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Reconstruction of the Vistula ice stream during the Last Glacial Maximum in Poland

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The variability of ice movement directions within the Vistula lobe of the Main Stadial ice sheet of the last glaciation is analysed. Reconstruction of the ice movement directions is made based on analysis of the orientation of glacial morpholineaments. Linear glacial landforms are analysed on the basis of data from 26 map sheets of the *Detailed Geological Map of Poland* (DGMP), scale 1:50 000, compiled earlier by various authors. The morpholineaments were investigated in a belt of morainic plateau that adjoins the Vistula valley on both sides. The analysis revealed that the last glaciation ice sheet advanced directly from the north within the broadly understood Vistula ice lobe zone, and that the ice flow direction was constant. However, within a narrow belt of the pre-Vistula River valley that was formed in the Eemian Interglacial, the 30–50 km wide ice stream was characterized by locally variable ice flow directions consistent with the pre-existing valley trend. Changes in ice flow direction are recorded in the locally variable orientation of linear glacial landforms, indicating that the ice stream was active until the deglaciation period when the present-day shapes of the glacial landforms developed.

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INTRODUCTION

The term “ice lobe”, as referred to the Pleistocene continental ice sheets, has been used in the geological literature in a very broad and ambiguous sens. It refers to both local fragments of ice sheets a few kilometres wide (e.g., Skompski, 1969) and regional ice sheet zones measured in hundreds of kilometres (e.g., Kurimo, 1982; Patterson, 1997). The latter include large fragments of the last glaciation ice sheet that covered N Poland, referred to as the Odranian, Vistula, Warmian and Masurian ice lobes (Marks, 2005; Morawski, 2005*a*).

It is commonly assumed that ice lobes differ from one another in the time of occurrence and in ice flow direction (e.g., Punkami, 1997*a*; Stokes and Clark, 2001; Marks, 2005). Distinguishing of individual ice lobes is also justified by the occurrence of belts of specific glacial landforms, especially of crevasse origin, called interlobe zones (Morawski, 2005*a*; 2009*a*, *b*) or “interlobate moraines” (Veillette, 1986; Dredge and Cowan, 1989; Dyke and Dredge, 1989; Punkari 1997*a*, *b*). Deposits composing the landforms are referred to by Brodzikowski and Van Loon (1991) as supraglacial crevasse deposits. Areas of variable size, often of neotectonic or/and glaciotectonic origin with a highly uplifted pre-Pleistocene basement, are treated as interlobe areas (Marks, 1988; Aber and Ruszczyńska-Szenajch, 1997; Ber, 2000, 2008). In turn, the characteristic semicircular arrangement of frontal moraines is assumed to be coincident with the maximum limit of individual ice lobes, especially those smaller ones of local significance. It seems that, of these and of other less important indicators that allow identification of particular ice lobes, variability of ice flow (advance) direction within each lobe is the diagnostic feature. Therefore, attempts to reconstruct ice sheet movement directions seem to be the basic element in analysing processes related to ice sheet advance during the Pleistocene glaciations in the European Lowlands. Analyses of ice flow directions and, in addition, attempts to determine variations in ice flow velocity, allow the distinguishing of the ice streams i.e. relatively narrow ice sheet zones within which the ice flow was much faster and locally changed its direction. Knowledge about ice streams refers to both processes operating within modern ice sheet covers and processes reconstructed for the Pleistocene continental ice sheets (Clark *et al*., 2003).

There are two main types of ice stream formation. The first one is related to a rapid linear acceleration of ice movement

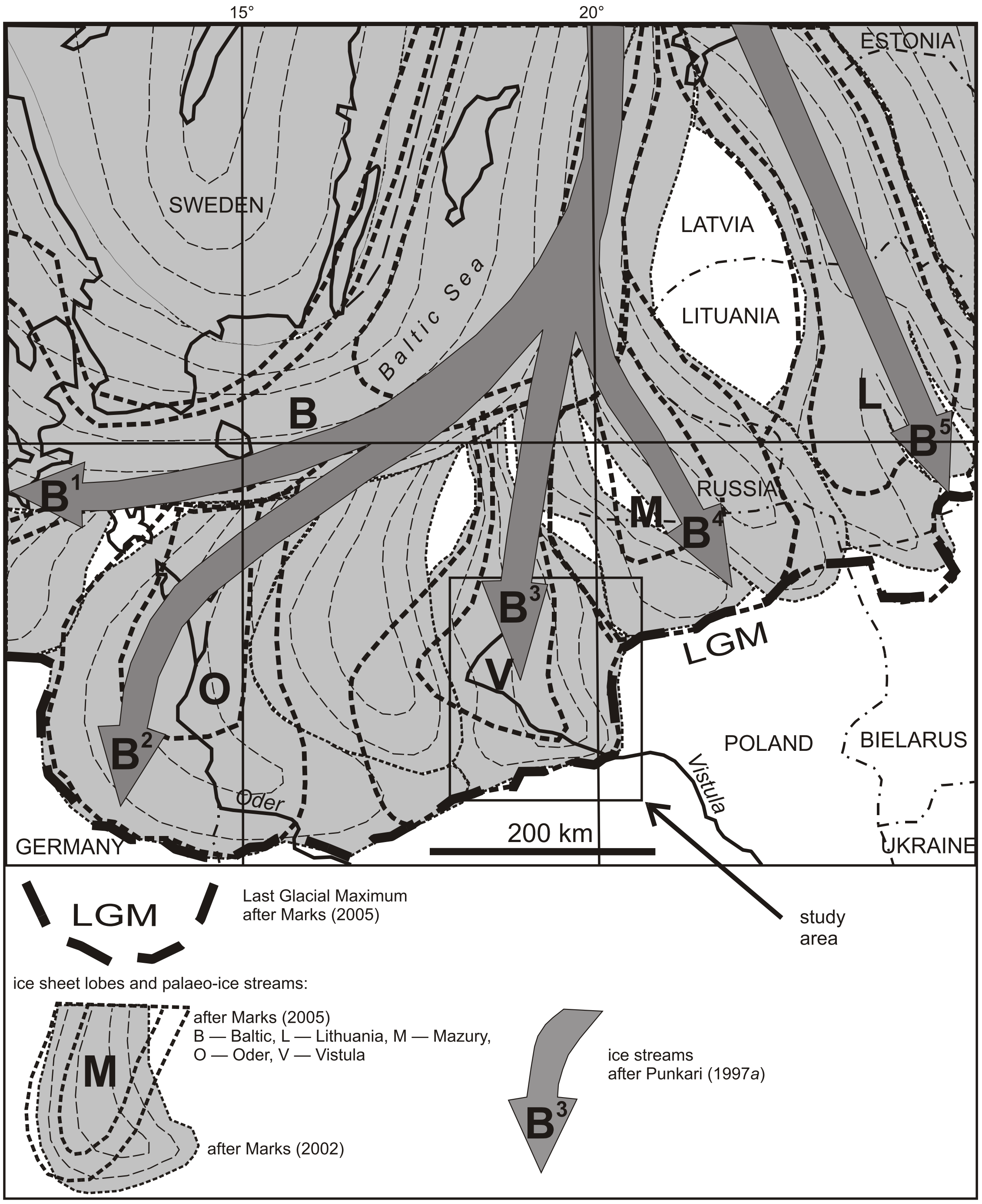

Fig. 1. Ice streams in the southern peribaltic region during the Last Glacial Maximum

without changing of direction — a good example is the Drygalski ice tongue in the Antarctic. The other is manifested also by local changes of ice movement direction as, for example, in the case of recent ice streams of the Ross Ice Shelf, in Antarctica (Howat and Domack, 2003), that can be compared with a meandering process. This phenomenon is commonly stimulated by the basement relief (Tulaczyk *et al*., 2000): its descent or the occurrence of valleys as in the case of the pra-Vistula valley.

