site location (arrowed); B — sedimentary logs from the Włodzienin site

For explanations see Figures 2, 3 and Table 1 critical currents in shallower zones of the channels (the origin of lithofacies Gh). The sandy lithofacies represent deposition during stages of lower water in the main channels, or flood stages in second-rank channels.

The thickness of the lithofacies indicates that they were deposited in a river with high discharge. Therefore, they do not seem to be deposits of the Troja River. However, the Osobłoga River was dammed by the ice sheet a dozen kilometres to the NW of the site (Figs. 2 and 5A). Its waters very probably overflowed the low watershed and ran through the Troja–Psina valley system at the time. Such an origin is supported by the eastwards direction of the palaeocurrents, and by the petrographic composition of the gravel, which includes mostly material derived from the Osobłoga River catchment area, i.e. Carboniferous sandstones. The presence of crystalline rocks suggests that the river system was also fed by glacial water. The sediments were probably deposited while the ice sheet advanced in the valley area.

Facies association (2) reflects a distinct change of depositional environment. The predominantly horizontally stratified fine-grained sands (Sh) were deposited by very shallow currents under upper-stage plane-bed conditions. The wide extent of this lithofacies indicates deposition from sheetflows. This probably occurred on a distal glaciomarginal fan (Zieliński and Van Loon, 1999, 2000) prograding over an alluvial plain (Fig. 5B). The waters of the Osobłoga River then probably no longer flowed into the Troja–Psina valley.

The overlying facies association (3) of the very thick lithofacies St represents completely different hydrodynamic conditions. Lithofacies St formed in a deep zone in a channel with high-energy currents. The erosion/accumulation structures probably represent sets of large dunes. Comparable, 1 m thick, lithofacies St have been described by, among others, Gibling and Rust (1987), who also related them to large 3-D dunes. This suggests a very large size of the channel and great power of the currents. In my opinion, the genesis of the St unit was, however, somewhat different, viz. by sedimentation during one or several flood episodes in the Troja–Psina valley. Many researchers relate this type of lithofacies with the deposits formed in the main sand-bed channels of braided systems (Cant, 1978; Zieliński and Van Loon, 2003) because they must result from strong fluctuations in discharge, typical of the proglacial river environment (Miall, 1978; Cant and Walker, 1978; Brodzikowski and Van Loon, 1991). The thickness of the trough structures and their occurrence between the lithofacies associations representing shallow currents of low power and competence indicate that facies association St was rather the result of allogenic (non-glacial) parameters in a very large fluvial system. The deposits are presumably related to periodic drainage events of an ice-dammed lake in the neighbouring valley of the Osobłoga River. After the interval when this river ran towards the SE through the Troja–Psina valley (Fig. 5A), the advancing ice sheet blocked the narrow zone of the low watershed between these two valleys (Fig. 5B), and a terminoglacial lake started to form in the ice-dammed valley of the Osobłoga River. However, ice front oscillations in this zone probably caused intermittent sudden releases of lake water, which then flowed into the Troja–Psina valley (Fig. 5C).

The overlying deposits of facies association (5) were deposited in a sand-bed braided river of moderate energy. Small transverse bars (the origin of lithofacies Sp) were the main elements of the system. Lithofacies St records megaripples developing in deeper parts of the channel, whereas

