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Reconstruction of ice sheet movement from the orientation of glacial morpholineaments (crevasse landforms): an example from northeastern Poland

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Analysis of the orientation of both positive and negative glacial morpholineaments (crevasse landforms) was performed on the areas covered by 12 selected map sheets of the *Detailed Geological Map of Poland*, scale 1:50 000, situated in NE Poland. Axes of these landforms form a net composed of four conjugate sets. This is a classical joint net developed due to horizontal stress, and composed of an orthogonal (extensional) system consisting of longitudinal and transversal sets, and a rhomboidal (shear) system consisting of two diagonal sets. Based on the orientation of glacial morpholineaments, inherited after the original joint net in the ice body, ice sheet advance directions — averaged for the area — were determined. This method of reconstructing ice flow direction creates new possibilities of making synthetic regional analyses, in particular in terms of Pleistocene palaeogeographic investigations. The best potential for the method's use lies in areas of young post-glacial relief. In the region of NE Poland analyzed, these investigations enabled determination of different directions of ice flow within the Mazurian, Warmian and Vistulian ice sheet lobes of the last glaciation. Local changes in ice sheet movement directions were identified, and these reflected basement elevations (e.g. the Wiżajny Elevation). In other cases, basement irregularities influenced the opening of separate crevasse sets (e.g. outside of the Góra Dylewska massif) giving rise to a dominance of individual directions (sets) in the morpholineament orientation. This method can also be used in geological mapping.

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INTRODUCTION

Among morphologically and genetically diverse glacial landforms, only a few possess irregular shapes and chaotic distribution with no distinct ordering. Most glacial landforms occur as well-ordered phenomena of the landscape. For example, ice-marginal landforms follow the course of a stagnant ice sheet front, as belts of marginal moraines. In a glacial upland landscape, outside the marginal zone, most positive and negative glacial landforms show a linear course or a linear arrangement, i.e. in a cartographic image they occur as morpholineaments. Both the linear courses of some glacial landforms and the present understanding of their origin indicate that these landforms are inherited after a joint system, and subsequently after crevasses formed in the ice body. These were crevasses or linear crevasse zones probably of nearly vertical walls, cutting through the entire ice thickness. Such crevasses were opened probably during phases of active ice movement, as observed in present-day surging glaciers (e.g. Johnson, 1975; Sharp, 1985). In this process, both the nature of the underlying topography and its deformability due to the load of the advancing ice sheet most probably played important roles.

Opening and widening of crevasses subsequently took place during stagnation of the ice sheet and within dead-ice blocks, mostly as a result of both the pressure of englacial waters and of dissolution by in-crevasse flowing waters. After the widening and deepening phase, some of the crevasses were filled with meltwater-transported deposits and with morainic material that melted out directly from crevasse wall; after the ice melted out they formed positive (sediment-filled) landforms on the post-glacial landscape. These landforms are represented by ramparts or belts of elongated hills which can be collectively termed positive glacial crevasse landforms (crevasse infillings). Other fractures in the ice were pathways for flowing meltwaters, also during deglaciation. They were subjected to widening and deepening, being periodically preserved by ice that resulted in their conservation in the post-glacial landscape as negative glacial crevasse landforms.

Analysis of the orientation of such glacial morpholineaments, i.e. positive and negative glacial crevasse landforms occurring in the post-glacial landscape of NE Poland, indicates that they form an ordered network analogous to the classical tectonic joint system developed due to stress induced by horizontal compression (e.g. Jaroszewski, 1994). It can be generalized that such a network of original joints was formed in the ice body as a result of its advance. Thus, the spatial orientation of glacial morpholineaments, whose orientation was inherited after the original joints in the ice sheet, allows reconstruction of the direction of horizontal stress i.e. the direction of ice movement. Such a conclusion gave rise to a development of a method of statistical analysis of the orientation of linear landforms (glacial morpholineaments) in a given area. Another aim of this study was to develop a methodology for reconstruction of the directions of ice sheet movement, and to explain the reasons for regional and local deviations from the main ice flow direction.

All the conclusions on the orientations of crevasse landforms (morpholineaments) and on their relation to the orientations of original joints in the ice body, made in this study, are based exclusively on field observations i.e. measurements of the orientation of landforms mapped in the field.

REVIEW OF STUDIES ON GLACIAL LINEATIONS

Reconstructions of ice sheet movement directions, in relation both to the general advance of ice masses and to local ice streams, are one of the main concerns of palaeogeographical investigations of glaciated areas in recent and Pleistocene times.

The investigations include the study of ice streams i.e. narrow fast-flowing zones within the ice sheet. Reconstructions of palaeo-ice-stream directions are made via geomorphological studies of glacial lineations i.e. linear landforms formed subglacially as a result of active ice flow, in particular mega-scale glacial lineations (Clark, 1993). Such studies have concentrated on the Pleistocene ice sheet centres, both onshore and offshore. In particular, they concern the determination of regional directions of ice stream flows in Scandinavia and adjacent areas (e.g. Kleman, 1990; Kleman *et al.*, 1997; Punkari, 1997; Boulton *et al.*, 2001; Arnold and Sharp, 2002; Houmark-Nielsen, 2003; Houmark-Nielsen and Kjær, 2003; Sejrup *et al.*, 2003) and in Canada (e.g. Parent *et al.*, 1995; Andrews and MacLean, 2003; Jansson *et al.*, 2003). Ice-stream directions are determined from glacial lineations in a similar way also in the Irish Sea (Evans and Ó Cofaigh, 2003), the Antarctic continental shelf (Ó Cofaigh *et al.*, 2003) and in Greenland (Long and Roberts, 2003). In such regional studies, the commonly used method is the reading of lineations from air photos (e.g. Jansson *et al.*, 2003) and satellite images (e.g. Boulton and Clark, 1990; Clark, 1990), with the use also of two-dimensional spectral analysis (Mugglestone and Renshaw, 1998), remote sensing and GIS (Clark, 1997) as well as numerical modelling (Christoffersen and Tulaczyk, 2003). Geophysical methods, such as 3D seismic data obtained from the Barents Sea (Rafaelsen *et al.*, 2002) and the North Sea floor (Sejrup *et al.*, 2003), have also been used for reconstructions of ice-stream directions. Other methods in use include by acoustic profiling e.g. in the Ross Sea, Antarctica (e.g. Howat and Domack, 2003), producing a shaded relief image based on multibeam echo soundings e.g. in the Skagerrak (Sejrup *et al.*, 2003), and radar remote sensing (Vencatasawmy *et al.*, 1998).

Those investigations concerned both the main regional ice-stream directions analysed over large areas and more detailed analyses allowing for palaeogeographical conclusions about local changes through time (e.g. Stockes and Clark, 1999, 2001). The Quebec–Labrador region can serve as an example area where eskers and till lineations mapped on air photos (Prest *et al.*, 1968) are radially oriented (see Boulton and Clark, 1990 on large area of Canada) forming flow trace fans (Kleman *et al.*, 1994). Those linear glacial landforms occur in large numbers (as landform swarms). They were mapped using aerial and satellite images and are referred to as drumlins, crag-and-tails, horned crag-and-tails and flutes. Individual, partly overlapping fans have been considered to represent ice streams of several generations (Jansson *et al.*, 2002). Another comparably sophisticated analysis of lineations and linear glacial landforms in Labrador (N Quebec) enabled the drawing of palaeogeographical conclusions concerning the evolution of directions of successive ice sheets in that region (Vellette *et al.*, 1999).

In many areas, analysis of directions of local ice streams is conducted also on the basis of integrated field studies comprising, for example, research on till fabric patterns (e.g. Andersen *et al.*, 1987; Jonsdottir *et al.*, 1999), on striations in boulder pavements and drumlin orientations (e.g. Aario, 1977; Piotrowski, 1987; Haavisto-Hyvärinen *et al.*, 1989; Wysota, 1994; Colgan and Mickelson, 1997), and in a few cases detailed sedimentological investigations (e.g. Stalsberg *et al.*, 2003).

Identification of ice-stream directions has been sometimes accompanied by determination of palaeo-ice-stream speed, based on analysis of till texture, orientation and shape of boulders, and of glaciotectonic structures (e.g. Lian *et al.*, 2003).

Palaeo-ice-stream investigations can lead not only to palaeogeographical conclusions but also, for example, to predicting the influence of currently glaciated areas on climate changes (Clark *et al.*, 2003*b*).