The Vistula lobe was one of several ice lobes of the Scandinavian ice sheet of the last glaciation, advancing on to the European Lowlands (Fig. 1). Many previous studies (Ehlers, 1990; Punkari, 1997*a*; Boulton *et al*., 2001; Marks, 2002, 2005; Marks *et al*., 2003; Wysota and Molewski, 2007) indicate the presence of an ice stream within the Vistula lobe of the last glaciation, stimulated by the pre-Vistula River valley of the Eemian Interglacial.

These data provided an assumption for a reconstruction of ice flow directions within the Vistula lobe. The analysis was performed over an area of about 17 000 square km, covering the glacial upland belts adjoining the Vistula valley on both sides, in the area extending from the maximum limit of the Pomeranian retreat phase in the north (near Grudziądz) to the maximum limit of the Vistula ice lobe south of Płock.

STUDY METHODS

The reconstruction of ice movement directions presented in this paper was performed based on spatial analysis of the orientation of glacial morpholineaments. Theoretical principles of this method and previous research results from NE Poland were given in earlier publications of the author (Morawski, 2003, 2005*b*). The research method is based on the following main assumptions:

- the spatial orientation of most of glacial morpholineaments is inherited after the original joint net in the ice body;
- its orientation in the ice body was the effect of horizontal stress due to movement of the advancing ice sheet;
- the net of joints is composed of a rectangular (extensional) system consisting of longitudinal and transverse sets, and of an acute-angled (shear) system composed of two diagonal sets;
- the ice flow direction vector is consistent with the longitudinal set of the extensional system and is a resultant of the two oblique sets of the shear system;
- the original joint net was reoriented due to local changes in ice flow direction.

The author is aware that the above assumptions may give rise to some concerns, in particular as regards theoretical knowledge concerning the physics of ice. These concerns can refer especially to the problems of the possible formation of original joint nets in the continental ice bodies, the timing of their development, their vertical extent within the ice mass and the process of further evolution to form a system of crevasses. The problems can be resolved both by special investigations on modern ice sheets and theoretical studies involving considerations on ice mechanics in continental ice sheets. The theoretical assumptions presented above should be treated as a hypothetical and working thesis developed from the real analogy between the mutual orientation of glacial morpholineaments and the mutual orientation of tectonic lineaments, a horizontal stress-generated joint net in solid rocks.

The analysis of morpholineament orientation used in the present study is a reconstruction of ice movement, uniformly and proportionally characterizing large areas. However, it should be noted that direct determination of ice flow directions from the orientation of linear glacial landforms developed in ice crevasses and glacial tunnel valleys leads to significant misinterpretations. According to the above assumptions and previous experience with the use of the research method, most glacial linear landforms inherited their spatial orientations from the joint net in the ice body. The net is composed of four joint sets forming two conjugate systems. Among these, only the extensional longitudinal set is consistent with the general stress direction i.e. the ice movement direction. Commonly, most of the dominant landforms belong to the shear system, i.e. the landforms are oriented obliquely to the ice movement direction. Therefore, reconstruction of ice flow directions must be based on a joint analysis of both positive and negative glacial morpholineaments in the study area to compile the directions on composite diagrams. The diagrams are the basis for the identification of individual sets and for the determination of the resultants of ice movement direction separately for the two conjugate systems identified.

Previous results of reconstructions of ice movement directions from a complex analysis of the orientation of glacial morpholineaments (Morawski, 2003, 2005*b*; Pochocka-Szwarc and Piątkowska, 2006; Roman, 2008) seem to form encouragement wards a broader use of this method. The main limitation is that the method allows for analyzing only morainic plateaus, excluding marginal zones. That is why the idea of making of such an analysis on the basis of observations from small parts of the morainic plateaus adjoining both sides at the Vistula valley, seemed to offer little promise. However, the research results presented below far exceeded expectations.

The reconstructed ice sheet movement directions presented in this paper within the Vistula ice stream should be considered as preliminary and as encouragement for further detailed studies using different methods to both reconstruct a more accurate direction of the ice stream and to determine its movement velocity relative to the velocity of the whole ice body.

However, it must be borne in mind that the method provides a regional image of evenly distributed information, while fieldwork carried out for determination of ice flow directions provide only point data (from good exposures) and the only way to get regional conclusions is to acquire a much denser net of data measuring points.

The analysis of spatial orientation of glacial morpholineaments was performed on geological maps previously constructed by various authors. It was supported by analysis of topographic maps. Orientations of glacial morpholineaments (crevasse landforms) and results of reconstruction of ice movement directions were obtained from analysis performed on 26 map sheets of the *Detailed Geological Map of Poland* (DGMP), scale 1:50 000, covering a broad area of the Vistula River valley and neighbouring morainic plateaus: Nowe (Listkowska, 1980); Gardeja (Kozłowski, 1980); Lubiewo (Heliasz and Ostaficzuk, 2000); Chełmno (Butrymowicz, 1980); Grudziądz Rudnik (Maksiak, 1981); Grudziądz (Uniejewska, 1980); Skarlin (Lichwa and Wełniak, 2003); Żołędowo (Kozłowska and Kozłowski, 1985); Unisław (Kozłowska and Kozłowski, 1986); Chełmża (Trzepla and Drozd, 1999); Wąbrzeźno (Trzepla and Drozd, 2003); Rzęczkowo (Wrotek, 1986); Złotniki Kujawskie (Wrotek, 1991); Gniewkowo (Jeziorski, 1992*a*); Aleksandrów Kujawski (Jeziorski, 1992*b*); Ciechocinek (Łyczewska, 1973); Lipno (Dzierżek, 2006); Pakość (Listkowska, 1989); Bobrowniki (Jeziorski, 1987); Fabianki (Lamparski, 1985); Tłuchowo (Lamparski, 1980); Piotrków Kujawski (Molewski, 1999); Brześć Kujawski (Brzeziński, 2001); Dobrzyń (Skompski, 1968); Płock (Skompski and Słowański, 1962); Lubień Kujawski (Baraniecka, 1988).

Morpholineament orientation measurements and analysis of ice movement directions were made separately in morainic plateau areas composing individual DGMP map sheets. Although this method of data compilation is not supported by palaeogeographic data, it considerably facilitates construction of a regional data compilation at a preliminary stage of regional analysis.