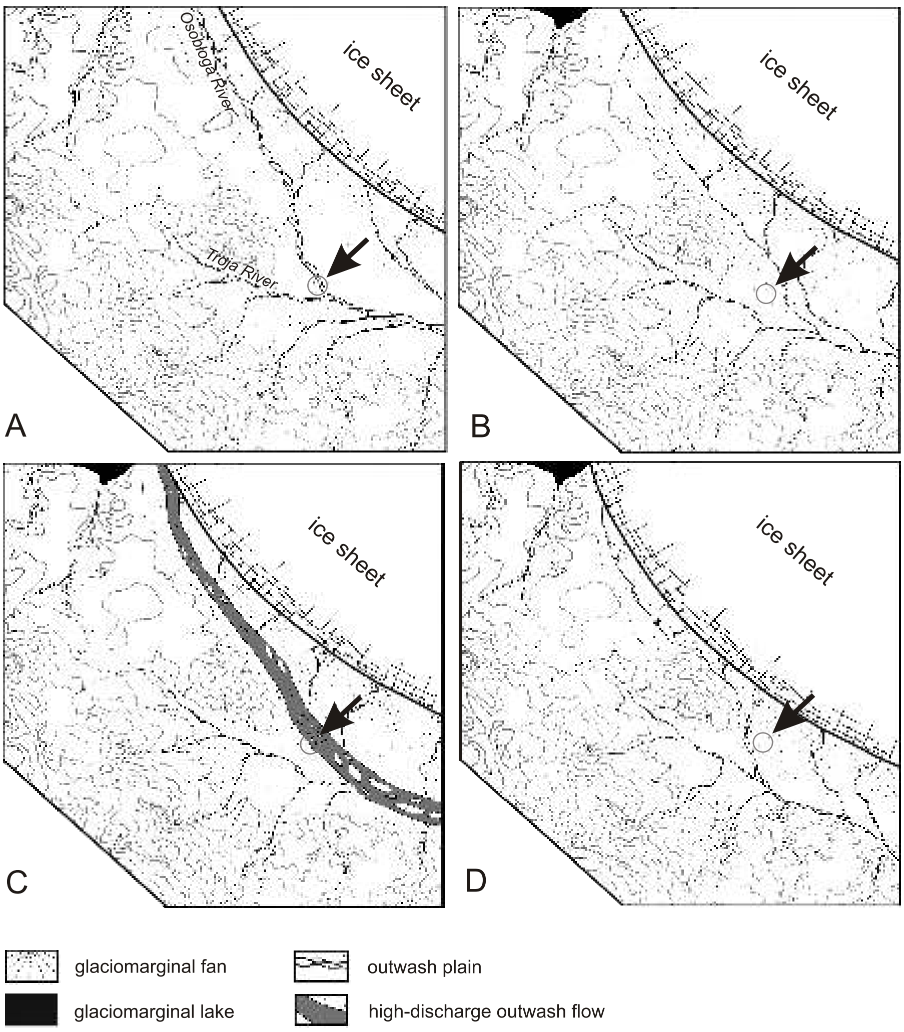


Fig. 5. Palaeogeography of the glaciomarginal zone in the surroundings of the Włodzienin site

Study site is arrowed; detailed explanation is in the text lithofacies Sh reflects plane-bed and shallower, supercritical currents. The rippled cosets (Sr) were deposited during low-water stages. The dominance of southwards running palaeocurrents indicates a glacial water supply. The deposits of this association are therefore interpreted to represent the proximal part of a glaciomarginal fan (Fig. 5D).

The facies associations (2) and (5) form a succession reflecting the progradation of glaciomarginal fans into the Troja–Psina valley, which was interrupted by phases when water of a terminoglacial lake in the ice-dammed valley of the Osobłoga River entered the Troja–Psina valley after having overflowed the low watershed between both valleys. The energy level of the water currents on the fans was not very high, so that primarily sandy deposits accumulated in the foreland of the ice sheet.

Extraglacial rivers in the southern part of the catchment area shifted systematically towards the southern sides of the valley (Fig. 5D), and ran sporadically through the area directly in front of the ice sheet. This is indicated by lithofacies association (4), within which cross-stratification indicates that palaeocurrents flowed towards the N.

The profile is topped with a diamicton (6) that can be explained reasonably only as a glacial till. This supports the interpretation of ice sheet advance in the area of the Troja–Psina valley. The lower part of the diamicton is a basal till related to active ice, as indicated by fractures and shear planes resulting from horizontal stress, and the strongly preferred orientation of the clasts. The upper part of the diamicton is a flowtill. Its deposition was the result of cohesive flows of ablation material from the ice sheet surface (*cf*. Lawson, 1981, 1989). The intercalations of layers with a higher gravel content reflect mass flows of lower density and fluvial redeposition (*cf*. Ruszczyńska-Szenajch, 1982; Hubert and Filipov, 1989; Kozarski, 1990; Blair and McPherson, 1994). The deposition of the flowtill occurred during recession of the ice.

LEWICE SITE

The Lewice site is situated about 5 km WSW of the Włodzienin site (Fig. 2). The sandpit is located within a flat area that is several hundred metres wide and strongly dissected, at 290–300 m a.s.l., at the foot of the hills bordering the Troja River valley in the SW (Fig. 6A). Badura *et al.* (1996*a*, *b*) described this flat area as a kame terrace.

LITHOFACIES CHARACTERISTICS

Sandy and sandy gravelly deposits with a total thickness of about 15 m are exposed in the sandpit. Two series of deposits are distinguished (Fig. 6B).

In series 1, two facies associations are distinguished (Fig. 6B). The first association (1a) — Sp, Sh, (Sl, St, SGp) — consists of medium- and coarse-grained sands, locally fine-gravelly sands forming mostly lithofacies of intermediate thickness with planar cross-stratification (Sp). Sands with horizontal stratification (Sh) are slightly less frequent. Sands with low-angle planar cross-stratification (Sl) and trough cross-stratification (St) are of secondary importance.

