Postglacial morpholineaments as an indicator of ice sheet dynamics during the Saale Glaciation in the Białystok Plateau and Sokółka Hills (NE Poland)

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The palaeogeographical reconstruction of the deglaciation process in NE Poland during the Odranian Glaciation Wartanian Stadial (Saale MIS 6) is based mainly on the analysis of glacial morpholineaments, performed using the GIS programs that provide us with better understanding of the glacial landscape evolution, spatial reconstruction of glacial processes, and postglacial landscape development. Analysis of postglacial morpholineaments was carried out based on the Digital Elevation Model (DEM) as well as geological, geomorphological and topographic maps. It resulted in the delimitation of visible linear postglacial landforms, their identification and classification, and the determination of their genetic and chronological relations. Directions of the lineaments were determined through quantitative analysis. Qualitative analysis was applied to determine the spatial and temporal sequence of events, directions of ice movement and its range. Two glacial lobes, Bielbrza and Neman, existed in the north-western part of the Białystok Plateau and Sokółka Hills during the last glacial advance. The lobed nature of the ice sheet can be confirmed by field data collected from, e.g., sites in Krzyzwicz, and by topographic analysis of Quaternary sediments, combined with their thickness and genesis. The obtained reconstruction of the last glacial advance and retreat in the study area can be used in further regional discussions on the character and dynamics of the last glaciation in this region.

Key words: morpholineament, Saalian ice sheet movement, lobe, NE Poland.

INTRODUCTION

Morphological linear elements of the relief, more and more easily detectable through the use of digital data on the land surface (satellite and aerial images, digital terrain and elevation models – DTM and DEM), have long attracted the attention of researchers. Their origin has been associated primarily with the deep geological structure of a given area as a structural foundation of the land relief (cf. Tirén and Beckholmen, 1989; Graniczny, 1989; Graniczny et al., 1995; Gabrielsen et al., 2002). In areas covered by Pleistocene glaciations and contemporarily glaciated, a correlation is observed between linear morphological elements and the activity of ice sheets (e.g., Boulton and Clark, 1990; Clark, 1993, 1997; Fahnestock et al., 1993; Pun-kari, 1995a, b; Bindschadler and Vomberger, 1998; Boulton et al., 2001; Morawski, 2009a, b). Attempts have been made to reconstruct ice sheet movement directions based on selected, positive and negative linear glacial morphological forms, such as mega-scale glacial lineations (e.g., Stokes and Clark, 2001, 2002; Przybylski, 2008; King et al., 2016), drumlins (e.g., Benn and Evans, 2010; Lamsters, 2012) crevasses (Morawski, 2005), frontal moraines (Kalm, 2012) or subglacial channels and kame plateaux (Bitinas, 2012). They are referred to as glacial morpholineaments (Morawski, 2005) or glacial lineations (cf. Kleman and Borgstrom, 1996) and used to reconstruct the direction of ice flow and ice sheet movement.

In the context of glacial geomorphology and its development, it appears necessary to use GIS to integrate and analyse morphological data obtained from various sources, and to investigate spatial relationships between particular elements of the postglacial landscape for further temporal reconstruction of its evolution (Napieralski et al., 2007). Landforms presented on the map may represent phenomena and processes of diverse age. Digital data interpretation in the GIS environment was conducted to identify them as morpholineaments and divide into groups and layers (Napieralski et al., 2007). Analysis of the relationships between morpholineaments allows for reversing the sequence of events, i.e. for developing an inverted relief model which presents the sequence of glacial events and gives insight into the ice sheet (or its parts) dynamics in both time and space (cf. Greenwood and Clark, 2009a, b; Stokes et al., 2009; Evans et al., 2014).

However, so far the application of GIS and DEM in the reconstruction of the direction of Pleistocene ice sheet advance is restricted to areas glaciated during the Vistulian Glaciation. These areas are characterized by a fresh relief, unchanged or transformed only to a small degree by post-sedimentary pro-
cesses. Due to this, the identification of particular forms does not raise any problems. On the contrary, the morphology of areas beyond the range of the LGM and glaciated during older ice-sheet advances could have undergone deep transformation both in the interglacial periods and in periglacial conditions of younger glaciations. Such transformation included reorganization of the river network (Kasse, 1997; Kasse et al., 2003; Rychel et al., 2015; Woronko et al., 2016), and activation of slope (Dylik, 1953; Dzieduszyńska et al., 2014) and aeolian processes (Kasse, 1997; Zeeberg, 1998; Renssen et al., 2007; Zielinski et al., 2016). The Sokółka Hills (NE Poland) and the Grodno Plateau (E Belarus) are examples of such areas. They were glaciated during MIS 6, were twice under the influence of periglacial climate during the MIS 6 and the Vistulian ice-sheet retreats (Gilewska, 1991), and twice under the influence of processes during warmer, interglacial periods (MIS 5e and MIS 1). Therefore, the reconstruction of the directions at which the ice-sheet advanced in areas with the landscape shaped during older glaciations requires the application of multistage morpholineament analysis (MMA), in contrast to the previously conducted glacial morpholineament analysis (GMA) (e.g., Mora