Both positive and negative linear landforms of glacial origin were measured (see Morawski, 2005*b*). Previous experience with the method suggests that it is a better way to analyse all linear landforms, even those whose origin cannot be considered as strictly glacial (of crevasse origin), than to use a subjective elimination process to analyse only selected landforms. Any elimination of poorly expressed or unidentified landforms may risk losing the whole of locally poorly predisposed direction sets. In turn, a loss of a set may give rise to significant difficulties in identification of any of the two (extensional or shear) systems composed of conjugate sets. This methodical assumption obviously results in a greater scatter of directions and requires construction of separate diagrams for individual systems. However, such a procedure enables simultaneous verification of the ice movement directions determined from each system separately. Correspondence of the directions reconstructed from both the systems separated from a single composite diagram is the best guarantee that the analysis is correct.

The analysis involved 6226 measurements made on the map sheets under consideration. The data were subsequently put into rosette diagrams using the *StereoNet* software. A landform up to 1 km in length was considered a single measurement. The number of measurements on individual DGMP map sheets varies from 95 to 724.

RECONSTRUCTION OF ICE SHEET MOVEMENT DIRECTIONS

The orientation of all glacial morpholineaments measured on individual DGMP map sheets is shown in composite diagrams presented in Figure 2. Figures 2, 3, 4 illustrate a division of the study area into DGMP map sheets indicating their names. Morainic plateau areas are also indicated (Figs. 2, 3 and 4). The analysis covered small fragments of the morainic plateau immediately adjoining the Vistula River valley and its tributaries. The number of landforms measured is usually proportional to the morainic plateau area; hence, some of the map sheets contain only a small number of measurements. To reconstruct the directions of ice sheet movement outside the valley, the analysis was also performed for a few map sheets covering the morainic plateau on either side of the valley. The number of landforms measured in these areas is commonly significant.

The analysis of composite diagrams (Fig. 2) enabled identification of four sets; two sets conjugate of the extensional system and two sets conjugate in the shear system. The results of the analysis are presented as diagrams constructed separately for the extensional (Fig. 3) and shear (Fig. 4) systems. The ice movement directions were determined for each system separately. A combined analysis of diagram pairs (Figs. 3 and 4) for each map sheet enables assessment of the coincidence between the reconstructed ice flow directions obtained for each system.

The morainic plateau area of some map sheets shows a clear arrangement of the orientation of linear landforms, indicating a constant and ordered ice flow. On other map sheets, a significant scatter of the directions is locally observed. This required further detailed analyses that usually enabled identification of two or three superimposed generations of conjugate systems, suggesting changes in ice movement directions within a single map sheet. Interpretation of the generations is shown as a reconstruction of two or three ice flow directions within the map sheet area. Locally, only one direction caused by the extensional system is dominant, while the shear system displays a superimposition of two slightly different directions (e.g., Bobrowniki sheet, see Figs. 3 and 4). In other cases, with one direction resulting from the shear system, the extensional system shows two directions (e.g., Złotniki Kujawskie sheet, see Figs. 3 and 4). These cases also suggest a conclusion that, within the limited area of a given map sheet, a local change in ice movement direction is observed.

Insufficient number of measurements in small fragments of morainic plateau sometimes causes significant difficulties in identification of individual sets and systems. For example: morpholineaments in the Aleksandrów Kujawski sheet form two generations of the extensional system. No shear system was identified there (Figs. 3 and 4).

As the DGMP map series is finished, it will be possible to extend the analysis into areas currently lacking map sheets. It seems that the next stage of the reconstruction of changes in ice sheet movement direction in the study area should be an attempt to identify areas of the same characteristic direction irrespective of the division into individual DGMP map sheets. However, it should be borne in mind that analysis of smaller and smaller areas is limited by the amount of identifiable linear glacial landforms (glacial morpholineaments). An insufficient number of landforms makes the analysis less reliable.

ICE MOVEMENT DIRECTION OUTSIDE THE NARROW BELT ADJOINING THE VISTULA RIVER VALLEY

Ice movement directions were reconstructed in the morainic plateau within the Vistula ice lobe outside the zone immediately adjoining the river valley. In the northern part of the study area to the west of the Vistula River (Lubiewo sheet), the ice flow direction was from the north with a slight eastward deviation towards the valley. On the eastern side, about 40 km from the valley (Skarlin sheet), the ice flow direction is well ordered and oriented north-south (Figs. 3 and 4). A still better arrangement (exactly from the north) is observed closer to the Vistula River valley in the Wąbrzeźno sheet (Figs. 3 and 4). The reconstruction of ice movement direction in this area is especially convincing because it is based on as many as 664 measurements of morpholineaments. A distinct trend in the directions is observed within the four sets composing the two conjugate systems. The ice flow direction determined from both the systems has the same, azimuth of about 180°.

A similar ice movement direction from the north is suggested from analysis of the orientation of morpholineaments found within the Pakość and Piotrków Kujawski map sheets located south of the Vistula River valley. Identification of the two systems is a little bit difficult in this area. Two generations of the extensional system (Fig. 3) are probably observed in the Piotrków Kujawski sheet, suggesting a local fan-like spread of the ice mass as the ice sheet overstepped the Vistula River valley at its submeridional section. However, both the resultant of

