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# Palaeoglaciology of the Weichselian Odra ice lobe, NE Germany and NW Poland

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**Abstract:** Southern part of the Scandinavian Ice Sheet terminated in large lobes projecting tens of kilometres beyond the main ice sheet margin. One of the main ice lobe was the Odra lobe localized in NE Germany and NW Poland. In this study concise description of current morphology of the Odra lobe area is given with special reference to subglacial hydraulic conditions during the ice sheet advance. Subglacial conditions were simulated by using time-dependant three-dimensional numerical model, and obtained results were compared to geological observations. The results show entire groundwater system alternation that affected the ice/bed coupling and influenced formation of specific subglacial landforms. Coupling the simulation results with empirical estimates of basal melting rate suggests that only a small fraction of basal meltwater could have drained to the ice forefield as groundwater. Adverse slope of the low-permeable ice bed hampered water drainage, and led to water accumulation at the ice/bed interface that in turn facilitated basal sliding and bed deformation.

**Key words:** subglacial drainage, subglacial landforms, Odra lobe, Weichselian glaciation, ice movement dynamics

## Introduction

Occurrence of an ice sheet, in any location, is linked with specific alternations of environment and groundwater as well as production of glaciologically induced geomorphological features. Land-forming consequences of the Scandinavian and Laurentide Ice Sheet activity provide accurate records of ice flow direction (e.g. Colgan & Mickelson 1997, Sejrup et al. 2003, Jørgensen & Piotrowski 2003, Przybylski 2008) and could be used as proxies in the estimation of subglacial conditions. Temperature glacier can slide over its bed and produce large volumes of meltwater which performs subglacial erosion while beneath frozen ice erosion is minimal (Evans 2002). Basal sliding of temperature glaciers is a result of basal melting induced by geothermal heat flux and frictional heat (Paterson 1994, Hooke 2005) but it is also connected with hydrogeological properties of ice bed (e.g. Piotrowski 2006, Piotrowski et al. 2009, Boulton et al. 1995). Rattas & Piotrowski (2003) demonstrated that the subglacial conditions are of primary importance in case of formation of specific subglacial landforms such as drumlins as well as subglacial channels (Shoemaker 1986) or eskers (Shreve 1985). Furthermore, subglacial streamlined forms and marginal features, and their specific assemblages can by diagnostic of ice streams or lobate outlet glaciers (Clark 1999, Kehew et al. 2005, Jennings 2006) and can be useful for ice dynamics reconstruction (Patterson 1997). Support for the interpretation of recently glaciated regions could be found in geophysical images of the Antarctic shelf in the vicinity of the west Antarctic ice streams (Shipp et al. 1999, Anderson et al. 2001, Howat & Domack 2003). Study all of this aspects in areas of past glaciations with comparison to currently glaciated regions may lead us to a solution of how did glaciers and ice sheets behave, what was their motion and how did they reorganized environmental system that had existed before ice sheet advance.

The article originates from Piotr Hermanowski Ph.d. thesis "Paleoglaciology of the Odra lobe in Vistulian Glaciation time; north-west Poland and north-east Germany" defended in 2008 and awarded in the contest for the best doctoral thesis in geomorphology.

Currently observed land-forming consequences of the last Scandinavian Ice Sheet activity during its advance to the European Lowland are represented by abundant geomorphological glacial features such as end moraines, tunnel valleys, eskers, drumlins, kames and outwash plains. Since little work, emphasizing relationships between various geomorphological features and subglacial hydrogeology, had previously been done in this area this paper presents concise analysis of spatial distribution of the subglacial landforms with respect to the processes operating at the ice/bed interface (full description and broaden analysis included in the PhD thesis is currently in preparation).