All of these investigations, directly or indirectly leading to reconstructions of ice sheet movement directions, refer to recently glaciated areas and to centres of Pleistocene glaciation. The studies concentrate on subglacial processes under active ice.

A separate issue is the reconstruction of ice sheet movement directions from analysis of the orientation of glacial crevasse landforms. Only a few studies conducted in recently glaciated areas relate linear glacial landforms directly with the infilling of vertical crevasses formed in active ice. This includes studies of, for example, crevasse-fill ridges which developed due to subglacial flow of morainic material into open crevasses through overburden pressure (Sharp, 1985), as well as to other similar landforms that formed in supraglacial open crevasses filled with ablation material (Johnson, 1975; Brodzikowski and Van Loon, 1991; Dreimanis, 1995). It should be noted that these landforms, observed in the forefields of glaciers, commonly form two major crossing sets oblique to the ice sheet front (e.g. Johnson, 1975; Sharp, 1985).

It has been generally assumed that the orientations of linear glacial landforms (morpholineaments), formed as a result of deglaciation of the Pleistocene ice sheets of the European Lowlands, follow ice advance directions. This concerns, in particular, glacial tunnel valleys, if these are assumed to have been perpendicular to the ice sheet front (e.g. Majdanowski, 1947, 1950; Ber, 2000 and others).

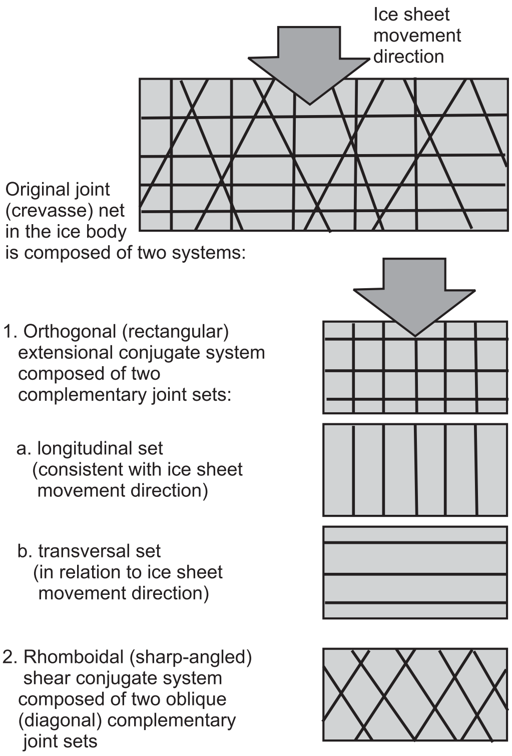
Analysis of the spatial orientation of linear glacial landforms or of axes of relief landforms has to date been rarely used for purposes others than the reconstruction of ice sheet movement directions. Such analysis has been performed to show, for example, the relationships between the orientation of relief landforms and the orientation of basement structures (Klajnert, 1978; Rdzany, 1997).

ORIENTATION OF CREVASSE LANDFORMS AND THE ORIGINAL JOINT NET WITHIN THE ICE BODY

Most glacial morpholineaments developed during the Pleistocene as a result of deglaciation of lowland areas are represented by supraglacial crevasse landforms (see Introduction). Their spatial orientation does not directly indicate directions of dynamic ice movement, but reflects the original joint net in the ice body. However, analysis of the orientation pattern can lead to the reconstruction of ice sheet movement directions.

THE CLASSICAL HORIZONTAL STRESS-GENERATED NET OF ORIGINAL JOINTS IN THE ICE BODY, AS A RESULT OF ICE ADVANCE

Both the crevasse origin of these morpholineaments and their well-ordered spatial pattern, as observed in the Warmia region (Morawski, 2003*b*), suggest that they reflect a joint net that subsequently transformed to a crevasse system in the ice body. This is the classical horizontal stress-generated joint net, composed of rectangular and sharp-angled systems (Fig. 1). Such a net is typical of folds, although Jaroszewski (1994) opined that there is no reason to assume that a net is genetically related to folding because nets are also observed in unfolded areas. The rectangular (extensional) system is composed of longitudinal and transverse sets. The identification feature for the rectangular system is that they cross exactly at a right angle. The sharp-angled — shear system consists of two diagonal sets. Studies of the orientation of glacial morpholineaments, conducted in the Warmia region (Morawski, 2003*a*), indicate that the diagonal sets cross at an unusually large angle for a shear system. The angle is sometimes more than 80° i.e. close to a right angle as in the case with planes of the greatest shear stress. If, despite this, we assume that the system analyzed is a conjugate system developed due to shear, then the shear angle for the ice sheet would be more than 40°, and the inner friction angle is only several degrees.



Terminology after W. Jaroszewski (1994)

Fig. 1. The classical pattern (net) of joints (crevasses) in an ice sheet body, developed as a result of stresses caused by ice movement

Thus, the question arises whether these are two separate systems developed due to two different mechanisms and at different times, or only one conjugate system is involved. In the rare cases morpholineaments formed during retreat of the same ice sheet have crossed, no shift of individual morpholineaments of both the shear and extensional systems in relation to each other has been observed (see also Pasierbski and Krupa, 2000). This may indicate that they probably developed simultaneously. The similarities of the resultant azimuths of the stress vector calculated separately for individual morpholineament systems also seems to indicate that the whole pattern composed of four sets can be treated as one conjugate system characteristic of the orientation of joints created due to compressional stress. Thus, the resultant azimuths of the stress vector for the entire crevasse system or a net composed of two original joint systems in the ice body, determined from the orientation of negative and positive glacial crevasse landforms, fixes the direction of ice sheet movement which caused the development of the joint net.

Thus, this well-ordered net of orientations of linear (crevasse) glacial landforms indicates that the joint net developed within the Pleistocene continental ice sheets, due to horizontal stress exerted by the ice body as it advanced. This movement was disturbed by obstacles occurring in the foreland of the ice sheet, and hampered by friction. At the next stage, a system of crevasses (zones of crevasses) developed, followed by their opening, a process influenced by local conditions. It may be assumed that, in case of continental ice sheets, extensional fractures (crevasses) resulting from bending, as in the case of open folds, developed as a result of ice movement over basement elevations, as well as on a macro-scale (due to the Earth's sphericity). Undoubtedly, the probable lability of the basement, caused by both a variable ice mass load and neotectonic movements, influenced that process.

THE FORMATION OF POSITIVE AND NEGATIVE GLACIAL LANDFORMS WITH AN ORIENTATION INHERITED AFTER THE ORIGINAL JOINT NET WITHIN THE ICE SHEET

If the joint net within the ice sheet developed due to horizontal stress, it most probably took place early during its advance. Joints, created at that time and oriented according to the original stress field developed parallel to the ice sheet movement, can therefore be considered as original.

The first stage of the process leading from the original joint net to the formation of glacial crevasse landforms was a transformation of joints (Fig. 2A) into crevasses (Fig. 2B). Individual joint sets were obviously prone to opening, i.e. to the formation of crevasses, to different degrees. This process was hindered most in the case of the transverse system, because this was permanently tightened due to ice sheet movement. This observation refers to the zone of overall deglaciation because, in the marginal zone, the transverse set — parallel to the nearby ice front — may be favoured during deglaciation (see e.g. Pasierbski, 2003). The remaining sets tended to open, assuming that the ice sheet advanced not only due to plastic flow while cryogenic pressure counteracted the opening of any fractures, but also that the ice behaved as a rigid body with block shifts occurring along the fractures. It may be supposed that englacial waters played an important role in the early stages of crevasse formation. These waters undoubtedly used the joint net as migration pathways towards the front of the ice sheet (Fig. 2B). Thus, they used the joints during formation of channels and caverns, and during widening of crevasses, as a result of both hydrostatic pressure and erosion. The effectiveness of that process depended on the amount of hydrostatic pressure which was in opposition to cryogenic pressure tightening the crevasses. The widening of crevasses and the formation of subaerially exposed (supraglacial) crevasses was a process likely associated with slowing of ice sheet movement, and then with the transformation into dead ice (Fig. 2C). Depending on local circumstances, some of the crevasses were subsequently filled with sediment, positive landforms being formed, while other crevasses were deepened and widened by meltwater erosion leading to the formation of negative landforms (Fig. 2D). Observations of the orientation of glacial crevasse landforms indicate that this process was complex and that individual crevasse sets were favoured through the activity of a number of local factors such as variable relief of the basement, non-uniform movement of the ice streams or blocks, preferred directions of water outflow in the forefield of the ice sheet and so on. Variability in these factors meant that, with no change in the orientation of the entire network of the crevasse landforms, individual directions (sets) come to be locally dominant in the present-day post-glacial relief (landscape).