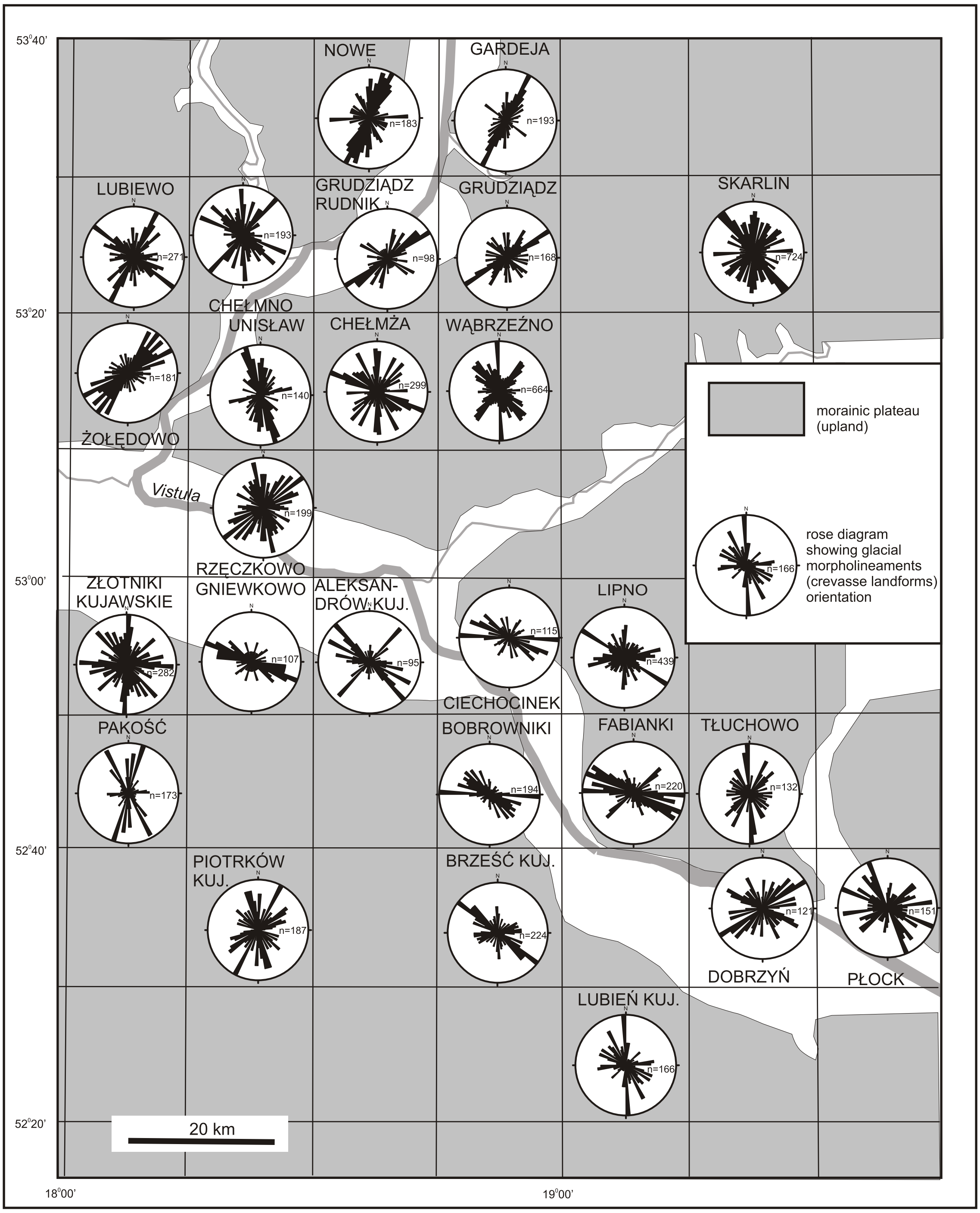

Fig. 2. Orientation of glacial morpholineaments (crevasse landforms) from selected map sheets (*Detailed Geological Map of Poland*) in the Vistula valley zone — composite diagrams

these directions and the direction determined from the shear system (Fig. 4) show a general ice flow direction from north towards south.

A similar situation is observed on the eastern side of the Vistula River valley, where a clearly visible N–S trend in ice flow direction is observed on the Tłuchowo sheet (Figs. 3 and 4).

The above data from selected areas located outside the Vistula River valley show that the ice sheet movement direction within the Vistula lobe was well ordered and constant over a large area and oriented from north towards south.

ICE MOVEMENT DIRECTIONS IN THE NARROW BELT ADJOINING THE VISTULA RIVER VALLEY

All of the DGMP map sheets covering fragments of glacial uplands along the Vistula River valley were analysed for the orientation of morpholineaments in the study area.

A distinct westward turn in ice flow direction was reconstructed in the north, on either side of the valley (Nowe and Gardeja sheets). This especially well accentuated to the east of

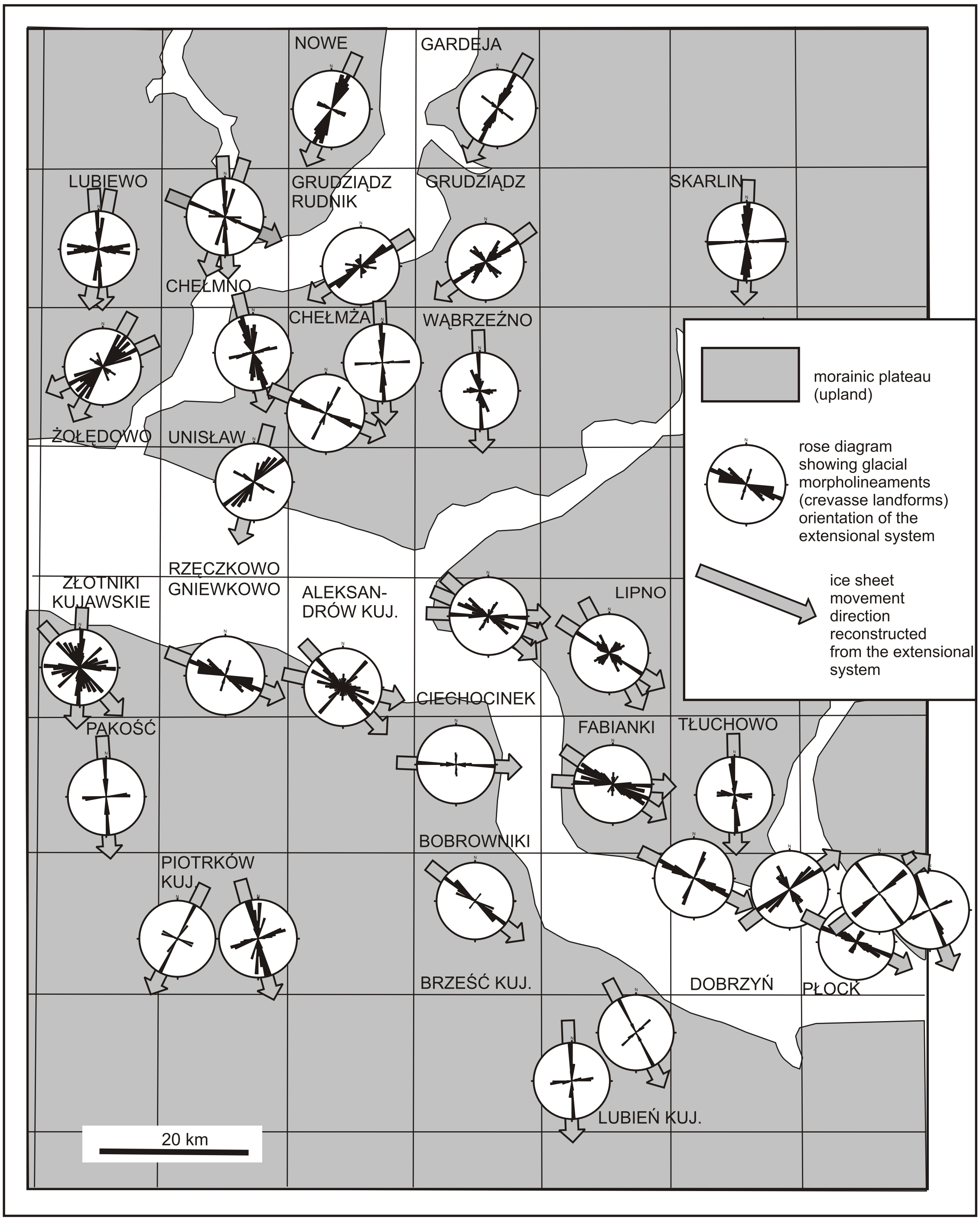

Fig. 3. Reconstruction of ice sheet movement directions from the extensional system of the glacial morpholineaments orientations

the valley on the Gardeja sheet (Figs. 3 and 4), where both the extensional and shear systems show very similar ice flow azimuths of about 208° and 204°, respectively.

Tracing the changes in ice movement direction when moving southwards along the river valley, the westward turn in the flow direction is better expressed; it is manifested by the directions reconstructed on the Grudziądz and Grudziądz Rudnik sheets (Figs. 3 and 4). The directions are well ordered here and there is no problem with identification of the two systems in the composite diagram. The ice movement direction azimuths determined from both the systems are similar: in the Grudziądz sheet 233° (extensional system) and 228° (shear systems) with averages of 230° i.e.; in the Grudziądz Rudnik sheet 238° (extensional system) and 249° (shear systems) with an average of 243° i.e. — the ice directions was almost westerly by about 13° (Figs. 3 and 4). This trend continues further southwards along the river valley on the western side of the valley in the Żołędowo sheet (Figs. 3 and 4), although there are two distinct generations of ice flow directions, indicating a gradual change in direction back to N–S.

