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LATE SAALIAN (WARTANIAN) GLACIAL PALAEOGEOGRAPHY AND FORMATION OF END MORAINES AT THE NORTHERN SLOPES OF SILESIAN RAMPART, SOUTHWESTERN POLAND

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Abstract: There is evidence, hitherto often denied, for the ice marginal features, including the end moraine hills along the Silesian Rampart, SW Poland. These end moraines are attributed to the regional advance of the Wartanian ice sheet into its maximum position, which is also marked by subglacial till bed. The end moraine hills are located on the northern slopes of the Silesian Rampart and they are very rare, partly due to subsequent erosion, but mainly due to conditions not favourable for a remarkable proglacial accumulation. The Wartanian end moraines of southwestern Poland possess several features that suggest that they are end moraines with dominant waterlain, stratified sediments. They are interpreted as alluvial fans, where the ice margin is represented by a 'scarp'. They have semi-conical form, often plano-convex geometry and an average distal slope of 2–25°. These fans are equivalent to sheetflow-dominated or 'humid' alluvial fans in non-glacial environments. Sedimentary sequences of the end moraines consist mainly of coarse-grained material, with boulders up to 1.8 m in diameter, with typical sediments of 'proximal fan' with a highly pulsatory water discharge. The formation of the end moraine followed the formation of a proglacial lake and strong erosion after its drainage. The end moraine was formed during oscillation of the ice margin that resulted in local glaciotectonic deformation of the end moraine fan sediments (push) and a set of parallel hills, with successive younger alluvial fans (retreat).

Key words: proglacial environment, end moraines, ice-marginal sediments and processes, landscape evolution, Late Saalian, SW Poland

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INTRODUCTION

A set of 50–100 m high ramparts, stretching from northwest Germany to central Poland, was originally interpreted by Woldstedt (1927) as the end moraine zone of the Wartanian ice sheet (Warthe Stadium; Late Saalian). In southwestern Poland, these arcuate ramparts were named the Silesian Rampart which, as a whole, was interpreted by Berger (1937) as the Wartanian push moraine (Stauchmoräne). Meister (1935) and Schwarzbach (1942) found the Wartanian till bed truncating the deformed strata, as well as Wartanian proglacial deposits of sandur plains and of the Magdeburg–Wrocław Pradolina (Urstromtal, ice-marginal valley) in the southern foreland of the hills. Deformation of sediments down to a depth of *c.* 200 m (Połtowicz, 1961; Rotnicki, 1967; Brodzikowski, 1982) led to a conclusion that the deformation took place during earlier, more extensive glaciations (Early Saalian, Elsterian) rather than during the Wartanian (Krygowski, 1950; Walczak, 1951; Pachucki, 1952; Woldstedt, 1954; Rotnicki, 1967; Dyjor & Chlebowski, 1973; Winnicki, 1988, 1991; Krzyszkowski, 1992). Some authors even neglected the occurrence of Wartanian ice limit along the Silesian Rampart (Winnicki, 1988, 1991). However, recent investigations (*e.g.* Czerwonka *et al.*, 1997; Krzyszkowski *et al.*, 1997) provide data that confirm the presence of the Wartanian end moraines along the Silesian Rampart, but in a position suggesting that the Rampart itself is not an integral part of the ice marginal system.

The aim of this paper is to examine the Wartanian proglacial morphology and sedimentary facies, with special emphasis to the end moraines, and then to discuss them in a broad context of the pre-existing landforms and subsurface stratigraphy. The interpretation is based on data from several outcrops, three of them from the end moraine hills (Krzyszkowski *et al.*, 1997), and from surficial geology (Winnicki, 1979; Michalska, 1980; Łabno, 1998; Chachaj, 1998).

LANDFORMS AND SUB-SURFACE GEOLOGY

The study area comprises the eastern part of the Dalków Hills, the Wińsko Hills and the western part of the Trzebnica Hills (Figs 1, 2). The hills within the study area form five parallel arcuate ramparts that are dissected in their central part by the Odra river valley (Fig. 1). The hill axes reach up to 220 m a.s.l., whereas the main valley is located at 80–90 m a.s.l. Northwards and southwards of the hills, flat or slighty undulating till plateaux occur, either of early Saalian (Odranian; south) or late Saalian (Wartanian; north) in age. The latter is separated from the hilly zone by the 2–10 km wide valleys of the Odra and Barycz rivers (Fig. 1).

The Miocene clay (Poznań Clay) is sporadically exposed on top and slopes of the large hills, up to 170–220 m a.s.l. (Figs 1, 2). The *in situ* surface of this clay in the surrounding plateau is located at 80–110 m a.s.l. (Czerwonka *et al.*, 1997), and its recent position in large hills suggests glacitectonic thrusting. The arcuate hills have been inter-

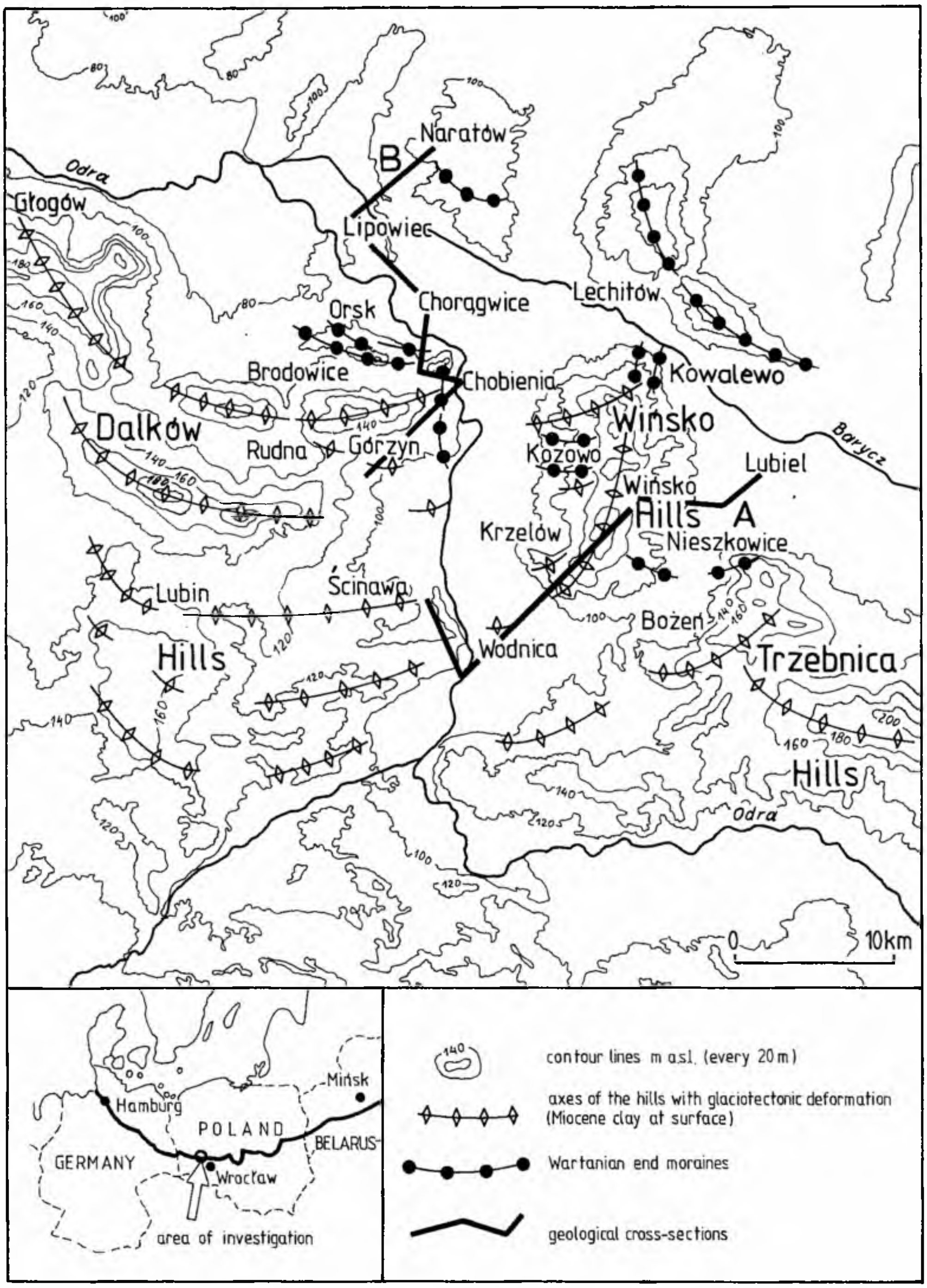

Fig. 1. Position of the Late Saalian (Wartanian) end moraines in relation to the glaciotectonic Dalków, Wińsko and Trzebnica Hills (Silesian Rampart) in southwestern Poland. Lower left: position of the studied area in the background of the Wartanian (Warthe) ice limit in Europe

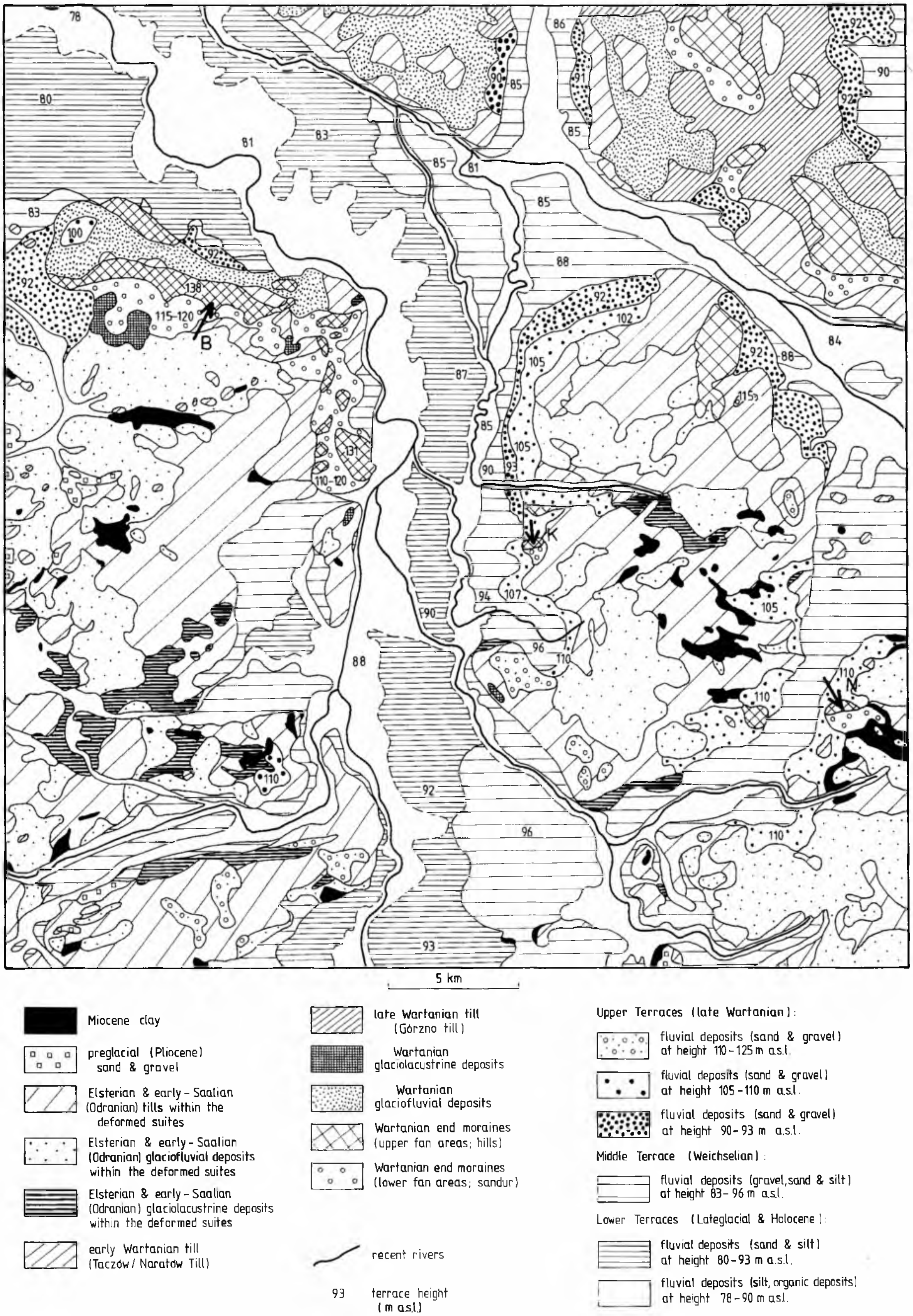

Fig. 2. Geological map of the study area (after Winnicki, 1979; Michalska, 1980; Chachaj, 1998; Łabno, 1998, modified). Arrows indicate positions of studied sections