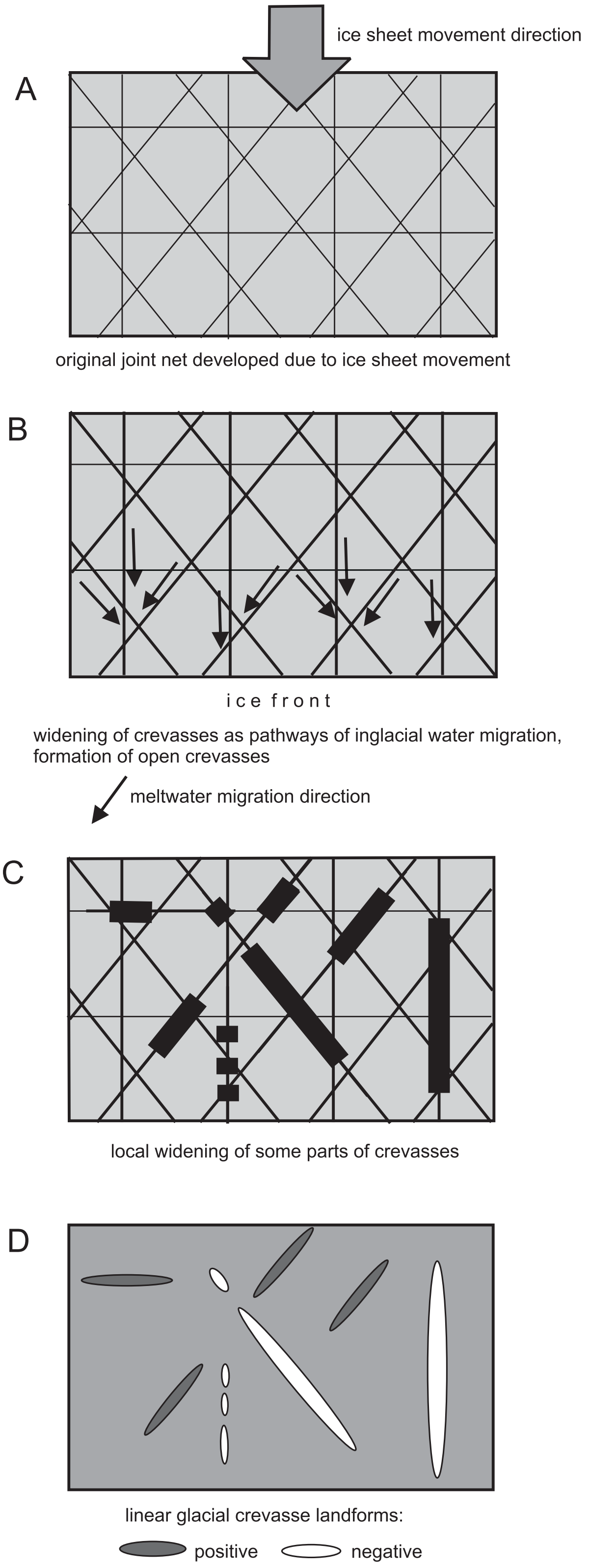


Fig. 2. A model for the formation of glacial crevasse landforms

RECONSTRUCTION OF THE ORIGINAL ICE SHEET MOVEMENT DIRECTION, BASED ON ANALYSIS OF THE ORIENTATION OF CREVASSE LANDFORMS

The orientation of shear joints is strictly dependent on stress direction, allowing for accurate reconstruction of the action of the pair of forces. In the case of the Pleistocene ice sheets, the original joint net probably formed in dynamic ice during its advance resulting in horizontal stress. Thus, the question arises whether the ice sheet advancing into Poland was already fractured or whether the fractures developed sometime later but when? This is a difficult problem, and perhaps one without an unequivocal solution. However, this question is a theoretical one, and has no practical effect on considerations regarding the orientation of glacial crevasse landforms.

If the direction of ice movement was unchanged between the time of formation of the original joint net and the period of ice sheet stagnation, the orientation of glacial crevasse landforms reflects the orientation of the original joint net (Fig. 3A). In this case, the orientation of glacial landforms enables determination of the original direction of ice sheet movement (e.g. from N towards S as in Fig. 3A). Direction of the vector of ice sheet movement is the resultant of two oblique sets (shear system) which are commonly best developed. This direction is also consistent with the longitudinal set of the extensional system, which is often the dominant one. Thus, some of the linear landforms composing this set may directly indicate the direction of ice sheet movement. If an ice stream or an ice sheet lobe changed its direction after the original joint net had formed, then a reorientation of the entire joint net occurred, adjusting to

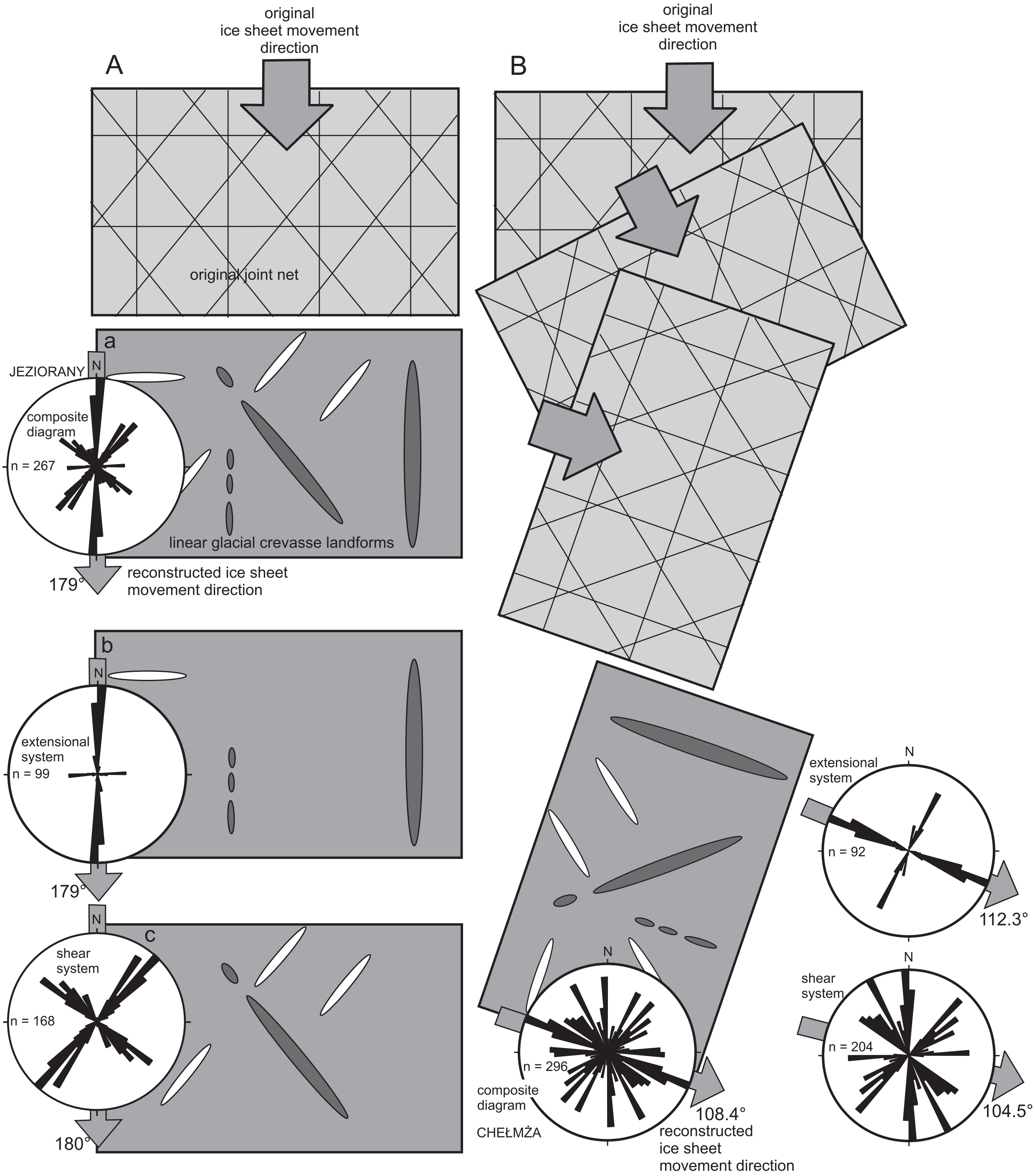


Fig. 3. Reconstruction of ice sheet movement direction from the orientation of glacial morpholineaments (see Fig. 2)

A — during constant ice movement direction, diagrams show examples of the orientation of glacial morpholineaments in the Jeziorany region (Warmian lobe; see Fig. 8); **B** — during a change in ice movement direction, diagram shows an example of the orientation of glacial morpholineaments in the Chełmża region (Vistula lobe; see Fig. 8) the change of the direction of ice sheet movement (Fig. 3 B). In such a case, the orientation of glacial landforms reflects the final direction of ice sheet movement in a given area before the ice sheet stopped and became stagnant.

