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The maximum ice sheet limit of the Vistulian Glaciation in northeastern Poland and neighbouring areas

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This paper outlines a new approach to reconstructing Vistulian ice sheet limits in NE Poland and adjacent areas of Lithuania and Belarus. It is based on geological investigations of landforms and deposits either of a hypothetical boundary to the Vistulian ice sheet limits. The main conclusions are: 1 — the area was covered twice by the Vistulian ice sheet; the first time during the Świecie Stadial (67–50 ka BP) and the second time during the Main Stadial (24–12 ka BP); 2 — the limit of the older stadial was farther to the south a that of the younger one; 3 — due to covering of the Eemian sediments by the ice sheet of the Świecie Stadial the limit of the Vistulian Glaciation has moved about 15–20 km southwards.

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Key words: northeastern Poland, Vistulian Glaciation, Eemian Interglacial, ice sheet limit, tills.

INTRODUCTION

This paper deals with the limits of the Vistulian Glaciation in northeastern Poland and neighbouring territories of Lithuania and Belarus. It is a summary of the Ph. D. thesis (Krzywicki, 1999*b*).

The aim of the work was to investigate which of the ice sheets of the Vistulian Glaciation advanced onto the area of northeastern Poland, as well to reconstruct and delimit its maximum extent.

The Oldest (Toruń) Stadial, two thin glacial tills found by Makowska (1976) and Drozdowski (1986) in the Lower Vistula region, is not considered in this paper, which deals with the ice sheet limits of the two Vistulian Glaciations: the Świecie Stadial and the Main Stadial.

Many Polish authors have suggested that the ice sheet of the Świecie Stadial extended into northern Poland, though its presence east and south of the Mazury Great Lakes District has not been proved. Both Lithuanian and Belarussian authors suggest that there was no ice sheet in their countries at that time (Astapova *et al*., 1987; Karabanov, 1987; Valtchik *et al*., 1990; Gaigalas, 1995; Kondratiene, 1996; Satkunas *et al.*, 1997).

The other ice sheet of the Vistulian Glaciation that certainly advanced onto the area of northern Poland was that of the Main Stadial (Leszno-Pomeranian). At the end of the glaciation a continuous retreat of the ice sheet occurred, interrupted by short stagnation events (of the rank of phases and subphases) marked by moraine belts. A similar idea was earlier postulated by Żurek (1975), Ber (1990) and Lisicki (1993). The stagnation periods were usually stable, rarely with oscillatory fluctuations, locally of a transgressive character. It seems that the only exception was the local Wigry transgression that occurred between the maximum advance of the ice sheet and the Pomeranian Phase (Lisicki, 1993).

In the north the research area embraces uplands and outwash plains of young-glacial relief. These are fragments of the Mrągowo Lakeland and Mazury Great Lakes District, Mazury Plain, part of the Ełk Lakeland and Rajgród Lakeland, as well as the Augustów Plain, Dainava Plain and part of the Central Neman Lowland. In the south, the study area covers fragments of old-glacial uplands of the Kolno Upland, Białystok Upland, Sokółka Hills, Hrodna Upland and Lida

Plain, with intervening depressions of the Kurpie Plain, Biebrza Valley, High Neman Lowland. The research area covers 26 sheets of the *Detailed Geological Map of Poland*, scale 1:50 000 and occupies a total area of approximately 7700 km^2. The Lithuanian and Belarussian parts cover about 3000 km^2.

PREVIOUS RESEARCH

Before 1939 Polish investigations of the last glaciation in northeastern Poland were limited to the Suwałki area (Wołłosowicz, 1926, 1928; Pietkiewicz, 1928; Pawłowski, 1933). Woldstedt (1935) published a map of the Quaternary deposits of East Prussia with the ice sheet limit of the Vistulian Glaciation marked, trending along the Narew River valley near Łomża, south of Mońki and north of Sokółka (Fig. 1). The maximum extent of the Pomeranian Stadial was shown as runing across the northern margin of the Mazury Lakeland. The first Polish attempt to summarise the Quaternary studies of East Prussia was the paper by Galon (1937), which also included a map of morphological landscapes of East Prussia constructed on the basis of Woldstedt's map (1935). Galon (1937) included the whole Lakeland within the extent of the ice sheet of the Pomeranian Stadial, with its limit running across the area of Mikołajki, Orzysz and Ełk.

After 1939, studies of Quaternary deposits and extents of ice sheets in northeastern Poland became more systematic. Majdanowski (1947) drew the ice sheet limit of the Vistulian Glaciation south of Szczytno, north of Rozogi, between Pisz and Biała Piska, north of Grajewo, south of Rajgród, north of Sztabin and along the Wołkuszanka River valley. Halicki (1950, 1951) recognised, on the basis of palynological studies, deposits of two more glaciations above Eemian Interglacial deposits: Glaciation V (North Polesie or North Polish Glaciation) and Glaciation VI (Baltic Glaciation). The former reached the area of Supraśl, Gródek and Jałówka (Halicki, 1951). Farther east, Belarus, Halicki drew the limit of Glaciation V across Svisloch, Porozow, Lyskov, Ruzhana, Byten and south of Baranovitchi. Pachucki (1961) mapped the Neman Ice Lobe in the Suwałki area. Kondracki (1952) distinguished 9 belts of frontal moraines deposited during the Baltic Glaciation. That author drawn its maximum ice sheet limit across Nidzica, Szczytno, Śniardwy Lake and Ełk.

Since the beginning of the 1960s most authors assumed, after Galon and Roszkówna (1961), that the maximum limit of the Baltic Glaciation in northeastern Poland coincided with the Leszno Phase. Those authors drew the limit line between Lipowiec and Szczytno, north of Rozogi, across Jeże, north of Szczuczyn, north of Grajewo, south of Rajgród, across the northern slopes of Sztabin "Island" and south of the Wołkuszanka River valley. A general outline of this limit remained basically unchanged in later papers, although several authors introduced some modifications. The limits were drawn across the area of Szczytno, Rozogi, Jeże, Grajewo, Rajgród and the southern part of the Augustów Plain. In the Kolno Upland, Szafer (1955), Rühle and Sokołowska (1961), Mojski and Rühle (1965) and Mojski (1972) drew the limit of the Leszno Phase slightly farther south, across the area of Szczuczyn and Wąsosz, approaching the macroforms described later by Musiał (1984) as the slope of a marginal contact and glaciofluvial kame rampart.

In the Kurpie Plain, Rühle and Sokołowska (1961), Słowański (1971), Bogacki (1976) and Kozłowska and Kozłowski (1995*b*) drew the ice sheet limit of the Baltic Glaciation across "old" frontal moraines surrounded by the youngest outwash plain deposits.

Galon and Roszkówna (1961), Kalniet and Karaszewska (1972), Różycki (1972*a*, *b*, 1978), Mojski (1972), Straszewska (1975), Wołk-Musiał (1980) and Żurek (1984) drew the line across the northern border of the Biebrza Valley. Żurek (1975), moreover, considered that the ice sheet entered the Biebrza marginal valley as far as the Ełk and Jegrznia rivers, as shown by the Kuwasy kettle hole.

Ber (1972*a*, *b*, 1974, 1982) and Żurek (1975) claimed that the ice sheet limit of the Leszno Phase in the southern part of the Augustów Plain ran across the northern slopes of the "Islands" of Sztabin, Jastrzębna, Nowy Lipsk and Lipsk. A similar opinion was expressed by Bogacki (1976), who assumed that the ice sheet reached the Biebrza Valley, covering the whole of the Augustów Plain.

Ber (1975*b*) reported that the ice sheet limit of the Leszno Phase which, as he assumed, coincided with the maximum extent of the North Polish Glaciation, trends across the Kolno Upland and along the northern end of the Biebrza Valley (from Cwaliny through Kowalewo, Łodygowo, Bęćkowo, Grajewo, Danowo, Kosiły, Dręstwo Lake, Woźnawieś and Tajno Lake). Recently, Ber (1999, 2000), quoting Liszkowski (1993), has considered that glacioisostasy had an impact on the maximum extent of the Vistulian Glaciation and the position, direction and extents of recession-oscillation marginal zones. Glacioisostasy operated primarily along longitudinal tectonic faults of the deeper basement. The marginal zone of the Main Stadial of the Vistulian Glaciation coincides, according to Ber (1999, 2000), with the longitudinal Sajno-Rygol fault.

Marcinkiewicz (1973) reconstructed the extent of young-glacial relief on the basis of the analysis of topographic maps of the South Mazury and the Suwałki area, at a scale of 1:25 000, understanding its limit as a boundary between an area abounding with kettle holes and an area with a regular drainage system. Marcinkiewicz (1973) suggested that this boundary corresponded to the maximum extent of the last glaciation.

Kociszewska-Musiał (1978) alone assumed that the Vistulian ice sheet advanced only onto the East Suwałki Lakeland, whereas in the western part it filled major depressions and valleys.

In recent years there were also some attempts to draw the ice sheet limit of the Vistulian Glaciation farther to the south. These attempts were based on thermoluminescence dating, and were stimulated primarily by the consciousness that there is a difference (*cf*. Halicki, 1950, 1951) between the degree of denudation in the zone typical of old-glacial areas and that in the area located to the north — although outside the commonly accepted extent of the Baltic Glaciation. These are the Mława and Przasnysz areas, the Białystok Upland and the Sokółka Hills, as well as the Biała Piska region and northern areas of the Kolno

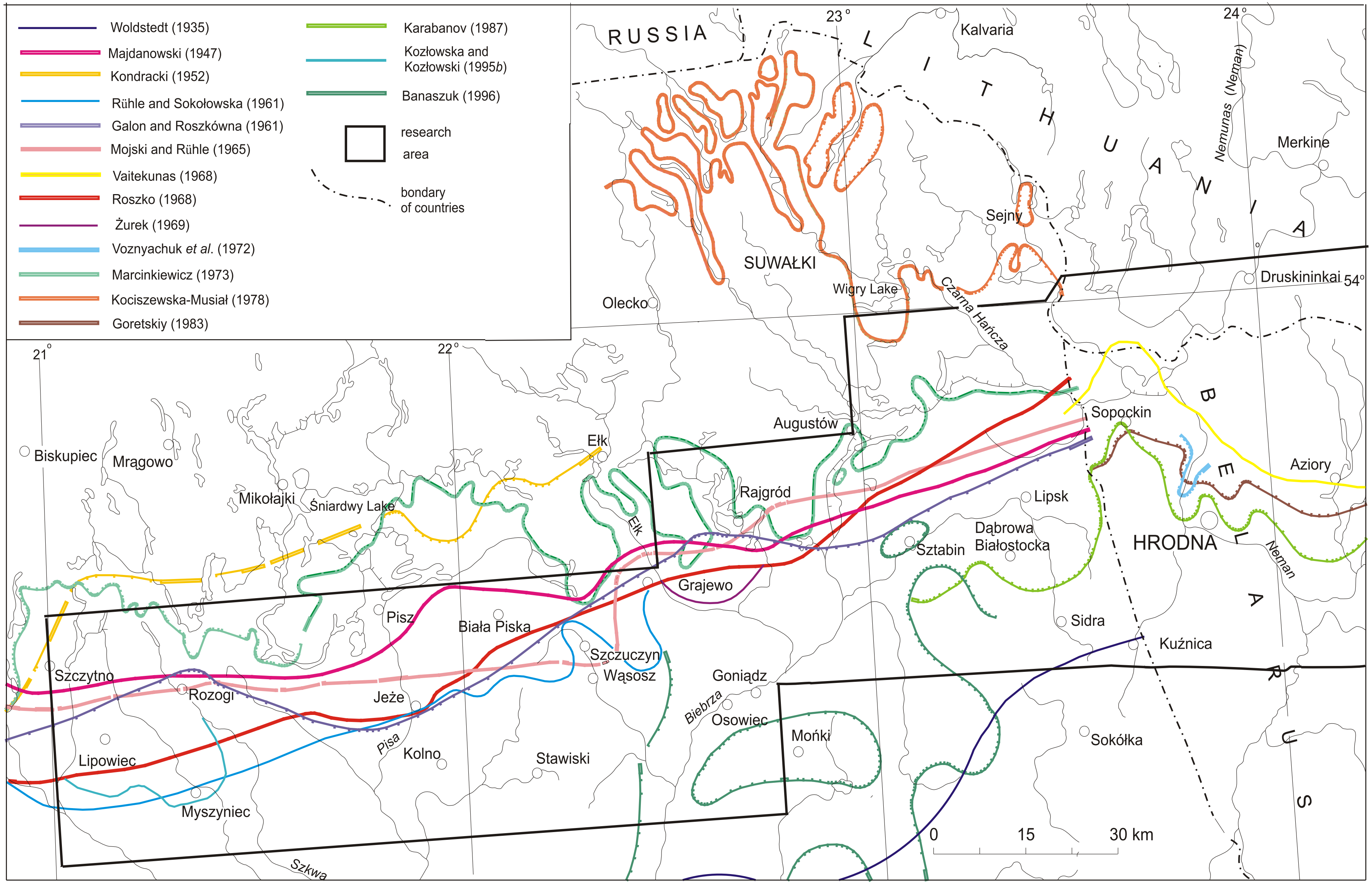


Fig. 1. Location of research area and maximum ice sheet limits of Vistulian Glaciation (Nemunas [Neman], Poozierie) according to different authors