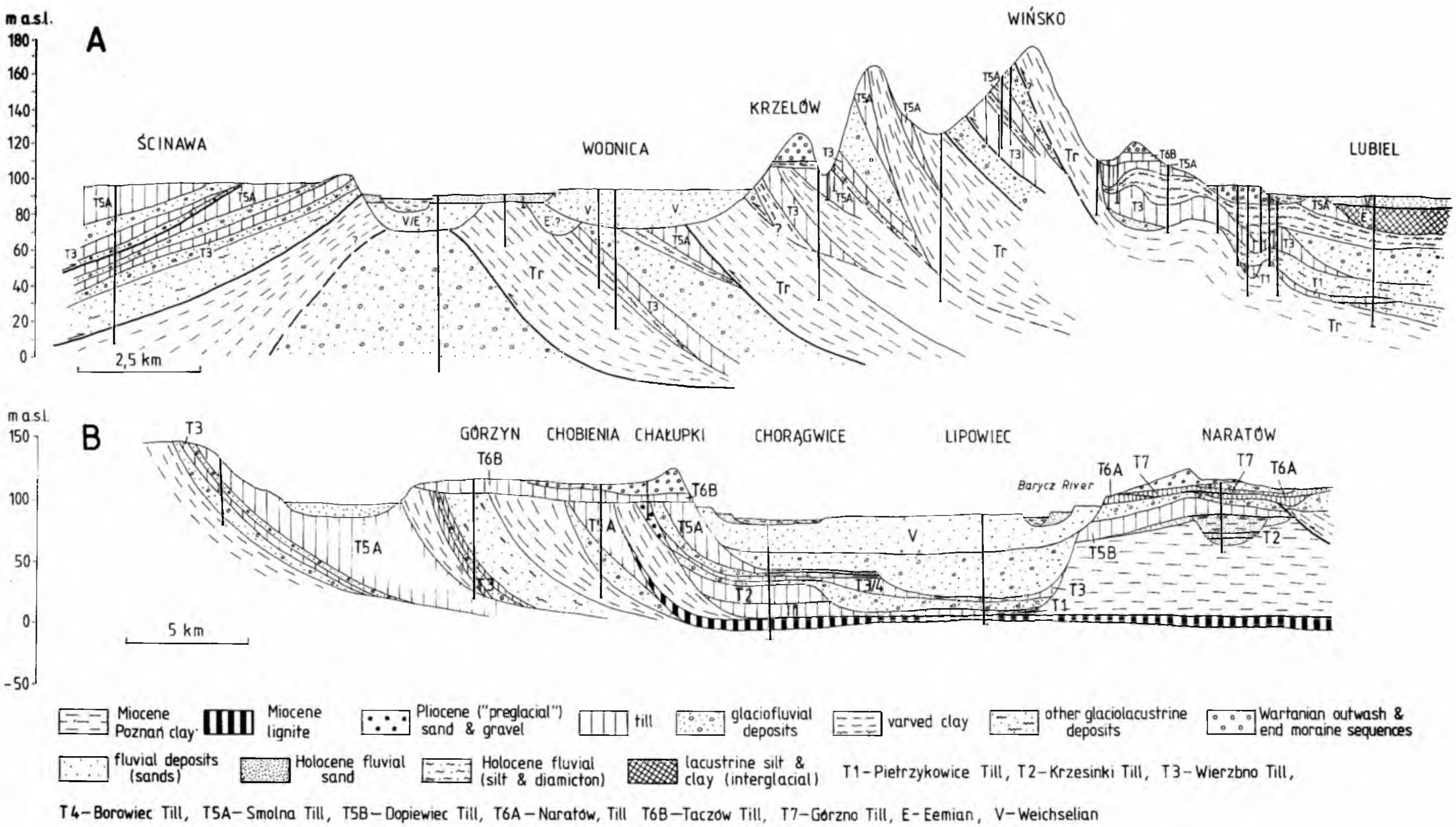

Fig. 3. Geological cross-sections through the Wińsko Hills (A) and the northeastern part of the Dalków Hills (B). Location in Fig. 1. Tr – Tertiary deposits, T1–T4 – Elsterian tills, T5A, T5B – early Saalian Smolna and Dopiewiec Tills, T6A – late Saalian (Wartanian) Naratów Till, T6B – late Saalian (Wartanian) Taczów Till, T7 – late Saalian (Wartanian) Górzno Till, E – Eemian deposits, V – Weichselian deposits

preted as glaciotectonic thrusts (Fig. 3), with the décollement surface near the bottom of the Poznań Clay at *c.* -20/+20 m. Pliocene and Pleistocene deposits, such as fluvial sands, tills, glaciofluvial sand and gravel and glaciolacustrine silt and clay are deformed in a similar fashion as the Poznań Clay.

Czerwonka *et al.* (1997) suggested that sediments from four glacial cycles may be involved within the deformation structures, as up to three Elsterian till beds (Pietrzykowice, Krzesinki and Wierzbno/Borowiec Tills) and one from the early Saalian glaciation (Smolna/Dopiewiec Till) have been found there. Additionally, on the northern slopes of large, arcuate hills with deformed sequences, a series of glacial deposits is superposed on the deformed strata (Figs 2, 3). This series comprises a till (Taczów Till; Czerwonka *et al.*, 1997), glaciolacustrine deposits and glaciofluvial sands and gravels. The sands and gravels occur in two geomorphological positions: (1) on uplands, forming 10–20 m high, asymmetrical hills, and (2) on the main valley sides, forming terrace levels (Figs 2, 3). The asymmetrical hills indicate fan morphology, that is, they have semi-conical form, often plano-convex geometry and an average slope between 2° and 20°. They are mostly composed of coarse-grained material and have a highly restricted occurrence, limited to the areas between Orsk and Chobienia, and Kozowo, Kowalewo and Nieszkowice (Fig. 1). These asymmetrical hills are discussed in detail in the paper as they are supposed to represent the Wartanian end moraines.

In more northern areas, outside the deformation zone, two till beds have been found above the early Saalian Dopiewiec Till, the Naratów and Górzno Tills, as well as glaciofluvial sand and gravel that form another end moraine zone (Figs 2, 3). All deposits younger than the Smolna Till have been included into the Wartanian stage (Czerwonka *et al.*, 1997). The Taczów Till of the deformed zone and the Naratów Till represent age-equivalent beds and they are presumably the products of an early phase of the Wartanian ice sheet advance, whereas the Górzno Till represents a younger Wartanian ice sheet advance (Czerwonka *et al.*, 1997). Younger deposits of the study area are represented by fluvial deposits, including three terraces, one of Weichselian and two of Lateglacial/Holocene age, some lacustrine deposits of Eemian age and abundant aeolian deposits on the terraces (Fig. 2).

LITHOFACIES

We have identified sixteen distinctive lithofacies types within the sedimentary successions of asymmetrical hills at Nieszkowice, Kozowo and Brodowice (Fig. 1). Eleven lithofacies are sediments unambiguously connected with end moraine depositional processes; the other five occur only in older sedimentary sequences that are exposed at Brodowice. Lithofacies description and interpretation are presented in Table 1.

Two lithofacies, namely the Gi and Si, need additional description as they can be easily misinterpreted. They represent thick, sheet-like bodies of gravel and sand with sediment stratification that can be related to the local morphology, that is bedding is paralell to the inclined morphological surface, which in this case represents the sedimentary (fan) surface. Both the fan surfaces and bedding are usually inclined between 10° to 25°. From the genetic point of view, lithofacies Gi and Si represent sheetflow beds formed on the inclined fan surface. These parallel inclined gravel (Gi) and sand (Si), when exposed in small outcrops, may be misinterpreted as large-scale planar cross-bedded gravel or sand (Fig. 4) or as horizontally bedded gravel or sand (see Fig. 5). However, observations in large outcrops show undoubtedly that the bedding is conformable with the primary sedimentary surface (Figs 6, 7).

Two facies associations are present in the asymmetrical hills, which may be connected with the end moraine environment. The first one (1) comprises mainly alternating beds of parallel inclined gravels, massive gravels and matrix-supported gravels (lithofacies Gi, Gm and Gms), with a minor occurrence of parallel inclined sand (lithofacies Si), cross bedded gravels (lithofacies Gt) and matrix supported boulders (lithofacies Gms(b)). Medium- and small-scale cross-bedded sands (lithofacies St and Sr) and massive silts (lithofacies Fm) occur sporadically and form thin beds.

The most spectacular deposits within this facies association are matrix-supported gravels (lithofacies Gms) and, especially, matrix-supported boulders (lithofacies Gms(b)). Both lithofacies contain diamictic (sandy-clayey) gravels, usually massive to crudely bedded, which fill narrow and relatively shallow erosional channels forming palaeochannel-like bodies. The lithofacies Gms(b) contains additionally several large boulders, with diameter up to 1.8 m, and common clay balls formed of Miocene clay and till. The Gms and Gms(b) lithofacies were most probably formed during the high-energy (Gms) to catastrophic (Gms(b)) flows and represent the infills of channel flows (hyperconcentrated flows with deposition by 'freezing' during the torrential flood events) (Johnson, 1970, 1984; Nemec & Steel, 1984; Maizels, 1989; Russell & Marren, 1999). The diamictic matrix comes from redeposition of melt-out tills or debris-flow sediments from the ice margin. Usually, this diamictic matrix becomes more sorted upwards, and the uppermost parts of the catastrophic channel flow facies may contain well-sorted, stratified sand related to lower energy streams. These erosional channels are probably the equivalents of feeder channels (trunk channels) on alluvial fans (Blair & McPherson, 1994).

Single till balls and large boulders occur also within the Gm and Gi lithofacies. Three boulders are especially large, 1.3 x 0.7 m, 1.0 x 0.65 and 1.0 x 0.6 m in diameter. These large boulders, although limited in number, were probably deposited during the peak water discharge on the alluvial fan. They could have been transported over a short distance in suspension during the catastrophic flows (Maizels, 1989, 1997), but more probably they were transported frozen into the ice (Russell & Knudsen, 1999).

Facies association (1) may be interpreted as the proximal fan sedimentary sequence formed mainly due to sheetflows and partly in localised channels (hyperconcentrated flows). It was deposited during the high-energy flows (catastrophic floods), as suggested by the occurrence of Gms(b)

Table 1

Description of lithofacies found in the end moraine zone of Late Saalian (Wartanian) Stage, southwestern Poland

Lithofacies	Description	Interpretation
Gms	Pebbles and cobbles up to 0.5 m in diameter, massive, poorly sorted, with granule-coarse sand matrix and some admixture of silt. Clasts indicate chaotic orientation; large clasts usually concentrated near the upper boundary. Many clasts are strongly weathered. Clay and till balls are frequent and up to 0.2 m in diameter. This lithofacies is usually 0.5–1.0 m thick and forms laterally continuous beds interbedded with lithofacies Gm and Gi. Lower boundary is usually distinct, although not erosional. Upper boundary can be erosional.	Hyperconcentrated flow deposit formed during high-energy water discharge
Gms(b)	This lithofacies indicates the same characteristics as lithofacies Gms, except for the size of clasts. It contains additionally large boulders, 0.5–1.2 m in diameter (max. 1.8 m) and till balls up to 0.5 m. The thickness of the lithofacies is up to 2–3 m. It forms lenses of limited lateral distribution, usually about several metres.	Hyperconcentrated flow deposit formed during high-energy, catastrophic water discharge
Gm	Massive gravels (cobbles, pebbles and granules), usually with diameter up to 0.3 m; sporadically large boulders up to 1.3 m and clay and till balls up to 0.5 m. Large clasts usually have chaotic orientation, although imbrication has been noticed at places. The lithofacies forms laterally extensive beds with thickness from 0.5 to 2.0 m and is interbedded with lithofacies Gi and Gms.	High-energy deposition: longitudinal bars in a braided river environment and/or shallow channels on alluvial fans
Gi	Gravels bedded parallel to the inclined surface (fan). Lithofacies comprises alternating beds of well sorted pebbles and granules (openwork) and moderately sorted gravels and coarse-grained sand (closework). Inclination of beds is 10–25°, it is parallel or almost parallel to the slope inclination. The lithofacies forms laterally extensive beds with thickness from 0.5 to 3.0 m and is interbedded with lithofacies Gm and Gms.	Sheetflow deposit accumulated on the inclined alluvial fan surface during pulsatory high-energy water discharge
Gt	Medium to large scale trough cross bedded gravels. Medium troughs are up to 0.3 m high and are filled with crudely laminated or massive gravels, whereas large troughs are up to 1 m high and comprise only cross-bedded gravels. Both types of troughs occur in cosets. The thickness of the lithofacies varies from 0.3 to 1.0 m.	Scouring and formation of three-dimensional bedforms in channels. Deposition during high-energy water discharge
Si	Sands or sands with gravels parallel bedded to the inclined surface (fan). Lithofacies comprises alternating beds of coarse to medium sand and coarse sand with single gravels. Inclination of beds is 10–30° , it is consistent over long distances and parallel or almost parallel to the slope inclination. The lithofacies forms laterally extensive beds with thickness from 0.1 to 0.5 m and is interbedded with lithofacies Gi and Gm.	Sheetflow deposit accumulated on the inclined alluvial fan surface during medium water discharge
Sh	Horizontally bedded, medium to coarse sand or sand with rare gravels. The largest clasts reach up to a few centimetres. This lithofacies forms beds with thickness up to 2 m and is interbedded with lithofacies Gm, Gt, St and St(m).	Channel deposition (upper plane bed) between bars of the braided river. Medium to high water discharge
St	Medium- to large-scale trough cross bedded sands or sands with single gravels. Troughs are from 0.1 to 0.6 m high and occur in cosets or separately. The thickness of lithofacies is from 0.2 to 1.0 m.	Formation of three-dimensional structures and deposition in braided river channels. Medium to high water discharge
St(m)	Single troughs, of height from 0.1 to 0.5 m and lateral extent up to 1 m, filled with poorly sorted, massive sand or sand with single granules (diamictic sand). Granules, if present, concentrate in the upper part of troughs. The sand comprises a substantial admixture of mud and is cohesive. The troughs occur within the lithofacies Sh.	Hyperconcentrated flows in small channels
Sm	Massive, medium to coarse-grained sands; partly crudely laminated. This lithofacies occurs in beds varying in thickness from several centimetres to a few metres. It occurs in deformed sequences only.	Braided river deposits that have lost structures during the deformation. Partly colluvial, when associated with lithofacies Dms