We may assume that the ice sheet advanced mainly by streams (ice sheet lobes), behaving as a plastic body. Then, the whole joint net, even if created originally i.e. before the ice sheet had reached Poland, was subsequently oriented consistent with the contemporary local direction of the ice sheet (a stream or a lobe) advance, i.e. it always reflected the contemporary direction of ice sheet movement as late as the last phase of the movement before stagnation.

Therefore, taking into account the doubts about the place and timing of formation of the original joint net, regional and local directions of ice sheet advance can always be reconstructed from orientations of a net of linear glacial landforms. This means that such analysis of the orientation of glacial morpholineaments always leads to determination of the last (final) direction of ice sheet movement.

STUDY METHODS

Currently, analysis of the orientation of crevasse landforms (glacial morpholineaments) is based on individual sheets of the *Detailed Geological Map of Poland*, scale 1: 1 50 000, covering about 300 km^2 each. The analysis was performed on selected sheets from NE Poland, covering a glacial plateau from the Main Stadial of the Vistulian Glaciation.

Examples of the orientation of the glacial morpholineaments performed on selected regions (map sheets of the *Detailed Geological Map of Poland*) studied in NE Poland are given on Figures 3–7; for location of the selected regions see Figure 8.

Detailed analysis of all the surface morpholineaments led to identification of glacial landforms which, simplifying, can be identified with both positive and negative glacial crevasse landforms. In doubtful cases problematic landforms were also measured, assuming that, with a large number of measurements, landforms unrelated to the original joint net in the ice body, i.e. those whose directions are caused by other reasons, will not significantly affect determination of the dominant directions.

As positive morpholineaments, we include all linear crevasse-fill landforms that can be conventionally termed positive glacial crevasse landforms. Therefore, the analysis referred to landforms defined by the authors of various geological mapping projects as crevasse landforms, eskers, supraglacial eskers and glaciofluvial kame bars. These are landforms that have developed as a result of the filling of open crevasses in the ice body with material supplied by gravity and the dynamic flow of meltwaters. This is granulometrically heterogenous material, both vertically and laterally along these elongated landforms, which were assigned by Brodzikowski and Van Loon (1991) to the category of supraglacial crevasse deposits (I-A-6-b). I suggest that landforms formed under those specific conditions should be treated as a separate genetic type in the classification of glacial landforms. The analysis also dealt with hills of various origin (excluding marginal landforms) arranged in linear rows. Edges of kame terraces were also considered, assuming that they as well represent morpholineaments with an orientation inherited after one of the original joint (crevasse) sets in the ice sheet net.

Of negative morpholineaments, different glacial tunnels, small dry valleys on a glacial plateau, outwash plain belts and series of kettle-hole were analyzed. Glacial tunnel valleys are often the dominant negative morpholineaments of the post-glacial landscape. At the present day, they are occupied by lakes, river channels or streams, sometimes very small by comparison with the large dimensions of the glacial tunnel valleys. Rarely, there occur dry valleys with narrow and flat floors. It is possible that the small, usually dry valleys that transect glacial plateaus in various orientations were originally glacial tunnel valleys. The drainage system of a young glacial plateau is usually poorly developed. However, there are a number of dry that valleys that sometimes connect kettle-holes. All of these are negative landforms commonly showing a linear trend, and forming a system inherited both after troughs on the ice surface and after englacial or subglacial channels or tunnels. Outwash plain belts commonly comprise small, elongated areas being either infills of channels or linear outwash plain covers, usually slightly lowered in relation to the surrounding glacial plateau. The boundaries of these areas show a linear trend with an orientation inherited probably after one of the sets of original joint nets in the ice body. It may be that meltwater flows during deglaciation followed and widened ice-free belts between individual joints, or along wide zones of joints. Apart from kettle-holes after dead-ice blocks, locally deep, occurring in the glacial plateau and recently occupied by lakes or artificially drained peat bogs, there are also numerous small and shallow kettle-holes. Some of these are distinctly elongated in shape, or are arranged in linear rows indicating that they follow the original joint net in ice.

Measurements of all linear landforms were used to construct composite diagrams of their orientations (Fig. 3Aa). Separate diagrams may also be produced for positive and negative landforms (see Fig. 4). In some areas, the orientations of negative and positive landforms is the same (e.g. Fig. 4B), while in other areas, they may differ (e.g. Fig. 4A). It is therefore necessary to analyze all the linear landforms to obtain accurate ice flow directions.

Subsequently, the diagrams were analyzed to distinguish both of the conjugate systems to obtain the resultant vectors for each system separately: an extensional (rectangular) system and a shear (sharp-angled) system (Fig. 3Ab and c). The first phase of discrimination of the two systems includes detecting the extensional (rectangular) system which should be represented by two perfectly perpendicular but nonequivalent sets. The longitudinal set is commonly very well developed, whereas the transverse one is usually subordinate. In most of the study areas, the longitudinal set (in the extensional system) in the whole net of morpholineament orientations typically dominants. A separate diagram may be constructed exclusively for the extensional system (e.g. Fig. 3Ab). With the extensional system distinguished, the mean (resultant) direction of the longitudinal set may be calculated and identified with the direction of ice sheet movement. The remaining measurements, after excluding the extensional system, will denote the shear system composed of two oblique