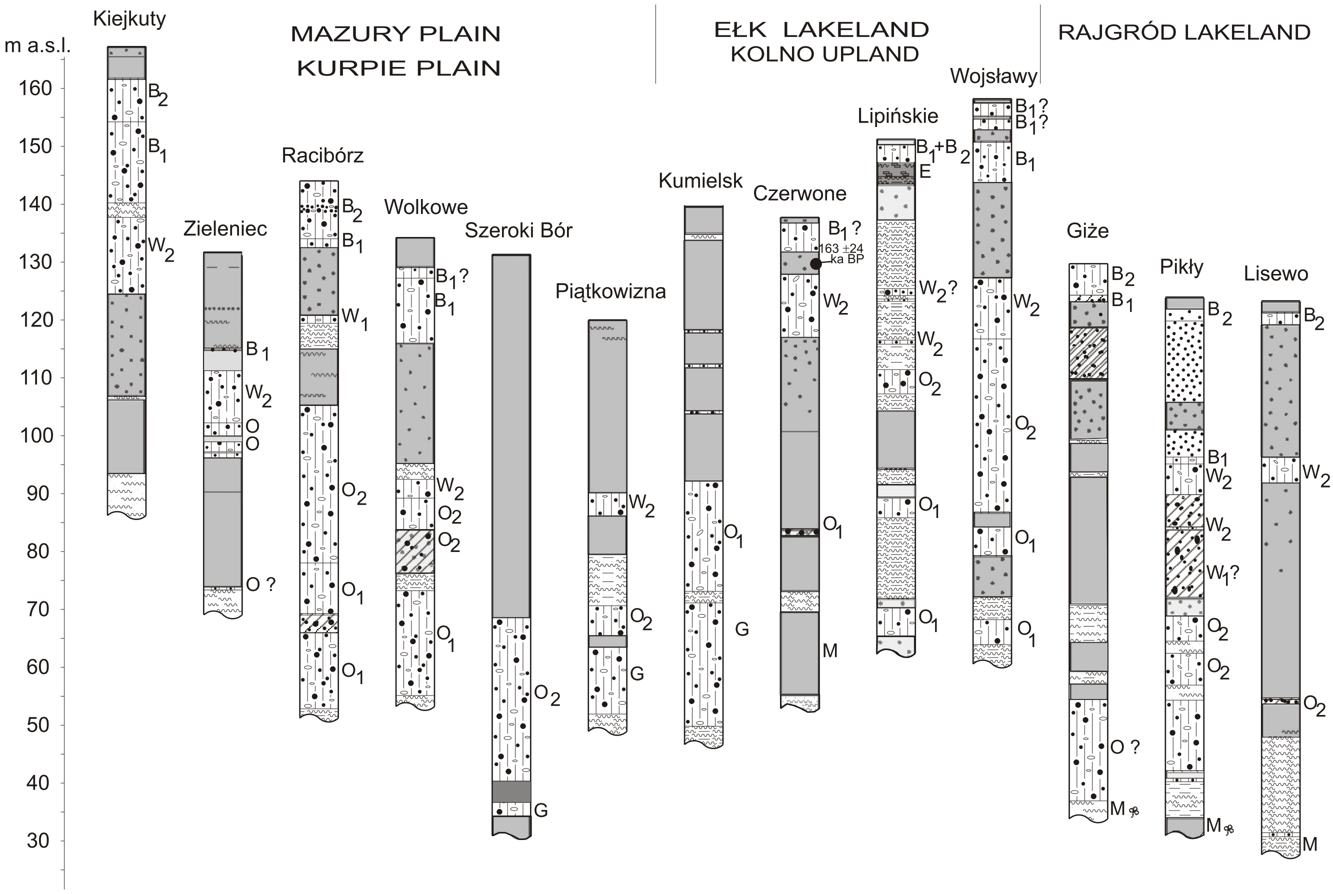


Fig. 2. Borehole

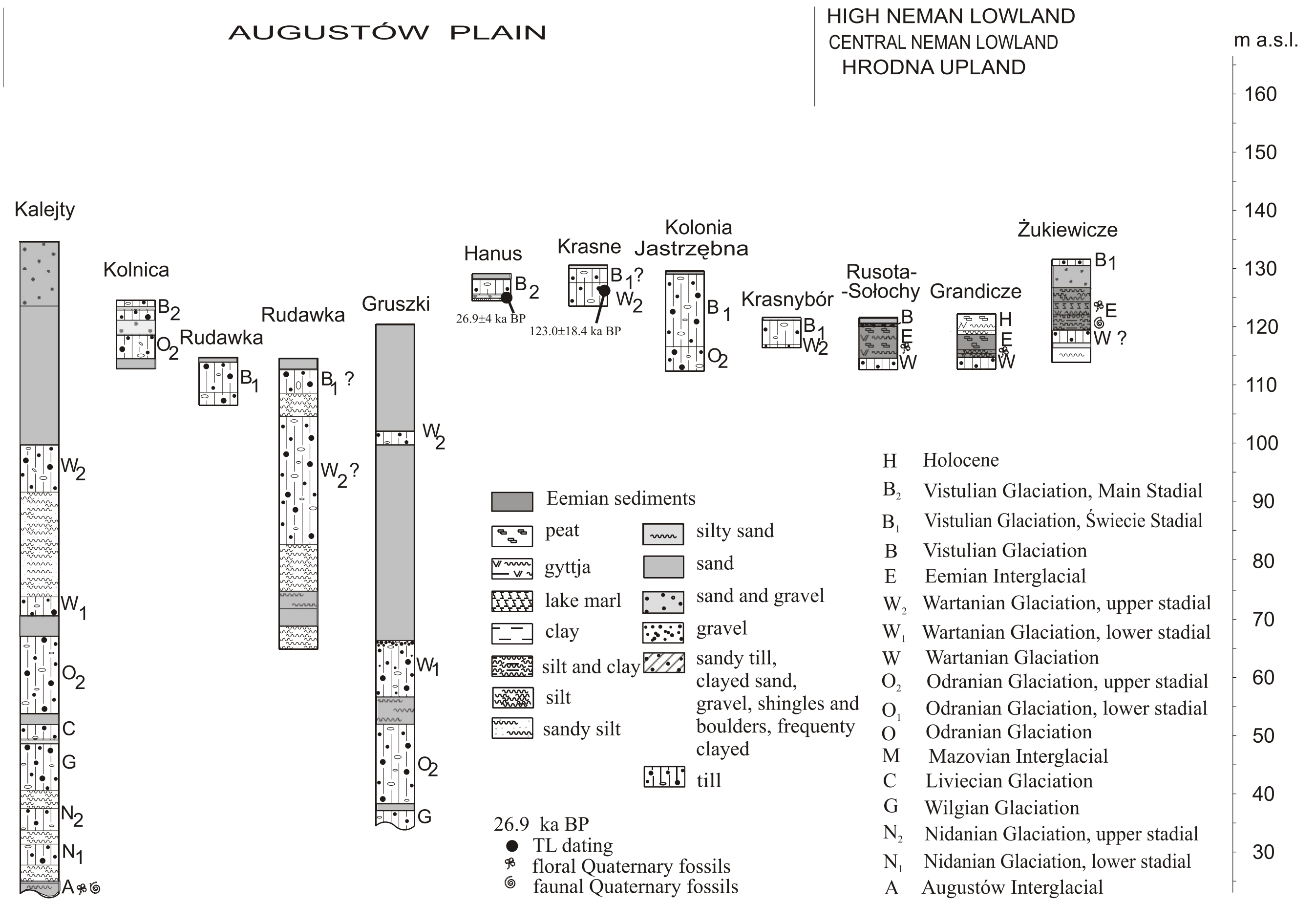
Upland. Research workers emphasize the freshness of the landscape of the area, the varied topography, steep slopes and a dense system of small valleys.

Fedorowicz *et al*. (1995), using TL datings, ascertained that the ice sheet front of the Vistulian Glaciation may have reached the area of Białystok. Banaszuk (1995) based his stratigraphical conclusions mainly on TL datings from the Knyszyn Forests, young-glacial areas of northeastern Poland (Banaszuk *et al*., 1994) and the Narew River valley (Banaszuk, 1996). The results of his investigations show that the Toruń Stadial ice sheet had the greatest extent of all the Vistulian ice sheets (approximately 110 ka BP), reaching Brańsk, Wysokie Mazowieckie and the Nurzec River. The Świecie Stadial ice sheet covered only the East Suwałki Lakeland, and it was the last glaciation in that region. It is possible that the ice sheet front of the Main Stadial stopped in the extreme north of the lakelands, with ice tongues moving southwards into depressions.

After the publications by Makowska (1976, 1979, 1980) on the stratigraphy of the Vistulian Glaciation deposits in the Lower Vistula region, studies on the possible greater extent of tills older than the Main Stadial were also initiated in the neighbouring areas.

Marks (1988) discovered that the ice sheet W3, coeval with the Świecie Stadial (60–55ka BP), reached the areas of Płock, Lidzbark Warmiński, Nidzica and Szczytno. In Warmia and the West Mazury Lakeland, the limit of the ice sheet W3 coincides with the maximum extent of the Vistulian Glaciation. In succeeding papers Marks (1990*a*, *b*, 1991, 1994, 1997*a, b*) upheld these ideas. Lindner (1992) was of the opinion that the Świecie Stadial ice sheet advanced again onto the Lower Vistula region and, possibly, onto Warmia and the northern part of the Mazury Lakeland. On the basis of petrographical studies and examinations of erratics Lisicki (1998) and Gałązka *et al*. (1998) moved the hypothetical line of the maximum extent of the Świecie Stadial southwards to the Mława area.

There is no controversy among geologists on the extent of the last glaciation (Poozerie Glaciation) in Belarus. The ice sheet limit was drawn by Voznyatchuk (1956) and upheld by Vaytekunas (1968) and Voznyatchuk *et al*. (1972), and is commonly accepted by Belarussian research workers. It runs across the northern slopes of the Hrodna Upland, enters the Neman River valley near Hrodna and then turns southwards to the



type sections

Aziory area (hence the name of the ice lobe). Goretskiy (1983) and Karabanov (1987) moved the line several to tens of kilometres southwards. There is a common opinion that the ice sheet did not enter the Neman River valley south of Skidel. Only Chepulite (1978, 1986) claimed that the youngest glaciation tills spread as far as south of the Dainava Plain, the Central Neman Lowland and Hrodna Upland.

Astapova *et al*. (1987) considered that the ice sheet of the Late Poozerie Stadial had its greatest extent during the Poozerie Glaciation (Baltijskij horizon, Orshanskij Megastadial) 17–18 ka BP.

Belarussian scientists (Karabanov, 1987; Astapova *et al*., 1987; Valtchik *et al*., 1990) have not found any deposits and geomorphological features of the early Poozerie Glaciation. According to Astapova *et al.* (1987), the ice sheet of the Srednie-Poozerskij Megastadial (Dvinskij subhorizon), that corresponds to the Świecie Stadial, probably reached the northern border of Belarus, not overstepping it.

Lithuanian geologists and geographers, among others Gaigalas (1995), Kondratiene (1996) and Satkunas *et al.* (1997), agree that ice sheet transgressions occurred only during the later phase (Upper Nemunas) of the Nemunas Glaciation. They distinguished the Gruda Stadial (including Ž¦iogeliai Phase) and Baltija Stadial. The stadials reflect two ice sheet advances, of which the former had a greater extent.

RESEARCH METHODS

The present report is based on the analysis of geological investigations of deposits and landforms in the broadly understood zone of maximum extent of the Vistulian Glaciation, the analysis of topographic maps with particular regard to geomorphological problems, an analysis of the results of petrographical-lithological investigations (used to construct the *Detailed Geological Map of Poland*, scale 1:50 000), palynological studies of Eemian Interglacial sites, and thermoluminescence datings of tills, lacustrine and ice-dam lake deposits.