A finer-grained facies association (1b) — Sh, Sr — also occurs in series 1 (Fig. 6B), but has a limited extent. It is composed mainly of fine-grained sand. The association is dominated by horizontally laminated lithofacies (Sh) of intermediate thickness. This facies contains also cosets with trough cross-lamination (Sr). Lithofacies Sp, Sl and St are rare.

Series 2 consists of somewhat coarser-grained deposits that form two facies associations (Fig. 6B). In the lower facies association (2a) — Sh, SGh, (GSm, Sl) — medium- and coarse-grained sands and gravelly sands with horizontal stratification (Sh, SGh) are the most frequent. The sandy lithofacies are dominated by 15–30 cm thick units. The lithofacies SGh are usually thinner (5–10 cm). Intercalations several centimetres thick of fine-grained gravel also occur in the sands. Together they form fining-up rhythms. Thin (up to 10 cm) lithofacies of massive sandy gravel (GSm) and lithofacies of intermediate thickness, consisting of gravelly sand and sand with low-angle cross-stratification (Sl) are of secondary importance. Rare lithofacies of massive gravel (Gm) with thicknesses of 30–50 cm, are found in the upper part of the association. Sandy lithofacies with planar cross-stratification (Sp) and trough cross-stratification (St, SGt) are of minor importance.

The thin facies association (2b) — Sp, Sh, (Sl, GSm, St) — that is present in the uppermost part of the series, is characterized by a smaller grain size and thinner units (Fig. 6B). It consists mainly of medium-grained sand. Lithofacies with planar cross-stratification (Sp) and horizontal stratification (Sh) dominate. Lithofacies with low-angle planar cross-stratification (Sl), lithofacies with trough cross-stratification (St) and thin lithofacies of massive sandy gravel (GSm) occur as secondary components.

The dip azimuths of cross-stratifications were measured in several parts of the section. They indicate a great variability of palaeocurrent directions, from SW to E (Fig. 6B). In the lower series, the SE direction dominates, whereas the directions vary from SW to SSE in the upper series.

Petrographic analyses of gravel from the lower and upper parts of the profile did not show significant differences. Quartz is predominant (39–42%). Crystalline rocks, from both Scandinavia and the Sudetes, make up about 20%. Carboniferous (Culm) sandstones are somewhat less frequent (15–18%). Other rock types reach only a few percent.

INTERPRETATION OF THE SEDIMENTARY ENVIRONMENT AND PALAEOGEOGRAPHY

The deposits of the lower series, developed as facies association (1a) were deposited by a relatively shallow braided river system with many shoals (lithofacies Sh) and small transverse bars (lithofacies Sp, SGp), which were often eroded to lower forms (lithofacies Sl). Sinuous megaripples (cosets St) developed locally in the zones of the main gullies.

Facies association (1b) was formed under conditions of lower energy. Lithofacies Sh was deposited from very shallow currents of a transitional regime, whereas lithofacies Sr was formed in the lower part of the lower flow regime. These sediments were probably deposited in a second-rank channel of the braided system.