The MMA provides a basis for a hypothesis of the predominant lobe style of glaciation and former ice-sheet dynamics in the region that needs to be checked in a broader area.

The analysis was aimed at the reconstruction of:

- directions of ice sheet advance of the Odranian Glaciation, Wartanian Stadial, in the boundary zone between NE Poland and Belarus;
- ice sheet dynamics;
- functioning of the Biebrza lobe (NE Poland) and Neman lobe (W Belarus) in time and space.

**GEOLOGICAL SETTING**

The study area is located in northeastern Poland and includes the Sokółka Hills (excluding their southeastern limits), the northwestern part of the Białystok Glacial Plateau (Kondracki, 2009), and the western part of the Grodno Plateau.
Belarus (Fig. 1). The area is more than 2,500 km² in size and extends to the south of the maximum range of the Vistulian Glaciation – Last Glacial Maximum (LGM). It is one of the northernmost upland areas, formed during the retreat of the last continental glacier of the Middle Polish Glaciation (MIS 6) (Karabanov, 1987; Marks and Karabanov, 2011). The area represents an old-glacial landscape. The relief is characterized by considerable variations (>100 m) and expressive glacial landforms, e.g. glacial plateaux, sandurs, kames and end moraines (Fig. 2). The highest elevations are observed in the end moraines of the Sokółka Hills, near the village of Gliniszczce Wielkie – 236.6 m a.s.l., and on Horczaki Knoll (hump) near the village of Wojnowice – 226.3 m a.s.l. The lowest elevations are noted in the bottoms of river valleys southwest of Janów, i.e. the Kumiłka River – 136.6 m a.s.l. and the Sidra River (north of the village of Sidra) – 129.5 m a.s.l.

A characteristic element of the landscape in the area is long dry valleys with numerous side valleys, and abundant landlocked depressions adjacent to high hills (Rychel et al., 2012). The older basement played a significant role in shaping the landscape of the area (e.g., the Horczaki Knoll; Karabanov, 1987; Boratyń, 2006; Rychel et al., 2015).

According to Karabanov (1987) and Ber et al. (2012), the ice sheet of the Wartanian Stadial in the area advanced from different directions corresponding to two lobes. Ber et al. (2012) distinguished the Biebrza lobe, which advanced from the NW to the SE, and the Neman lobe, with a general NE-SW orientation. Banaszuk (2010) described the presence of a Middle Vistulian (Świecie Stadial – MIS 4) ice sheet in the North Podlasie Lowland. This concept was confirmed by the authors of the Detailed Geological Map of Poland (DGMP) (e.g., Sztabin sheet – Kacprzak and Lisicki, 2007; Dąbrowa Białostocka sheet – Wrotek, 2009).

METHODS

The analysis of the Sokółka Hills and the Białystok and Grodno Plateaus (Fig. 3) was conducted using nine sheets of the Detailed Geological Map of Poland (scale 1:50,000) located in NE Poland (Krzywicki, 2005; Boratyń, 2006; Kmiciecki, 2006; Kozłowski, 2006; Kacprzak and Lisicki, 2007; Majewska, 2008a, b; Pionczyński et al., 2009; Wrotek, 2009) and the central and southern part of the Geological Map of the northern borderland between Poland and Belarus at the scale of 1:250,000 near Sokółka and Grodno (Marks and Karabanov, 2011).

The morpholineaments were determined on the basis of surface geological data, the digital elevation model, and the topographic map at the scale of 1:10,000 and 1:25,000. An exaggerated DTED 2 terrain model, rectified to the PUWG “92” projection, and a coordinates system (State Geodetic Coordinate System “92”) with the spatial resolution of the raster cell of 30 m was used in shaded, coloured and greyscale layouts. The topographic map of Poland was visualized in the WMS service from the servers of geoportal.gov.pl.