Topographic and geomorphological maps, at a scale of 1: 25 000, were also analysed. These gave evidence for distribution of frontal and dead-ice moraines, kames, eskers and glacial tunnel valleys, outwash fans, moraine "islands" of an older morainic plateau within outwash plain deposits, outcrops of a till basement within outwash plain and ice-dam deposits, topographic lows which in the past may have formed marginal val-

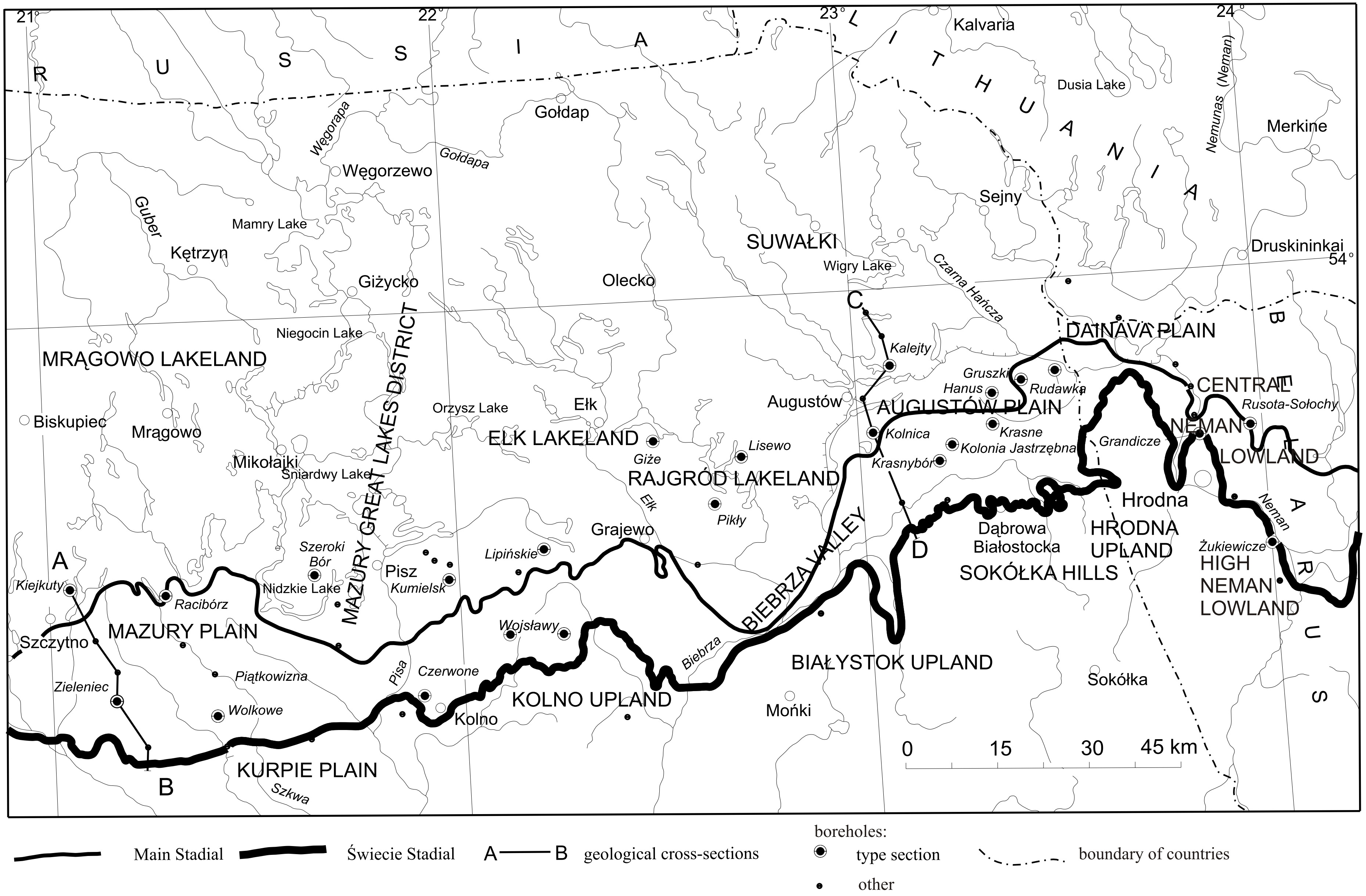


Fig. 3. Research area map

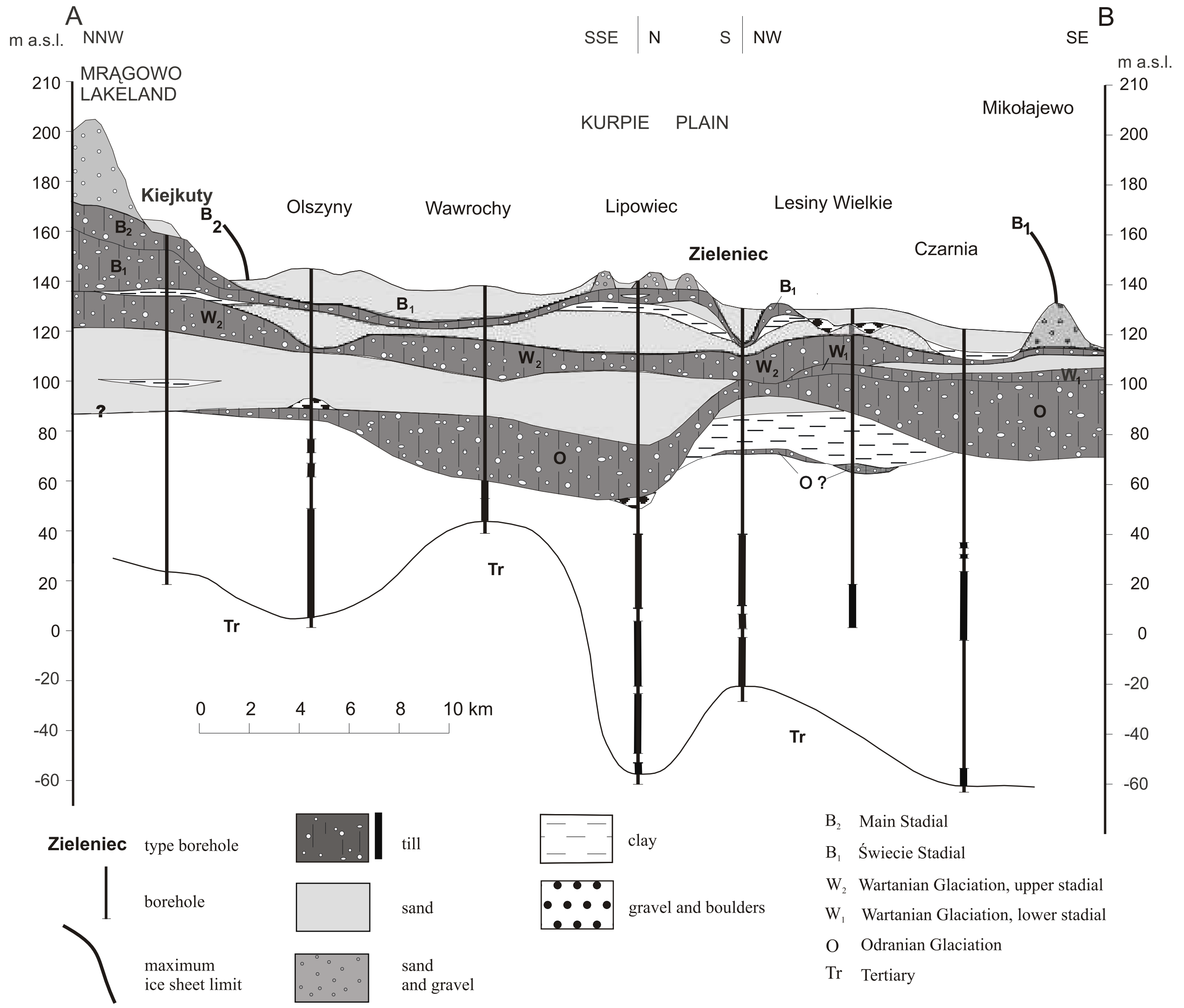


Fig. 4. Geological cross-section A–B: Mrągowo Lakeland, Kurpie Plain

leys or drainage routes for the pra-Neman (Nemunas) River, channel lakes and dead-ice troughs.

62 cartographic borehole sections were analysed from the Polish part of the research area, and several tens of borehole sections from Belarus and Lithuania. 24 type sections were selected. These are characterised by the following features:

— the profiles were analysed for palynology and age determinations;

— the age of any one of the lithologic horizons is supported by 2 methods, e.g. the lithotype is determined using petrographical studies with additional TL datings;

— they possess the most complete sequences of the Vistulian Glaciation deposits;

— they show a characteristic development of deposits, most typical for the study area.

These profiles prove the age of Late Pleistocene deposits, in particular the Vistulian Glaciation and the Eemian Interglacial deposits, throughout the study area. In some cases they also illustrate the typical geological structure of the sub-surface Pleistocene deposits, and form a basis for the construction of geological cross-sections and further analyses (Fig. 2).

Especially detailed analyses were made on 16 sheets of the *Detailed Geological Map of Poland*, at a scale of 1:50 000, (Maksiak, 1992; Kozłowka and Kozłowski, 1993, 1995*a, b*, 1996*a, b*, 1997, 1999; Krzywicki, 1996, 1999*a*, 2001*a, b*; Żuk, 1997, 1998*a, b*; Kacprzak, 2000; Lichwa, 2000; Ber, in preparation). Geological documentations were also analysed, providing much information on the lithology of end moraines, kames and outwash fans.

The aim of the work was to study the youngest glacial deposits, including tills. Their distribution, extent, thickness and lithology were examined. Supposed extents of the youngest ice-dam lakes, which came into existence during the transgression and regression of the youngest glaciation ice sheet, as well as the drainage routes of the ancient Neman River waters to the drainage systems of the Biebrza, Narew and Vistula during the

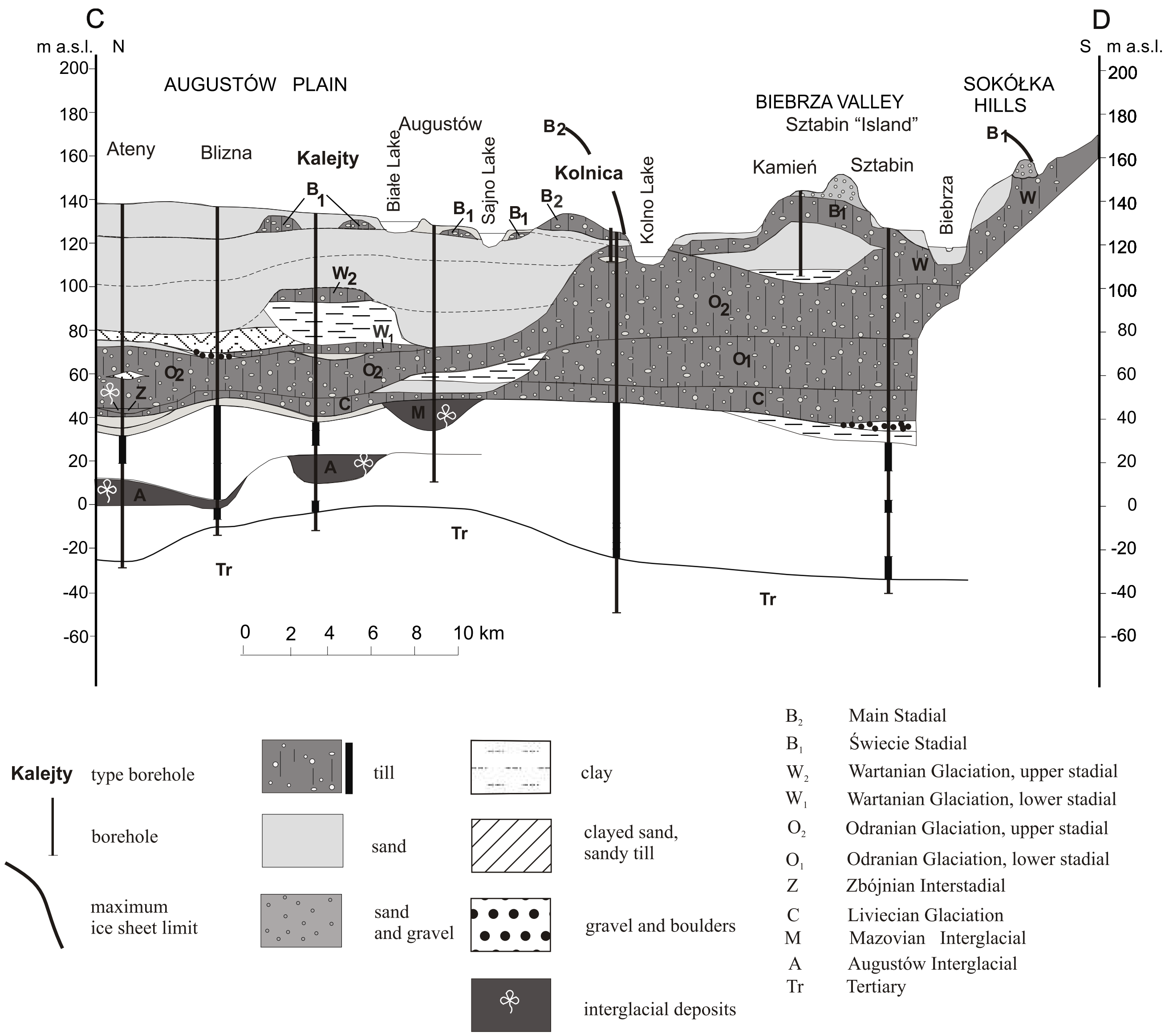


Fig. 5. Geological cross-section C–D: Augustów Plain, Biebrza Valley, Sokółka Hills

ice sheet retreat of the Vistulian Glaciation, were also investigated. A number of geological cross-sections were constructed. They show the geological structure of the Mid-Late Pleistocene deposits in the research area (Figs. 3–5).