Table 1 (continued)

Description of lithofacies found in the end moraine zone of Late Saalian (Wartanian) Stage, southwestern Poland

Lithofacies	Description	Interpretation
Sr	Fine-grained sands forming cosets with small scale trough or planar lamination. The thickness of the lithofacies reaches up to 0.5 m. Lateral extent is very limited. It usually forms lenses within beds of lithofacies Sh or Si.	Migration of current ripples. Waning flood deposition in abandoned channels and/or on bars
Fr	Sandy silt or coarse-grained silt with wavy lamination or climbing ripplemarks of type B. This lithofacies usually forms thin beds, but occasionally up to a few metres in deformed sequences.	Rapid deposition from suspension in zones of increased aggradation; waning flood deposition in abandoned channels and/or on bars
Fm	Massive or crudely laminated sandy silt or silt with thickness up to several centimetres. This lithofacies occurs usually within the sandy lithofacies Sh, Sm, Sr or Fr, and is less common within the lithofacies Si.	Deposition from stagnant water in ponds (abandoned channels or bar tops)
Vc	Finely laminated sandy silt, silt and clay, often brecciated with occasional gravel clasts up to 2 cm. The thickness of the coarse unit is usually 0.5–3.0 cm and that of the fine-grained unit is 0.5–1.0 cm. Boundaries between laminae are usually sharp. The lithofacies forms beds with thickness from several centimetres up to 2 m.	Annually laminated lacustrine deposit (varved clay). Gravel clasts represent dropstones
Dmm	Massive diamicton with silty-clayey matrix and numerous large clasts, including single boulders. Occasionally it comprises lenses and laminae of well-sorted coarse sand. The diamictons are greyish brown to reddish brown, and are 1 to 5 m thick.	Glacial till
Dms	Silty and sandy diamicton forming beds with thickness up to 15 cm. The thin beds may be massive but the thick ones are usually interbedded with coarse to fine sands. This lithofacies usually occurs within sequences with lithofacies Vc, Fr and Sm.	Mud flow deposit (flow till)

lithofacies and large boulders within the Gm and Gi facies. This proglacial environment is an equivalent of proximal parts of the 'humid', sheetflow-dominated alluvial fans in non-glacial settings (Bull, 1972; Blair & McPherson, 1994; Miall, 1996).

Facies association (2) comprises mainly horizontally bedded and/or parallel inclined sand and some cross-bedded sand (lithofacies Sh and St), with minor occurrences of massive to cross-bedded gravels (lithofacies Gm, Gt). Fine sand with ripplemarks (Sr) and massve silt (Fm) occur sporadically, although more frequently and in thicker beds than in facies association (1). Moreover, several large- to medium-sized troughs, filled with poorly sorted massive sand or sand with single granules (diamictic sand) are present in this facies association. This facies was most probably deposited by hyperconcentrated flows in small channels.

The facies association (2) may represent a braided river sedimentary sequence, where massive gravels (Gm) may represent longitudinal bars and cross- or horizontally bedded sediments of the inter-bar channels (Miall, 1977, 1978, 1996; Ashley *et al.*, 1985). However, the most common lithofacies is here a horizontally bedded or parallel inclined sand, which forms laterally extensive sheet beds (see Fig. 9). This suggests sheetflow as a main depositional process, with channel flows being only subsidiary ones, and, hence, also possible alluvial fan sequence (Bull, 1972; Blair & McPherson, 1994; Miall, 1996). Moreover, the common occurrence of hyperconcentrated flows, suggesting more torrential flood events, is more typical of alluvial fans (Blair & McPherson, 1994). The replacement of gravel by sand in the alluvial fan sequences is typical below the intersection point which marks less energetic conditions of the medial or distal fan. Also, medial/distal parts of the fans are characterised by increased channelised flows (Blair & McPherson, 1994) and common transition to braided streams (Boothroyd & Ashley, 1975; Church & Gilbert, 1975; Boothroyd & Nummedal, 1978; Ashley *et al.*, 1985). It follows from the above that the facies association (2) may represent more distal parts of the 'humid' alluvial fan or even transition zone from an alluvial fan to a braidplain (Zieliński, 1992).

MORPHOLOGY AND SEDIMENTOLOGY OF THE END MORAINES

Nieszkowice

The outcrop is located at the top of a slighty elongated and asymmetrical hill (Fig. 4). The northern, proximal slope of the hill is inclined at 30°, and its southern distal slope at 8–20°. The sequence consists of undisturbed sediments with two, *c.* 2 m thick, sets of facies association (1). The lower set comprises lithofacies Gi and Gms, and the upper set includes lithofacies Gi, Gms and Gm. Fine sand with ripplemarks and trough cross-bedded gravel occur only occasionally in the sequence (Fig. 4). The coarsest gravel is found in

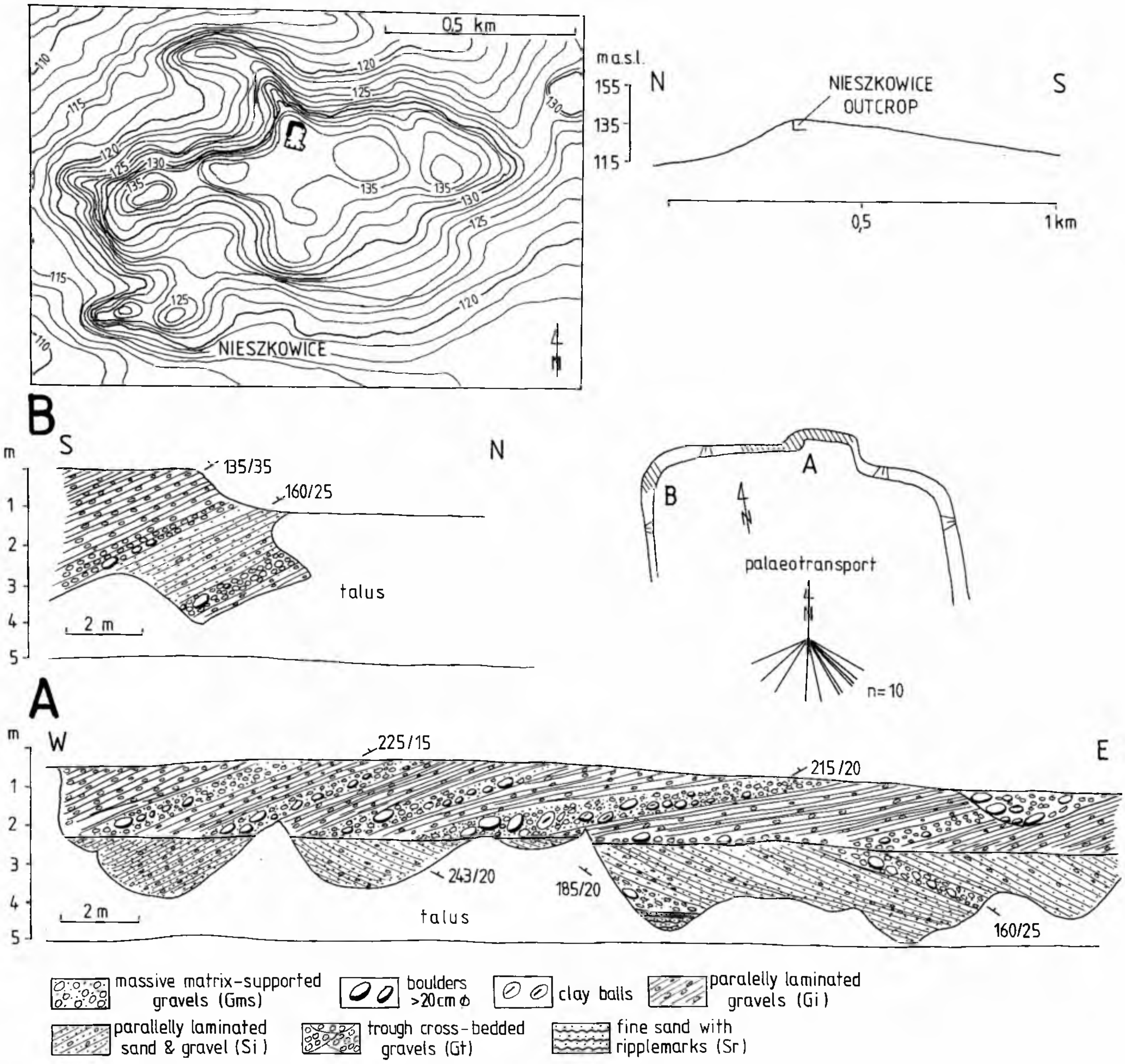

Fig. 4. Morphological position and sedimentary sequence of the end moraine hill at Nieszkowice

the Gms facies (0.5 m). The laminae of Gi lithofacies in the upper layer are inclined at 15–20°, almost parallel to the hillslope, whereas Gi laminae of the lower layer are steeper (20–25°). Palaeotransport was from the north, perpendicular to the axis of the hill.

Kozowo

This outcrop is also located at the top of an elongated and asymmetrical hill (Fig. 5), where the northeastern, proximal slope is inclined 5–10° and its original, southeastern slope at only 2–4°. The sequence consists of undisturbed sediments at least 3 m thick and comprising facies association (1), (mainly lithofacies Si), with two, *c.* 0.5 m thick beds of Gms lithofacies (Fig. 5). The maximum size of gravel in the Gms lithofacies is 0.6 m. The laminae inclination of the Si lithofacies is 10–25°, much steeper than the slope inclination, but comparable with those of Nieszkowice. Palaeotransport was from the NW, perpendicularly to the axis of the hill.