The multistage morpholineament analysis (MMA) was conducted in subsequent stages. Landforms related to the following processes were distinguished:

- ice sheet advance: subglacial channels, terminal basins (Fig. 4A);
- stabilization of the ice sheet front, including positive (end moraines, eskers, proximal parts and edges of outwash plains) and negative landforms (subglacial channels; Fig. 4B);
- ice sheet retreat, including negative (kettle holes) and positive landforms (crevasses, kames, hummocky moraines; Fig. 4C);
- interglacials (river valleys; Fig. 4D).

The available elevation and geological data enabled the identification of glacial morpholineaments and permitted their geomorphological classification into individual genetic groups. Visual analysis of elevation and geological data was used to identify morphological lines within the glacial forms (ridges) and the longer axis of the landform outline. Eight different positive and negative genetic groups of landforms were distinguished, directly or indirectly related to the glacial environment (Fig. 4 and Table 1).

![Fig. 2. Geological map of the study area (after Marks et al., 2006, changed)](image-url)
Most of them were landforms of direct glacial or glaciofluvial origin. Positive forms included: crevasse accumulation forms and eskers, moraine hills, proximal parts and edges of outwash plains (sandurs) and fans, kame hills, and ridges of hummocky terrain/moraines, whereas negative landforms were represented by subglacial channels and terminal basins. In addition, landlocked depressions – kettle holes (pits and depressions within glacial plateaux) as well as flat-bedded dry valleys (gullies) and small river valleys, whose existence had no direct connection with the ice-sheet activity, were also distinguished. The aim of distinguishing the two last groups of landforms was the assumption that their location and orientation were inherited after the former ice-sheet configuration (e.g., varying thickness, pattern of cracks/joints), which might have had a relationship with the stress field during the glaciation.

The terminal basin (vast depressions of the upland surface that stretch over several kilometres) are hollows that originated in consequence of stress exerted against the basement under compression-tension conditions of a regional stress field that developed during the ice sheet transgression as a result of its progressive movement (cf. Nye, 1952 after Jania, 1997; Patterson, 1994). When viewed in plan, they form a low-angle joint system of the morpholineaments, where the bisector of the obtuse angle between both maxima may be identified as being identical with the resultant direction of the ice flow (Fig. 4) - the main driving stress vector.

The arrangement of subglacial channels reflects the system of channelled subglacial drainage (cf. Kehew et al., 2012), whose development is (in general) concordant with the driving stress vector within individual ice sheet sectors. The orientation resultant (average vector), determined from the orientation of these glacial forms, may render the direction of ice advance (Fig. 4). Being of glacial origin, these landforms directly indicate the direction of ice sheet advance (Majdanowski, 1995; Galon, 1972). The presence of subglacial channels and terminal basins in the analysed area was assumed to be the only subglacial system landforms whose arrangement directly reflects the direction of ice sheet advance and dynamics.

Crevasse accumulation forms, eskers, moraine hills, kames, proximal parts and edges of outwash plains (sandurs) and fans represent elements of the marginal zones, the distribution and arrangement of which indicate subsequent phases of ice sheet stagnation (Bitinas, 2012; Morawski, 2015). Moraine hills of various origins, hummocks, pits and depressions are com-
mon elements of the relief of glacial plateaux. Based on their elongated shape, orientation and concentration, indirect conclusions may be drawn about the dynamics of the deglaciation process in the study area. The orientation and distribution of zones of marginal and intra-lobe landforms reflect local stress systems within the marginal parts of the ice sheet. On a regional scale (between a dozen to several tens of square kilometres), the spatial arrangement of these morpholineaments is bidirectional, which may be related to a lobe formed in the distal zones of particular channelized ice flows – palaeo-ice stream (cf. Patterson, 1997; Kasprzak, 2003; Turkowska, 2006; Jennings, 2006). In the study area, the ice-flow direction may be identical with the direction of the mid-perpendicular to the chord connecting the maxima of morpholineament sets in the marginal and intra-lobe landform systems.

Valleys are among the most distinctive elements of the present-day landscape of the Polish Lowlands. They were distinguished on the basis of the assumption of their indirect relationship with post-glacial foundations of the valley network development in the study area (Bryczyński, 1986). Landforms, classified as morpholineaments, were grouped in a vector database according to their geomorphological category.