## Study area

The study area is localized in north-western part of Poland and north-eastern part of Germany (Fig. 1), and it corresponds to the location of clearly discernible the Weichselian Odra lobe. End moraines zone of the lobe represents main ice margin during the Pomeranian phase (ca. 14.6 ka BP – cosmogenic $^{10}$Be age, Rinterknecht et al. 2005) which has been recognized as a recession phase. However, it is believed that the Odra lobe had been formed at initial time of the ice advance to the European Lowland and later its extent was repeated and alternatively slightly modified (Mojski 2005, Hermanowski 2007). The margin of the Odra lobe was mainly described on the basis of geomorphological analysis (Keilhack 1898, Woldsted 1931, Galon & Roszkówna 1961) pointing its morphological diversity with vast selection of glacial features. The southern border of the Odra lobe stretches from Feldberg on the west to Hohenwutzen where it crosses state border and continue further, on the Polish part, through Moryń, Barlinek, and next makes its way towards north up to Ińsko where it bends to the east (Fig.1). Northern border of the study area is represented by the present day Baltic Sea coast. Above specified area covers about 18,500 km$^2$ (ca. 7.9 km$^2$ in Germany and ca. 10.6 km$^2$ in Poland) and protrude at least 40 km beyond the main Pomeranian phase ice marginal zone.

## Methods

Development of numerical solutions and GIS methods provides scientists ability to simulate past and feature behaviour of different environmental matters. The use of GIS is very useful in examination of spatial patterns of glacial landforms and it could be used for coherent interpretation that could lead to better understanding evolution of glaciers and ice sheets and as it was recently postulated can decipher glacial landforms genesis (Boots 2000, Jakobsen 2003, Napieralski et al. 2007) especially when is connected with hydrogeological investigations.

In order to simulate hydrogeological conditions under the ice, and ice motion it was necessary to reconstruct the lobe substratum as well as determine hydraulic properties of the ice substratum. It was carried out on the basis of Quaternary lithofacies (Lithofazieskarten Quartär) map sheets (18 map sheets) at a scale of 1: 50,000 supplemented by borehole logs obtained from the German Geological Survey of Brandenburg and Macklenburg-Vorpommern (LBGR and LUNG M-V), and geological map sheets at a scale of 1:200,000 (6 map sheets), and 1:50,000 (12 map sheets) supplemented by boreholes logs obtained from the Polish Geological Institute. All obtained borehole logs were grouped into extensive GIS database which collects at least information about coordinates, lithology and stratigraphy of 5876 borehole logs each more than 50 m deep. Morphological interpretation of the study area was carried out on the basis of the SRTM (Shuttle Radar Topography Mission) terrain model and the DTED (Digital Terrain Elevation Data, Level 2; for the Polish part of the lobe).

For groundwater flow simulation underneath the ice and some distance in front of it experiments in time dependant three-dimensional numerical modelling of subglacial groundwater flow have been used to constrain interactions between ice, water and sediments. For numerical simulations VisualMODFLOW Pro 4.2 package was used that is one of the most popular hydrogeological tool for groundwater modelling. The transient finite difference hydrogeological model refers to the ice advance from the current Baltic Sea coast line to the maximum ice extent during the Pomeranian phase. In order to validate numerical simulations, model results were compared to geomorphological observations.

## Subglacial forms

*Tunnel valleys*

One of the crucial subglacial landforms which are created parallel to ice movement are tunnel valleys (Wysota 1999). This extensive erosional features can be useful in order to delimit ice margin (Bentley et al. 2005) while its morphometric analysis could provide evidences for ice margin fluctuations (Glasser et al. 2004). Tunnel valleys are usually formed in areas where ice substratum has not sufficient capacity to drain all meltwater (Shoemaker 1986, Alley 1989, Piotrowski 1997) due to high ice basal melting rate or low hydraulic conductivity of the ice bed, one way or another its location indicate a surplus of meltwater at the ice/bed interface.