PALYNOLOGY

Approximately 45 Eemian Interglacial sites have been described so far and investigated within the zone of the maximum extent of the Vistulian Glaciation in northeastern Poland, western Belarus and southwestern Lithuania. These are sites of lacustrine organic sediments both uncovered and covered by glacial deposits, most often by the Vistulian Glaciation till, its residuum or glaciofluvial deposits (Fig. 6). The climatic optimum of the Eemian Interglacial is recorded in 10 sites, and in 2 more it is probable. The thickness of the interglacial deposits varies from 0.5 to 7.2 m (Fig. 7a, b).

In the Hrodna Upland, and High and Central Neman Lowland interglacial deposits fill abandoned river channels in the Neman River valley (Pavlovskaya, 1998). Some Belarussian and Lithuanian geologists suggest that in this area the whole of Eemian Interglacial deposits are overlain by a till or its residuum (Voznyatchuk, 1956; Chepulite, 1966; Kryger *et al.*, 1971). Other authors (Voznyatchuk, 1960; Pasyukievich *et al.*, 1972; Goretskiy, 1980) considered that some of the Eemian Interglacial sites (Pyszki, Poniemuń and Druck) possess only a periglacial solifluction cover. Karabanov (1987) claims that there is no precise answer to the question whether the Eemian deposits are covered by a till or not in the peripheral zone of the Hrodna Upland near the Neman River. In western Belarus, the most widespread Eemian deposit is bog lime, often covered with peat, 1–8 m in thickness (Karabanov, 1987).

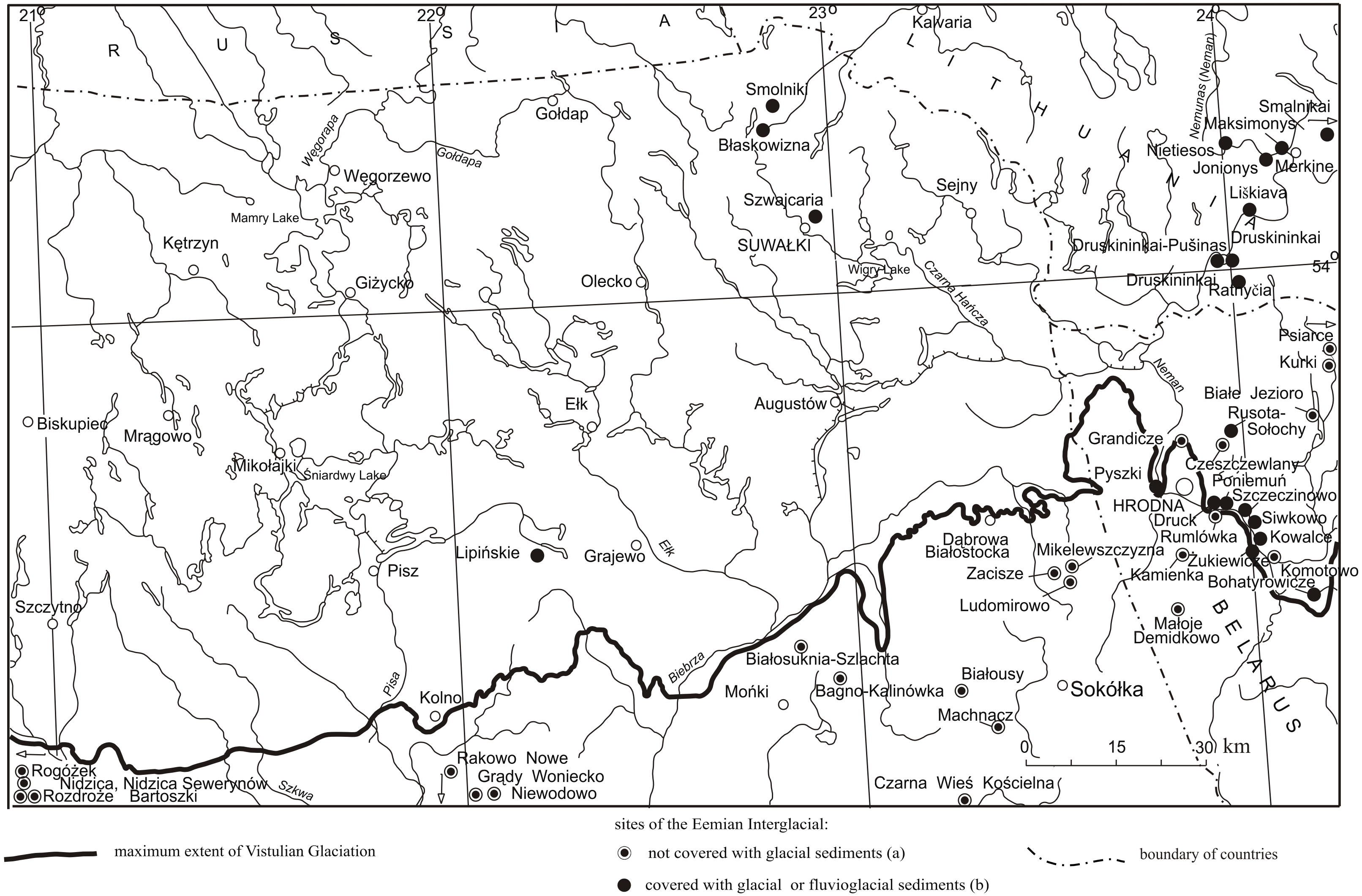
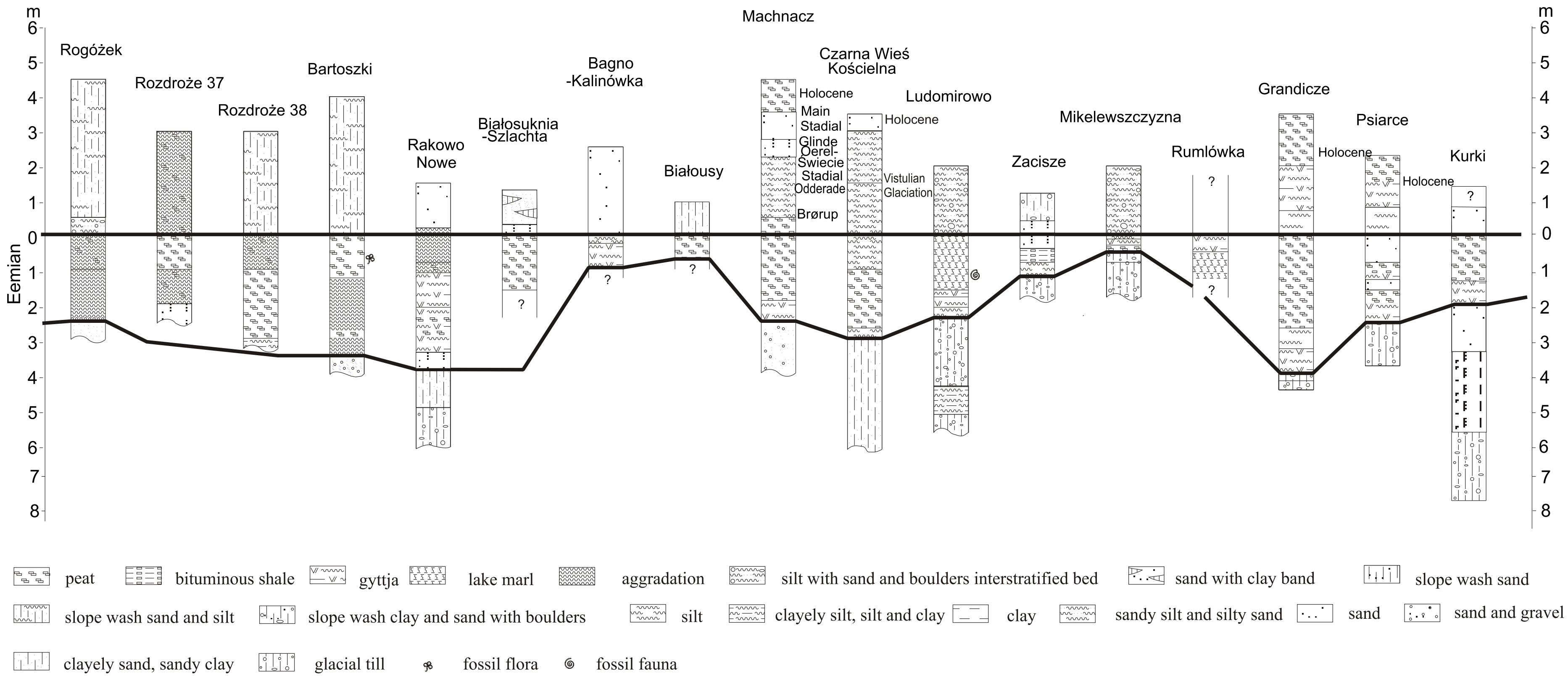