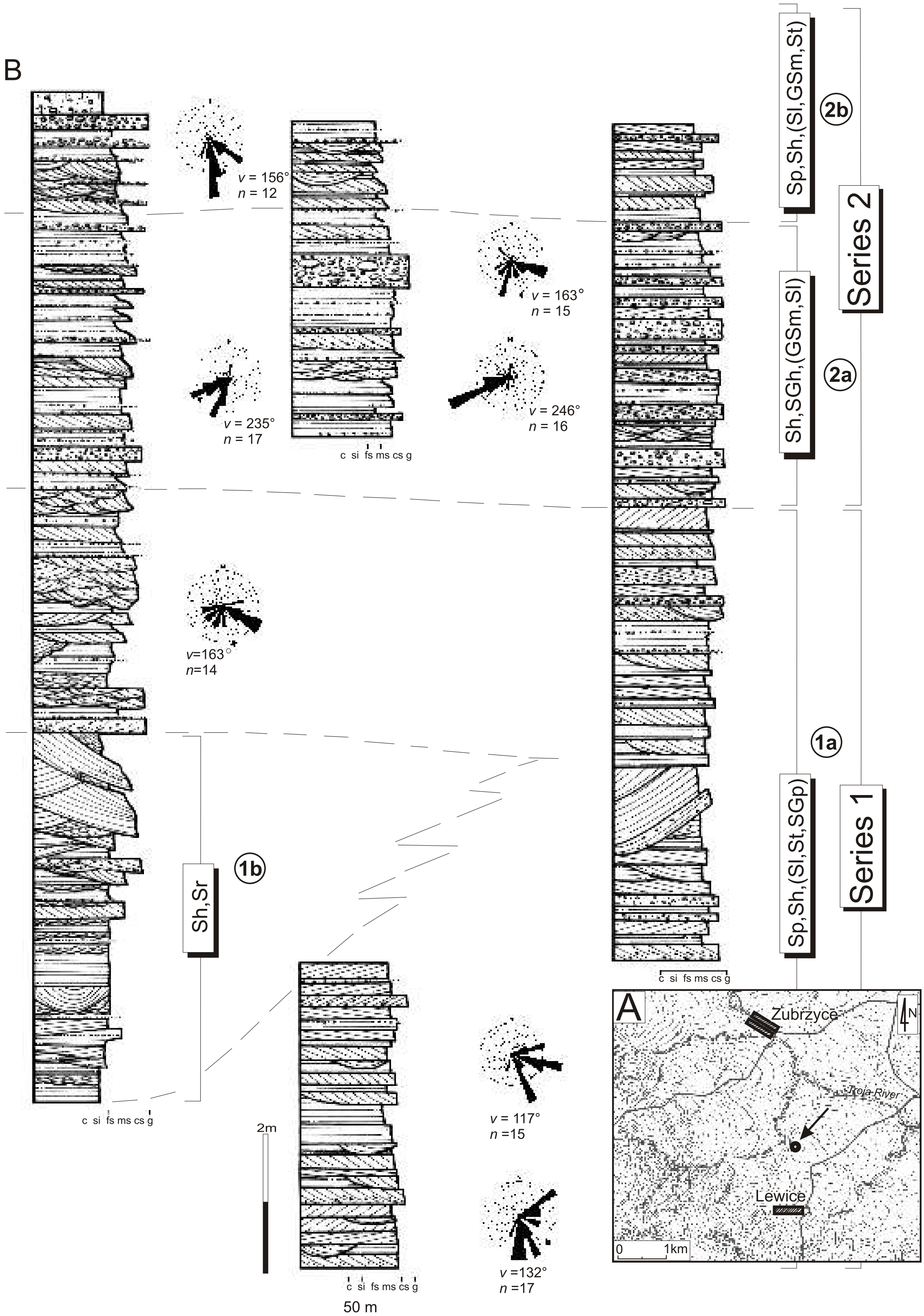


Fig. 6. A — topography of the study area with the Lewice site location (arrowed); B — sedimentary logs from the Lewice site

For explanations see Figures 2, 3 and Table 1

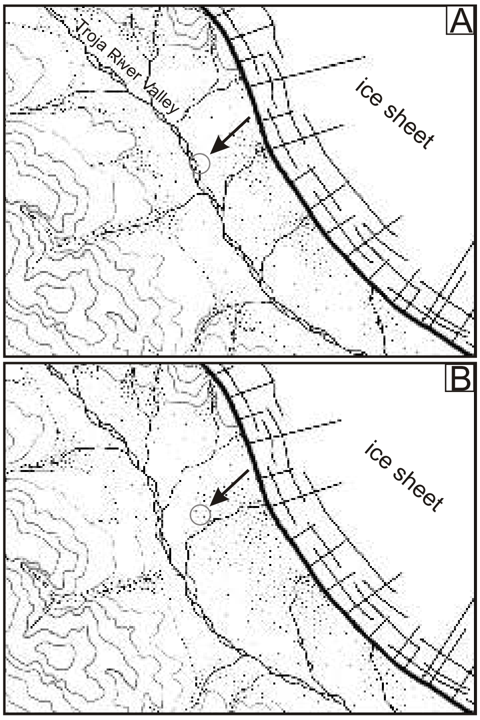


Fig. 7. Palaeogeography of the glaciomarginal zone in the surroundings of the Lewice site

Detailed explanations is in the text, for other explanations see Figure 5

Series 1 was deposited in a valley outwash plain in the upper reaches of the Troja River valley (Fig. 7A). Thus, they were probably associated with a typical sand-bed braided river flowing along the valley axis, approximately parallel to the supposed ice sheet front. This system thus functioned as an ice-marginal river. This is confirmed by directions of palaeoflows (Fig. 6B).

In the upper series, facies association (2a) is characterized by somewhat higher energy and shallower currents. The predominant lithofacies of sand and gravelly sand with horizontal stratification (Sh, SGh) was deposited by supercritical sheetfloods under upper-stage plane-bed conditions. The thin sandy/gravelly rhythms represent brief floods controlled by cyclic ablation (*cf*. Klimek, 1972; Olsen and Andreason, 1995; Zieliński and Van Loon, 1999). The lithofacies of massive sandy gravels (GSm) and gravels (Gm) formed during high-energy floods. In the first stages of these floods, water covered a wide area and the river bed was flat. The lithofacies Sh, SGh and GSm were deposited as thin sheets. Flat mid-channel bars without distinct progradational fronts were the parent forms of lithofacies Sl. Locally, in somewhat deeper zones, dunes were formed (the origin of lithofacies St, SGt). The sediments of this association were deposited in shallow, wide channels, in which the predominant currents were similar to sheetfloods. Rare, low-relief forms occurred locally on the bottoms of these channels. The second facies association (2b) was associated with somewhat more channelized flows, as indicated by the larger frequency of lithofacies Sp, which represents transverse bars. The limited thickness of the lithofacies and the somewhat finer grain size suggest a lower current energy.