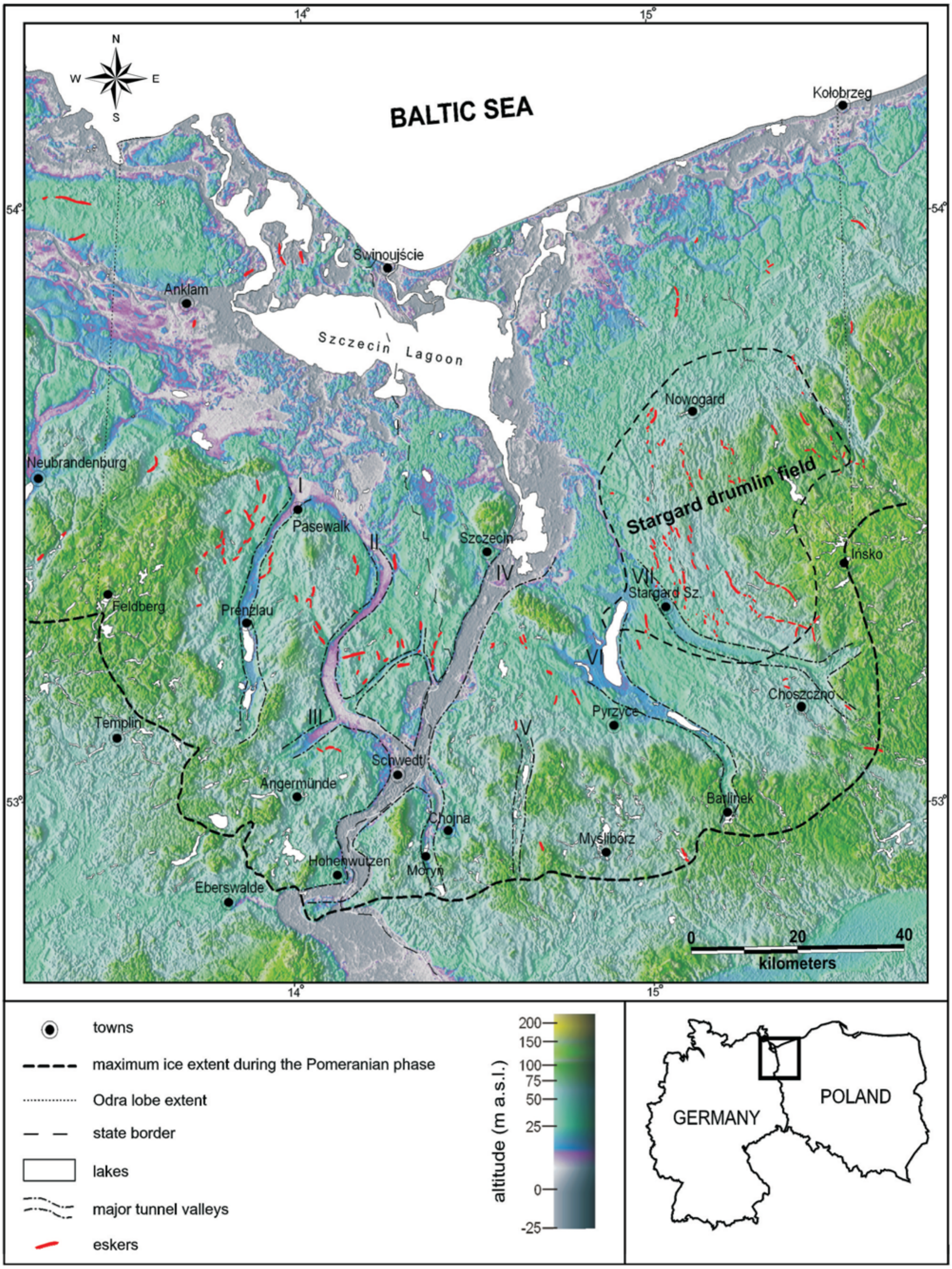


**Fig. 1.** Morphology of the study area with location of subglacial landforms: tunnel valleys, eskers and the Stargard drumlin field. Marked major tunnel valleys are: I – Pasewalk-Prenzlau, II – Löcknitz-Moryń, III – Greiffenberg, IV – Odra, V – Banie, VI – Barlinek, VII – Stargard-Recz