Fig. 6. Map of the Eemian Interglacial sites

Sites of the Eemian Interglacial: a — not covered with glacial sediments: in the **Mława Upland** — Nidzica (Marciniak and Kowalski, 1978), Nidzica Sewerynów (Mamakowa, 1988), Rogóżek, Rozdroże and Bartoszki (Morawski *et al*., 1998, 1999); in the **Kolno Upland** — Niewodowo (Musiał *et al*., 1982), Grądy Woniecko (Banaszuk, 1980), Rakowo Nowe (Bałuk and Krupiński, 2000); in the **Białystok Upland** — Białosuknia-Szlachta (Janczyk-Kopikowa, 1958; Ber, 1975*b*), Bagno-Kalinówka (Borówko-Dłużakowa and Halicki, 1957), Białousy (Janczyk-Kopikowa, 1958), Machnacz (Żurek, 1990,1992; Kupryjanowicz, 1991,1994; Fedorowicz *et al*., 1995), Czarna Wieś Kościelna (Bitner, 1956; Buczyński, 1960); in the **Sokółka Hills** — Ludomirowo, Zacisze and Mikelewszczyzna (Czaplicka, 1952; Bitner, 1957; Ber, 1972*b*); in the **Hrodna Upland** — Rumlówka (Środoń, 1950; Karabanov, 1987), Grandicze (Pasyukievich *et al*., 1972), Małoje Demidkowo, Kamienka, Czeszczewlany; in the **Central Neman Lowland** — Białe Jezioro (Karabanov, 1987),); in the **High Neman Lowland** — Komotowo (Voznyatchuk, 1956; Dorofieyev, 1963); in the **Lida Plain** — Psiarce and Kurki (Pasyukievich *et al*., 1972); b — covered with glacial or fluvioglacial sediments: in the **Ełk Lakeland** — Lipińskie (Janczyk-Kopikowa, 1998); in the **Suwałki Lakeland** — Szwajcaria, Błaskowizna and Smolniki (Borówko-Dłużakowa and Halicki, 1957; Andrzejeszczak, 1971; Borówko-Dłużakowa, 1971; Ber, 1973, 1974; Kociszewska-Musiał and Leciejewicz, 1982; Krzywicki, 1993); in the **Lithuania Lakeland** — Netiesos, Maksimonys and Jonionys (Bremówna and Sobolewska, 1950; Borówko-Dłużakowa and Halicki, 1957; Chepulite, 1986; Kondratiene, 1996; Satkunas, 1997*b*; Satkunas *et al*., 1998); in the **Dainava Plain** — Ratnyčia, Druskininkai, Druskininkai-Pušinas, Liškiava, Smalnikai (Kondratiene, 1996); in the **Central Neman Lowland** — Rusota-Sołochy (Karabanov, 1987); in the **High Neman Lowland** — Pyszki (Chepulite, 1966), Druck (Halicki, 1951; Chepulite, 1986), Poniemuń (Karabanov, 1987), Szczeczinowo (Halicki, 1951; Chepulite, 1986), Siwkowo (Halicki, 1951; Chepulite, 1986), Kowalce (Halicki, 1951; Chepulite, 1966), Żukiewicze (Halicki, 1951), Bohatyrowicze (Halicki, 1951; Voznyatchuk and Valtchik, 1978; Chepulite, 1986) a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Eemian
Rogóżek
Rozdroże 37
Rozdroże 38
Bartoszki
Rakowo Nowe
Białosuknia -Szlachta
Bagno -Kalinówka
Białousy
Machnacz
Holocene
Main Stadial
Glinde
Oerel-Świecie Stadial
Odderade
Brørup
Czarna Wieś Kościelna
Holocene
Vistulian Glaciation
Ludomirowo
Zacisze
Mikelewszczyzna
Rumlówka
Grandicze
Holocene
Psiarce
Holocene
Kurki
peat
bituminous shale
gyttja
lake marl
aggradation
silt with sand and boulders interstratified bed
sand with clay band
slope wash sand
slope wash sand and silt
slope wash clay and sand with boulders
silt
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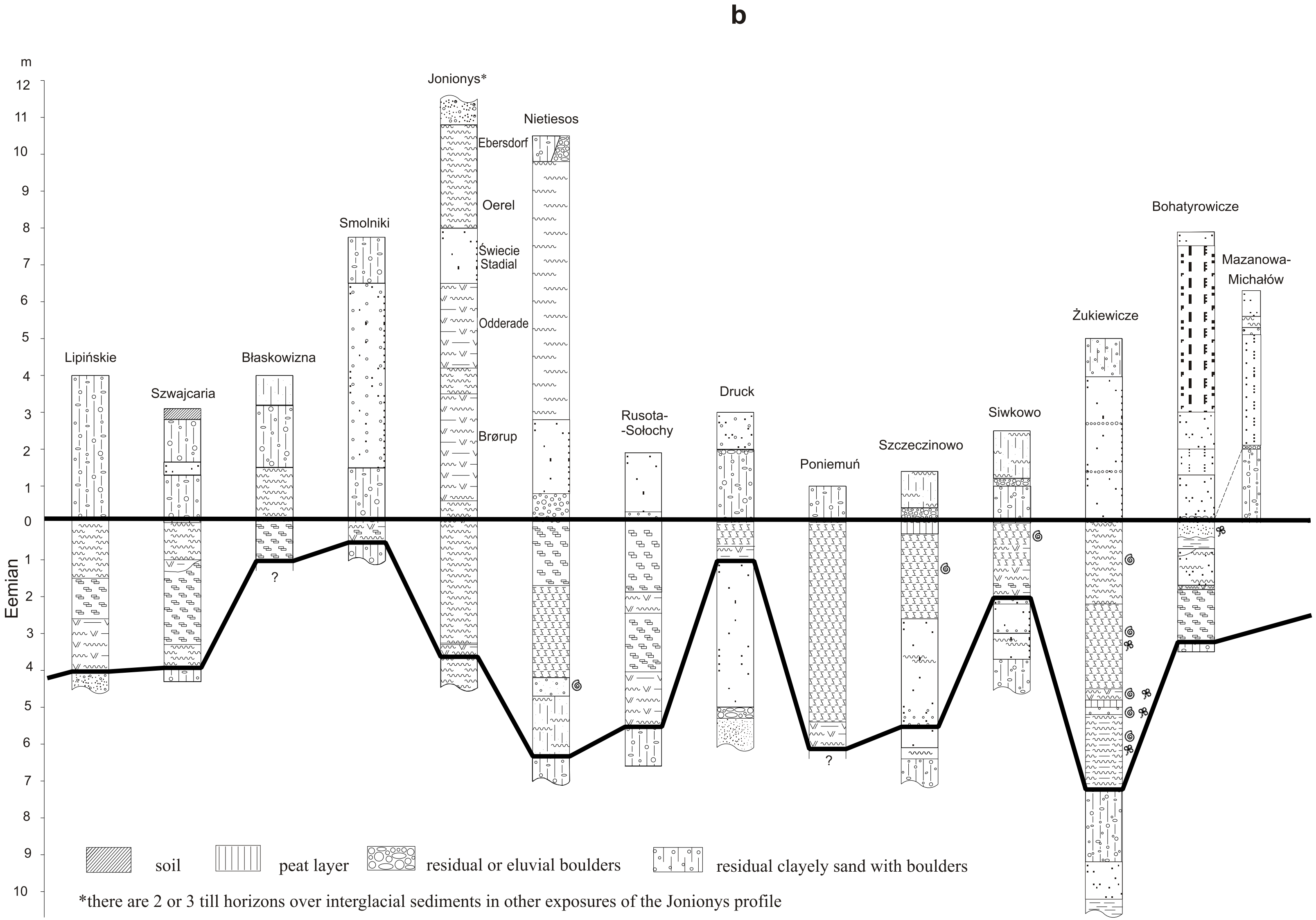

Fig. 7. Eemian Interglacial profiles: **a** — non covered with glacial sediments, **b** — covered with glacial or fluvioglacial sediments

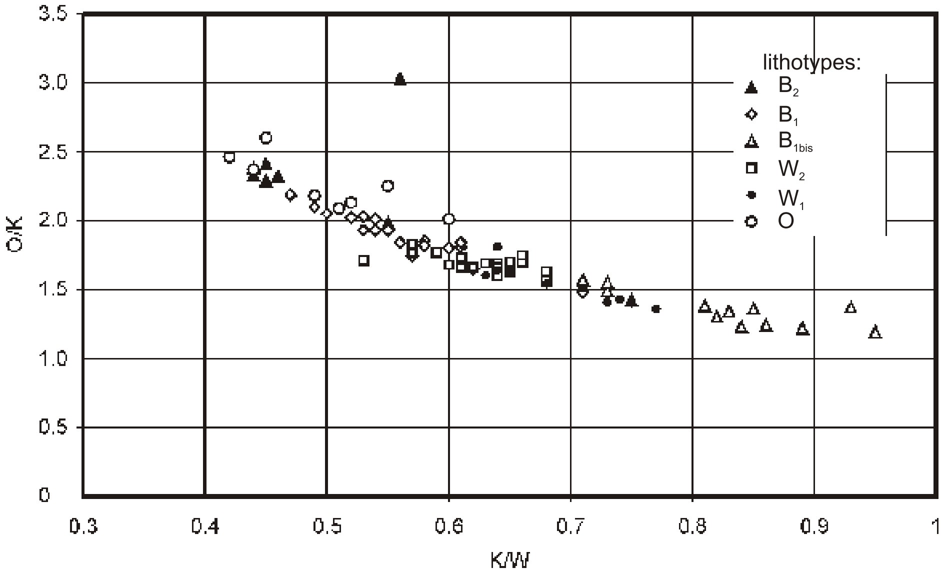

Fig. 8. Diagram of the coefficients O/K and K/W in the upper tills of NE Poland

The sites at Czeszczewlany, Białe Jezioro and Komotowo are undoubtedly located within the extent of the youngest ice sheet. The lack of a till horizon above Eemian Interglacial deposits results probably from later erosional and denudation processes.

A geological (palaeobotanical) criterion is one of the most important criteria permitting the delineation of the ice sheet limit, showing that the Vistulian ice sheet did not advance onto the Mazovian and Podlasie lowlands (Banaszuk, 1995, 1996, 1998; Fedorowicz *et al.*, 1995).

LITHOSTRATIGRAPHY OF TILLS

The major feature that allows the distinction between tills is the petrographical composition of the gravel fractions. This paper compares the petrographical composition of pebbles from the uppermost tills from the Polish part of the research area, using this data to constract a stratigraphical succession.

The methodology of petrographical studies was outlined by Lisicki (1998). Samples must contain at least 100 grains, 5–10 mm in diameter. The analysis includes the calculation of the percentage contribution of particular groups of Scandinavian rocks (crystalline rocks, limestones, dolomites, sandstones, quartzites and quartz grains) and local rocks (limestones, marls, sandstones, siltstones and claystones). Proportions between different rocks in each sample are characterised by petrographic coefficients: O/K, K/W and A/B, where: O — total of sedimentary rocks (limestones, dolomites, sandstones and shales), K — total of crystalline rocks and quartz grains, W — total of carbonates (limestones, dolomites), A — total of rocks non-resistant to weathering (limestones, dolomites, sandstones and shales), B — total of weathering-resistant rocks (crystalline rocks, quartz grains and sandstones).

Results of lithological-petrographical investigations performed for the following sheets of the *Detailed Geological Map of Poland*, at a scale of 1:50 000, were analysed: Wielbark (Jeleński, unpubl.), Lipowiec (Zawidzka, unpubl.), Świętajno and Spychowo (Fert *et al.*, unpubl.), Myszyniec (Komacka-Makowiecka, unpubl.), Ruciane-Nida, Łyse, Pisz and Kolno (Makarewicz and Zaczkiewicz, unpubl.), Biała Piska (Honczaruk, unpubl.), Rajgród, Rygol and Rudawka (Gronkowska-Krystek, unpubl.), Augustów Station (Kenig, unpubl.). Vistulian Glaciation tills are absent from the boreholes in the western part of the research area (near Ruciane-Nida, Łyse, Pisz and Kolno).

Furthermore, a special report was prepared (Gronkowska-Krystek, unpubl.) for 26 till samples collected for investigations in the southern part of the Augustów Plain and Upper Biebrza Valley (near Sztabin and Lipsk) (Krzywicki, 1997*a*, *b*).

Petrographical analyses of gravels from 62 cartographic boreholes, hand-auger holes and exposures were performed. Petrographic coefficients were calculated for each sample. Arithmetic means of these coefficients for individual till horizons were also calculated. Figure 8 shows the mutual relationships between the groups of coefficients. 5 lithotypes can be distinguish among the uppermost till horizons: B_2, B_1, B_{1bis}, W_2 and W_1. Lithotype B_1 occurs only east of Suwałki and Augustów (Table 1). Figure 9 shows examples of borehole sections containing tills of various lithotypes. These results were compared with the results of petrographical investigations conducted by Kenig (1998) in the Mazury and Suwałki lakelands (Fig.10).

Values of petrographical coefficients O/K, K/W and A/B (within the same lithotype) differ slightly from one study to another. The following conclusions arise from the analysis of petrographical investigations:

1. They may have a great utility in the lithostratigraphy of tills.

2. Tills B_2 can be correlated with the younger stadial of the Vistulian Glaciation, tills B_1 and B_{1bis} correlate with the older stadial of the Vistulian Glaciation, tills W_2 correlate with the younger stadial of the Wartanian Glaciation, tills W_1 correlate with the older stadial of the Wartanian Glaciation.

3. It should be stressed that the youngest till (lithotype B_2) occurs in the fresh morainic plateaux with glacial tunnel valleys. This supports Majdanowski's proposal (1947) that glacial tunnel valleys are the best indicator of the limit of the youngest glaciation, considered here as the Main Stadial of the Vistulian Glaciation, 32–13 ka BP (*cf.* Shackleton and Opdyke, 1973). In 4 cases (Kiejkuty, Wojnowo, Racibórz and Pikły) out of 6, tills B_2 are underlain by tills B_1.

4. Tills B_1 or B_{1bis} from the area located outside the maximum extent of the Main Stadial always form the highest horizon (except for two cases: the Krasne and Hanus boreholes in the Augustów Plain, where the upper till is weathered and its lithotype cannot be defined).

5. In the Augustów Plain, Odranian Glaciation tills are situated very high (boreholes Kolnica, Kolonia Jastrzębna, Jastrzębna II, Nowy Lipsk), and they are often overlain by tills B_{1bis} (in the last 3 boreholes). In Krasnybór, tills W_2 occur near the surface and are overlain by tills B_{1bis}.

6. Deviations from the average values of petrographic coefficients O/K, K/W and A/B are very rare. They can result from the occurrence of detached till fragments of a different age. Till from depths of 13.8–15.4 m (Nowy Lipsk borehole), with coefficients of 0.77–1.61–0.54, can serve as an example.

7. In at least 7 borehole sections, the upper tills are weathered and the results had to be rejected. Weathering processes operated over some areas during glaciations (periglacial climate) and warmer periods (moderate climate), and were probably influenced by local geomorphological and microclimatic conditions. Weathering zones often occur in the upper parts of the youngest tills.

8. In 10 borehole sections from the areas of Ruciane, Pisz, Łyse and Kolno, the first till (from top) is the Odranian Glaciation till.

TL DATINGS

The thermoluminescence method (TL) was broadly used for absolute age determinations in the 1980s and early 1990s. It was primarily employed to examine clays and muds, but also tills and sands. This was a standard method to establish the stratigraphy during the preparation of the *Detailed Geological Map of Poland*.

The author had at his disposal results of 34 TL dates of near-surface deposits from the study area. 17 of them come from the Augustów Plain and Upper Biebrza Valley. One dates was kindly rendered accessible to me by Professor Żurek. Another one comes from the paper by Żurek (1990). The most important datings for the present study are those from the Augustów Plain and Upper Biebrza Valley (Fig. 11). They can be grouped into 4 time groups.