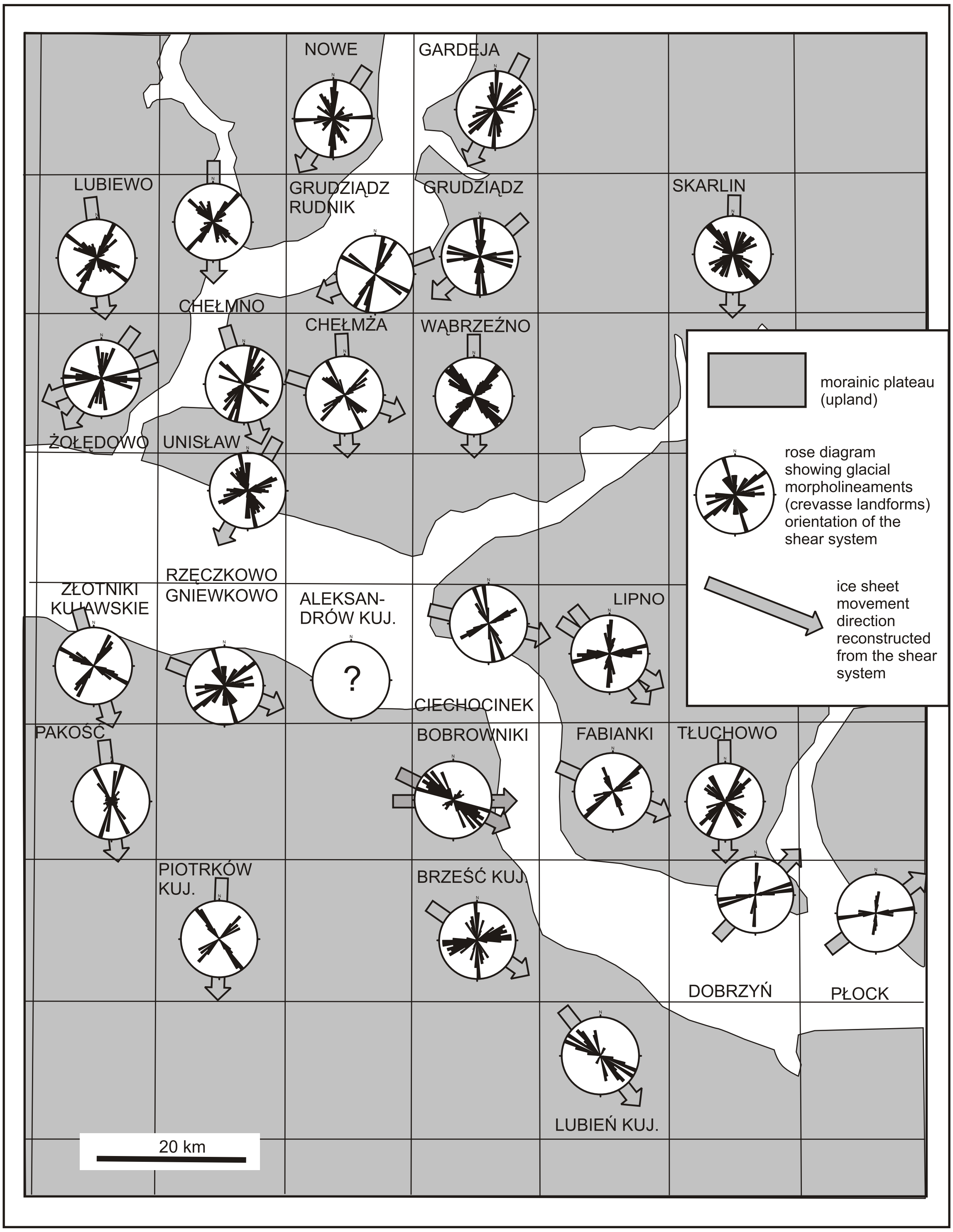

Fig. 4. Reconstruction of ice sheet movement directions from the shear system of the glacial morpholineaments orientations

This trend continues on the eastern side of the river valley in the Unisław sheet (Figs. 3 and 4), where the reconstructed ice movement direction changes to N–S even with a slight eastern deviation. In the Chełmża sheet, adjoining to the east, there are two distinct generations of ice flow directions. Closer to the valley there is a better accentuated eastwards turn, whereas further from the valley there prevails a N–S direction as in the neighbouring Wąbrzeźno sheet (see above) where the ice movement direction is constant and typical of the Vistula ice lobe, as recorded outside the river valley.

The map sheet row below encompasses a river valley and ice-marginal valley. The lack of morainic plateau areas makes any analysis impossible. The next map sheet row extending to the south includes small morainic plateau fragments where morpholineament analysis indicates a well-accentuated eastwards turn of the reconstructed ice movement direction, on

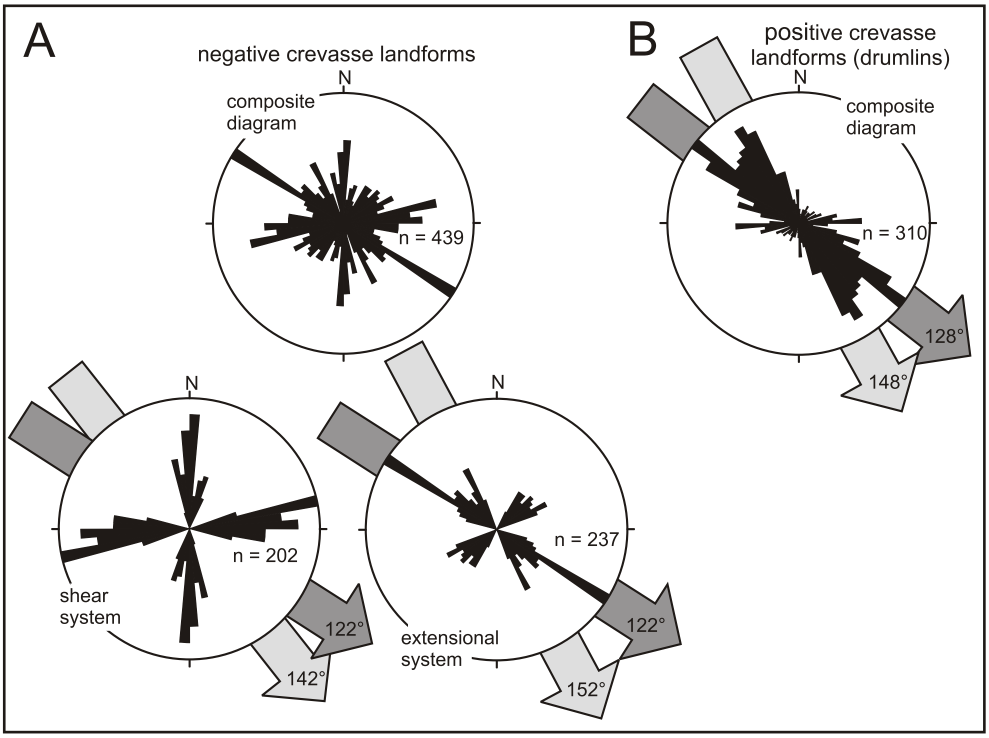

Fig. 5. Reconstruction of the ice movement directions (arrows) from the orientations of glacial morpholineaments in the Lipno region (based on the Lipno sheet of the *Detailed Geological Map of Poland* scale 1:50 000; Dzierżek, 2006)

the Gniewkowo and Aleksandrów Kujawski sheets (Figs. 3 and 4). Further eastwards and southwards, this direction becomes better accentuated and the reconstructed ice movement direction on either side of the river valley is from west to east, partly with a slight southern deviation, on the Ciechocinek, Bobrowniki and Fabianki sheets (Figs. 3 and 4).