Major tunnel valleys formed during the Pomeranian phase of the Weichselian in the study area are: Pasewalk-Prenzlau, Greiffenberg, Löcknitz-Moryń, Odra, Banie, Barlinek and Stargard-Recz (Fig. 1). Most of them begin at the southern part of the Szczecin Lowland and Uckermünde Heine (areas characterized by the lowest altitude within the whole Odra lobe), from these areas tunnel valleys continue radially towards the Pomeranian phase ice sheet extent. Nowadays, mentioned tunnel valleys are typically occupied by fingerlakes and northward flowing rivers. This erosional features are tens of kilometers long and usually more then 1 km wide excepting the Odra tunnel valley which is ca. 5 km wide in places. Their southern segments are deeply cut into substratum (e.g. Moryń tunnel valley ca. 60 m, Barlinek tunnel valley ca. 70 m) with steep valley sides while their northern segments are represented by shallow valleys. Within some valleys we can distinguish at least two channels with different altitudinal position of its bed, the most representative one is the Barlinek tunnel valley with elevation difference between channels beds of about 15 m. Similar situation is observed within the Pasewalk-Prenzlau, Löcknitz-Moryń and Banie valley. Altitudinal gradient between northern and southern segments of all valleys beds represents noticeable adverse slope of the glacial substratum especially visible along the Pasewalk-Prenzlau, Löcknitz-Moryń and Barlinek tunnel valley where exceeds 40 m.

Besides mentioned prominent valleys analysis of the numerical terrain model let to distinguish same similar erosional features within the Odra lobe which terminate at the maximum ice extent. Analyses of the DTED and SRTM demonstrate that all subglacial channels cross-cut all other landforms in the study area.

*Eskers*

Another subglacial landforms commonly observed within the Odra lobe are eskers. These features are often preserved in the landscape and define subglacial drainage paths (Hooke 2005). However, eskers in the study area are not as frequent as on the Fennoscandian Shield where reflect substratum nature – hard vs. soft bed (Clark & Walder 1994). Deposition of sediment, usually gravel and sand, creating eskers mainly take place within R-type subglacial channels (Röthlisberger 1972) but also within englacial or supraglacial conduits. Sediments delivery depends on the melting rate of the conduits walls, debris concentration in the ice (Shreve 1985) and pressure gradient influencing intrusion of substratum sediments into the channel (cf. Boulton & Hindmarsh 1987).

In the study area the highest density of eskers is observed within about 40 km wide zone localized in


**Fig. 2.** Representative esker (about 3 km long and 43 m high) of the Pasewalk-Prenzlau area

the central part of the lobe (Fig. 1), outside this zone only small number of eskers were formed. Eskers are frequent landscape components in the western part of the lobe, especially between Pasewalk and Prenzlau. One of the representative form of this area is about 3 km long and 43 m high, its major azimuth is 210° (Fig. 2). In the Polish part of the lobe representative eskers could be found in the area of nature reserve 'Ozy Kiczarowskie' (Kiczarowskie Eskers, Kunkel 1966) where their major azimuth is 160°. Southern border of the eskers zone stretches at the distance of about 20 km form the maximum ice extent on the western and eastern flank of the lobe and about 40 km at its central part.

*Drumlins*

Another subglacial landforms which are products of specific hydraulic conditions are drumlins. Its origin is still not fully recognized, however dominates theories suggesting deformation of soft subglacial bed (e.g. Hart 1997, Hindmarsh 1998) and subglacial meltwater action (e.g. Shaw 2002). Rattas & Piotrowski (2003) provided evidences that spatial morphometric characteristic of drumlins is strongly dependant on the nature of an ice substratum which influence meltwater discharge pattern.

In the eastern part of the Odra lobe is localized the Stargard drumlin field which is the most extensive drumlin field in the European Lowland (Fig. 1). The drumlin field covers about 1800 km$^2$ where over 1000 forms were formed. They are typically more than 10 m high, up to about 4.5 km long and often hundreds meters wide (600 – 700 m at the southern fringe of the field, Karczewski 1987, Karczewski 1995), the drumlins length increases southwards. Their internal composition consists of sandy sediments with gravel covered by till (Karczewski 1995, Rachlewicz 2001a). Rachlewicz (2001b) observed till deformation within a drumlin, to a depth of 6.5 m with stress direction parallel to the axis of the drumlin. Southern border of the Stargard drumlin field is located at least 10 km up-ice from the maximum ice extent during the Pomeranian phase. In the southern part of the Stargard drumlin field, drumlins coexist with eskers.