The study area was subdivided into 20 sectors (Fig. 5A). Their size varies from 12 km² to ca. ~300 km², and they were classified as inter-lobe (moraine junction – MJ) and intra-lobe zones (L) (Fig. 5B). Next, a sequential analysis of the spatial arrangement of morpholineaments was performed in the distinguished sectors. Collective quantitative analysis of their orientation was made by plotting various rose diagrams of the morpholineaments orientation (example in Fig. 5C.1–C.3). Quantitative
The resultant directions of ice flow by genetic groups of morpholineaments in the sectors, and the proposed sequence of glacial events

<table>
<thead>
<tr>
<th>Sector</th>
<th>RESULTANT DIRECTION ICE-MASSES FLOW [in degrees]</th>
<th>Succession</th>
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<tbody>
<tr>
<td></td>
<td>Terminal basins</td>
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<td>MJ5</td>
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</tbody>
</table>

BIEBRZA LOBE [B] hypothetical direction of transgression
older subglacial drainage system [B1] younger subglacial drainage system [B2]

NEMAN LOBE [N] hypothetical direction of transgression
older subglacial drainage system [N1] younger subglacial drainage system [N2]

STAGE OF DEGLACIACION
the youngest [D5] [D4] the eldest [D1]

RESULTS

The MMA has allowed for distinguishing 15 sectors of intra-lobe zones (L1–L15) and five sectors referred to as moraine junction zones (MJ1–MJ5; Fig. 5A). Landforms reflecting the advance and retreat of the Saale ice sheet (MIS 6) in the areas of the Sokółka Hills, the Białystok Plateau and the Grodno Plateau were identified in each of these zones.

The advance of the Saale (MIS 6) ice sheet resulted in the formation of terminal basins and subglacial channels. The obtained results allowed distinguishing two orientations of terminal basins in the morainic plateaux (1→2→4 and 3→5→4). The resultant directions of the first group of results cluster in the central and western part of the area, that is in sectors from L1 to L4, L8–L9 and L12 (Fig. 5B, C.1 and Table 1). The results of the second group occur in the eastern sectors (L5–L7), L10 and L14 (Table 1). In sector L10, the resultant direction is 14°, and in L11 – 353° (Fig. 5A and Table 1). Both sectors represent the most extreme fields of the study area. The first is located in its easternmost part and lies directly adjacent to the Neman River Valley. In turn, L11 covers an area in the western part of the study area.
**Fig. 5. The main assumptions of the analysis**

A – division of the study area into sectors in relation to general geomorphic features and inferred ice sheet limits; B – typical post-glacial morpholineaments pattern in one of the sector (L8, conformal LonLat projection); C.1 – resultant ice-flow direction based on discrete depressions; C.2 – ice-advance direction based on the subglacial channels; C.3 – hypothetical ice-flow direction during ice sheet margin stagnation (steady-state conditions), reconstruction of palaeo-ice sheet lobe outline (limits). All calculations of resultant directions (vectors) were computed based on vector algebra (addition). For each calculation, all the morpholineaments from all genetic groups considered in particular sector where added to each other one by one and the resultant vector parameters (strike and length) were obtained. Depending on the morpholineaments group(s) the strikes of the resultant vector were rotated by 90° to refer to the resultant ice-flow direction. Every calculation covers the 180° interval of morpholineaments strike according to distribution of the data analysed. Strikes of the morpholineaments were computed in GIS environment after vector transformation to conformal latitude-longitude projections. Length of each morpholineament was determined as a weighted unit by every 1 km of its length measured in equal-area projection of PUWG 92 coordinate system. n – total weighted nominal length of morpholineaments. All graphical constructions were presented on rose diagrams. In graphical construction, only the local maxima (peaks of frequency) in morpholineaments distribution were considered. Morpholineaments clustered within 9° intervals

Subglacial channels found in the western part of the study area have an orientation in a wide range from 282 to 345°. They comprise two sets: the first with an orientation between 282 and 294° (L3, L6, L9, L11), and the second with an orientation between 317 and 345° (L4, L8, L12, L13) (Fig. 5A, C.2 and Table 1). Forms with an orientation of 4° (L10), 5° (L14) and 40° (L07) have also been observed. In turn, in the eastern part of the area, subglacial channels were registered only in two sectors, L6 and L12. Their orientations lie in a relatively narrow range between 36 and 45° (Fig. 5A, C.2 and Table 1).