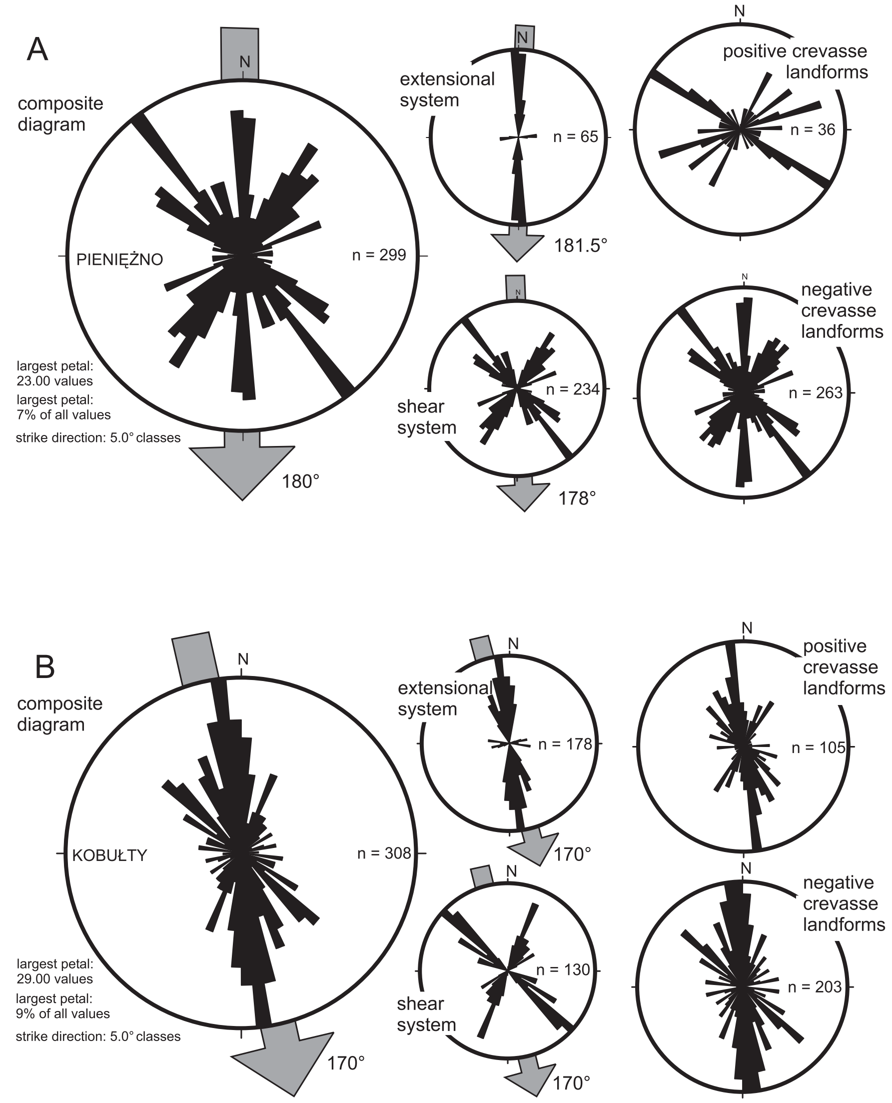


Fig. 4. Examples of the orientation of glacial morpholineaments (A) at different orientations of positive and negative morpholineaments (Pieniężno region — Warmia lobe; see Fig. 8) and (B) at similar orientations of positive and negative morpholineaments (Kobułty region — Masurian lobe; see Fig. 8)

(diagonal) sets (e.g. Fig. 3Ac). Having constructed a separate diagram for the shear system, the resultant azimuth of the shear stress vector may be determined and identified with the direction of ice sheet movement.

With this procedure one can obtain the direction of ice sheet movement separately for each conjugate system. Averaging of the results provides the resultant direction of ice sheet movement for the study area. In the Jeziorany region these two systems yield the same direction, reinforcing the effectiveness of this method (see Fig. 3A). In other areas the divergences between the results obtained from each system were small, commonly of the order of several degrees.

The similarity of the resultant azimuths of the stress vector calculated separately for individual morpholineament systems seems to indicate that the entire pattern of four sets may be treated as one conjugate system characteristic of the orientation of joints created due to compressional stress. Thus, the resultant azimuths of the stress vector for the entire system of crevasses or of a net composed of two original joint nets in the ice body, determined from the orientation of negative and positive glacial crevasse landforms, can be considered as reflecting the general direction of the advancing active ice sheet.

RESULTS OF RECONSTRUCTION OF THE ICE SHEET MOVEMENT DIRECTION

WARMIAN LOBE

The first research on the orientation of glacial morpholineaments, including in particular glacial tunnel valleys and crevasse-fill landforms, was made by me in the Warmia region, on the Jeziorany sheet (Morawski, 2003*a*, *b*), and then over a slightly larger area occupied by the Warmian lobe (Morawski, 2004*a*, 2005) within the extent of the ice sheet of the Main Stadial of the Vistulian Glaciation. It has been stated that the orientation of all positive and negative morpholineaments are arranged in a pattern (net) composed of four sets (Fig. 3Aa): a well-ordered near-meridional N–S-trending set, a very subordinate near-longitudinal E–W-trending set and two oblique sets oriented NW–SE and NE–SW.

Similar, but not so clearly ordered, orientations were also obtained from the other four sheets of the Map (Gałązka and Marks, 2001; Rabek and Młyńczak, 2003; Trzmiel, 2003; Gałązka, 2003) covering the area of the Warmian lobe (Fig. 8). For example, in the Pieniężno sheet, covering the north of the area, morpholineaments are more poorly ordered (Fig. 4A). The analyzed distribution of the orientation of morpholineaments is characterized by a distinct dominance of the longitudinal set over the transverse set (almost absent) in the extensional system. The longitudinal set is highly concentrated; in fact it is contained only in a 10° wide interval. Within the entire morpholineament net, the NW–SE-oriented oblique set of the shear system is dominant (with a distinct concentration in the 140–145° interval). This is a rare situation because the longitudinal set of the extensional system is normally dominant. It was thus the direction of a local preferred orientation of crevasse opening. It cannot be precluded that such a distribution of glacial morpholineament orientations

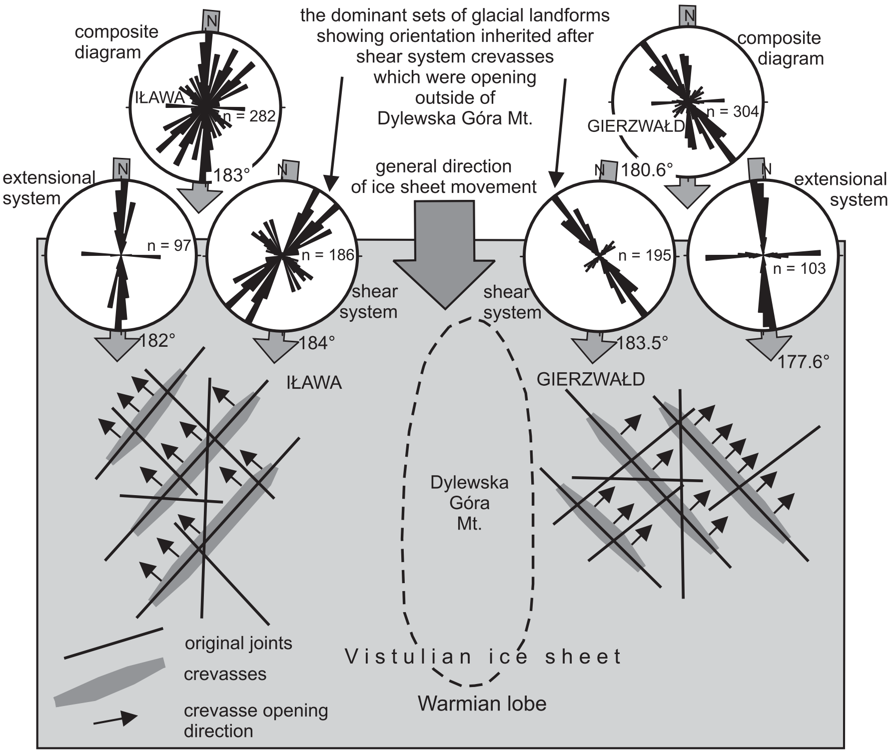


Fig. 5. Asymmetry (inequality) of glacial morpholineament sets of the shear system in the Góra Dylewska Mt. region, caused by predisposition to opening of crevasses in the ice body in the area located outside of a basement obstacle (see Fig. 8)

might have been influenced by the Górowo Elevation situated to the NE (see Ber, 2000). If this elevation already existed during advance of the Main Stadial ice sheet, then, assuming the constant direction of ice sheet advance from the north, the preferred direction of tensional opening of ice crevasses was located in the area outside of the elevation, i.e. crevasses of the NW–SE-oriented set tended to open.

In the Gierzwałd sheet, located SW of Olsztyn (see Fig. 8), a very well-ordered arrangement of morpholineaments is present (Fig. 5). The extensional system is clear. The transverse set is especially well developed, although it is distinctly subordinate. Development of the shear system is untypical. The NW–SE direction is dominant. It also dominates the whole net. This results from the occurrence of negative landforms; glacial tunnel valleys that are the dominant linear landforms in this area. The second, NE–SW-trending oblique set is very poorly developed. The average direction of ice sheet movement, calculated separately for each system, differs by almost 6°. The resultant azimuth of the ice sheet movement vector (average for both the systems) is 180.6° (Fig. 5).

In the Iława sheet, situated near the western boundary of the Warmian lobe (see Fig. 8), the distribution of the orientation of morpholineament directions (Fig. 5) is poorly ordered. Both the longitudinal set of the extensional system and the oblique sets of the shear system are bipartite: there are two maxima. Such a distribution of directions may suggest a stage-by-stage change of ice sheet movement in the study area. Gałązka (2004) considered that this is the area of the maximum limit of the Pomeranian phase, which may locally be of transgressive character. The local resumption of ice sheet advance may have been associated with a local change in direction. The regional analysis is however based on averaged directions which, calculated separately for each system, differ by merely 2°, and the resultant azimuth of the ice sheet movement vector (average for both of the systems) is 183° (Fig. 5). Thus, in the western margin of the Warmian lobe, the direction of ice movement was the same as within the entire lobe.

Summing up, in all the four areas analyzed in the Warmia region, the direction of ice sheet movement was almost identical, from due north.