Especially interesting results of ice movement reconstruction were obtained on the Lipno sheet (Fig. 5). This is an area of numerous drumlins showing a well-ordered orientation. Analyses of positive landforms (mainly drumlins; Fig. 5B) — directly from the composite diagram, and positive landforms (Fig. 5A) — from both the systems, were made on this map sheet. The reconstruction shows the occurrence of two generations of ice flow directions indicating a change in the ice movement direction in this area from SE to SES. It is symptomatic that almost identical resultant ice flow directions of the two generations were obtained from the orientation of drumlins and from negative landforms. It seems that geological data from this region not only record the precise ice movement direction but also have a methodological significance. This refers not only to support for the correctness of the reconstruction of ice movement direction from the two morpholineament orientation systems, but also as regards the theoretical assumptions of the method presented.

Eastwards as regards the reconstructed ice movement directions, there is a rapid return to a well-ordered arrangement of the directions (N–S) typical of the Vistula lobe in the area outside the narrow belt adjoining the river valley. This change occurs over a relatively short interval outside the narrow belt immediately next to the valley in the area of the Tłuchowo sheet adjoining to the east (Figs. 3 and 4).

Further to the south, immediately close to the river valley in the area extending as far as the end of the Vistula ice lobe near Płock, the general ice flow direction was still from NW to SE. To the north of the valley (Płock sheet), the general ice movement direction locally changes (Fig. 6Aa and Ab) and ranges within the azimuth of 115–155°. Two very similar generations of ice movement direction were reported by Skompski (1969) from the Płock region. They were interpreted based on till fabric analysis (Fig. 6Ba and Bb). There is also another ice flow direction SW–NE, in this area (azimuth of about 50°) — i.e. to the outside of the valley towards the glacial upland (Fig. 6Ac). This direction was already reported by Skompski (1969) from the Płock and Dobrzyń regions, following detailed field mapping investigations supported by numerous till fabric measurements (Fig. 6Bc). That author claimed that the ice sheet, advancing in the pre-Vistula River valley, was flowing towards the NE i.e. to the outside of the valley. A similar situation is observed to the south of the valley within the Włocławek, Gostynin and Gąbin sheets (Fig. 7). Reconstruction of ice movement directions in this region was performed by Roman (2008) who identified a general ice flow direction from NW to SE using both the morpholineament analysis method and detailed field observations of a number of ice flow direction indicators including till fabric, vergence of compressional glaciotectonic structures and orientation of subglacial deformation structures and glacial striae. Apart from this general ice movement direction, that author found that the ice flow direc-

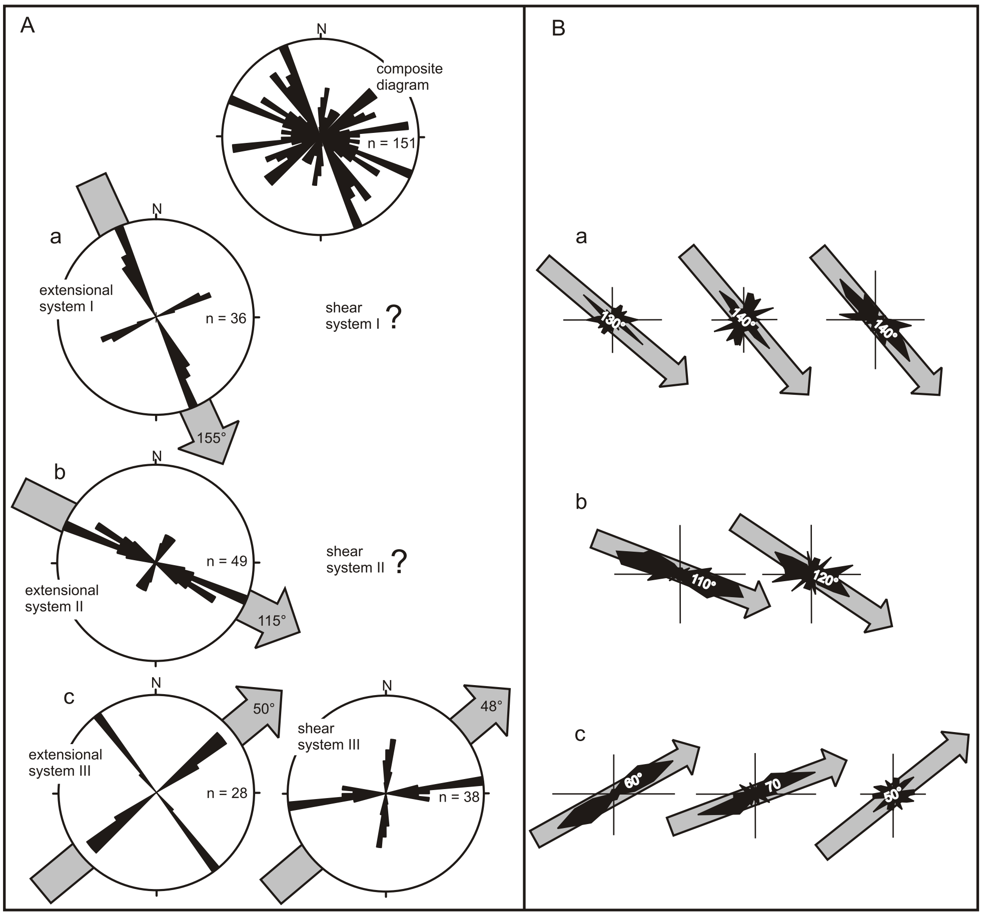

Fig. 6A — reconstruction of the ice movement directions (arrows) from the orientations of glacial morpholineaments in the Płock region (based on the Płock sheet of the *Detailed Geological Map of Poland* scale 1:50 000 — Skompski and Słowański, 1962); B — reconstruction of the ice movement directions from till fabric after Skompski (1967), arrows added

tion was towards the south with a western deviation indicating an ice expansion to the outside of the pre-Vistula River valley. The same local ice movement direction (azimuth of about 190°) was reconstructed by Skompski (1969) in the Gostynin region from field studies, including till fabric investigations.

CONCLUSIONS

The following conclusions can be drawn from these study:

1. The Vistula lobe (ice stream) entered the Eemian Interglacial pre-Vistula River valley. It was followed by the Masurian lobe which covered the Mazury region. The general ice movement direction of the Vistula lobe was from north to south, whereas the Masurian lobe advanced from north to south with a slight eastern deviation (from NNW to SSE). A general ice-front limit in the Mazury region was perpendicular to that direction and trended WSW–ENE. Such an ice-front configuration and general ice flow direction persisted in the Mazury region until the Last Glacial Maximum.