Table 1

The coefficients O/K, K/W and A/B in the upper tills of NE Poland

Litho-type	Number of samples	Mean values of petrographical coefficients O/K- K/W-A/B
B_2	7	2.39–0.45–2.14
B_1	21	1.92–0.55–1.71
B_{1bis}	13	1.38–0.80–1.10
W_2	22	1.69–0.62–1.49
W_1	11	1.53–0.72–1.38

The first group includes only one date of 180.0 ka BP (Żurek, 1990) (profile 1 in Fig. 11). The second group contains 2 dates — 118.4±17.8 (UG-2606) and 123.0±18.4 ka BP (UG-2611) (profiles 2 and 3 in Fig. 11) (Fedorowicz, unpubl.). The third group includes 5 dates (profiles 4–8 in Fig. 11), from 47.0±7 to 63.0±9 ka BP (Lub-2088-90, UG-172) (Butrym, unpubl.; Olszak and Fedorowicz, unpubl.; Olszak, unpubl). 4 of them were made on tills, one (the youngest) on clayey mud. The fourth group includes 4 dates from muds and muddy clays — from 23.5±3.5 to 31.8±4.8 ka BP (profiles 9–12 in Fig. 11) (UG-2607-09, 2619) (Fedorowicz, unpubl.).

The analysis of TL and petrographical investigations from the Augustów Plain and Upper Biebrza Valley were the subject of a separate paper (Krzywicki, 1997*a*). Its main conclusion was that tills occurring at the surface are not of the same age everywhere, and the "islands" are composed of 2 or more tills of different ages.

Dates from the Augustów Plain point to the occurrence of older and younger tills of the Wartanian Glaciation and one till of the Świecie Stadial. The younger dates from muddy deposits suggest the Grudziądz Interstadial and Main Stadial, prior to the ice sheet advance.

TL dates can often help in stratigraphy when considered together with the results of other investigations.

If we assume the greater reliability of petrographical studies over TL datings, and tie down the above-mentioned groups of coefficients to particular lithotypes (resulting in stratigraphical conclusions), we must reject 2 of the thermoluminescence datings from the Augustów Plain.

STRATIGRAPHY OF VISTULIAN GLACIATION DEPOSITS

Until the 1950s it was commonly accepted (Woldstedt, 1929; Kondracki, 1952; Szafer, 1953) that the last glaciation was divided into the Leszno, Poznań and Pomeranian phases (corresponding to latives of the Brandenburgian, Frankfurtian and Pomeranian phases in Germany). The Leszno Phase was considered to have the greatest extent.

Studies by Makowska (1976, 1979, 1980, 1986) resulted in the new stratigraphy of the Vistulian Glaciation in Poland. 5

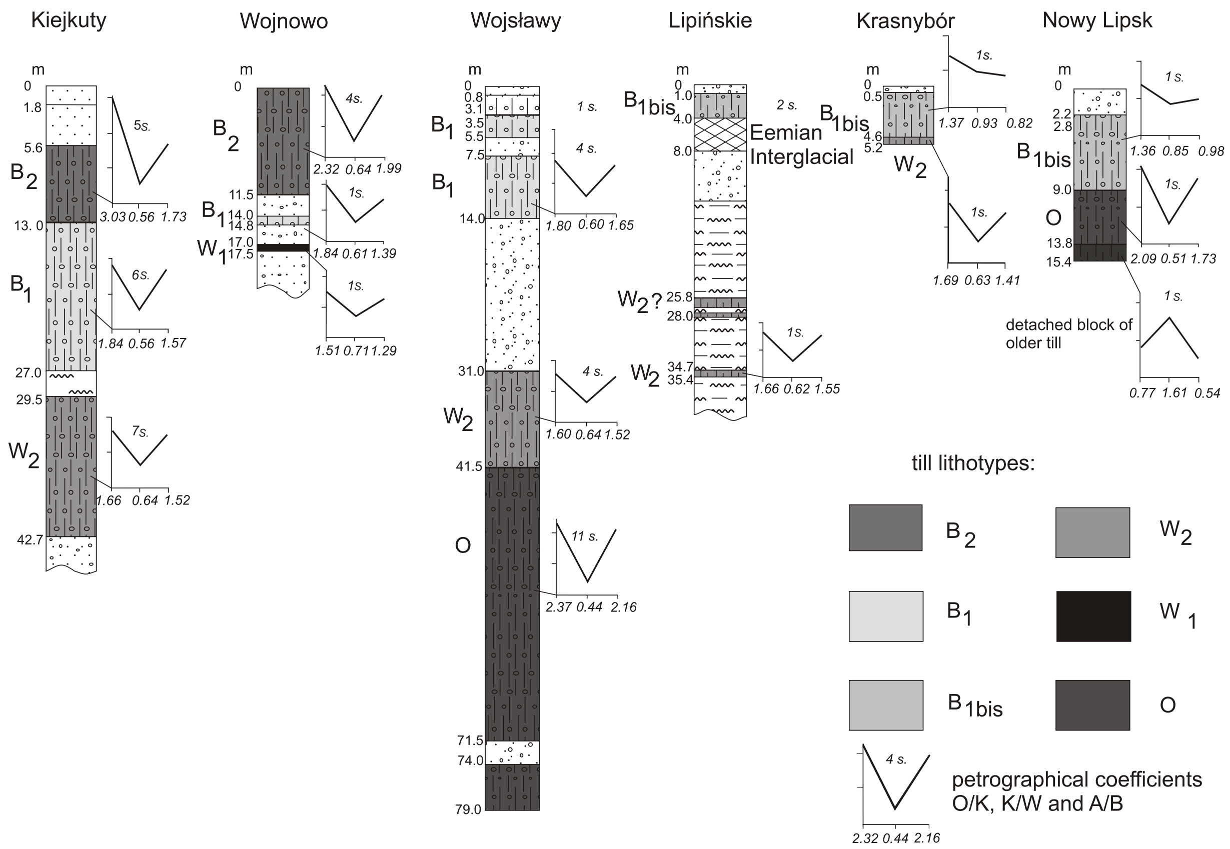

Fig. 9. Examples of boreholes with different till lithotypes

tills distinguished by her were ascribed to 3 stadials (Toruń, Świecie and Main stadials) or to 2 glaciations: Toruń and Baltic (Vistulian) glaciations, which are separated by dated marine deposits. A warm period between the Toruń and Świecie stadials was termed by Makowska the Gniew Interstadial or Krastudy Interstadial (1976, 1980), later named the Krastudy Interglacial (1986).

Results of Makowska's (1976, 1979, 1980, 1986) investigations in the Lower Vistula region were later partly upheld by Drozdowski (1986) and, in Warmia and the western part of Mazury, by Marks (1988). Marks recognised 3 tills of the Vistulian Glaciation (W2, W3 and W4), corresponding to the tills BII, BIII and BIV of Makowska (1976).

A similar subdivision of the North Polish Glaciation was also accepted in the *Instruction for the Detailed Geological Map of Poland* (1991).

Currently, some Polish authors (Lindner, 1987; Marks, 1990*a*; Mojski 1997) accept stratigraphic schemes of the Vistulian Glaciation based on Makowska's papers with three main tills (1979, 1980). These schemes are well tied to stratigraphic schemes of the Upper Pleistocene of northern Europe (e.g. Behre, 1989), and to their correlation with ^{18}O isotope stages (Shackleton and Opdyke, 1973; Mangerud, 1992), as well as to the climatostratigraphic scheme proposed by Wysoczański-Minkowicz (1982), and supported by age determinations.

The Belarussian authors use the stratigraphic scheme proposed by Voznyatchuk (1972, 1976). He divided the Poozerie (Valdai) Glaciation into 5 zones or subzones, equivalents to stadials and interstadials. Starting with the Middle Vistulian these are as follows: Dvinskij (Kalininskij, Srednie-Poozerskij Megastadial) subhorizon, Srednie-Poozerskij subhorizon (Krasnaya Gorka Megainterstadial) and Baltijskij horizon (Ozerie, North Poozerie, Late Poozerie, Poozerie, Poozerie Glaciation *sensu stricto*). More detailed stratigraphic schemes, based on palynological studies, have recently been worked out (Yelovicheva *et al.*, 1996, Yelovicheva, 1997; Yelovicheva and Sanko, 1999). Yelovicheva *et al.* (1996) divided the middle and upper parts of the Poozerie Glaciation into 2 parts: the Medium Level and Naroch Level — Late Glacial. The Medium Level is subdivided into 8 minor units: megastadials (cool periods) and interstadials (warm periods). Miezhinskij I Stadial corresponds to the Świecie Stadial. The Orshanskij IV Stadial corresponds to the Main Stadial. The latest paper by Yelovicheva and Sanko (1999) quotes a series of radiocarbon and TL dates from deposits of the Poozerie Glaciation in Belarus. These dates are not given in the chart of stratigraphic schemes of the Vistulian Glaciation (Fig. 12).

In Lithuania, there are two equivalent stratigraphic schemes of the Vistulian Glaciation, named the Nemunas Glaciation. The first scheme was proposed by Gaigalas and Yartsev (1992) and Gaigalas (1995). It refers to palynology sites in southern and northern Lithuania (Jonionys, Rokai and Biržai). The Varduva Stadial (69 ka BP) is an equivalent of the Świecie Stadial. The youngest cool period is divided into 2 stadials: the Gruda Stadial (22 ka BP) with the Žiogeliai Phase, and Baltija Stadial (17 ka BP). The stadials are separated by the Pavyte Interstadial.

Guobyte and Pavlovskaya (1998) made an attempt to link the upper parts of the Lithuanian and Belarusian stratigraphic schemes of the latest glaciation (Upper Nemunas and Orshanskij Stadial of the Poozerie Glaciation, corresponding to the Main Stadial of the Vistulian Glaciation). Research around the Lithuanian/Belarusian border resulted in the conclusion that the upper stadial of the Nemunas/Poozerie Glaciation can be divided into the Gruda/Ozerie; Šventiany/Švenčionys and Baltija/Braslav phases, corresponding to the Brandenburgian (Leszno), Frankfurtian (Poznań) and Pomeranian phases.

Another Lithuanian stratigraphic scheme, postulated by Satkunas and Grigyene (1997), and correlated with other European stratigraphic schemes (Satkunas, 1997*b*), also refers to palynostratigraphy.

The Nemunas Glaciation was divided into the lower, middle and upper parts. Palynologically studied deposits of warm periods of the lower and middle Nemunas (7 units) were investigated in 2 sites at Jonionys-on-Nemunas near Merkine and Mickunai near Vilnius. Warm periods are separated by 7 cool periods, labelled with the name of Nemunas followed by a number and a letter. A cool period corresponding to the Świecie Stadial is marked by a symbol Nemunas 2a. The upper Nemunas deposits (Nemunas 3) of the Gruda Stadial, Ž¦iogeliai Phase and the Baltija Stadial are separated in this scheme by deposits of the Antaviliai and Ula interstadials (Satkunas, 1997*a*), although the stratigraphical position of these interstadials is unclear, being currently under revision.

The latest Lithuanian research (Blazhauskas *et al*., 1998) has shown that organic deposits (peats, gyttja), exposed in high banks of the Ula River and earlier considered to have represented interstadial deposits, are younger and represent the Older Dryas, Allerød and Younger Dryas. Recent investigations of the Antaviliai section located near Vilnius (Satkunas and Hütt, 1999) also show that lacustrine deposits, correlated with the Antaviliai Interstadial, are older and represent the Drenthe-Warthe (Lublin) Interstadial. Satkunas and Hütt (1999) considered that there are no sites with interstadial or interphasial deposits of the younger part of Vistulian Glaciation in Lithuania and other Baltic countries. Therefore, there is no climatostratigraphical evidence for establishing stadials, phases and interstadials during that period.

VISTULIAN GLACIATION — RECONSTRUCTION OF CLIMATIC CHANGES AND ICE SHEET LIMITS

A reconstruction of geological events of the Early Vistulian Glaciation can only be approximate because no deposits of this age have been found in northeastern Poland.

During the period of 74–59 ka BP (*cf*. Mangerud, 1992) another cooling of the climate resulted in an ice-advance. In Poland this period is called the Świecie Stadial (Makowska, 1986) or Pre-Grudziądz Stadial (Mojski, 1979). The Świecie Stadial ice sheet advanced, according to Lisicki (1996, 1997), onto the Mrągowo Lakeland from the north. Gałązka *et al*. (1998) consider that the till of the older Vistulian Glaciation contains more erratics from the Baltic-Cland and Finnish area, i.e. coming from the east, than from Sweden. A similar domination, but still more accentuated, is also observed within the younger till of the Vistulian Glaciation. It suggests that the centre of this glaciation was located to the east (Finland, Cland Islands) during both these stadials, but in the Świecie Stadial it moved to the western part of the area.