## Numerical modelling

Important part of hydrogeological modelling procedure is conceptual model that provides a picture of the hydrogeological setting. The collected boreholes database was used for regional geological interpretation and generalization of hydrogeological units. In this step base of the whole model area was specified, and is represented by the bottom of Jurassic sediments (about 2750 m b.s.l.). Below this surface low-permeable Triassic sediments were recognized (mainly claystones). On the basis of hydrogeological properties aquifers and aquitards were distinguished partly corresponding to its stratigraphy (Fig. 3). Sediments younger then Eemian were deleted, and instead layer of equal thickness representing basal till was applied. It is almost impossible to estimate thickness of the till that existed under the ice during its advance so the thickness of 2 m was assumed referring to basal till deposition rate measured by Mickelson (1973) under the Borroughs Glacier (Alaska) and estimated velocity of the Weichselian ice sheet advance to the Polish Lowland (Stankowski 1983). Eventually, the ice sheet substratum is represented in the model by 9 layers representing geological architecture, and additional layer (layer I) imitating the ice sheet and used in order to assign potentiometric pressure. It was assumed that the ice sheet in the study area was at its flotation level what means that water pressure at the ice/bed interface counterbalance ice pressure. Piotrowski & Kraus (1997) had suggested such conditions for the area of north-western part of Germany, and later sedimentological evidences of the ice decoupling were presented (Piotrowski & Tulaczyk 1999) what justified this assumption.

Bottom surface of each layer was implemented on the basis of information included in the database, and all were interpolated using the kriging procedure followed by variogram analysis what is the most common and realistic geostatistical approach in geological and morphological investigations (Davis 1986, Goldsztejn & Skrzypek 2004). For each layer hydrogeological parameters such as hydraulic conductivity and porosity were prescribed based on hydrogeological literature (Table 1). Only for two uppermost aquifers (layer III and V) hydraulic con-

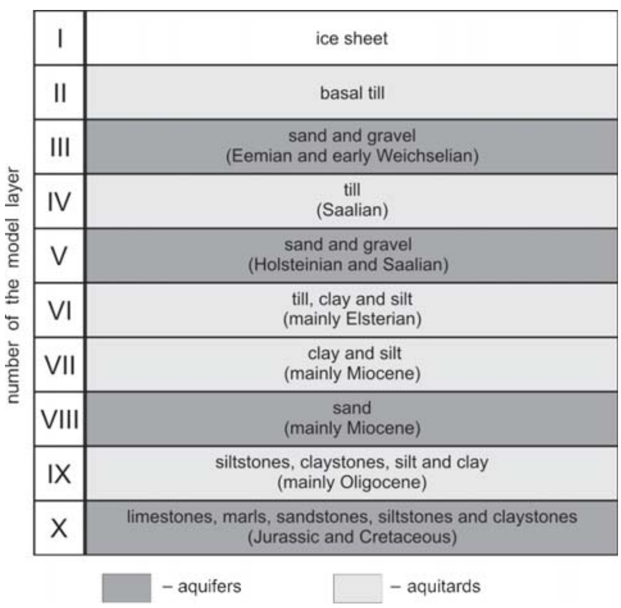


**Fig. 3.** Schematic representation of the numerical model

**Table 1.** Thickness and hydrogeological parameters of the model layers

| Layer no. | Average thickness [m] | Horizontal hydraulic conductivity [m/s] | Vertical hydraulic conductivity [m/s] | Effective porosity [–] |
|---|---|---|---|---|
| I | layer representing the ice sheet | | | |
| II | 2.0 | $2.48\times10^{-7}$ | $2.48\times10^{-8}$ | 0.03 |
| III | 8.5 | $1\times10^{-3}$–$2\times10^{-4}$ | $1\times10^{-4}$–$2\times10^{-5}$ | 0.24–0.33 |
| IV | 25.9 | $2.48\times10^{-7}$ | $2.48\times10^{-8}$ | 0.03 |
| V | 27.6 | $1\times10^{-3}$–$2\times10^{-4}$ | $1\times10^{-4}$–$2\times10^{-5}$ | 0.24–0.33 |
| VI | 33.0 | $8\times10^{-8}$ | $8\times10^{-9}$ | 0.02 |
| VII | 39.9 | $3\times10^{-8}$ | $3\times10^{-9}$ | 0.01 |
| VIII | 25.2 | $5\times10^{-4}$ | $5\times10^{-5}$ | 0.18 |
| IX | 47.7 | $2.5\times10^{-10}$ | $2.5\times10^{-11}$ | 0.08 |
| X | 1187.4 | $3\times10^{-5}$ | $3\times10^{-6}$ | 0.12 |