Series 2 was probably deposited on a glaciomarginal fan that prograded over an outwash plain (Fig. 7B). The tabular lithofacies Sh, SGh and GSm, typical of sheetflow-dominated fans (*cf*. Heward, 1978; Abdullatif, 1989; Blair and McPherson, 1994; Zieliński and Van Loon, 1999, 2000), prevail in this series. Moreover, the directional data indicate that currents ran most commonly perpendicular to the front of the ice sheet, not parallel to it as they had done earlier. The more channelized currents of the upper association could be the result of incision of the fan surface during retreat of the ice.

The sediments at this site must have been deposited somewhat later than those at the Włodzienin site, probably when the ice sheet was near its maximum extent. They represent a system of fans passing distally into the valley outwash plain that stretched along the ice sheet front (Fig. 7B). Such a situation makes it possible to interpret these deposits morphologically as kame terraces, as suggested by Badura *et al*. (1996*a*, *b*).

ZOPOWY SITE

The Zopowy site is situated in the upper reaches of the Troja River valley (Figs. 2 and 8A), at the foot of a hill separating the valleys of the Troja and the Łącznik (a tributary of the Psina River). The hill, composed of Early Carboniferous sandstones and mudstones, reaches 312–324 m a.s.l. It is covered with loess that locally, on the NE slopes of the hill, is underlain by till (Badura *et al*. 1994). The sandpit is located within a small area 295–300 m a.s.l., at the foot of a concave slope.

LITHOFACIES CHARACTERISTICS

Sandy and gravelly deposits with a total thickness of 10–12 m directly overlie the hard-rock substratum that forms the floor of the excavation. Numerous fragments of these rocks are found as clast in the overlying sands, especially in their lower part. Three facies associations are distinguished (Fig. 8B).

The lowest facies association (1) — Sh, SGh, (Gm) — is dominated by a sand lithofacies of intermediate thickness, with horizontal stratification (Sh) (Fig. 8B). These poorly sorted medium- or coarse-grained sands often alternate with thin (up to several centimetres) units of gravelly sand (SGh), forming fining-up sequences. Poorly sorted, fine-grained, usually matrix-supported massive gravels (Gm) are less frequent. Their matrix consists of sand. The mean thickness of lithofacies Gm is 10–20 cm (maximum 50 cm). Just like the sandy lithofacies, most units have a tabular shape and a wide horizontal extent. Individual lithofacies of gravel-rich sandy/silty diamicton form rare elements of this association. They form lenses with thicknesses of up to 50 cm and widths of a dozen or so metres. Silty sand (lithofacies SFh) occurs also rarely.

The overlying facies association (2) — Sp, Sh, (Sl, St) — contains thin (usually less than a few centimetres) sand lithofacies with horizontal stratification (Sh) and sand lithofacies of intermediate thickness, with planar cross-stratification (Sp) (Fig. 8B). Sand lithofacies (up to 15 cm thick) with low-angle cross-stratification (Sl) and (St) occur less frequently.