Brodowice

The Brodowice outcrop is located on the southern slope of a large, elongated hill (Fig. 6), which is one of several similar hills in the Orsk–Chobienia area (Figs 1, 2). The hill is up to 30 m high, about 6 km long and strongly asymmetric: the northern, proximal slope is very steep (20–40°), whereas its southern, distal slopes are only 5–20°. The morphology of the northern slope is uniform and more or less

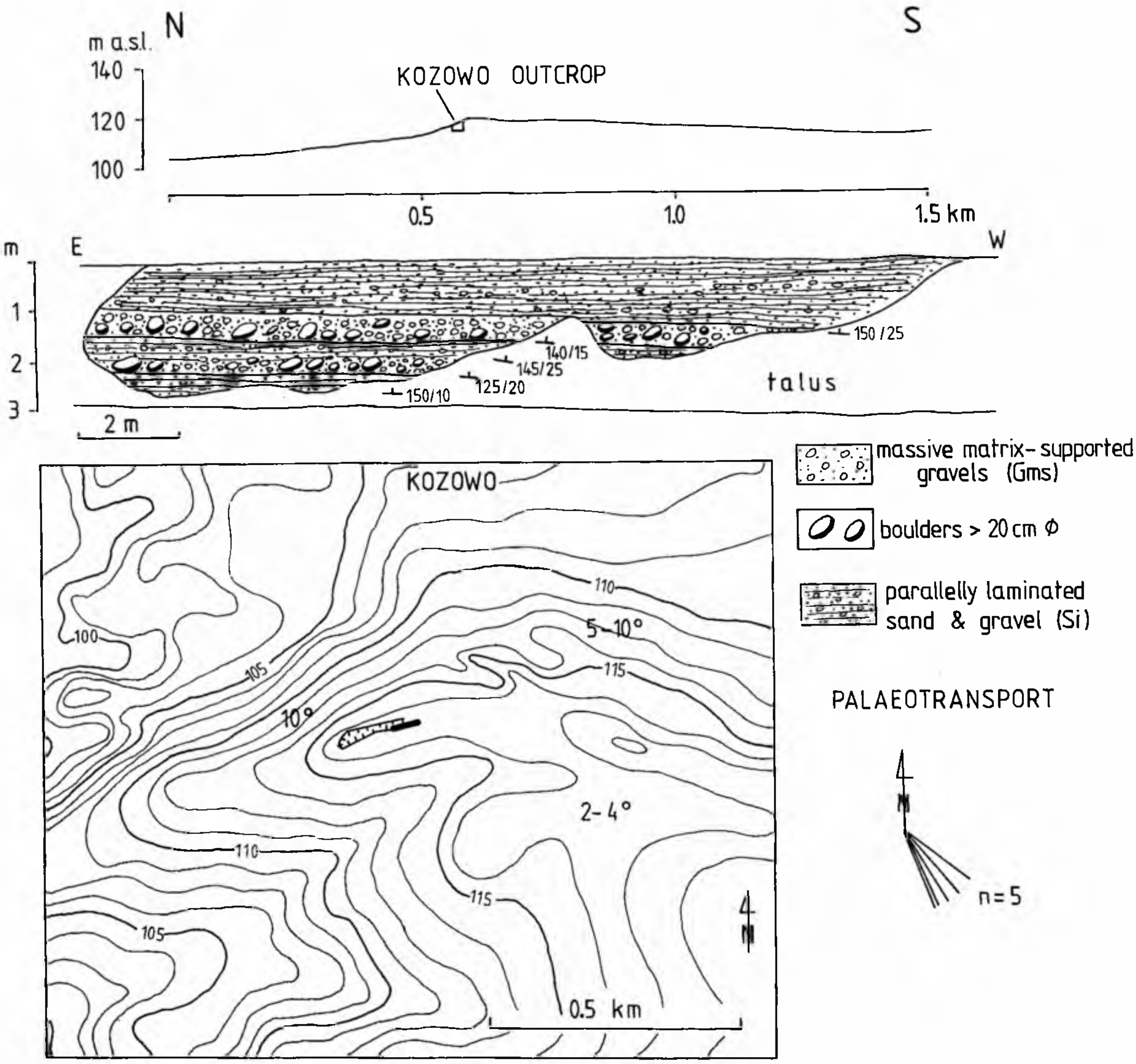

Fig. 5. Morphological position and sedimentary sequence of the end moraine hill at Kozowo

planar. The southern slope has planar or plano-convex surfaces, whose continuity is locally interrupted by irregular hills, that form ridges perpendicular to the axis of the main hill (cross sections 2 and 4 in Fig. 6). The outcrop is located within one of these small ridges. The outcrop is quite large (500 x 250 m) and contains *c.* 20 m of sediments (112–133 m a.s.l.) exposed at three levels, named here as Brodowice 1, 2 and 3 (Fig. 6).

Brodowice 1

This section comprises three lithostratigraphic units, from the bottom (Fig. 6A) upwards:

- 3 m thick, fine to medium grained, white sand with thin, green silty laminae; the upper part of the bed is deformed. This unit represents the older glaciofluvial series, probably including redeposited Pliocene fluvial material (Krzyszkowski *et al.*, 1997);
- 2 m thick, massive, in part laminated greyish-brown, matrix-supported diamicton with a $CaCO_3$ content of about 6%. The diamicton forms a tabular bed with a sharp and planar lower boundary. The matrix is silty-sandy, poorly sorted and contains scattered pebbles and cobbles with preferred, NE–SW axes orientations. The sorted stringers are from a few milimetres to 4–5 cm thick and they usually form laterally extensive laminae. At places, the stringers consist of erosional scours which are filled with cross-bedded sand. This unit is most probably a subglacial till formed during the ice sheet advance. The stringers of sorted material may indicate ice/basement separation during till deposition and the occurrence of water film beneath the temperate ice sheet. The top surface of the till is erosional (scours filled with gravels and till balls);
- Gravel and sand of facies association (1).

Gravelly sediments at Brodowice 1A (Fig. 7A) are 3–4 m thick and are dominated by lithofacies Gi, Gm and Gms, with frequent Gt lithofacies recurring near the bottom of the series. The sediments of facies association (1) at Brodowice 1B are up to 7 m thick (Fig. 7B). They comprise mainly lithofacies Gi and Gm, with several beds of lithofacies Si, Gt and Gms and occasionally lithofacies St, Sr and Fm. The laminae of lithofacies Gi and Si at both sections are inclined at about 20°, which is almost parallel or only slighty greater

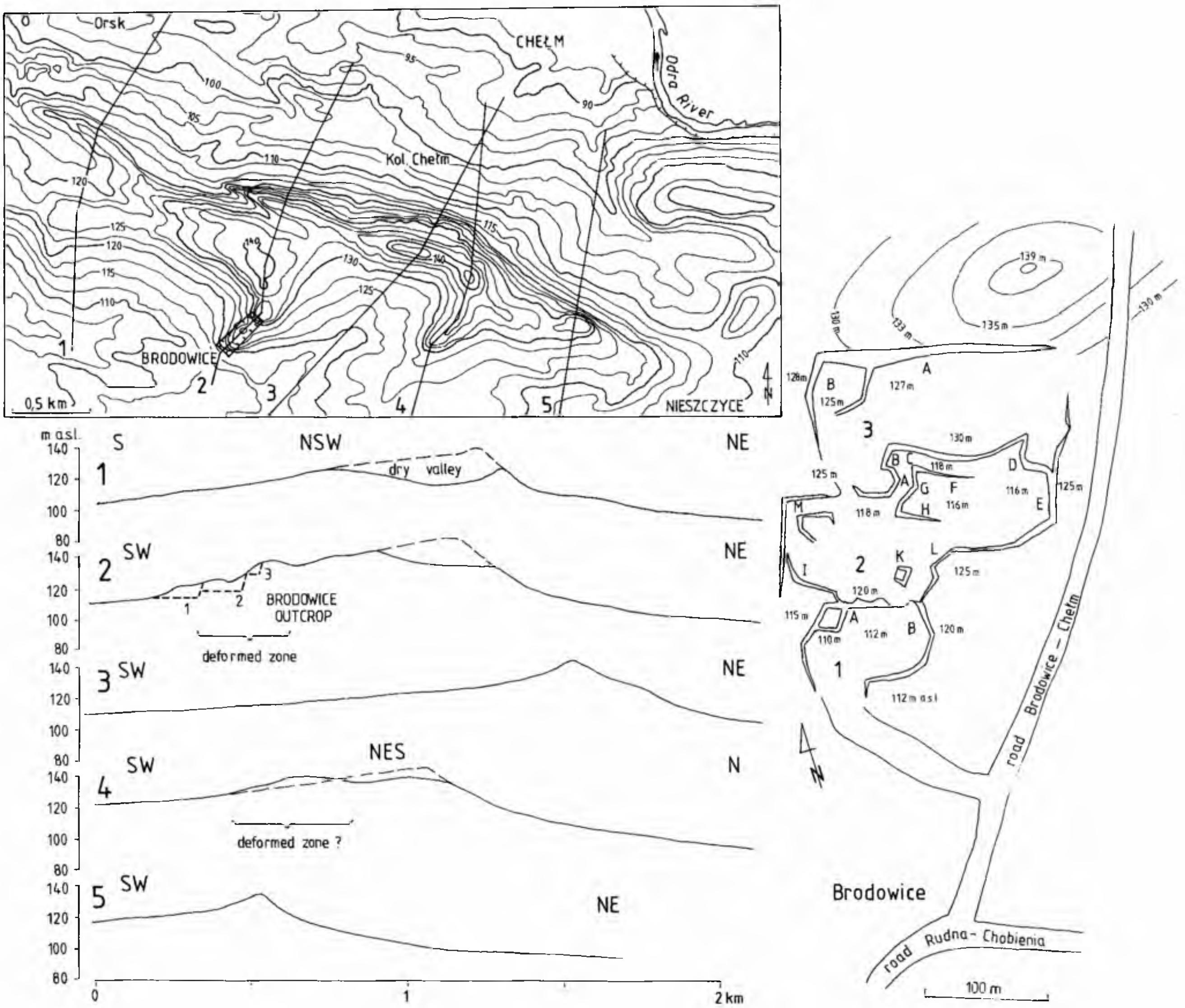

Fig. 6. Morphology of the Orsk–Nieszczyce end moraine hills and a map of Brodowice outcrop with the location of sections discussed in the paper

than the slope inclination. The maximum size of gravel found in the Gm lithofacies is 1.3 m and that of the lithofacies Gi is 1.0 m. Till balls reach up to 0.5 m in diameter and clay balls are 0.3 m across. Palaeotransport was generally from the north (Gi, Si), but troughs indicate palaeotransport from the NW (Fig. 7).

Brodowice 2

This outcrop has a complex stratigraphy which is exposed at several sections (Fig. 8). The sections 2K and 2I comprise 1–2 m thick lenses of Gms(b) lithofacies, where the average size of large boulders is between 0.5 and 1.0 m, with a maximum of *c.* 1.8 m. Gradual transition into the Gi lithofacies has been observed at the top and bottom of the Gms(b) bed, as well as passing laterally into the Gm lithofacies.

Section 2L comprises a deformed sequence with an overturned fold. The core of the fold is formed of greyish-brown till, which is superposed by sediments of facies association (1), mainly Gi and Gm lithofacies (Fig. 8).

Sections 2A-G contain several lithostratigraphic units which are exposed within the deformed sequence. These are, from the bottom upwards (Fig. 8):

- Miocene green clay; scarcely exposed in the section 2C,
- Preglacial (Pliocene) white sand, exposed in the same section,
- Lower glaciofluvial gravel and sand (deformed lithofacies Gm, Gh and Sh); exposed at sections 2A, 2C and 2D,
- Lower till; 2 m thick, massive, brown diamicton ($CaCO_3$ 5%); exposed at sections 2A, 2C and 2D,
- Inter-till deposits: sand (Sh) and gravel (Gh), occasionally with till balls and boulders exposed at sections 2C and 2D, and fine sand, silt and sandy silt (Sr, Fr, Fm) with thin beds of laminated diamicton (Dms) in section 2A,
- Upper till; 2–3 m thick, massive, greyish-brown diamicton ($CaCO_3$ 14%); exposed at sections 2A, 2G, 2C and 2D,
- Varved clay; 1–2 m thick bed of finely laminated varved clay (lithofacies Vc), that contain also thin beds of Dms lithofacies; exposed at section 2C,