ductivity values were interpolated based on data from pumping tests. Bearing in mind anisotropy of sediments vertical hydraulic conductivity values ($K_z$) were assign order of magnitude lower then horizontal ones ($K_x$, $K_y$). Hydrogeological properties such as effective porosity, specific storage and specific yield were also prescribed for each model layer. Eventually, 9 model layers were distinguished (4 aquifers and 5 aquitards) characterized by different hydrogeological properties and additional layer, the uppermost one, which represents the ice sheet. The ice sheet imitating layer was used for simulation of potentiometric pressure that was given by the ice to its substratum. The model is built by rectangular grid divided into 383 columns and 355 rows what gives cells of 500×500 m in *x* and *y* dimension, and *z* dimension corresponds to the thickness of the respective model layer.

In order to calculate potentiometric pressure it was necessary to estimate the ice thickness. Several different methods can be used to estimate ice thickness (Shreve 1985, Clark 1992, Larsen et al. 1995), however in this case Orowan's (1949) empirical formula that based on thermal properties of ice and mechanical properties of its bed was used. The estimation takes into account variable topography of the ice bed and its soft, deformable nature. The Orowan's formula assumes ice as a perfectly plastic material, and its thickness H at a distance L from ice margin is calculated by the expression:

$$H=AL^{1/2}$$

coefficient *A* represents thermal properties of ice and mechanical properties of its bed. The *A* value is usually between 1 and 4.7 (for details see: Piotrowski & Tulaczyk 1999). For soft bed glaciers the value is about 1.0 (Mathews 1974, Colgan & Mickelson 1997). Taking into account variable geomorphology of the study area and variable hydraulic transmissivity of the ice bed for the *A* coefficient different values were taken – equal 1 for the central part of the Odra lobe and 1.3 for the rest part. For the final ice sheet thickness calculations topographic correction was also applied (for details see: Sauer et al. 1993). The estimated ice thickness is ca. 400 m at the present day Baltic Sea coast sloping gradually southwards up to the zone where advancing ice margin produced a distinct lobe which lowered the ice surface elevation. As it was mentioned, it was assumed that the ice reached ice flotation level, such conditions are possible when potentiometric pressure at the ice/bed interface equals about 90% of ice thickness (Paterson 1994, Piotrowski & Tulaczyk 1999). Thus, in this simulation the hydraulic head for layer I was prescribed at 90% of the estimated ice thickness. Along northern model boundary constant hydraulic head was prescribed to simulate groundwater inflow from the north. At the ice forefield hydrogeological boundary representing river was assign to simulate, in this case, influence of the Toruń-Eberswalde ice marginal spillway on groundwater flow pattern. To estimate numerically influence of the ice sheet advance on subglacial groundwater system, 35 time steps were simulated corresponding to different position of the advancing ice margin yielding temporal and spatial data.

## Subglacial drainage

Based on the numerical simulations significant influence of the advancing ice sheet on subglacial hydrogeology especially in layers I – IX could be noticed. Calculated groundwater table and flow directions in the model layer X represent regional trend which has no importance for the ice motion so it was neglected from further discussion. Thus, this paper focus on groundwater flow directions and velocities in the uppermost model layers (II and III) that have direct influence on the ice/bed hydraulic conditions.