Forms recording the interval/intervals of a longer stop of the ice sheet front, represented by end moraines, e.g. near Knyżewicze, Janów and Gliniszczewo Wielkie (Fig. 2), edges of outwash fans and eskers have also been identified. For example, in sector L8, the orientation of end moraines is in the range between 47 and 120°, which corresponds to the orientation of the edges of outwash fans and side valleys (Fig. 5B). A subdivision into two zones is also visible as regards the orientation of forms of marginal zones. In the western part of the study area the probable resultant direction of ice-mass flow is in the range of 338 to 360°. A detailed analysis of the collected data indicates a bipartition of the ice sheet flow directions. The first direction is between 344 and 352° (L1–L7, L9 and L11). A similar direction of ice sheet advance was registered in sectors L14 and L15 located in the northernmost part of the study area, in direct vicinity of LGM moraines (Fig. 5C.3). The second direction is
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Fig. 6. Results of distribution of glacial morpholineaments in the Knyszewicze marginal zone, and measurement directions faults of glaciotectonic deformation in Knyszewicze outcrop (after Rychel et al., 2015, completed)
between 355 and 3° (L8, L10, L12, L13). In turn, in the eastern part of the study area, the direction of ice sheet advance is between 23 and 40° (Table 1).

In sectors MJ1–MJ5, which represent the moraine junction, the resultant direction of ice-mass flow was from the NWW (325–355°) and NE (8–45°) (Table 1). Height differences between particular hills in these areas are from 10 even to 30 m. Their orientation in sectors MJ1, MJ3 and MJ4 is NNW–SSE, and in sector MJ2 – N–S (Fig. 5A).

An interesting example of the marginal part of the Saale ice sheet is the area analysed in sectors L1 and L2. They cover the area of the villages of Knyiszewicze (L1) and Horczaki Knoll (L2) (Fig. 7). Detailed analysis of the post-glacial morpholineaments carried out at the Knyiszewicze site resulted in the identification of two glacial segments, i.e. Horczaki Knoll and Knyiszewicze, which is confirmed by different directions of the ice sheet movement, i.e. 171° and 23°, respectively (Fig. 6). The dip of faults found at the Knyiszewicze site is in the range of 11–44°, which corresponds to a NNE direction of the advance (Szymczuk, 2014; Rychel et al., 2015), being a field evidence confirming the palaeoglaciological interpretation derived from the analysis of morpholineaments arrangement. The resultant azimuth of the dominant ice sheet advance (171°) is widespread over the entire study area and likely corresponds to the main transgression direction from the NWW. The second azimuth (23°) corresponds to the thrust-fault measurements made on the eastern wall of the Knyiszewicze outcrop (Rychel et al., 2015). This is indicated by the ice sheet movement from the NNE in the Knyiszewicze region (Fig. 6).

Fig. 7. Results of sequential analysis of morpholineaments
A – active drainage systems, B – sectors of potential active ice sheet lobes (B – Biebrza lobe, N – Neman lobe), C – D1–D5 stages of the area deglaciation, vide Table 1
DISCUSSION

Characteristic elements of the morphology of the marginal part of Pleistocene ice sheets on land were glacial lobes, which represented their most dynamic part (Booth et al., 2003; Mickelson and Colagan, 2004; Winguth et al., 2004; Turkowska, 2006; Przybylski, 2008; Wysota and Molewski, 2011; Dzieduszyńska et al., 2014). Mechanisms of development and evolution of ice sheet lobes in the European Lowland and North America during the Pleistocene have been broadly discussed by many researchers over the last decades (Evans and Rea, 2005; Boulton and Hagdorn, 2006; Jennings, 2006; Narloch et al., 2013). The morphological axis of the developing lobes are, e.g., depressions/old valleys existing in the landscape, on which the ice sheet advanced (Mickelson and Colagan, 2004; Wysota and Molewski, 2011; Dzieduszyńska et al., 2014; Hermanowski, 2015).

PALAEOGEOGRAPHIC RECONSTRUCTION OF THE SAALÉ GLACIATION IN THE SOKÔŁKA HILLS

Assumptions of the palaeoglaciological inversion model (Kleman and Borgstrom, 1996; Clark, 1997; cf. Benn and Evans, 2010) were used in the reconstruction of the varying Saale ice sheet dynamics and in setting the relative chronology of glacial events during deglaciation of the Sokólka Hills area (Figs. 7 and 8). The inversion model, i.e. reconstruction of the chronological sequence of events, is prepared based on the identification of forms starting from the youngest (best preserved) ones and continuing through the older forms whose level of preservation becomes worse.