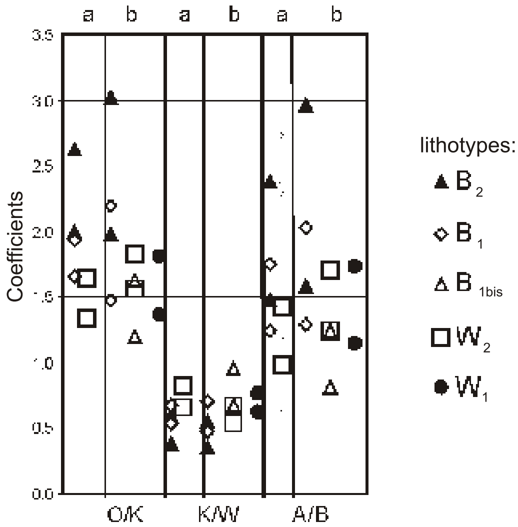

Fig. 10. Minimal and maximal values of petrographic coefficients according to: **a** — Kenig (1998) and **b** — author

The Świecie Stadial ice sheet covered the northern part of Kurpie Plain as far as Kolno, Wąsosz and Klimaszewnica, released a small ice tongue into the Biebrza Valley, reached the front of Sokółka Hills in the vicinity of Dąbrowa Białostocka, and released an ice tongue into the Nurka River valley. In Belarus the ice sheet bypassed the Hrodna Upland, releasing an ice tongue into the Neman River valley as far as Hrodna. It also reached the valley east of Hrodna, covering it with a large ice lobe as far as the Svisloch River Mouths and Dubrowlany. From there, the eastern edge of the ice lobe ran towards Skidel, Ostryna and Motyle, towards the present Belarus/Lithuania border.

The extent was delimited taking into account one of the most important geomorphological criteria, namely, the occurrence of glacial troughs with lakes (Majdanowski, 1947). The absence of lakes in the old-glacial landscape (only this kind of landscape is observed within the area of the Świecie Stadial extent) is a very important indicator of landscape maturity. Only scarce relict lakes occur within that zone. It is associated with the period of filling of lake troughs with sediments (Więckowski, 1966). Another geomorphological criterion — the presence (in some areas of maximum extent) of outwash plains — showing a kame terraces character, morphometrically associated with marginal forms — was also considered.

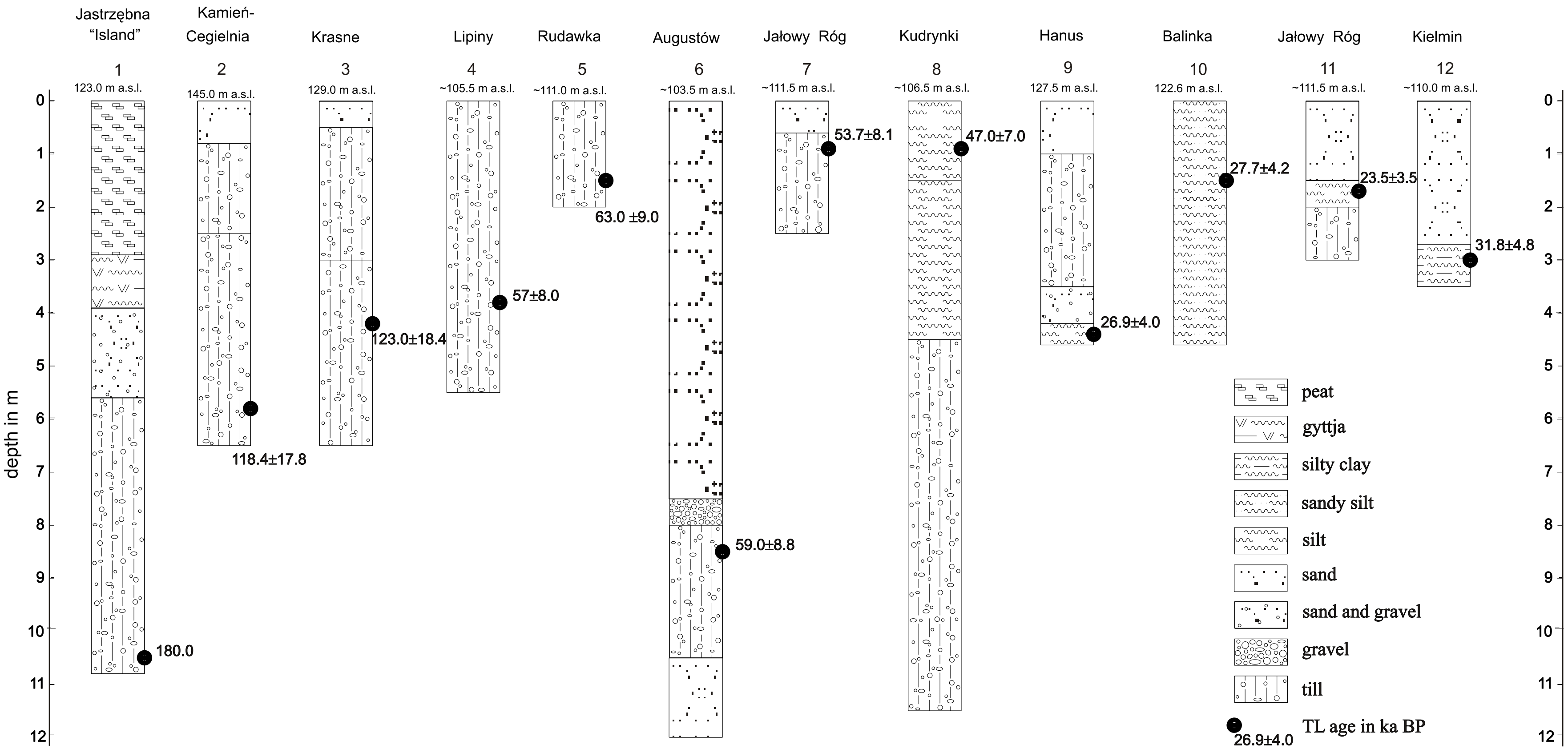

Fig. 11. Borehole sections with TL dating

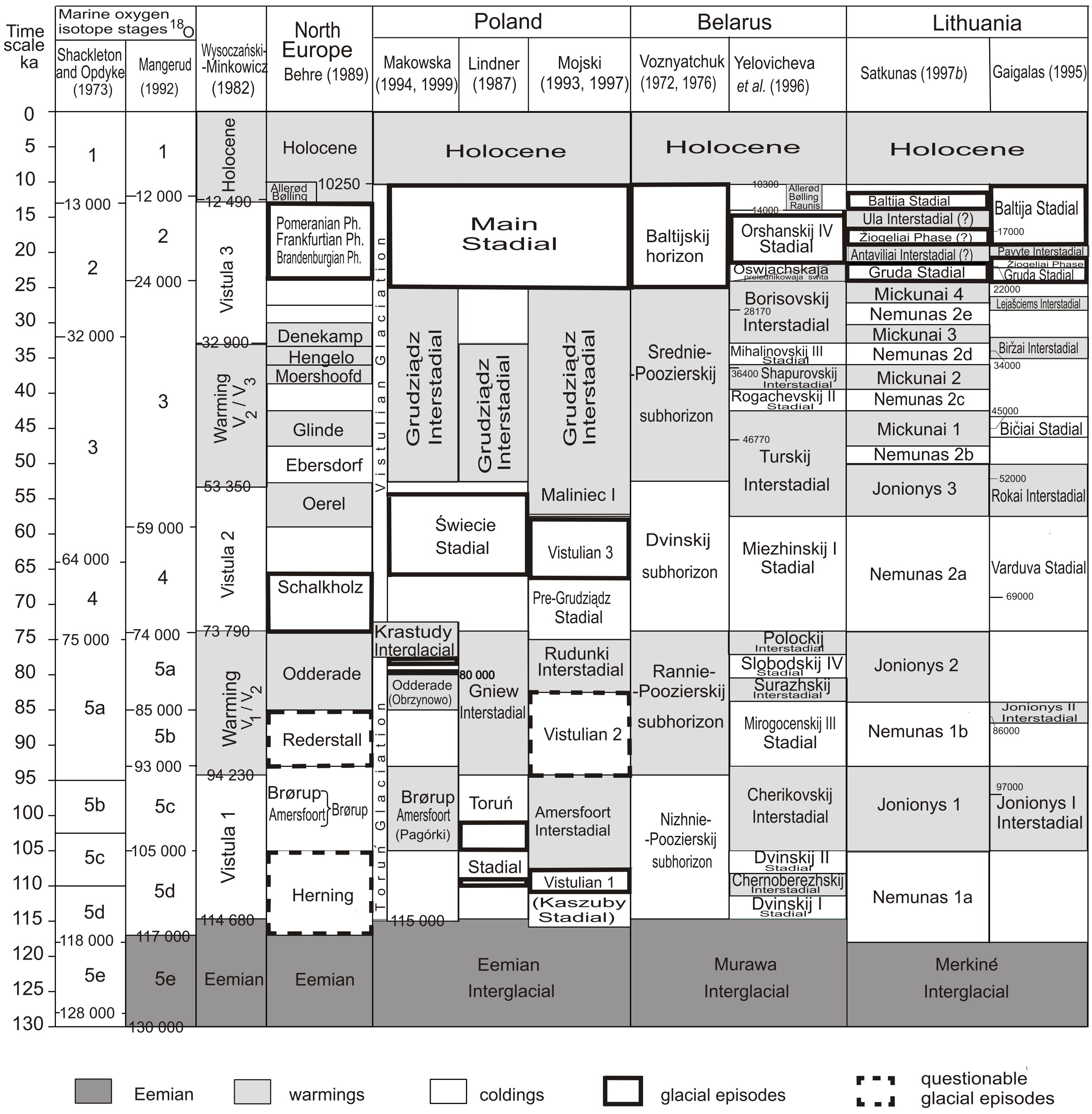

Fig. 12. Stratigraphical subdivision of the Vistulian Glaciation (Nemunas, Poozerie)

Among morphogenetic criteria, the occurrence of moraines, as well as the mutual relationships between end moraines and between moraine outliers on outwash plains were also taken into consideration. The most important group, however, are geological criteria. These include the extent of glacial till related to the ice advance. The Świece Stadial till was identified on the basic of petrographical investigations which comprised determinating the percentage distribution of petrographic groups in gravels extracted from tills.

The thermoluminescence method (TL) enabled age determination of glacial and glaciolacustrine deposits within the area of the maximum ice sheet limit of the Świece Stadial. The distribution of sites of Eemian deposits , which are not covered by glacial deposits, allows identification of the potential maximum extent zone of the Vistulian Glaciation.

After the retreat of the Świecie Stadial ice sheet, there began a warm period called the Grudziądz Interstadial or Interpleniglacial. It lasted from 59 to 24 ka BP (*cf*. Mangerud, 1992). Deposits of that age are known from many sites

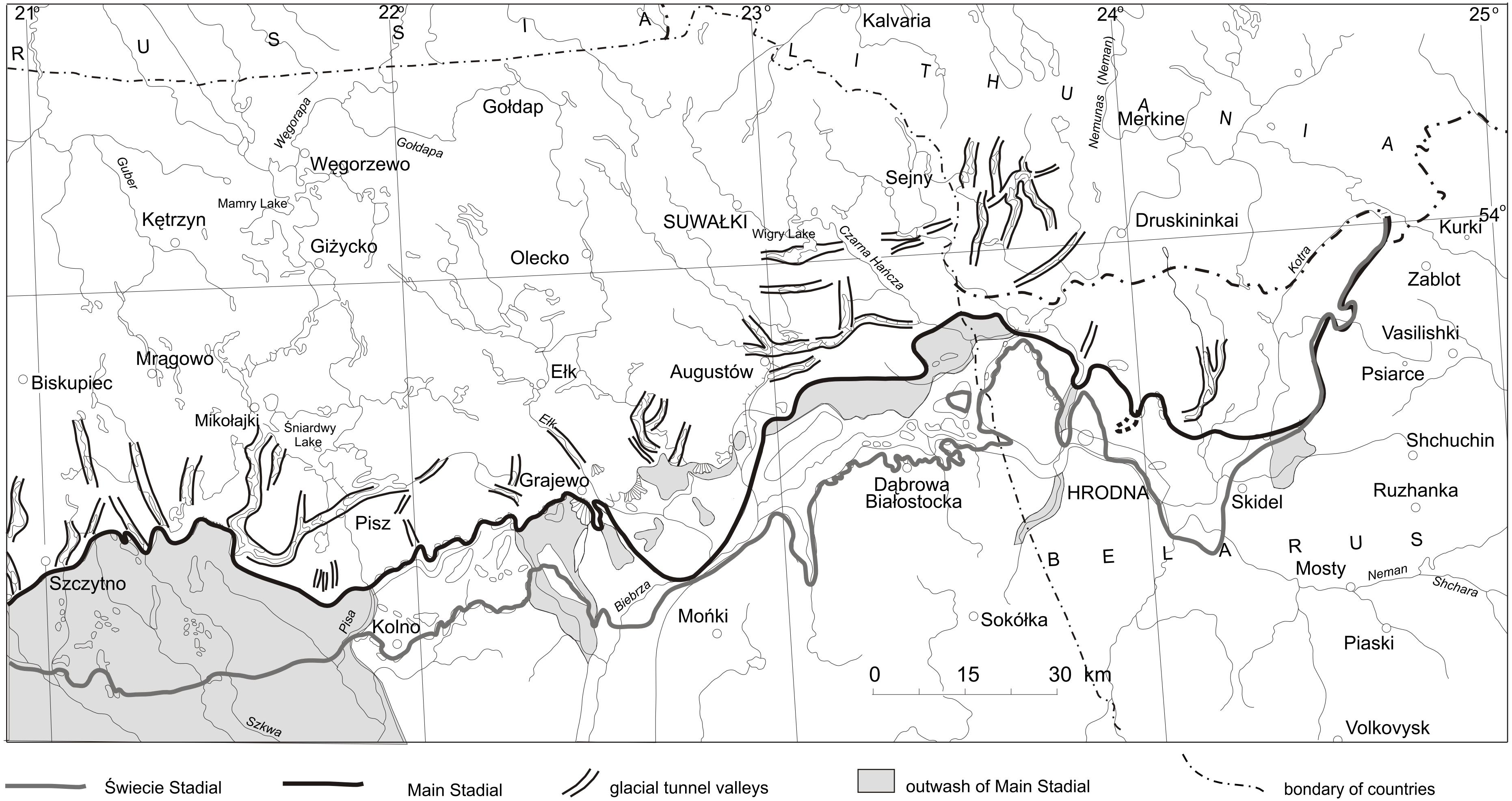

Fig. 13. Ice sheet limit of the Vistulian Glaciation in the Świecie Stadial and the Main Stadial