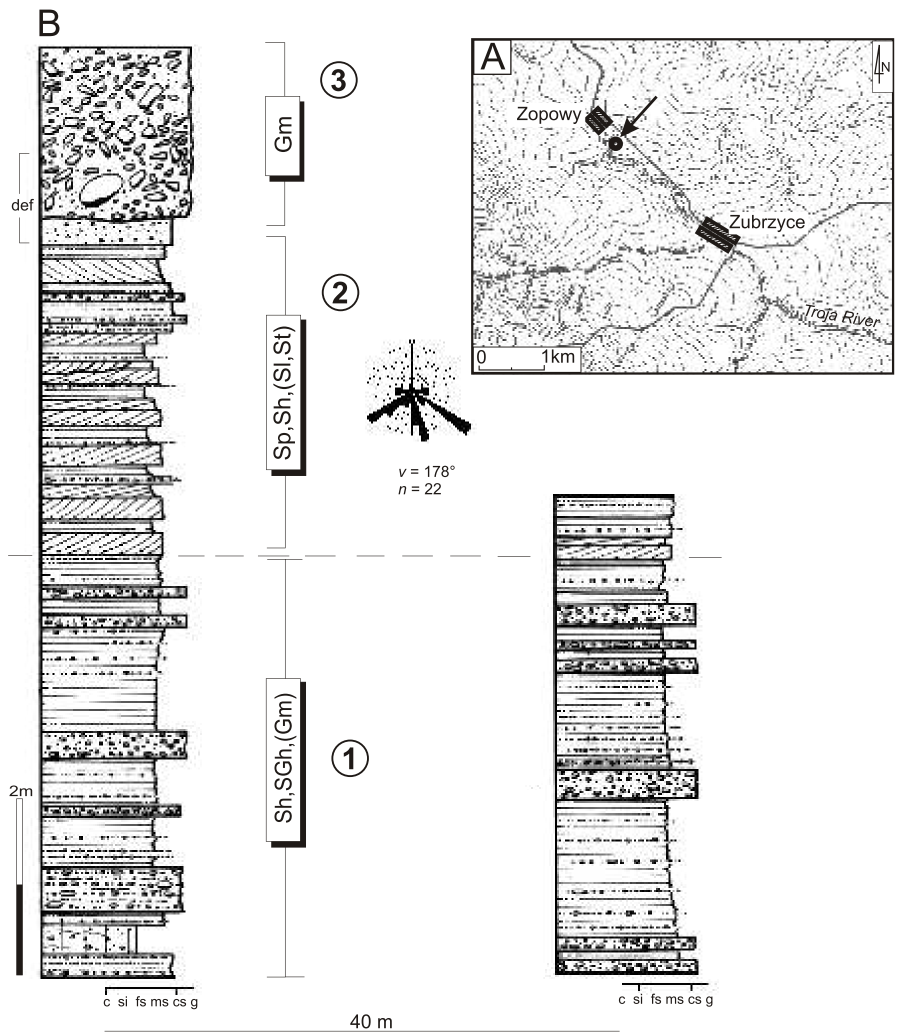


Fig. 8. A — topography of the study area with the Zopowy site location (arrowed); B — sedimentary logs from the Zopowy site

For explanations see Figures 2, 3 and Table 1

The uppermost facies association (3) — Gm — is composed of considerably coarser-grained deposits (Fig. 8B). It consists of very poorly sorted, usually matrix-supported massive gravels. The matrix consists of sands with an admixture of fine-grained gravel and some silt. These deposits form a bed 2 m thick. Clasts of several centimetres prevail, but some reach over 25 cm. The roundness of the coarse clasts varies strongly. Most common are clasts with sharp edges; slightly rounded clasts consist of Carboniferous sandstones. The rest of the clasts are usually well rounded and of various petrographic compositions. The lower boundary of this association is locally deformed, showing a convoluted nature.

The dip azimuths of the cross-strata were measured only within the middle association. They indicate a wide spread of current directions, from W to E. The mean direction is 178°.

Quartz (35%) and local Carboniferous sandstones (24%) dominate the gravel in the lower association, but crystalline rocks also constitute a rather large group (20%). In the uppermost association, Carboniferous sandstones dominate the coarse gravel. In finer fractions, the content of sandstones is slightly lower, whereas the percentage of quartz and crystalline rocks is higher.

INTERPRETATION OF THE SEDIMENTARY ENVIRONMENT AND PALAEOGEOGRAPHY

The sands and gravelly sands with horizontal stratification (Sh, SGh) that dominate the lower facies association (1) and the accompanying massive gravels (Gm) were deposited by shallow, supercritical flows. The large horizontal extent of these lithofacies indicates that the deposits formed thin sheets in streams that ran over wide areas. The current intensity changed rather often, as indicated by the several centimetres thick rhythms (SGh-Sh). The sediments of lithofacies SGh were deposited during flood peaks, whereas those of lithofacies Sh represent waning flood stages. The gravel sheets formed during floods with the highest energy. The sheet-like shape of the units within the lower facies association suggests an origin on a small fan dominated by sheetflows (*cf*. Krüger, 1997; Moreno and Romero-Segura, 1997).

The fan sediments were deposited at the distal side of the hill forming the watershed between the valleys of the Troja and the Psina rivers, which probably also marked the maximum extent of the ice sheet in this part of the valleys (Fig. 9A). This hypothesis is supported by the lack of till under the glaciofluvial deposits. The fan was fed by supraglacial meltwater. The admixture of local rocks indicates that also debris washed out from slope covers was also redeposited on the fan. Lobes of flowtill occasionally also reached the fan, as indicated by the occurrence of diamicts. However, these diamicts were usually reworked by streams.