As regards palaeogeographical considerations, the comparison of analyses performed for the areas of the Gierzwałd sheet and the Iława sheet located on opposite sides of the Góra Dylewska massif (312 m a.s.l.), an outstanding, vast hill (Fig. 5) — is of particular interest. It is evident that, if the ice sheet advance was from the north, the distribution of the orientation of morpholineament directions which are locally dominant in the same shear systems, oppose each other on either side of the massif (Fig. 5). On the western side (Iława), the NE–SW-oriented set is dominant, whereas on the eastern side (Gierzwałd) the NW–SE-oriented set predominates. This pattern is moderately symmetrical, the deviation from the latitudinal direction is 46° on the western side, and 38° on the eastern side. It may be supposed that they represent sets of ice crevasses with the orientation preferred for tensional opening, in both cases outside of the Góra Dylewska massif. The study area is situated within a zone of spreading of the stress field towards the outside of an obstacle in the basement of the ice sheet. The pattern of the spatial orientation of the entire net of morpholineaments may suggest that the Góra Dylewska massif was not a nunatak but was covered by ice which, despite the presence of this obstacle in the basement, flowed over it in a constant N–S direction. The massif did not cause any local changes in the general direction of ice sheet movement, as suggested by Marks (1988). This example also a need to review the commonly used methodology for determining of local directions of ice streams, based on the orientation of dominant glacial landforms; in this case, of glacial tunnel valleys.

MAZURIAN LOBE

In the area of the Mazurian lobe, but near the boundary with the Warmian lobe, the orientation of morpholineaments was analyzed within the three sheets of the *Detailed Geological Map of Poland* (see Fig. 8; Lisicki, 1995; Kacprzak and Lisicki, 1999*a*, *b*).

In the Kobułty sheet area, for example, situated slightly towards the south and further from the interlobe zone (see Fig. 8), the longitudinal set of the extensional system is clearly dominant (Fig. 4B). It is also dispersed and shows a weakly bipartite pattern that is also observed in the very subordinate transverse

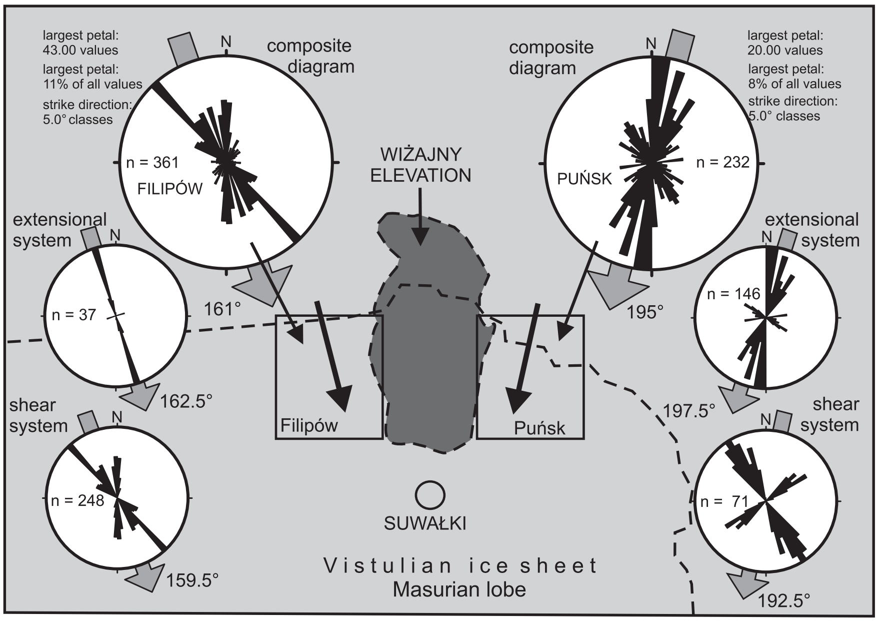


Fig. 6. Symmetrical pattern of movement directions of the ice sheet flowing around the Wiżajny Elevation, Masurian lobe (see Fig. 8)

set. The direction of ice sheet movement determined from the rectangular set shows a western deviation from the N–S direction; the azimuth of the vector is 170°. The acutely-angled set, although subordinate, is fairly well concentrated, but it shows a small bipartition. The acute angle between the oblique sets is very large as in the Warmia region, amounting to 84.8°. The azimuth of the ice sheet movement vector, determined from the resultant of both the oblique sets, is also 170°.

Two sheets of the *Detailed Geological Map of Poland* were analyzed in the NE region: the Filipów sheet (Krzywicki, 1987) and the Puńsk sheet (Krzywicki, 1990). The sheets are situated on two sides of the Wiżajny Elevation (Figs. 6 and 8), which was most likely an obstacle, around which ice streams flowed and locally changed direction (Ber, 2000).

The Filipów sheet area is situated on the western side of the Wiżajny Elevation. Interpretation of the composite diagram, and in particular identification of both of the conjugate systems, meets difficulties here (Fig. 6). The orientation of the entire net is untypical and in fact limited to the azimuth intervals of 115–180° with an outstanding maximum at 135–140°. A thorough analysis suggests that the rectangular system is subordinate in this case, as compared to the acutely-angled system, and is represented almost exclusively by the longitudinal set which, however, is easily distinguishable and concentrated. The system fixes the NNW–SSE direction of ice sheet movement; the azimuth of the vector is 162.5°. The remaining morpholineaments form the acutely-angled system, and the acute angle between the two oblique sets is unusually small, merely 44°. The acutely-angled system shows a pronounced asymmetry. A NW–SE-oriented set is dominant. The azimuth of the ice movement vector derived from the acutely-angled system is 159.5°. Such a small difference in the directions derived from these systems (only 3°) seems to indicate that the interpretation of separating the systems is correct. The average vector of ice sheet movement in the Filipów region is 161° (Fig. 6).

The orientation of morpholineaments on the eastern side of the Wiżajny Elevation, in the Puńsk sheet area, is completely different (Fig. 6). The orientation is also well-ordered, but it falls mainly within the azimuth intervals of 0– 40°. Interpretation of the dominant interval is ambiguous, although it has been assumed that it is a bi- or even tripartite orientation of the longitudinal set of the rectangular system. The distinctly bipartite transverse set also seems to confirm it. The azimuth of the averaged direction of ice sheet movement for the rectangular system is 197.5°. The acutely-angled system is subordinate in relation to the rectangular system, and the angle between the two oblique sets is close to a right angle. The azimuth of the ice sheet movement vector derived from this system is 192.5°, and thus it differs by merely 5° from that obtained from the rectangular system. The average vector of ice sheet movement in the Puńsk region is 195° (Fig. 6).

Ice sheet movement directions on either side of the Wiżajny Elevation show a fairly symmetrical pattern (Fig. 6). Deviation from the meridional strike is 19° on the western side, and 15° on the eastern side. On the western side, a highly concentrated NW–SE direction is dominant in both positive and negative landforms. This probably results from tensional opening of crevasses towards the outside of a semicircularly arched ice stream. These results confirm the earlier conclusions (Ber, 2000) that ice streams flowed around the Wiżajny Elevation, causing a local change in ice sheet movement directions in this area. The analysis also indicates that the ice streams, which must have parted somewhere to the north of the Wiżajny Elevation, beyond the northern border of Poland, joined again within the study area.

The area of Mazury requires further detailed research on the orientation of the glacial morpholineaments. However, such investigations are hampered by the occurrence of large lakes and outwash plains, as well as by small areas of massif glacial plateaus. Nevertheless, the results obtained to date seem to suggest that the general movement directions of the Mazurian and Warmian lobes during the Main Stadial of the Vistulian Glaciation, differed from each other. The difference is well pronounced and amounts to 10–20°. The general orientation of the morpholineaments net of the two ice sheet lobes, and thus of the orientation of the original joint net in the ice body, suggests a temporal succession, the ice sheet lobes were active at different times (Morawski, 2005).