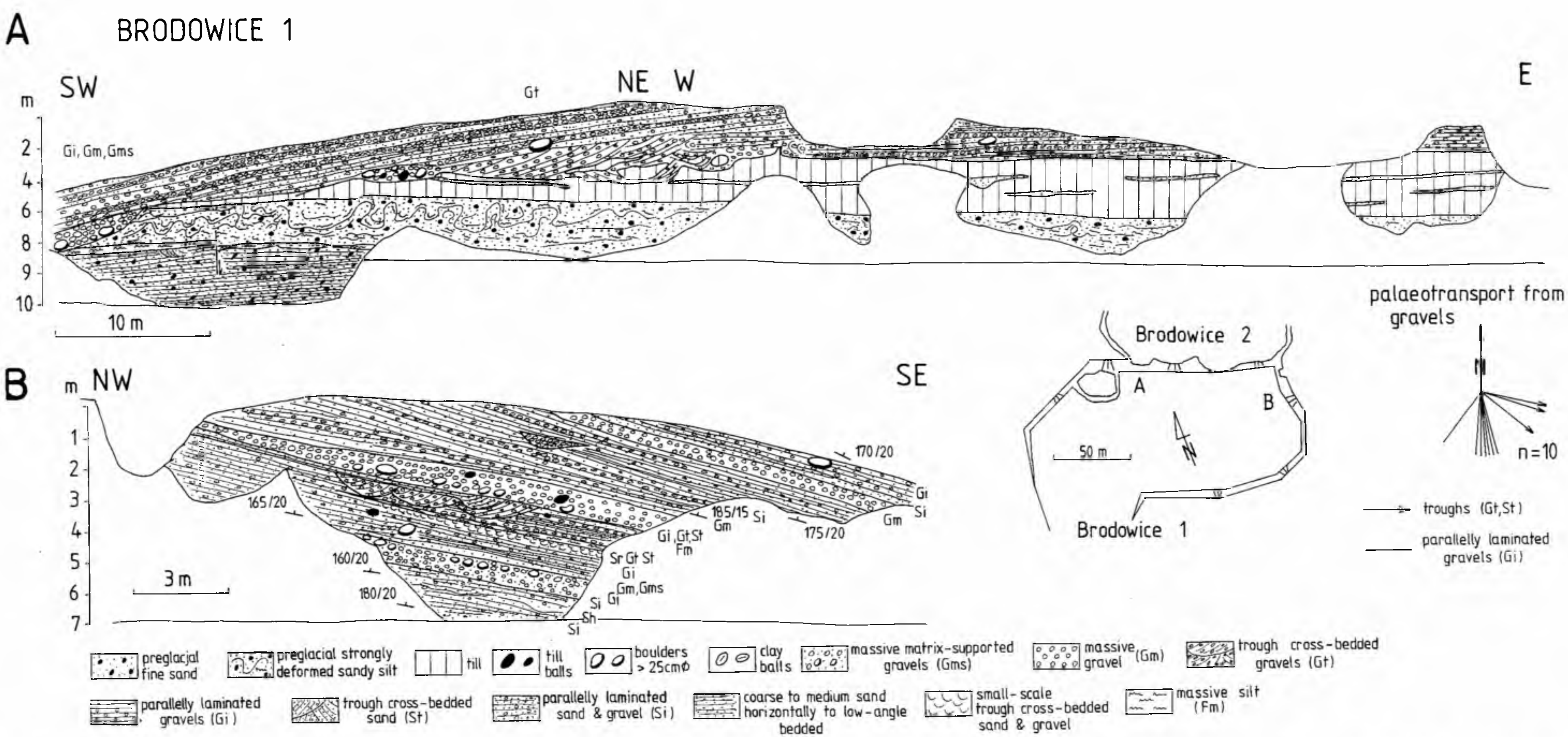

Fig. 7. Sediment sequences at Brodowice 1: **A** – facies association (1) lying on top of the till from the same ice sheet advance (Late Saalian), and **B** – facies association (1) with large boulders; note that the gravel beds in both sections are inclined parallel to the inclined morphological surface

– Gravel and sand of facies association (1) exposed at sections 2A, 2G, 2C-D, and sand and gravel of association (2) exposed at section 2E. Facies association (1) comprises Gi, Si, Gm and Gms lithofacies, with boulders up to 1 m in diameter, and facies association (2) contains only the lithofacies Sh and Gm.

All these units are strongly deformed, with dips of 20–40° (sections 2C-E, 2G-F) to 50–90° (sections 2A-C and D) (Fig. 8). Overturned folds have been observed at sections 2A-C and overturned folds and/or thrust planes at sections 2C-D.

Brodowice 3

This section comprises *c.* 5–8 m of deposits that belong entirely to facies association (2) (Fig. 9). The sediments are not deformed. The eastern part of the exposure is dominated by parallel inclined sand (Si lithofacies) or horizontally bedded sand (Sh lithofacies) and massive gravels (Gm lithofacies). The western part of the section comprises a much more complex sedimentary sequence, dominated by lithofacies Sh and Gm, Gt, St, with several troughs with diamictic sand incised into Sh/Si beds. Lithofacies Sr and Fm occur occasionally. The maximum size of gravels in the Gm lithofacies is 0.35 m. Palaeotransport was generally from the N and NE, although large troughs indicate palaeotransport from the N or NW (Fig. 9).

Stratigraphic and structural interpretation of the Brodowice sedimentary sequence

Three questions are crucial in the stratigraphic interpretation of the Brodowice sequence: (1) correlation of the till from Brodowice 1 with those of Brodowice 2, and then their correlation and possible age relation to the regional stratigraphy (Czerwonka *et al.*, 1997); (2) which part of the sequence is the end moraine depositional system? and (3) what is the complete succession of events documented in the Brodowice sequence?

The till at Brodowice 1 and the upper till at Brodowice 2 have a similar petrographic composition, that is, the Scandinavian crystalline rock/carbonate rock (K/W) ratio is about 1 (0.99–1.14) (Krzyszkowski *et al.*, 1997). Thus, they both provide petrographic composition very close to that of the Taczów Till (Czerwonka *et al.*, 1997). The lower till at Brodowice 2 contains much more crystalline rock (K/W ratio *c.* 1.6), and it most probably represents a different, older till bed, with petrographic composition similar to the Smolna/Dopiewiec Till (Czerwonka *et al.*, 1997). The sequence of tills at Brodowice correlates with the sequence of the Smolna and Taczów Tills which have been documented in boreholes in the surrounding region (Fig. 10; Czerwonka *et al.*, 1997). The other possibilities of correlation and arguments supporting the Taczów and Smolna Tills have been presented by Krzyszkowski *et al.* (1997) (Fig. 10).

The Taczów Till occurs in a sub-surface position, also in a 1–2 km wide belt southwards of the investigated asymmerical hills (Fig. 2). It covers a discordantly deformed sequence and in at least one borehole, at Chobienia, it is underlain by the Smolna Till (Fig. 3B; Czerwonka *et al.*, 1997). The Smolna Till is most probably of the early Saalian ice advance (Odranian) age and a till with similar features has been observed throughout the western and central Poland, including some sites with underlying Holsteinian deposits (Krzyszkowski, 1995; Czerwonka *et al.*, 1997). The Taczów Till represents the Late Saalian ice advance (Wartanian) and marks the maximum advance of this ice sheet (Czerwonka *et al.*, 1997). The Taczów Till has its southernmost limit in our field area, and has been found neither in the central and southern part of Dalków and Wińsko Hills, nor in the Silesian Lowland south of the Silesian Rampart (Figs 1, 2).

It follows from the above that glacial sediments lying below the Taczów Till must represent older glacial stages (lower till and lower glaciofluvial sediments) or the sediments from the Wartanian ice sheet advance (inter-till series). Those above the Taczów Till are of the Late Saalian (Wartanian) age and represent the series deposited during the steady-state at the southernmost extent of the ice sheet or the series from retreat phases. This succession, which occurs in Brodowice 2, contains varved clay series lying directly on the till and sediments of facies associations (1) and (2) above.

A structural interpretation of the sediments of Brodowice 2 is presented in Figure 11. Deformation is thought to have started from surficial folding and successively developed into deep folding (with overturning) and, finally, into a thrust plane, with the décollement in the deeper Miocene and Pliocene strata (Jaroszewski, 1991). Three cross sections through the Brodowice 2 outcrop (Fig. 11) show a little different pattern of deformation, probably with structures from different stages of deformation. The deforming force was overall from the NE, which correlates well with the presumed ice advance based on end moraine hill orientaion (Figs 1, 6).

INTERPRETATION OF THE END MORAINE DEPOSITIONAL SYSTEM

The asymmetrical hills have been commonly interpreted in Poland as ice marginal features (Kozarski, 1978, 1995; Ruszczyńska-Szenajch, 1982; Kasprzak & Kozarski, 1984, 1989; Kozarski & Kasprzak, 1987; Zieliński, 1992; Krzyszkowski & Gratzke, 1994; Dobracki & Krzyszkowski, 1997). Zieliński (1992) and Dobracki and Krzyszkowski (1997) considered, on the basis of the sediment sequences, that these hills are alluvial fans. If sorted, waterlain material dominates, as is the case of the studied sequences, these ice-marginal fans can be interpreted as equivalents of type II (sheetflow-dominated) alluvial fan, according to Blair and McPherson (1994), or a 'humid' fan according to Bull (1972) in non-glacial settings.

The proximal zone of the studied end moraine zone (facies association 1) is dominated by gravelly facies: gravel-bed sheetflow facies (Gi) and gravel-bed channel facies (Gm), with subordinate high energy channel (hyperconcentrated) flow facies (Gms, Gms(b)). The mass flow deposits (fine-grained diamictons) are not present, but proximity to the ice front is emphasised by common till balls within the waterlain sediments. Facies association (1) of the studied sections represents a sequence deposited in the proximity of

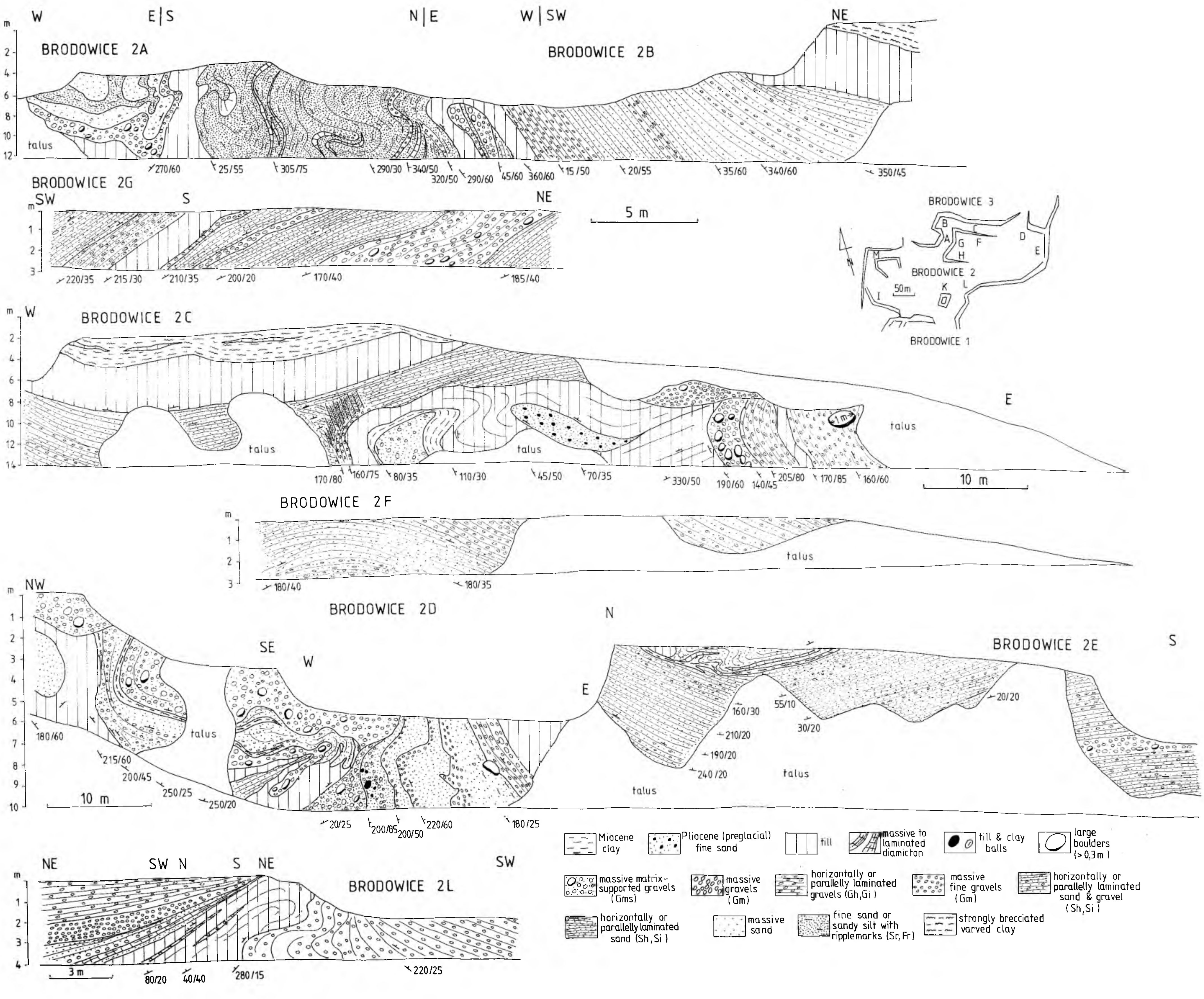

Fig. 8. Deformed sediment sequences at Brodowice 2: detailed description and discussion is in the text