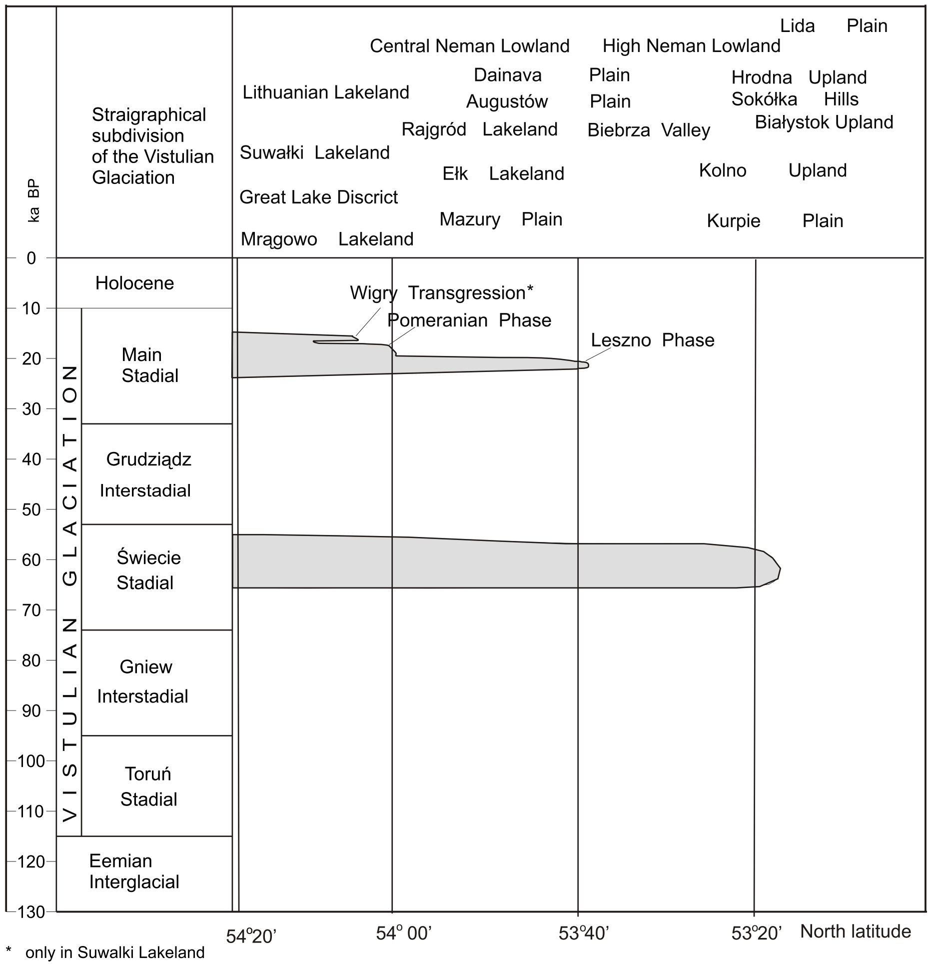

Fig. 14. Space-time schema of the Vistulian Glaciation in NE Poland and adjacent area

throughout Poland (Mojski, 1988), but the most characteristic section is a floristic succession from Konin-Maliniec I, where ancient flora is additionally ^{14}C-dated at > 42.9 ka BP (Kozarski, 1991). The Grudziądz Interstadial was characterised by a cool, subarctic climate. During its first phase, forestless tundra reigned with a willow-horsetail community. Later, stunted birch and herbs became dominant. Scattered birch-trees, typical of areas near the polar forest limit, appeared at the climatic optimum of the interstadial. There were also vast, open spaces overgrown with herbs and mugwort. At the end of the interstadial, stunted birch appeared again. Average temperatures in July for central Poland ranged from 10 to 11°C (Kozarski, 1991) during the climatic optimum.

Another cool period, called the Main or Leszno-Pomeranian Stadial, started at approximately 24.0 ka years BP. The Main Stadial ice sheet reached its maximum extent between about 18 and 20 ka BP (ice-dam lake deposits from Hoża-on-Neman underlying the Poozerie Glaciation till, dated at 18–200 ka BP). The Pomeranian Phase is dated in the Suwałki Lakeland at approximately 15.5 ka BP. The ice sheet retreated from northeastern Poland at approximately 14.0–14.5 ka BP (Kozarski, 1991).

The ice sheet limit of the Main Stadial was reconstructed in this work largely on the basis of the occurrence of glacial tunnel valleys (Majdanowski, 1947). However, the limit was modified in many places because of use of other criteria, first of all geological and geomorphological ones.

Więckowski's studies (1966) on the sedimentation rate in lake troughs suggest that the relief was shaped during a period younger that the Świecie Stadial. During a period of 12 000–13 000 years, after the ice sheet retreat from the area of Mazury, Suwałki and Central Neman Lowland, most of lake troughs may have become filled with sediments only by 20–35 %.

The Main Stadial ice sheet covered the Mazury Plain as far as Szczytno, Świętajno, Spychowo, Karwica Mazurska, Turośl, Łacha, Jeże and further along the high moraine belt separating the Kolno Upland from Ełk Lakeland, as far as the town of Grajewo. From there, the ice sheet released a broad ice lobe into the Biebrza Valley as far south as the Białystok Upland near Goniądz. The eastern edge of that lobe ran along the Netta River valley to the villages of Bór and Gabowe Grądy. The ice sheet covered the northern and middle parts of the Augustów Plain as far as Krasne, Ostryńskie and Gruszki. North of Rudawka the ice sheet limit crossed the Poland/Belarus border. In Belarus the ice sheet reached the northern slopes of the Hrodna Upland, released small ice tongues into the Neman and Hozhka River valleys, and reached the villages of Tabola and Lozy. Between Skidel and Ostryna the ice sheet limits of the Main and Świecie stadials ran along the same line.

Geomorphological, morphogenetic and geological criteria were used for delimiting the extent of the Main Stadial ice sheet. The most important were glacial tunnel valleys with lakes (Majdanowski, 1947). Assuming the lowest sedimentation rates and slow contraction of the lakes (Więckowski, 1966) we can suppose that the only lakes that could persist until the Holocene were those which formed after 50 ka BP, i.e. during the recession of the Main Stadial ice sheet. In the vicinity of Grajewo there is an outwash plain with a distinct outwash fan. This is the uppermost outwash plain level in that area, that is probably associated with the maximum limit of the Main Stadial ice sheet. Of morphogenetic criteria, leading to the determination of the origin and distribution of glacial forms, the occurrence of moraine belts from the area between Pisa and Grajewo were considered. The most important geological criterion was the distribution of till, identified by petrographical studies. The ice sheet limits of the Vistulian Glaciation are shown in Figure 13.

Karabanov (1987) considered that the Hrodna Upland separated two ice lobes during the Brandenburgian (Leszno) Phase. To the west the Kursk Ice Lobe advanced from the Baltic Sea area (from NW), while to the east the Riga Ice Lobe advanced from the north. During the Frankfurtian and Pomeranian phases, the Kursk Ice Lobe was separated into two parts in the Szeskie Heights area: the western part covered Mazury, whereas the eastern part formed an ice tongue reaching as far as the Švenčionys Upland in eastern Lithuania.

The ice sheet limit of the last glaciation was similarly drawn by Pachucki (1961). It ran from the vicinity of Wisztyniec, across Hańcza Lake, Krasnopol, Kapčiamiestis, Merkine, in the vicinity of Vilnius, to Pabrade and Švenčionys. If such an eastern tongue could formed during the retreat of the Main Stadial ice sheet, it is probable that it may have also existed earlier, during the Świecie Stadial. The considerations are based on characteristic petrographic coefficients for the Świecie Stadial tills observed in the east (Augustów Plain, Upper Biebrza Valley), which are different than those calculated in Mazury. These characteristic petrographic coefficients have resulted in the separation of lithotype B_{1bis}.

Therefore, it is highly probable that the Świecie Stadial ice sheet advanced onto eastern Mazury from N and NW, from western Finland, western Latvia and western Lithuania. The Suwałki and Hrodna areas were transgressed by the ice sheet advancing from the N, from Finland, Estonia, eastern Latvia nad eastern Lithuania. The area that separated both the ice tongues were the Szeskie Heights (or rather a basement elevation located west of Hańcza Lake and stretching to the south towards Suwałki), not the Hrodna Upland.

SUMMARY AND CONCLUSIONS

This paper summarises knowledge on the near-surface geological structure (deposits of the middle and younger part of the Vistulian Glaciation) of southeastern Mazury, the southern part of the Suwałki area and the Hrodna district. The major objective was to draw the ice sheet limits of the Vistulian Glaciation.

The main conclusions are as follows:

1. During the Vistulian Glaciation the ice sheet advanced twice onto the area of eastern Mazury and Suwałki and Hrodna districts: during the Middle Stadial (Świecie Stadial — approximately 55–67 ka BP) and during the Upper Stadial (Main Stadial — approximately 24–12 ka BP). The ice sheet extent was greater during the Świecie Stadial; it advanced from a few to about 30 km further to the south than the Main Stadial ice sheet (Fig. 14).

2. Results of petrographic composition of gravels from tills (lithotypes B_2, W_2 and W_1) tend to be highly convergent in the entire Polish part of the study area. Only the tills of the Middle Stadial of the Vistulian Glaciation have a different petrographic composition (lithotypes B_1 and B_{1bis}). The results of petrographic research allowed a stratigraphic separation of the highest tills.

3. The ice sheet limit of the Świecie Stadial is marked by frontal moraines, outwash fans, kames and, indirectly, by sites of Eemian Interglacial sediments. In the eastern part of the research area the Świecie Stadial ice sheet rested against the older uplands that extended to the south.

4. The ice sheet limit of the Main Stadial is delimited by glacial tunnel valleys and lakes (except for a few small reservoirs located outside this line). Glacial sediments of the Main Stadial have often not been preserved within outwash plains at its maximum extent line. The Main Stadial ice sheet advanced onto the middle basin of the Biebrza Valley. In the Suwałki Lakeland it only reached the northern end of the Augustów Plain, and farther south it released a small ice tongue which deposited a thin till in the Augustów Plain. A similar situation might have occurred in the Mazury-Kurpie, Dainava (Lithuania) and Porechje, Aziory and Bershty (Belarus) outwash fans. Glacial sediments of the Main Stadial have commonly not been preserved in the area of its maximum limit.

5. “Till islands”, emerging from beneath the afore-mentioned outwash fans, as well as the “islands” between the Augustów Plain and Biebrza Valley, are composed of the Świecie Stadial tills, at least as regards their upper parts.

Lithuanian and Belarussian scientists claim that during the Middle Stadial of the Vistulian Glaciation there was no ice sheet in the territories of their countries. Nevertheless, these studies indicate that the Middle Stadial till is represented probably by the highest till observed in southwestern Lithuania and northwestern Belarus, in the area between the limits of the Middle Stadial and the Upper Stadial. The Gruda Stadial till of southwestern Lithuania, and the Ozerie Phase (of the Baltijskij horizon, Orshanskij IV Stadial) till of northwestern Belarus, probably correspond to the Świecie Stadial till in Poland. On the basis of lithological sections of the Eemian Interglacial and the last glaciation deposits in the Neman River valley, the ice sheet limit of the Świecie Stadial of the Vistulian Glaciation is postulated to run 15 to 20 km to the south of its previously drawn location.

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