The differences in the orientation of terminal basins within the morainic plateaux in the Sokólka Hills, the eastern part of the Białystok Glacial Plateau, and the western part of the Grodno Plateau are indicative of the bipartition of ice sheet flow directions in the study area, which may serve as indirect evidence for the activity of two ice sheet lobes that covered its eastern (Neman lobe) and western (Biebrza lobe) parts (Ber et al., 2012). Likewise, Karabanov (1987) described variable directions of the Saale ice sheet advance in this region. His observations were based mainly on the analysis of glaciotectonic structures. The central part of the Sokólka Hills is an area where the zones of impact of the two lobes overlap, creating ice-lobes convergence forms (Fig. 8) – “interlobate moraines” (e.g., Punkari, 1980; Brennand et al., 1996). “Interlobate moraines” were formed in this zone (e.g., Punkari, 1980; Brennand et al., 1996). According to the DGMN, the moraine junction zones in the Sokólka Hills are composed of gravels, boulders and glacial tills of end moraines, which build the highest elevations in the area (Boratyń, 2006; Wrotek, 2009). The lithology of forms of such origin was also described by Brennand et al. (1996) in northern Quebec, Canada. Forms correlated with the ice-lobe convergence zone of the Saale ice sheet were also distinguished in the Łódź Plateau (Turkowski, 2006; Dzieduszyńska et al., 2014).

Clustering of resultant vectors within the study area may also be noticed in the orientation of the morpholineaments identified as former subglacial channels (Fig. 7A). A typical orientation for the western part of the study area (in the Biebrza lobe) is ca. 290 and 330°, whereas the eastern part (Niemenn lobe) is represented by resultant vectors with a more northeastern strike – ~40 and 5° (cf. Table 1). The above supports the hypothesis of two individual ice sheet lobes in the analysed area. Morpholineaments related to the subglacial drainage group prove multiple changes in the dynamics of the entire ice sheet and reveal the mutual relationships between the inferred ice sheet lobes. Trends in the changing orientation of the forms related to the subglacial drainage enabled us to reconstruct the range of the ice sheet lobes (Fig. 7B). Changes observed in the subglacial drainage system could be indicated the pulsating nature of the ice movement, and indicate episodes of intense subglacial drainage, which was particularly well-developed in the western sector. Episodes of intense ice flow, which ended in the creation of a system of subglacial channels, were probably preceded by periods of crawling of ice masses.

A complex orientation of the glacial forms of the marginal zone system within the individual sectors enabled us to draw conclusions on the chronology of the glaciation events. The prevailing direction from the NNW (290° – sector L4) seems to reflect more climatic rather than glacio-dynamic factors. The progressive improvement of the climatic conditions imposed a constant longitudinal sequence of deglaciation of the subsequent sectors across the study area. The sequence was only slightly modified by the active ice movement or by the re-advance of the individual parts of the ice sheet. The possible traces of the glacio-dynamic impact from the NE, ~40° (corresponding to the Neman lobe), are marked in the system of marginal morpholineaments as a second-level, coupled, lower frequency morpholineament system. The analysis of the resultant directions of the marginal morpholineament systems in the individual sectors and their relationships within the morainic junctions was used to reconstruct a likely scheme of deglaciation isochrones (Fig. 7C).

The Biebrza lobe has a fully developed system of post-glacial morpholineaments. Each of the systems is clearly represented and the number of morpholineaments is sufficient to perform a statistical analysis. In the case of the Neman lobe, the number of morpholineaments related to the subglacial system is low and therefore the results for these groups of morpholineaments should be considered only as indicative.

STAGES OF THE SAALÉ ICE SHEET ADVANCE IN THE SOKÔŁKA HILLS

Based on MMA, the reconstruction of MMA advances and retreats of the Saale ice sheet in the Sokólka Hills was performed:

Stage I – advance of the Saale ice sheet

The resultant directions of ice advance, derived from morpholineaments, have revealed that both the Biebrza and Neman ice lobes had a similar flow direction which suggests that they might have used one regional corridor for the ice sheet flow. The variable activity of the individual ice sheet sectors is assumed to be a result of local changes in the ice-mass balance and location of the local ice divide.