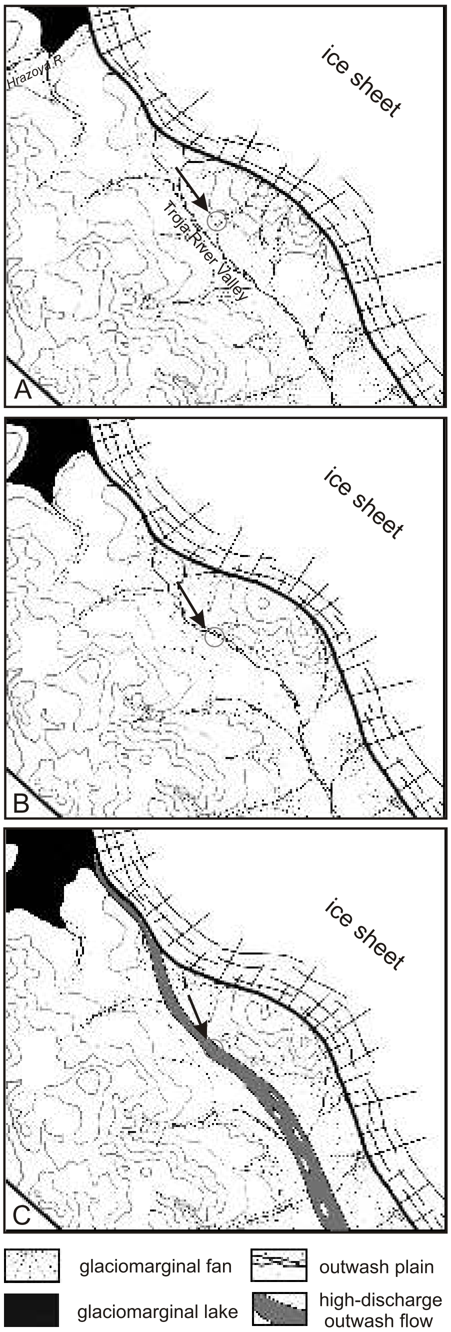


Fig. 9. Palaeogeography of the glaciomarginal zone in the surroundings of the Zopowy site

Study site is arrowed; detailed explanation is in the text

Facies association (2) indicates an environmental change into more channelized flows within a small braided river with mid-channel transverse bars (lithofacies Sp) that were washed out during floods (lithofacies Sh, Sl), and with somewhat deeper zones for the main current, where megaripples developed (lithofacies St). A considerable amount of channel sediment is often found in the central parts of alluvial fans (McGowen and Groat, 1971; Abdullatif, 1989; Zieliński and Van Loon, 1999, 2000). However, the change of sedimentation style is in this case not related with deposition in another part of the fan, because fan accretion probably stopped simultaneously with the first phase of ice sheet retreat. Ablation waters stopped overflowing the marginal hill but still ran along the Troja River valley from the NW (Fig. 9B). This interpretation is strongly supported by palaeocurrent measurements. Due to aggradation that took place in the valley, the fan was built up by deposits of a small braided river (Fig. 9B).

The succession is topped with the gravelly facies association (3), which was deposited from a high-energy hyperconcentrated current (lithofacies Gm). This is indicated particularly by the coarse grain size of the deposits, their considerable thickness, the lack of grading, the locally clast-supported character, and the rather low content of fines. The chaotic orientation of clasts, the massive structure of the deposit, and the convolution structures at the contact with the underlying sands indicate very sudden deposition from a strongly overloaded stream. A high competence of the current is interpreted from the size of the largest clasts (over 25 cm). Similar deposits are known from the foreland of Icelandic glaciers, where they form during megafloods of jökulhlaup type (Maizels, 1989, 1997; Russell and Maren, 1999). The sudden and significant increase of current energy may have been due to the same conditions that were associated with the St association at the Włodzienin site. The sudden deposition from a strong current, in combination with the predominance of local, sharp-edged material, suggests that the deposits were formed during drainage phases of the glaciomarginal lake that probably existed in the ice-dammed valley system of the Osobłoga River and its tributaries, NW of the Troja River valley. The valleys of the Hrazova (a small tributary of the Osobłoga River localized westwards from the Troja valley) and Troja rivers are now separated by a low watershed (Fig. 2) so that drainage can have taken place easily. According to this scenario, waters from the lake overflowed this barrier and flowed along the ice front towards the SE, into the Troja River valley (Fig. 9C). The regolith on top of the watershed was probably washed away and provided the majority of the gravels that were deposited in the Troja River valley. Sandstones and mudstone clasts are only slightly rounded because they were transported over just a short distance.