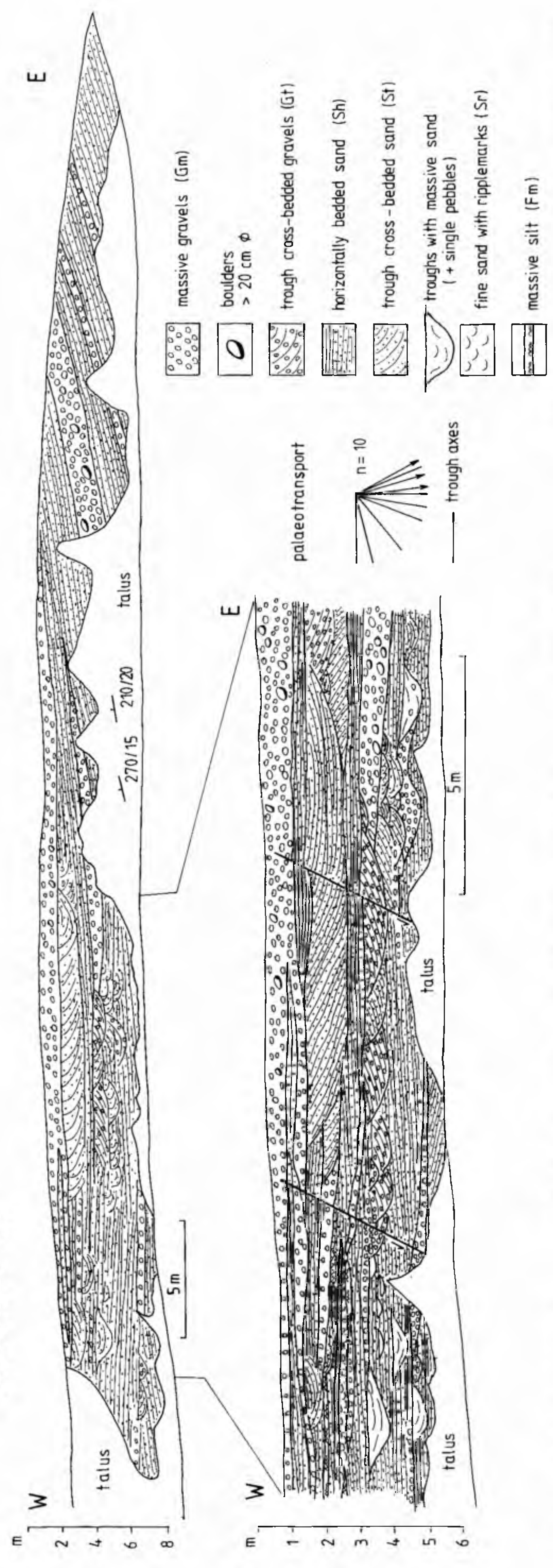

Fig. 9. Sediment sequence at Brodowice 3 with facies association (2); note limited lateral extent of Gm and Gt lithofacies and common occurrence of troughs with massive, diamictic sands (detailed discussion in the text)

the ice scarp by seasonal pulsatory water discharge. High-energy floods deposited gravels/sands parallel to the inclined fan surface. The alternating sequences of Gm, Gms, Gi and Si lithofacies could represent single flood waves with decreasing energy of flows. Lithofacies Gms(b) and large boulders which occur within the lithofacies Gm and Gi may represent deposition from a catastrophic flood and/or from a short-term peak water discharge. During the waning stages of the floods, channels would have been formed on the fan surface (Gm, Gt) which then became slowly abandoned (Sr, Fm). At Brodowice, lower gravel member derived from high-energy sheetflows or channels of proximal fan is succeeded by a thick sand division. The boundary between these facies associations is transitional, where facies association (1) gradually passes upwards into less gravelly facies association (2). Similar 'regressive' successions are quite common also in ancient alluvial fans (Hubert & Hyde, 1982; Hartley, 1993). Thus, the facies association (2) was formed most probably on the distal fan, with greater distance from the ice, that may be attributed to ice sheet retreat. However, Krüger (1997) suggested that some minor fans consisting mainly of sand-sized sediments were deposited by supraglacial streams even during the ice sheet advance or stagnation. Therefore, the upward grain size decrease in the end moraine fan sequence does not necessarily indicate radical changes in the proximal-distal environment or great ice margin oscillations.

The asymmetrical hills at Nieszkowice and Kozowo represent single alluvial fans. This may be deduced not only from their shape (e.g., hill asymmetry, plano-convex cross profile), but also from the sedimentary sequence. The latter contains facies association (1), that indicates the proximal fan lithofacies formed mainly by sheetflows and hyperconcentrated flows.

The Orsk–Chobienia hills, with the Brodowice sequence, are more complex, with a more complete sequence of events of the ice marginal zone. The general planar shape of the gentle slope of the Orsk–Chobienia hills probably formed due to the coalescence of several fans. This simple shape was modified at places by glaciotectonics, forming perpendicular ridges (Fig. 7).

The complete sedimentary sequence of the end moraine near Brodowice includes, besides the alluvial fan series on top (facies association 1 and 2), also a subglacial till and glaciolacustrine sediments of the same ice sheet advance, which indicates a more complex succession of events at the ice margin.

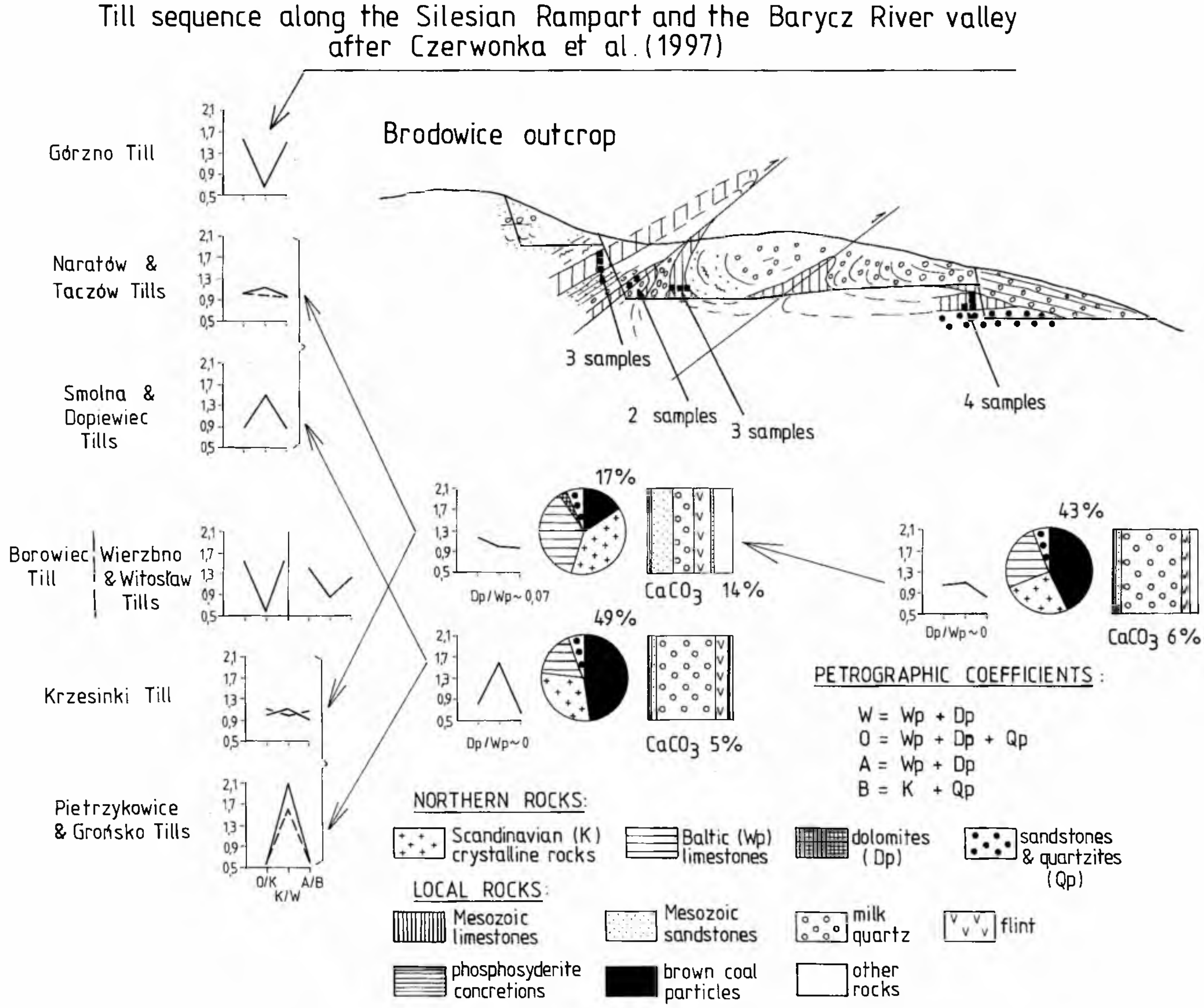

Fig. 10. Petrographic composition of tills at Brodowice outcrop and their correlation with till in the region (arrows indicate possible interpretations; detailed discussion in the text)

The glaciolacustrine series at Brodowice comprises varved clay (lithofacies Vc) and several thin beds of diamicton (Dms) (Table 1). At some other sites in the region, for example at Krzelów (Krzyszkowski *et al.*, 1997), only finely laminated silt and clay occur. Varved clays with distinctly separate coarse and fine laminae, as is the case of Brodowice, are attributed to distal parts of deep proglacial basins with pulsatory influxes of material and seasonal thermal stratification of the lake (Ashley, 1975, 1989; Sturm, 1979; Ashley *et al.*, 1985). However, the occurrence of diamicton beds and dropstones within the glaciolacustrine series may suggest an ice-contact lake with sedimentation directly from the ice (flow tills) or from icebergs (Ashley *et al.*, 1985; Ashley, 1989). Annual lamination may be formed in the ice-contact lake only within the "quiet", distal zones, and hence the diamicton layers most probably represent iceberg material. The duration of the proglacial lake, taking into account the number of laminae in the 1–2 m thick sequence at Brodowice, may be approximated to 50–100 years only. No direct contact has been found so far between the glaciolacustrine series and the next facies association (1). However, the alluvial fan sedimentation was preceded by strong erosion (Fig. 7A), very probably due to drainage of the lake, and varved clay and till were removed from many places.

In conclusion, it seems that the end moraine zone was formed during at least two retreat and one re-advance events, where the maximum ice limit is marked by the Taczów Till (Fig. 2). The following retreat stages created the proglacial lake, and then two zones of hills (Figs 1, 2), approximately 1–2 km apart, and the re-advance produced a local glaciotectonic deformation at Brodowice (Fig. 12). These retreats and re-advance may represent regional events, since similar pairs of hills have been noticed also near Kozowo and Kowalewo (Figs 1, 2).

GLACIOFLUVIAL (PRADOLINA) TERRACES

Three fluvial terraces older than the radiocarbon-dated Weichselian sediments/terraces have been found in the region investigated. The highest and the oldest one occurs only southwards of the Orsk–Chobienia–Kozowo–Nieszkowice end moraine zone; the other two lie also to the north (Fig. 2).

Terrace 110–125 m

This terrace occurs between Zaborów and Krzelów and near Nieszkowice (Figs 1, 2). The terrace basement is at 110 m a.s.l. and it usually consists of tills. The terrace deposits comprise sand and gravel of facies association (2) and at least in one case, at Krzelów, they are underlain by varved clay (Fig. 3A). These sediments are discontinuous and form isolated hills up to 125 m. a.s.l. (Figs 2, 3) due to subsequent erosion. The height range of this terrace sediments coincides with the occurrence of end moraine sediments at