2. The Vistula lobe expanded much further to the south than did the Masurian lobe and it occupied the pre-Vistula River valley as far as the area situated south and east of Płock. The ice stream within the Vistula lobe followed a basement depression of the pre-Vistula River valley developed during the Eemian Interglacial. The ice stream adjusted to the valley configuration and the ice movement direction locally changed along bends in the valley winded. In the northern area of the Grudziądz–Żołędowo region, the ice stream turned westwards and further south it turned eastwards as the river valley became oriented in a NW–SE direction. The NW–SE direction of the ice stream within the Vistula lobe remained the same as far as its front running to the SE of the Płock–Gąbin line. At the ice stream end zone, there was a local ice-mass thrusting and flowing to the outside of the pre-Vistula River valley towards the NE, S and SSW.

3. The Vistula lobe ice stream was narrow (30–50 km) and encompassed the pre-Vistula River valley and a very narrow belt on either side of it. At a distance of 10–20 km from the valley, the ice movement direction was constant from north to south.

4. The variable ice movement directions within the ice stream manifest themselves in the orientation of linear glacial landforms (glacial morpholineaments) which were ultimately shaped mainly during the deglaciation period only. This seems to indicate permanent activity of the Vistula ice stream during the Main Stadial of the last glaciation through the deglaciation period.

5. This method of reconstruction of ice movement direction can be employed not only in vast areas of glacial uplands but

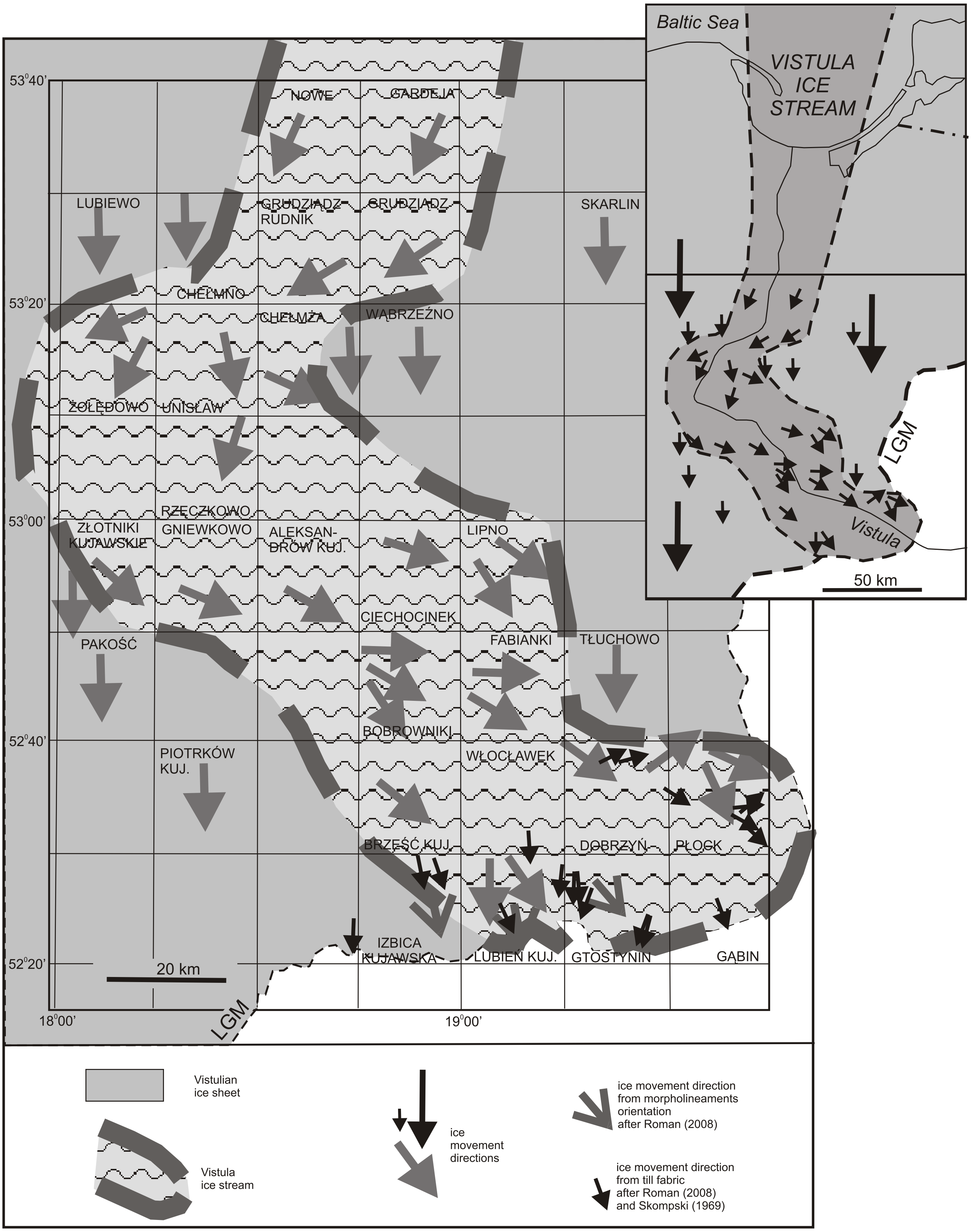

Fig. 7. Vistula ice stream reconstruction

LGM — Last Glacial Maximum

also in small fragments of such areas located close to river valleys and ice-marginal valleys. They also show that the method can be used not only for reconstructions of regional ice movement directions in large areas, but also for reconstructions of ice streams with local flow direction changes occurring at short distances. Ice flow directions reconstructed in such a way are precise and consistent with data acquired by other methods requiring time-consuming fieldwork.

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REFERENCES

ABER J. S. and RUSZCZYŃSKA-SZENAJCH H. (1997) — Origin of Elbląg Upland, northern Poland, and glaciotectonism in the southern Baltic region. Sediment. Geol., **111**: 119–134.

BARANIECKA M. D. (1988) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Lubień Kujawski. Państw. Inst. Geol.

BER A. (2000) — Pleistocene of north-eastern Poland and neighbouring areas against crystalline and sedimentary basement. Pr. Państw. Inst. Geol., **170**.

BER A. (2008) — Vertical stress of the Pleistocene continental glaciers and its evidence in present relief of Northern Europe. Quaternary of the Gulf of Gdańsk and lover Vistula regions in northern Poland: sedimentary environments, stratigraphy and palaeography. Internat. Field Symp. INQUA Peribaltic Group: 16–17.

BOULTON G. S., DOLGENMANS P., PUNKARI M. and BROADGATE M. (2001) — Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. Quatern. Sc. Rev., **20**: 591–625.

BRODZIKOWSKI K. and VAN LOON A. J. (1991) — Glacigenic sediments. Develop. Sediment., **49**. Elsevier, Amsterdam.

BRZEZIŃSKI M. (2001) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Brześć Kujawski. Państw. Inst. Geol.

BUTRYMOWICZ N. (1980) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Chełmno. Inst. Geol.