Huge floods caused by sudden drainage of dammed lakes occur in many regions (*cf*. Clarke *et al*., 1984; Sturm *et al*., 1987; Maizels, 1993; Rudoy and Baker, 1993). Many examples are found in mountain areas where advancing glaciers dam tributary valleys (*cf*. Hewitt, 1982; Johnson and Kasper, 1992).

DISCUSSION AND CONCLUSIONS

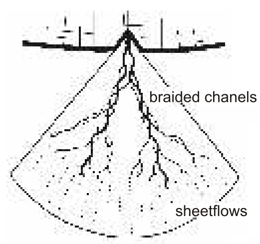
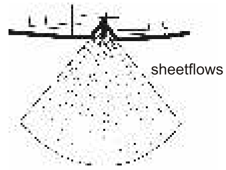
The three sites under study show the development of a glaciomarginal zone in morphologically different fore-mountain areas. The deposition in the Troja–Psina valley started when the ice sheet overflowed the local watershed separating the southern part of the plateau from the northern one. The ice sheet advanced from the NE, perpendicular to the valley axis. The relief of the glacial foreland was the main factor controlling the development of the glaciomarginal zone. The style of sedimentation varied with the changing position of the ice front with respect to the various morphological elements. Initially, the river network underwent strong transformation: in valleys perpendicular to the ice front and inclined toward the ice sheet, drainage became blocked and terminoglacial lakes formed, whereas rivers in valleys parallel to the ice front continued flowing along the ice front. Next, the evolution of the glaciomarginal zone was controlled by the morphology of the valleys themselves. Due to the water-level rise in the dammed lakes and to the rather low watersheds between the valleys, meltwater currents could flow from one valley to another. In some cases, these currents had a torrential character, particularly when thermal erosion of the ice sheet barrier took place by the waters of the dammed lakes, which were warmed during summer. When the ice barriers in the watershed area failed, sudden high-energy currents resulted.

The glaciomarginal fans that formed in the valley in front of the ice sheet passed distally into valley outwash plains. Different types of fans formed, two types being prominent (Table 2). The first type includes forms where, in the proximal part, water followed shallow channels with few mid-channel bars, whereas sheetfloods dominated in the distal part. This is characteristic of larger alluvial fans with a gentle slope (McGowen and Groat, 1971; Abdullatif, 1989). This type was found at the Włodzienin site. The second type of fan is represented by small forms, completely dominated by sheetflood deposits, as found at the Zopowy and Lewice sites.

The morphological differences between the fans resulted from differences in size of the feeding supraglacial streams (discharge, particle load, duration of deposition), and from different positions of the fans with respect to the relief of the substratum. The fan at the Włodzienin site was formed on a wide valley floor when the ice sheet front was in its northern part. The fan at the Lewice site was formed near the ice front during its maximum extent, within a considerably smaller accommo-

Table 2

Compilation of the most important elements determining the characteristics of glaciomarginal fans in the study area

Fan type	Sedimentary succession	Lithofacies	Mechanism of deposition	Model of glaciomarginal fan
middle-scale, slightly sloped fan		proximal part: Sp, Sh, St distal part: Sh, (Sr)	proximal part: deposition from shallow braided river distal part: deposition from sheetflows	
small-scale, steep fan		Sh, SGh, Gm, (Sl, SGl)	deposition from sheetflows	

dation space, which was limited by the southern walls of the valley. The fan at the Zopowy site was formed at the distal side of a hill that stopped the ice sheet.

The fans are characterized by rhythmic sediments that reflect short ablation rhythms. This is the most obvious within smaller forms, due to alternations of coarser-grained (mostly gravel or sandy gravel) and somewhat finer-grained (mostly sand) lithofacies (Zopowy and Lewice). The fans are also characterized by a lack (or scarcity) of diamictons which are typical of the ice-contact environment (Ruszczyńska-Szenajch, 1982; Kozarski, 1990; Zieliński and Van Loon, 1999). The fans dealt with here therefore belong to the fairly rare category of glaciomarginal fans composed almost exclusively of meltwater deposits (compare the classification by Krzyszkowski and Zieliński, 2002).

As the ice advanced, the zone of glaciofluvial deposition in the Troja–Psina River valley became increasingly narrower (resulting in a reduction of the accommodation space). This triggered a higher rate of fan aggradation in the southern part of the valley (Lewice site), where glaciofluvial deposition reached a level that was about 15–20 m higher than in the middle part of the valley (Włodzienin site).

The direct influence of rivers on the development of the glaciomarginal zone in the valley under study was fairly insignificant. Except for sudden occurrences of currents flowing in from the neighbouring valleys, the local rivers ran along the valley outwash plain only sporadically, forming thin alluvial units. This was due to the small sizes of the catchment areas and to the low current power of the Troja River and its tributaries running from the slopes of the Opava Mountains.

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