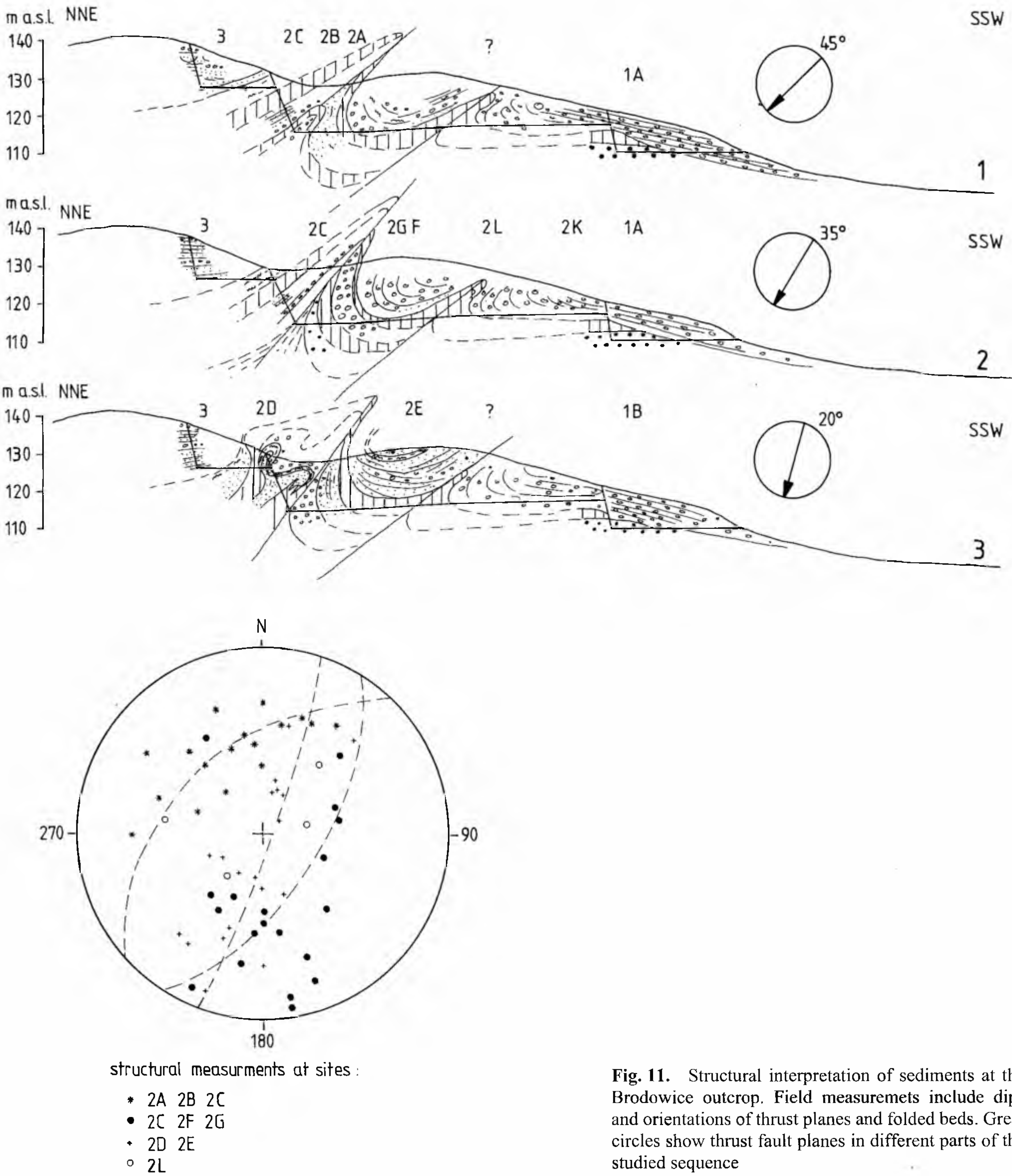

Fig. 11. Structural interpretation of sediments at the Brodowice outcrop. Field measuremets include dips and orientations of thrust planes and folded beds. Great circles show thrust fault planes in different parts of the studied sequence

110–140 m a.s.l., and thus they probably represent a very distal age-equivalent series of the active ice-marginal zone.

Terrace 100–110 m

This terrace occurs both south and north of the end moraine zone, but it is not present in the Barycz River valley and its tributaries (Fig. 2). The terrace sediments are represented by sand and gravel and are up to 5 m thick. The terrace is very continuous and slopes in northerly direction.

Terrace 90–93 m

This terrace occurs in the central and northern parts of the region, including the Barycz River valley and its tributaries (Fig. 2). The terrace sediments are either sand or gravel with a thickness of up to 3–5 m. This terrace forms also continuous shelves with a distinct gradient to the north. Both the 100–110 m and 90–93 m terraces, situated north of the terminal end moraines, were formed during the general retreat of the Wartanian ice sheet.

PALAEOGEOGRAPHIC RECONSTRUCTION OF THE WARTANIAN ICE-MARGINAL ZONE ALONG THE SILESIAN RAMPART

Our palaeogeographic reconstruction takes into account: (1) position of the end moraine hills a few kilometres north from the maximum ice sheet limit marked by till; (2) location of the end moraine hills (maximum height 145 m a.s.l.) at the edge of a set of large glaciotectonic composite-ridges with heights up to 220 m a.s.l.; (3) limited occurrence of end moraine hills, covering less than 20% of the length of the former ice marginal zone; (4) formation of the Odra River valley which crosses the large composite-ridges, as well as its relation to the pradolinas (ice marginal valleys) in the north and south; (5) the occurrence of two Wartanian tills of variable petrographic composition, that were formed during the two ice advances (Czerwonka *et al.*, 1997; Krzyszkowski *et al.*, 1997); (6) complex glaciotectonic history of the region. This interpretation also includes data from the Trzebnica Hills, located directly to the east (Figs 12, 13; Krzyszkowski 1992, 1993).

It seems that the large composite ridges of the Dalków and Trzebnica Hills already existed at the time of final advance of the early Wartanian ice sheet to this area. They could have been formed during the older glacial stages or at the front of the slowly advancing Wartanian ice sheet. In the latter case, shear stress was transmitted far away from the ice limit and older deposits were cylindrically sheared with the formation of a sequence of successively younger thrusts (Fig. 12A; Aber *et al.*, 1989; Jaroszewski, 1991). We prefer the Wartanian age of this deformation, because it explains the southerly position and extent of the Magdeburg–Wrocław Pradolina (ice-marginal valley). The pre-Wartanian drainage system was re-modelled when the deformed hills blocked the original outflow to the north. The new, Pradolina drainage system was thus formed 25–35 km southwards from the ice margin, as the Wartanian ice sheet reached only the northern slopes of the deformed zone (Taczów Till) (Fig. 13A; Krzyszkowski, 1993; Czerwonka *et al.*, 1997). Partial retreat and stabilisation of the ice front facilitated the formation of small proglacial lakes between the ice and the hills (Figs 12B, 13B). Elsewhere, proglacial sandurs were formed, for example at the southern margin of the Trzebnica Hills (Fig. 13B; Schwarzbach, 1942; Krzyszkowski, 1993).

The rising lake levels would have created outflow channels across the lowest parts of the deformed hills which, after progressive erosion and drainage of the lakes, produced one very wide proglacial valley running to the south, to the Magdeburg-Wrocław Pradolina (Fig. 13C). After lake drainage, the end moraine hills were formed along the new ice front (Orsk–Chobienia, Kozowo, Kowalewo and Nieszkowice hills), with the formation of alluvial fans characterized by high water discharge and sheetflows close to the ice scarp, and braided river valleys system more to the south. These rivers formed the 110–125 m terrace (Figs 12C, 13C). Local ice re-advances created glaciotectonic folding and thrusting, especially within zones with Miocene clays occurring at shallow depth (Fig. 12D). This is the case of the Brodowice outcrop, whereas Kozowo and Nieszkowice as well as, probably, a larger part of the Orsk–Chobienia hills comprise undisturbed sequences. It seems that this deformation phase was at least in part synsedimentary and the décollement surface is located at a much shallower depth than in the large composite ridges of the Dalków and Trzebnica Hills. Additionally, subsequent ice margin retreat could have created the second line of end moraine hills between Orsk and Chobienia and elsewhere, and a partial re-modelling of the first line (Fig. 2).

Final retreat of the Wartanian ice sheet from its maximum position caused the diversion of the drainage system, with rivers flowing now to the north, to the newly created Baruth–Głogów Pradolina (terrace 100–110 m; Figs 12E, 13D). This ice marginal valley would have been formed along the new terminal moraine located along the Wąsosz–Góra hills (Czerwonka *et al.*, 1997). This end moraine contains its own till in the substratum, the Górzno Till, which is superposed on the older Wartanian Taczów/Naratów Till and, hence, is assumed as formed by active ice (Fig. 12E). Also, the occurrence of both coarse grained material and glaciotectonic structures with Miocene clay in subsurface position, suggest similar processes as those which occurred along the Orsk–Chobienia end moraines (Czerwonka *et al.*, 1997).

Subsequent retreat of the Wartanian ice sheet produced the lowest terrace of the Baruth–Głogów Pradolina (90–93 m; Fig. 12F). The end moraines and pradolinas were finally remodelled during the Weichselian and Holocene (Fig. 12G).

The occurrence of the Wartanian end moraines in the studied region is highly restricted (Fig. 1), partly due to recent erosion, although it seems that many areas were not favourable to the formation of end moraine at all. Generally, the studied end moraines were formed in the transition zone from layer-cake in the north to deformed (thrust) subsurface geology in the south (Fig. 10; Czerwonka *et al.*, 1997). This change of the substrate characteristics may have caused a substantial change in subglacial hydrology, with

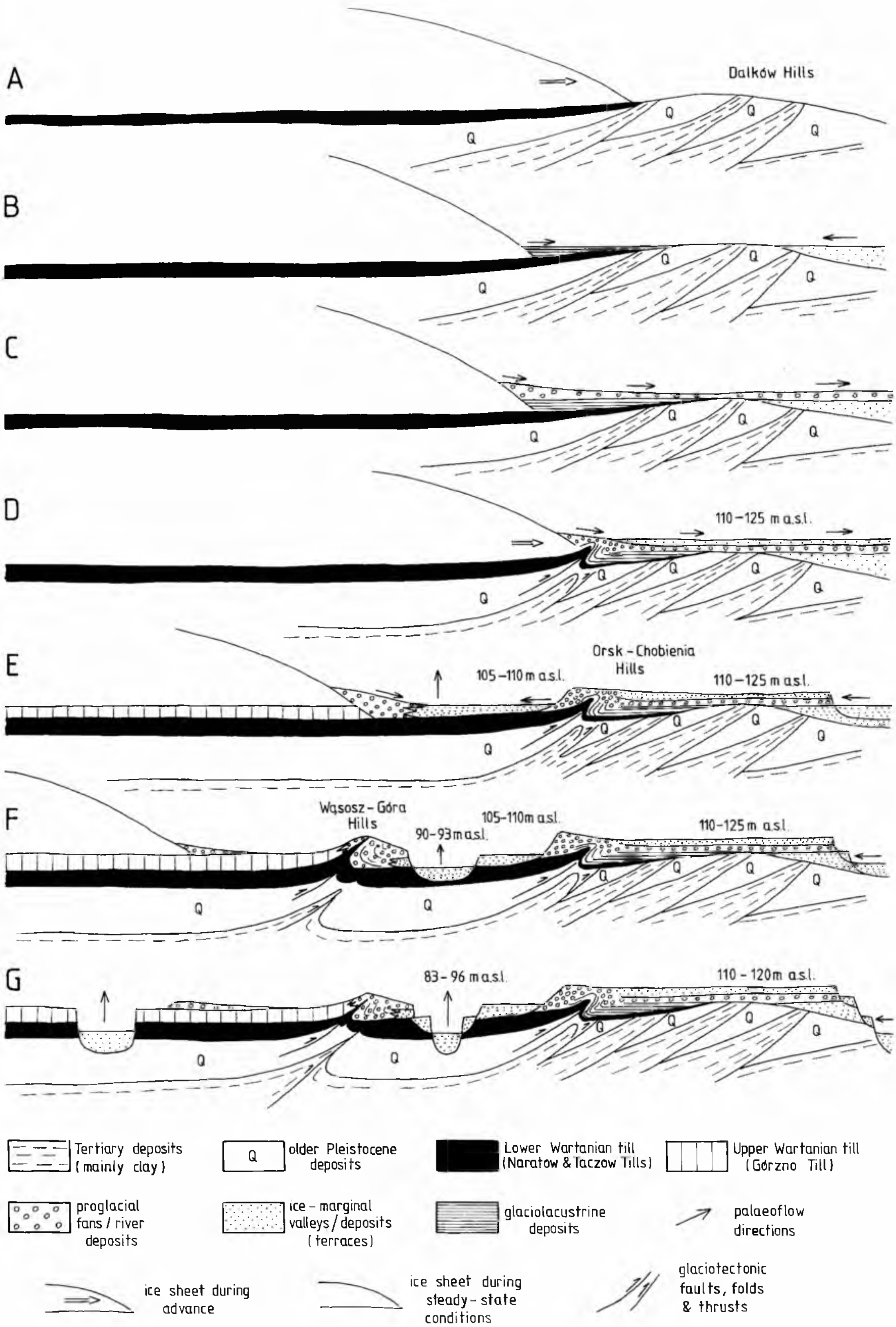

Fig. 12. Stages of development of the Late Saalian end moraine zone along the northern margin of the Silesian Rampart, southwestern Poland: **A** – regional ice sheet advance to its maximum position and large-scale glaciotectonic deformation, **B** – partial retreat of ice sheet, formation of short-term proglacial lakes and their subsequent drainage, **C** – stabilization of ice sheet front and formation of the end moraine fans, **D** – short-term ice margin oscillations and small-scale, local glaciotectonic deformation during re-advances, **E** – subsequent ice-sheet retreat and readvance and formation of new ice-marginal zone along the Wąsosz–Krotoszyn Hills, **F** – final ice sheet retreat and formation of Baruth–Głogów Pradolina valley, **G** – post-Saalian, Eemian, Weichselian and Holocene re-modelling of the valleys