VISTULA LOBE

For the southern part of the Vistula lobe, two sheets of the *Detailed Geological Map of Poland* were analyzed: the

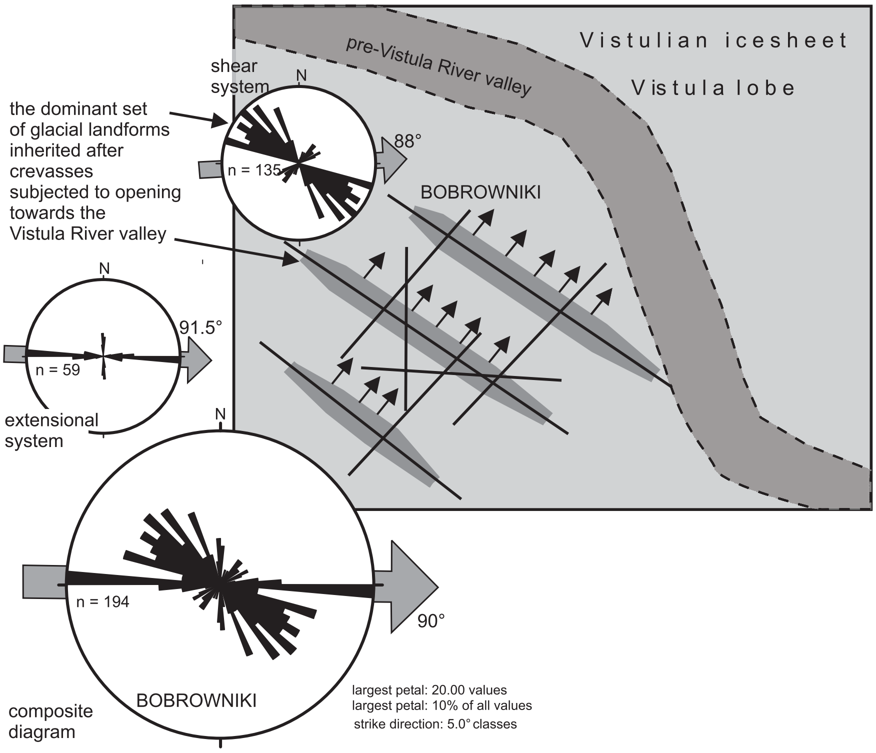


Fig. 7. The orientation of glacial morpholineaments in the southern part of the Vistula lobe, asymmetry (inequality) of glacial morpholineament sets of the shear system in the Bobrowniki region, caused by predisposition to opening of crevasses in the ice towards the pre-Vistula valley (see Fig. 8); for explanation see Figure 5

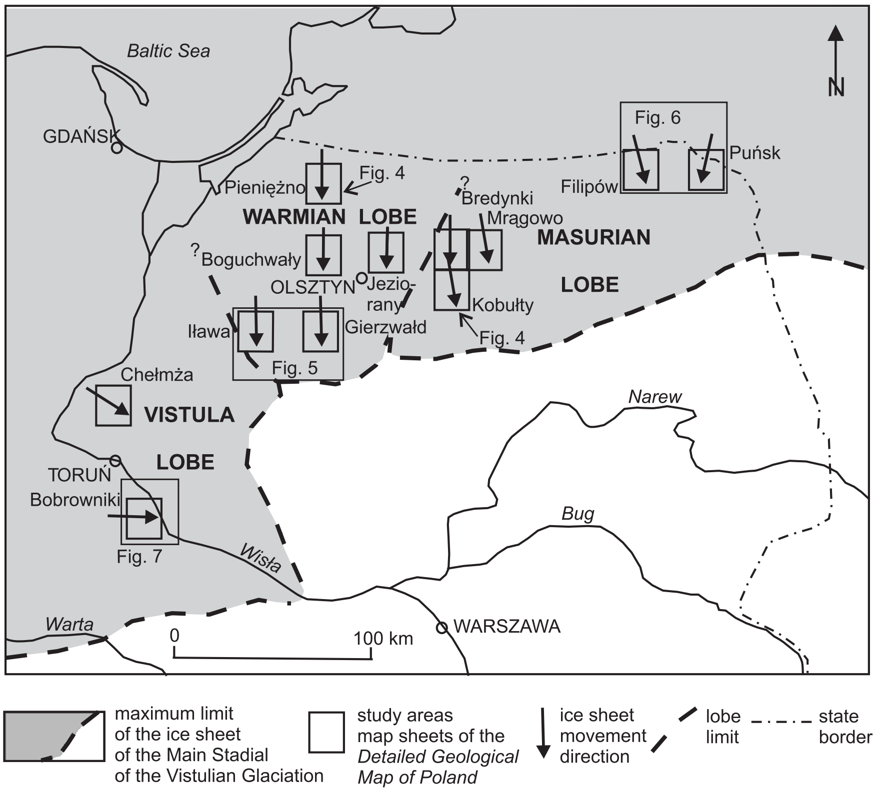


Fig. 8. Movement directions of the ice sheet of the Main Stadial of the Vistulian Glaciation in NE Poland, reconstructed from the orientation of glacial morpholineaments

Chełmża sheet (Trzepla and Drozd, 1999) situated north of Toruń, and the Bobrowniki sheet (Jeziorski, 1987) covering the area located south of Toruń (see Fig. 8).

The orientation of morpholineaments in the Chełmża region is highly disordered (Fig. 3B). Despite it, the rectangular system was identified based on both a concentrated dominant direction and a distinct rectangular pattern. This system fixes the azimuth of the ice movement direction vector, amounting to 112.3°. The analysis of morpholineaments, performed separately for positive and negative landforms, indicates that the well-developed transverse set is represented almost exclusively by positive landforms. This seems to suggest that the measurements may encompass, besides crevasse landforms, marginal landforms of a local stagnation phase, oriented perpendicular to the ice sheet movement direction. The remaining morpholineaments form the highly disordered acutely-angled system. This may indicate stage-by-stage changes of the ice sheet movement direction: a gradual eastwards turn of the Vistula lobe. Averaging of these directions into two oblique sets (the angle between them is 85°) enabled determination of the resultant vector of the ice sheet movement direction at 104.5°. Despite such a large scatter of the directions of morpholineament orientations, the direction of ice sheet movement derived from both the conjugate systems differs by nearly 8°. Thus, the average azimuth of the ice sheet movement vector in the Chełmża region is 108.4°. This means that the ice sheet advanced from the northwest.

The Bobrowniki sheet covers part of a glacial plateau adjoining the Vistula River valley to the west (see Fig. 8). The orientation of morpholineaments is well ordered (Fig. 7). The highly concentrated longitudinal set, forming the rectangular system with the transverse set, is dominant. This system fixes the ice sheet movement direction at 91.5°. The remaining directions form the highly asymmetrical acutely-angled system: the NW–SE oblique set, characterized by a huge direction scatter (about 55°), is dominant. After averaging, the resultant azimuth of the ice sheet movement direction for the acutely-angled system is 88^0. Thus, the difference in the directions obtained from the two systems is merely 3.5°, and the average azimuth of the ice sheet movement direction is 90° in this area, i.e. the ice advanced from the west. The enigmatic dominance of the NW–SE orientation may probably be interpreted in terms of tensional opening of crevasses of this set towards the pre-Vistula River valley which was a morphological depression in the basement under the advancing ice sheet (Fig. 7). Considerable directional scatter within this set may have been caused by radial opening of crevasses, and even by formation of additional crevasses that could have been a result of an ice sheet bending along the axis of the pre-Vistula River valley. It also seems that the valley was a pathway for such intense meltwater flow that, during deglaciation, only erosion could took place, and no crevasse-fill landforms were formed.

SUMMARY OF POSSIBLE APPLICATIONS

This paper gives preliminary results of testing of a new methodology of reconstructing movement directions of Pleistocene ice sheets, based on analysis of spatial orientation of linear glacial landforms. This analysis is based on detailed geological maps, and additionally, on topographic data collected earlier. All linear positive and negative glacial landforms (morpholineaments) were comprehensively analyzed. Previous investigations were limited to glacial plateaus of very young relief from northeastern Poland during the Main Stadial of the Vistulian Glaciation. They provided detailed data about directions of ice sheet movement, which enabled the distinction of individual ice sheet lobes which slightly differed in movement directions. Apart from these basic data, the method allows for obtaining completely new palaeogeographic information. This especially refers to local changes in ice-stream directions and to the dominance of individual sets of morpholineament orientations caused by unevennesses of the basement across which the ice sheet advanced.

These preliminary results already indicate that the proposed method of statistical analysis of spatial orientation of glacial morpholineaments also enables new data to be obtained for geological mapping in areas of young post-glacial relief.