CLARK C., EVANS D. and PIOTROWSKI J. (2003) — Palaeo-ice streams: an introduction. Boreas, **32** (1): 1–3.

DREDGE L. A. and COWAN W. R. (1989) — Quaternary geology of the southwestern Canadian shield. In: Quaternary Geology of Canada and Greenland (ed. R. J. Fulton). Geology of Canada, **1**: 214–235. Geol. Surv. Canada.

DYKE A. S. and DREDGE L. A. (1989) — Quaternary geology of the northwestern Canadian Shield. In: Quaternary Geology of Canada and Greenland (ed. R. J. Fulton). Geology of Canada, **1**: 178–214. Geol. Surv. Canada.

DZIERŻEK J. (2006) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Lipno. Państw. Inst. Geol.

EHLERS J. (1990) — Reconstructing the dynamics of the North-West European Pleistocene ice sheets. Quatern. Sc. Rev., **9**: 71–83.

HELIASZ Z. and OSTAFICZUK S. (2000) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Lubiewo. Państw. Inst. Geol.

HOWAT I. M. and DOMACK E. W. (2003) — Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution accoustic stratigraphy. Boreas, **32** (1): 56–75.

JEZIORSKI J. (1987) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Bobrowniki. Państw. Inst. Geol.

JEZIORSKI J. (1992*a*) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Gniewkowo. Państw. Inst. Geol.

JEZIORSKI J. (1992*b*) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Aleksandrów Kujawski. Państw. Inst. Geol.

KOZŁOWSKA M. and KOZŁOWSKI I. (1985) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Żołdowo. Inst. Geol.

KOZŁOWSKA M. and KOZŁOWSKI I. (1986) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Unisław. Państw. Inst. Geol.

KOZŁOWSKI I. (1980) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Gardeja. Inst. Geol.

KURIMO H. (1982) — Ice-lobe formation and function during the deglaciation in Finland and adjacent Soviet Karelia. Boreas, **11** (1): 59–77.

LISTKOWSKA H. (1980) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Nowe. Inst. Geol.

LISTKOWSKA H. (1989) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Pakość. Państw. Inst. Geol.

LAMPARSKI Z. (1980) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Tłuchowo. Inst. Geol.

LAMPARSKI Z. (1985) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Fabianki. Inst. Geol.

LICHWA M. and WEŁNIAK A. (2003) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Skarlin. Państw. Inst. Geol.

ŁYCZEWSKA J. (1973) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Ciechocinek. Inst. Geol.

MAKSIAK S. (1981) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Grudziądz Rudnik. Inst. Geol.

MARKS L. (1988) — Relation of substrate to the Quaternary paleorelief and sediments western Mazury and Warmia (northern Poland). Kwart. AGH, Geologia, **14**: 1–76.

MARKS L. (2002) — Last Glacial Maximum in Poland. Quatern. Sc. Rev., **21**: 103–110.

MARKS L. (2005) — Pleistocene glacial limits in the territory of Poland. Prz. Geol., **53** (10/2): 988–993.

MARKS L., GUOBYTE R., KALM V., PAVLOVSKAYA I. E., RATTAS M., STEPHAN H.-J., ZELES V., GOGOŁEK W., BIELECKI T. and KOCYŁA J. (2003) — Map of Weichselian directional ice-flow features of Central and Eastern Europe. 16th INQUA Congress, Programs with Abstracts, Reno, Nevada: 117–118.

MOLEWSKI P. (1999) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Piotrków Kujawski. Państw. Inst. Geol.

MORAWSKI W. (2003) — Reconstruction of ice sheet movement from the orientation of linear glacial landforms and glaciotectonic deformations near Kronowo (western Mazury, Poland). Geol. Quart., **47** (4): 339–356.

MORAWSKI W. (2005*a*) — The Warmia Palaeogeographic Province of the Pleistocene (north-eastern Poland) (in Polish with English summary). Prz. Geol., **53** (6): 477–488.

MORAWSKI W. (2005*b*) — Reconstruction of ice sheet movement from the orientation of glacial morpholineaments (crevasse landforms): an example from northeastern Poland. Geol. Quart., **49** (4): 403–416.

MORAWSKI W. (2009*a*) — Neotectonics induced by ice-sheet advances in NE Poland. Geologos, **15** (3).

MORAWSKI W. (2009*b*) — Differences in the regional stratigraphy of NE Poland caused by vertical movements due to glacio-isostasy. Geologos, **15** (3).

PATTERSON C. J. (1997) — Southern Laurentide ice lobes were created by ice streams: Des Moines Lobe in Minnesota, USA. Sediment. Geol., **111**: 249–261.

POCHOCKA-SZWARC K. and PIĄTKOWSKA A. (2006) — Wstępna interpretacja fotolineamentów z północnej części Pojezierza Mazurskiego. In: 13 Konf. Strat. plejstocenu Polski, Maróz, 4–8 września 2006. Państw. Inst. Geol., Warszawa.

PUNKARI M. (1997*a*) — Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian Ice Sheet. Quatern. Sc. Rev., **16**: 741–753.

PUNKARI M. (1997*b*) — Subglacial processes of the Scandinavian Ice Sheet in Fennoscandia inferred from flow-parallel features and lithostratigraphy. Sediment. Geol., **111**: 263–283.

ROMAN M. (2008) — Rekonstrukcja kierunku ruchu lądolodu lobu Wisły w obszarze Pojezierza Kujawskiego i Kotliny Płockiej. Acta Geogr. Lodz., **93**: 67–85.

SKOMPSKI S. (1968) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Dobrzyń. Inst. Geol.

SKOMPSKI S. (1969) — Stratygrafia osadów czwartorzędowych wschodniej części Kotliny Płockiej. Biul. Inst. Geol., **220**: 175–258.

SKOMPSKI S. and SŁOWAŃSKI W. (1962) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Płock. Inst. Geol.

STOKES C. R. and CLARK C. D. (2001) — Palaeo-ice streams. Quatern. Sc. Rev., **20**: 1437–1457.

TRZEPLA M. and DROZD M. (1999) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Chełmża. Państw. Inst. Geol.

TRZEPLA M. and DROZD M. (2003) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Wąbrzeźno. Państw. Inst. Geol.

TULACZYK S., KAMB W. B. and ENGELHARDT H. F. (2000) — Basal mechanics of Ice Stream B, West Antarctica 1. Till mechanics. J. Geophys. Res., **105** (B1): 463–481.

UNIEJEWSKA M. (1980) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Grudziądz. Inst. Geol.

VEILLETTE J. J. (1986) — Former southwesterly ice flows in Abitibi-Timiskaming region: implications for the configuration of the Late Wisconsinan ice sheet. Canadian J. Earth Sc., **23**: 1724–1741.

WROTEK K. (1986) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Rzęczkowo. Inst. Geol.

WROTEK K. (1991) — Szczegółowa mapa geologiczna Polski w skali 1:50 000, ark. Złotniki Kujawskie. Państw. Inst. Geol.

WYSOTA W. and MOLEWSKI P. (2007) — Ostatni lądolód skandynawski w lobie Wisły — kontrowersje i nowe spojrzenie. In: 14 Konf. Strat. plejstocenu Polski, 3–7 września 2007, Ciechocinek: 13–22.