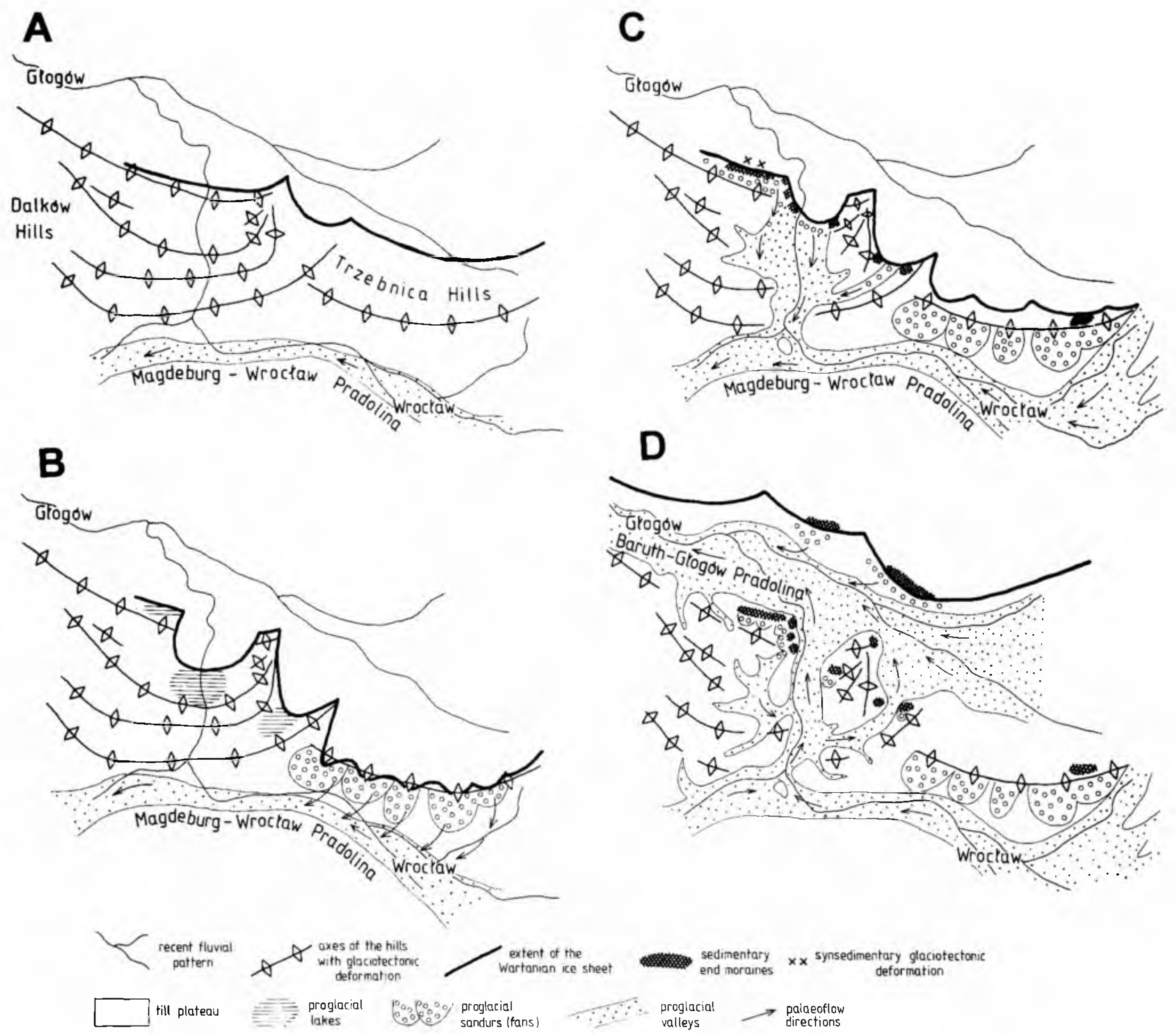

Fig. 13. Major stages of palaeogeographic evolution of the Wartanian ice-marginal zone between Głogów and Wrocław, southwestern Poland: **A** – regional ice sheet advance and formation of large glaciotectonic hills; maximum extent of the Wartanian ice sheet, **B** – steady-state ice marginal conditions and formation of proglacial sandur and/or proglacial lakes between the ice sheet and glaciotectonic hills, **C** – drainage of the lakes and formation of proglacial valley trending to the south, to Magdeburg–Wrocław Pradolina; formation of end moraine fans, **D** – ice sheet retreat, valley incision and diversion of rivers to the north, to the Baruth–Głogów Pradolina; new ice sheet limit along the Wąsosz–Krotoszyn Hills

escape of subglacial water in the thrust zones (subvertical position of strata). The subsequent reduction in ice-flow velocity and stronger compressive ice-flow conditions could have finally resulted in the formation of end moraines in zones with increased basement permeability. Furthermore, local conditions may have controlled specific positions of particular end moraine fans and their lateral extent.

CONCLUSIONS

The major conclusion of this paper is that there is sufficient evidence for the occurrence of the ice marginal features, including end moraine hills, along the Silesian Rampart. These end moraines are attributed to the regional advance of the Wartanian ice sheet into its maximum position, which is also marked by the subglacial till bed. The studied Wartanian end moraine hills are located on the northern slopes of the Silesian Rampart and they are very rare, partly due to subsequent erosion, but mainly due to conditions not favourable for a remarkable proglacial accumulation. We suppose, that similar situation was also present along the other parts of the Silesian Rampart, as end moraines have been seldom reported from this zone.

The studied end moraines exhibit several features that may be attributed to the formation of the end moraine controlled predominantly by sorted sediments:

1. The end moraine hills are small alluvial fans, where the ice margin represented the 'scarp' and ice tunnels the 'feeding channels'. They have semi-conical form, often plano-convex geometry and an average distal slope between 2–25° and proximal slope usually between 10–30°. The isolated end moraine hills comprising single fans are up to 5–6 km^2 in area, but those forming elongated ramparts accumulated with coalesced fans cover much greater areas, although their radial width is only up to 2–3 km.

2. The end moraine sedimentary sequence contains mainly coarse-grained material (lithofacies Gi, Gm, Gms, Gt, Si), with boulders up to 1.8 m in diameter (lithofacies Gms(b)), and is dominated by gravels or pebble sands that build layers conformable with the inclined fan surface (lithofacies Gi, Si). This sequence represents a typical proximal fan facies association with a highly pulsatory water discharge. The sequence was formed mainly by sheetflows, but also by localised, hyperconcentrated flows in shallow channels. Catastrophic floods, capable of transport of boulders up to 1.3 m in diameter in suspension, occurred locally. These fans are equivalent to the type II (sheet flood dominated) alluvial fans, described by Blair & McPherson (1994), or humid fans, as suggested by Bull (1972) in non-glacial environments. More distally, on the distal fan areas and on the plains of the ice marginal valleys, braided rivers occurred.

3. The end moraine was not formed at the maximum limit of the ice sheet as marked by the till, but a few kilometres to the north, along a short-term, recessional position,

4. The formation of the end moraine was preceded by the formation of a proglacial lake, and after its drainage, by strong erosion in the proglacial zone.

5. The end moraine was formed during oscillation of the ice margin that resulted in local glaciotectonic deformation of the alluvial fan sediments (push) or a set of parallel hills, with successive younger alluvial fans (retreat). The older fans could have been gravitationally deformed, especially in their proximal, ice-contact slopes (former head of outwash) or partly eroded, with the superposition of lower fan deposits.

It seems also that the present-day Odra river valley that trends S–N and connects the Magdeburg–Wrocław and Baruth–Głogów Pradolinas was formed initially during the Late Saalian (Wartanian) glaciation. Most probably, the initial gorge through the Silesian Rampart was due to strong erosion by catastrophic flood that followed drainage of proglacial lakes. At this stage, proglacial rivers have flown to the south, to the Magdeburg–Wrocław Pradolina. Subsequent ice margin retreat caused downstream erosion that resulted in river diversions to the north, to the Baruth–Głogów Pradolina.

Acknowledgements

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Streszczenie

PALEOGEOGRAFIA ZLODOWACENIA WARTY I POWSTANIE MOREN CZOŁOWYCH NA PÓŁNOCNYCH STOKACH WAŁU ŚLĄSKIEGO, POŁUDNIOWO-ZACHODNIA POLSKA

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Znaleziono dowody na istnienie moren czołowych i innych form oraz osadów strefy marginalnej ze zlodowacenia Warty na obszarze wzgórz Dalkowskich i Wińskich (Wał Śląski) w Polsce południowo-zachodniej, co było dotychczas często negowane. Moreny te powstały w czasie regionalnego awansu lądolodu Warty do jego maksymalnego zasięgu. Awans ten zaznaczony jest też istnieniem wyraźnego poziomu gliny lodowcowej. Glina ta posiada skład petrograficzny typowy dla glin typu Taczów, tj. z wyrównanymi ilościami skał krystalicznych i wapienie bałtyckich (K/W ok. 1,0) i wyraźnie różni się od regionalnie niższej gliny (typ Dopiewiec). Te ostatnie biorą udział w wielkoskalowych zaburzeniach glacitektonicznych na wzgórzach Wału Śląskiego, podczas gdy glina Taczów zazwyczaj zalega dyskordantnie i jest zaburzona tylko lokalnie.

Wzgórza moren czołowych występują na północnych skłonach wzgórz Dalkowskich i Wińskich i są bardzo rzadkie, częściowo w wyniku późniejszej erozji, lecz głównie z powodu braku sprzyjających warunków dla ich akumulacji w strefie marginalnej lądolodu. Badane moreny zawierają sekwencje osadów typowe dla moren czołowych zdominowanych przez procesy fluwialne. Moreny te zawierają głównie warstwowane i masywne osady gruboziarniste, żwiry i otoczaki oraz głazy do 1,8 m średnicy. W strefie proksymalnej są to głównie pakiety żwirów i otoczaków warstwowane równolegle, którym towarzyszą żwiry i piaski warstwowane przekątnie oraz masywne żwiry-głazy. Te ostatnie występują w dwóch facjach: żwirów wysortowanych, deponowanych w czasie silnych przepływów, oraz słabo wysortowanych żwirów gliniastych z głazami deponowanymi w czasie przepływów nadkrytycznych (supercritical flow). Pojedyncze duże głazy (do 1 m średnicy) występują też w osadach warstwowanych, wskazując na generalnie bardzo gwałtowne przepływy wód. W strefie dystalnej dominują piaski lub piaski ze żwirami z warstwowaniami horyzontalnymi i przekątnymi, z małymi domieszkami dobrze wysortowanych żwirów masywnych.

Moreny czołowe na Wzgórzach Dalkowskich reprezentują stożki aluwialne formowane przy czole lądolodu, z wyraźną stożkową morfologią moren, płaskim lub wypukłym profilem podłużnym i nachyleniu powierzchni dystalnej stożków 2–25°, w facjach typowych dla proksymalnych części stożków aluwialnych z wysoko zmiennymi przepływami wód (osady zalewów warstwowych oraz osady przepływów nadkrytycznych).

Wielkoskalowe zaburzenia glacitektoniczne na Wzgórzach Dalkowskich powstały albo w czasie poprzednich zlodowaceń albo na przedpolu nasuwającego się lądolodu warciańskiego. W każdym razie, gdy lądolód ten osiągnął swój maksymalny zasięg, wzgórza te stanowiły już tylko pasywną barierę morfologiczną. Powstanie warciańskich moren czołowych na badanym obszarze było poprzedzone występowaniem jezior proglacjalnych (pomiędzy Wzgórzami Dalkowskimi a lądolodem), a następnie silną erozją w czasie drenażu tych jezior. W czasie tego drenażu uformowana została dolina przełomowa poprzez wzgórza glacitektoniczne w kierunku południowym (do Pradoliny Wrocławsko-Magdeburskiej), która została nastepnie wykorzystana przez Odrę do przepływu na północ. W strefie tej obserwuje się trzy terasy warciańskie, jedną (najstarszą) pochyloną na południe (z czasu drenażu jezior proglacjalnych) oraz dwie młodsze (z faz recesyjnych) pochylone na północ.

Moreny były formowane w czasie krótkotrwałych oscylacji czoła lądolodu, które doprowadziły do lokalnych deformacji glacitektonicznych w obrębie stożków morenowych oraz do powstania kilku równoległych linii wzgórz z różnych (krótkotrwałych) faz recesji. Kierunek transportu lodowcowego zmierzony na podstawie orientacji fałdów i łusek oraz dłuższych osi głazików w glinach są ze sobą zgodne. Lądolód awansował do linii moren czołowych z północnego wschodu. Dwie młodsze terasy warciańskie powstały w trakcie postoju lądolodu warciańskiego na linii wzgórz Wąsosz–Krotoszyn, formując nową, w miarę długotrwałą strefę marginalną położoną kilkanaście kilometrów na północ od badanej strefy. Z tą oscylacją lądolodu warciańskiego wiążemy depozycję kolejnej gliny, typu Górzno, która w profilach występuje często razem z gliną typu Taczów i ponad nią.