This paper shows analysis of the orientation of linear glacial landforms (morpholineaments) based on already-constructed geological maps. The quality of the results obtained from individual areas significantly depends on the accuracy and level of detailed on the map sheets. Thus, this is a resultant analysis based on my classification of landforms and their visualization on a map. Similar analysis can however be performed prior to field mapping on the basis of topographic maps. At the initial planning stage, it is possible to produce a sketch map of all positive and negative morpholineaments and from these to construct diagrams. Using this procedure we can establish the orientation of preferred directions in a given area. This would help both field mapping and the documentation of data.

PALAEOGEOGRAPHICAL ANALYSIS

The analysis of the orientation of glacial morpholineaments described here indicate that such analysis can be a source of important palaeogeographical information. Special attention was paid to the reconstruction of the ice sheet movement directions. The results obtained seem precise. The precision of the measurements of azimuths of the movement vector is attainable by no other method.

This methodology requires further testing in other areas, including on glacial plateaus of older glaciations, where glacial landforms are less clearly legible. Such diminished legibility may cause serious problems in using this method. This methodology also requires further modification, in particular in analysing small, massif parts of glacial plateaus within a single stage of deglaciation. In the individual map sheets analysed within this study, an averaged regional pattern was obtained serendipitausly. In the case of palaeogeographically homogenous areas, we may expect considerable complications caused by local changes of ice sheet movement directions in individual stages. However, on the other hand, it is likely that very thorough analysis of morpholineament orientations could lead to an explanation of the ice sheet movement mechanism. The results achieved seem to confirm. This concerning, in particular, the level of ordering of directions i.e. to the concentration of individual sets. And so, in some parts of a glacial plateau where no ice sheet stagnation, even short-term, is observed (e.g. in areas of areal deglaciation), this orientation is well ordered (Fig. 9A). In other areas the orientation is locally markedly disordered, although distinct dominant patterns commonly occur. These indicate a stage-by-stage change in the ice sheet movement direction rather than a gradual one (Fig. 9B).

A separate issue is the dominance of specified sets (directions) within the entire set of morpholineament orientations in a given area. In the case of the extensional system, the matter is relatively simple: inequality of the two sets is probably caused by permanent tightening of the transverse set. The longitudinal set was predisposed to opening because it was probably used for block shifts or plastic flow of ice streams during their movement in this direction. It also seems that this is the reason for the common concentrations of directions within this set.

An interesting issue for palaeogeographic considerations is inequality (asymmetry) within the shear system (Fig. 9). An inequality of both the oblique sets sometimes occurs in case of both ordered (Fig. 9Ab) and disordered orientation (Fig. 9Bb). According to tectonic theory, this phenomenon is not related to the influence of the stress field. It means that the primary joint net probably developed symmetrically without preferring one direction (set) over another. Thus, an explanation of the locally distinct asymmetry in glacial morpholineament orientation should be sought from later palaeogeographical processes. It must be borne in mind that linear glacial landforms formed in only some of the original joints, those which, under favourable conditions, were sufficiently widened and transformed to open crevasses, englacial channels and caverns, and then became palaeogeographically preferred pathways for meltwater flow

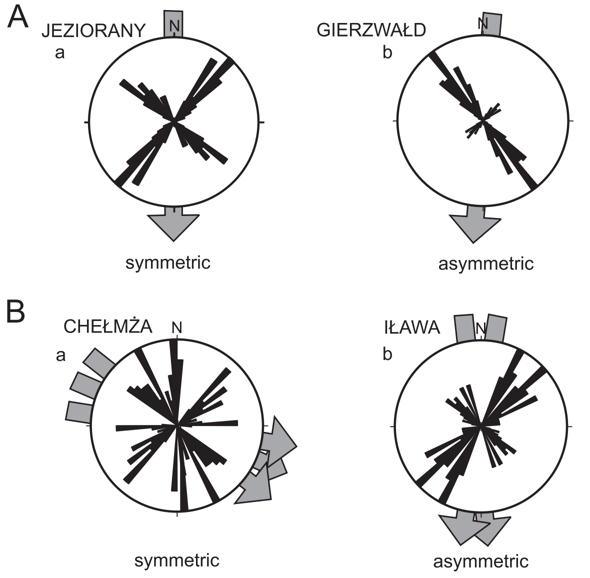


Fig. 9. Variable ordering and symmetry of the directions of glacial morpholineament orientations, exemplified by the shear system

A — well-ordered orientation, a single stage of ice sheet movement; B — disordered orientation, several stages of ice sheet movement

and/or for transport of material melted out of ice. Each asymmetry is thus a result of regional or local predisposition of the specified direction to create crevasses, to open and widen them, and subsequently to fill them (in the case of positive landforms) or to erode and periodically fill them with water which may subsequently freeze, in the case of negative landforms. This conclusion opens the possibility of achieving a diversity of palaeogeographical data through detailed analysis of the orientation of glacial morpholineaments. This refers to both regional and local research and investigations regarding individual genetic types of positive and negative landforms. Such considerations can concern the following: basement topography, possible basement lability, pathways for meltwater flows, transport directions of ice-derived material, and so on.

ADVANTAGES AND LIMITATIONS OF GLACIAL MORPHOLINEAMENTS ANALYSIS

To sum up the potential of using the analysis of glacial morpholineament orientations, the advantages and limitations of this method should be critically appraised.

Advantages:

— it can be resultant method based on previously constructed, commonly available geological maps at various scales,

— it may also be a preparatory method, preceding field mapping, based only on analysis of a topographic map,

— it may achieve very precise results enabling detection of very small changes in ice sheet movement,

— it may produce both regional syntheses and analyses of small areas,

— rapid in-office analysis is possible using a commonly available, simple computer software,

— it potentially yields a diversity of palaeogeographic data,

— combined or separate analyses of different positive and negative glacial landforms are possible,

— a relatively small degree of interpretational subjectivity is entailed, enabling comparable results to be obtained by different researchers in different areas.

Limitations comprise:

— the legibility of surface relief: areas of young glacial relief are particularly favoured,

— analysis is possible as a rule only in massif areas of glacial plateaus,

— effective analysis is conditioned by the accuracy and substantial correctness of the geological map and/or the accuracy of the topographic map.

CONCLUSIONS

Linear glacial landforms (glacial morpholineaments) are most probably genetically related to crevasses in the ice body. Joints in ice gradually transformed to crevasses which survived as negative landforms, or, if filled with deposits, formed positive ones. Positive morpholineaments are represented mainly by crevasse-fill landforms which should be treated as a separate type in the classification of glacial landforms.

The orientation of glacial morpholineaments forms a well-ordered net resembling that of tectonic joint sets created due to horizontal stress. Such a joint net developed in the ice body probably as a result of ice sheet advance and, thus, its orientation is dependent on the ice sheet movement direction.

The net of spatial orientation of morpholineaments is composed of two conjugate systems. The rectangular (extensional) system includes two sets: the longitudinal set, consistent with the direction of ice sheet movement, and the transverse set. The latter is acutely-angled (shear) and consists of two sets oblique to the direction of ice sheet movement. Analysis of the spatial orientation of linear glacial landforms enables reconstruction of the direction of ice sheet movement. It is in conformity with both the longitudinal set of the rectangular system and the resultant of the oblique sets (acutely-angled system).

In northeastern Poland the detailed data enabled discrimination of individual ice sheet lobes which slightly differed in movement directions.

Some of the sets are dominant, while others are poorly represented. This results from general regional predispositions to the opening or tightening of crevasses of individual sets. Both in the entire net and within individual sets, the level of orientation ordering is different. In some of the analyzed areas in NE Poland, the systems and individual sets within them are well ordered, being concentrated within a narrow interval, probably due to stability of the stress field, a constant direction of ice sheet movement. In other areas the patterns are scattered, probably indicating local changes in the direction of ice sheet movement.

With a stable and legible orientation of the systems, individual sets are locally preferred, landforms of such orientation being dominant in the landscape of the given area.

Analysis of both the orientation of preferred directions and the level of concentration can lead to a number of palaeogeographical conclusions concerning the mechanism of ice sheet movement and the effect of local basement relief on the ice sheet, and concerning basement lability. The research indicates that areas, for which the averaged direction of morpholineaments orientations can be obtained, should cover genetically homogenous glacial plateaus developed as a result of deglaciation during the same glacial phase or stage.

This analysis of glacial morpholineaments orientation indicate that these phenomena deserve more attention than before, in particular in geological mapping.

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