The early phases of ice sheet activity recognized in the Sokólka Hills are associated with the mutual confluent flow within both sectors of the ice sheet (Fig. 8A). The setting up of the terminal basins within the future glacial moraine plains should be related to this period. The range of the ice sheet at this stage of the Saale Glaciation in eastern Poland and western Belarus probably reached much further to the south of the study area.
Fig. 8. Palaeogeographic reconstruction of the last glaciation in the Bialystok Plateau and Sokółka Hills

A – glaciation; B – flow of ice masses in the Biebrza lobe; C – flow of ice masses in the Neman lobe; D – reorganization of ice-mass flow in the Biebrza lobe; E, F – deglaciation, confluent ice sheet lobes

Legend:
- Ice passive
- Ice active
- Hypothetical isochronous ice sheet range
- Hypothetical range
- Fast flow
- Slow flow
- Stagnation
- Dynamic stability of the fronts of ice sheet
- Proglacial outflow
- Area of kames and dead-ice moraines
Stage II – activation of the Biebrza lobe

The next event that could be identified was a concentrated flow towards the WNW within the Biebrza lobe, combined with the development of a channelled subglacial drainage system (−290° – the older drainage system; cf. Table 1). This stage was probably contemporaneous with the stagnation within the Neman lobe – the eastern sector of the ice sheet (Fig. 8B).

Stage III – activation of the Neman lobe

The reactivation of the Neman lobe occurred in the following stage, which was related to the evolution of the NE–SW (−40°) subglacial drainage system identified in the southeastern part of the study area (Table 1). This event may be related to the formation of glaciotectonic deformations described in a small lobe at Knyiszewicz, which was a protrusion of the Neman ice lobe, roughly 12 km long and 4 km wide (Rychel et al., 2015). During this episode, partial reorganization and overlapping of the terminal basins systems might have occurred within the morainic plateaux in sectors L6 and L7. Simultaneously, the development of proglacial outflows, related with a distinct marginal zone in the western part of the area, indicates continuous flow of the ice masses from the interior of the eastern sector of the ice sheet (Fig. 8C).

Stage IV – reorganization of the Biebrza lobe

Another rearrangement of the coupled lobe system took place during the deglaciation and the accompanying alinement system changes. The ice of the Neman lobe entered a stabilization phase, whereas the inflow of the ice masses into the Biebrza lobe concentrated in the axes of two terminal basins in the western and central part of the area (Fig. 8D).

Stages V and VI – deglaciation

The subsequent stages comprised successive deglaciation of the western area (with a noticeable trend towards the formation of ice sheet lobes extending along the main terminal basins axes) and the increased ice sheet dynamics in the eastern sector (Fig. 8E, F). The pattern and the orientation of the post-glacial morpholineaments within the two ice sheet lobes indicate slightly different glacio-dynamic conditions.

In the case of the Biebrza lobe, the changing orientation may be observed both in the post-glacial channels and in the morpholineaments of the marginal and intra-lobby system. It may be related to the pulsating nature of the ice inflow. Each episode of the concentrated flow (streaming) of the ice sheet ends with the development of a channelled subglacial drainage system and a stagnation period. The relief, extension and geomorphological expression of the marginal zones in the west are indicative of the prolonged periods of dynamic equilibrium of the ice sheet front, which could be achieved by continuous alinement of the ice margin by fresh ice (cf. Kozarski and Kasprzak, 1987). Considering the above statements, one should assume the existence of minor differences in the movement rate of the ice body during the concentrated (ice-streaming) and normal ice flow. A concentrated flow of the ice sheet is possible during periods of significant improvement in the climate conditions, when the climate warming causes an increased supraglacial meltwater production which, in turn, remains in relation to the rheological conditions in the ice sheet sole, causing more favorable conditions for basal sliding and other meltwater related forms of enhanced ice flow.

The morpholineaments pattern of the Neman lobe implies that the main area of its impact was located further to the east, and only part of its marginal limit may be observed in the study area. Low frequency of the subglacial morpholineaments leads to the hypothesis of different (more abrupt in its nature) ice flow mechanisms, i.e. surges. Both the expression of the marginal zones in the eastern part of the study area, and the periods of increased activity of the eastern ice sheet lobe (interpreted on the basis of the orientation of glacial morpholineaments more variable in the resultant direction, cf. Table 1) may be associated with the crossing of subsequent rheological barriers by the ice sheet. In this instance, areas of faster ice flow, marked by a distinct subglacial morpholineaments pattern, may be observed on the distal zones of basement elevations.

INFLUENCE OF BASEMENT MORPHOLOGY ON THE ICE SHEET MOVEMENT

The limits and dynamics of both the Biebrza and Neman ice sheet lobes and the smaller lobes in the marginal zones of the ice sheets (like those at Knyiszewicz) are largely pre-determined by the basement topography and its geological structure (rheological parameters of particular basement layers and its configuration). The Geological map of the northern borderland between Poland and Belarus at the scale of 1:250,000 (Marks and Karabanov, 2011) contains a supplementary geological map of the pre-Quaternary deposits. A model of the Quaternary deposits was generated with the use of interpolated isolines of the Quaternary floor elevation (Fig. 9).

Distinct elevation differences within the Neogene, Paleogene and the Cretaceous basement had a significant impact on the direction and rate of the ice sheet advance. Axes of both lobes, i.e. the Biebrza lobe and the Neman lobe, correspond to the outline of the main terminal basins in this area. Nowadays, the same alignment is recognizable in the network pattern of major rivers, after which the lobes were named. The intra-lobby zones, where the ice mass was assumed to be of greater thickness (allowing faster ice flow rates), were located in large depressions, for instance in the vicinity of Sztabin and Lipsk (northern sector of the study area). The moraine junction zones, recognized, e.g., near Gliniszczce Wielkie and Janów (Fig. 1), reflect elevations or escarpments of the pre-Quaternary basement. The ice sheet advance might have triggered tectonic movements within the basement, which is confirmed by the presence of glaciotectonically disturbed zones, e.g. to the west and north-west of Grodno, where Cretaceous rocks were uplifted and are at present extracted in open pit mines. Such an arrangement is observed mainly in the eastern sector, where the Neman lobe was delimited. Assuming the overlapping of the glacial sedimentological succession and repition of morphogenesis over particular glacial periods for certain regions of northeastern Poland (Morawski, 2009b), the dynamics of the ice masses and spatial limits of the Neman lobe were constrained by former structural elements which prevented the development of broad marginal zones in the area and fast-ice-flow features. The influence of tectonic structures on the origin of lobes during the Main Stadial of the Wisłian Glaciation in northeastern Poland was also described by Morawski (2005), and for the Saale ice sheet in central Poland – by e.g. Turkowska (2006) and Dzieduszyńska et al. (2014).

CONCLUSIONS

Analysis of the post-glacial morpholineaments in the areas of the Białystok Glacial Plateau and Sokółka Hills (NE Poland) has confirmed that the present-day landscape of this region was created during one glaciation by the activity of the Wartanian Stadial of the Odranian Glaciation.

The second-level differences in the pattern of morpholineaments have allowed distinguishing individualized domains
related to varying temporal dynamics of two ice sheet elements: ice-mass flow of the Biebrza and Neman lobes in the north-east.

The most probable model for the inferred dynamics of the ice sheet lobes may be explained by a cyclical reverse feedback where the greater activity of one lobe resulted in the stagnation of the second lobe fed from the same alimentation area.

The pulsating ice sheet movement during the Wartanian Stadial in the Sokółka Hills is confirmed by the general geomorphological character of the area, where glaciotectonically disturbed landforms (created during periods of intensive ice inflow) are accompanied by the zones of hummocky moraines or kames, that is landforms created in various sedimentary environments in areal deglaciation conditions (ice sheet stagnation). Correlation of the results of the structural measurements made at Knyszewicze with the analysis of the morpholineaments arrangement in the area positively verifies the remote method as indicative for the reconstruction of the palaeo-ice-sheet movement.

The ice sheet of the Wartanian Stadial of the Odranian Glaciation (Saale – MIS 6) advanced on the area that had been covered by sediments of various origins and with pre-Odranian relief. Both the thickness and the structure of the basement affected the ice movement dynamics (Dzierżek, 2009; Czubla, 2015). It is confirmed in the Horczaki Knoll that might have functioned as an elevation and a barrier for the ice body during the last ice sheet advance in the Knyszewicze area. This elevation functions above Neogene and Paleogene deposits, which are tectonically displaced.

The contemporary relief corresponds to the main features and structures detected in the basement of the Quaternary series. The basement relief was a very important factor differentiating the dynamics of particular ice lobes.

Application of the Geographic Information Systems (GIS) allows a detailed chronological reconstruction of the sequence of events according to the palaeoglaciological inversion models. They enable collecting, processing and integrating large
amounts of data from numerous sources. Thus, the analysis of post-glacial morlineaments applied in this study may represent a universal tool for integrated, (trans)regional palaeo-geomorphological and palaeo-geographical analysis, providing a new approach and opportunity to check varying hypothetical models of ice sheet development.

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