Model run shows strong influence of pressure gradient determined by the sloping ice sheet surface. Groundwater flows from the ice sheet interior towards the margin where it discharges to the ice forefield (Fig. 4). Almost the same groundwater flow directions can be observed in all layers representing aquifers (layers III, V and VIII) excepting layer X. Southern groundwater flow direction is also observed in periglacial territory towards the Toruń-Eberswalde ice marginal spillway. Cross-section through the simulated subglacial system shows

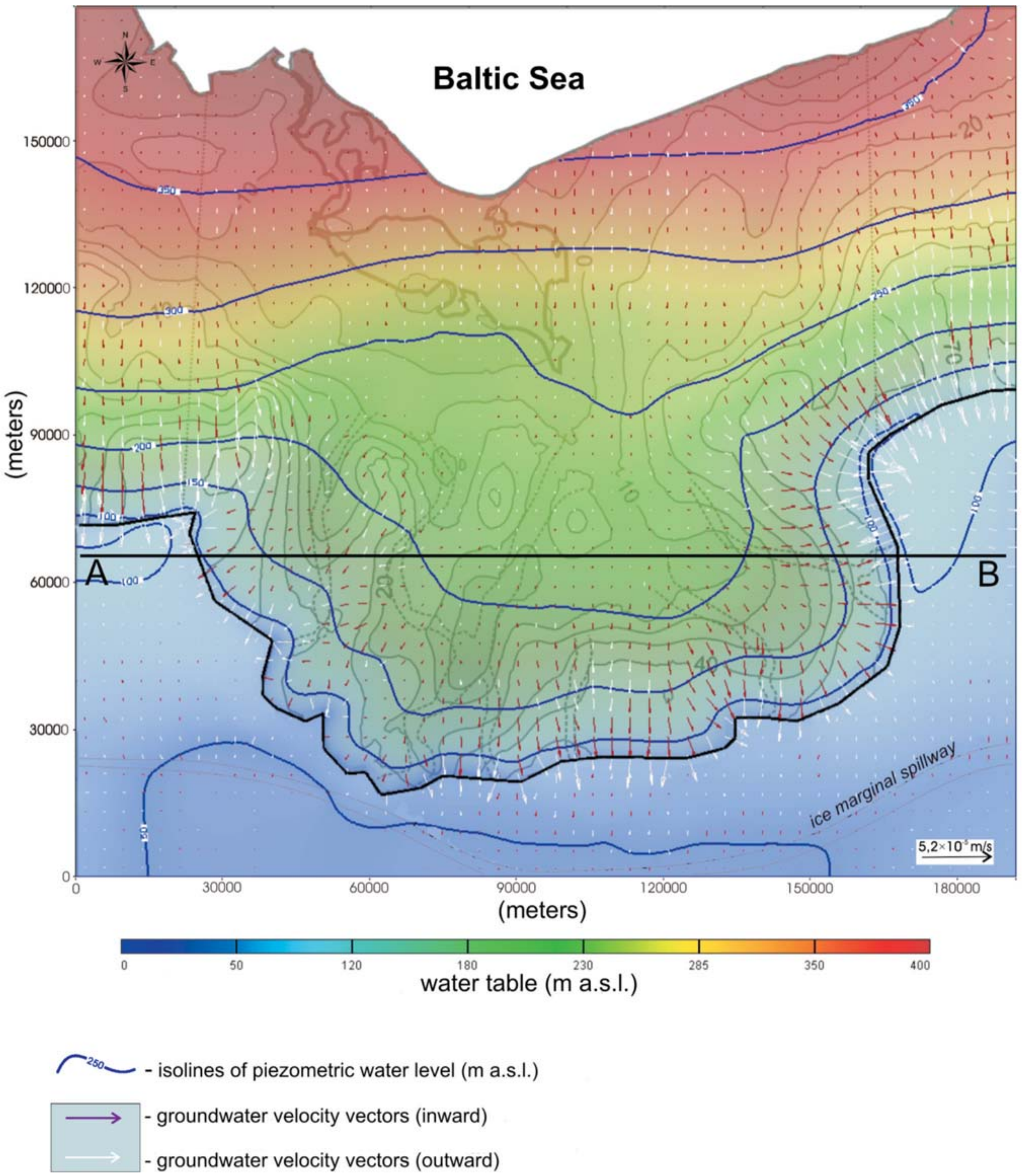


**Fig. 4.** Subglacial groundwater velocity vectors and potentiometric surface in layer III of the numerical model. Inward flow vectors represents areas where water is percolating into the substratum. Outward flow vectors represents areas of groundwater upwelling. The background illustrates ice substratum and the location of major subglacial tunnel valleys

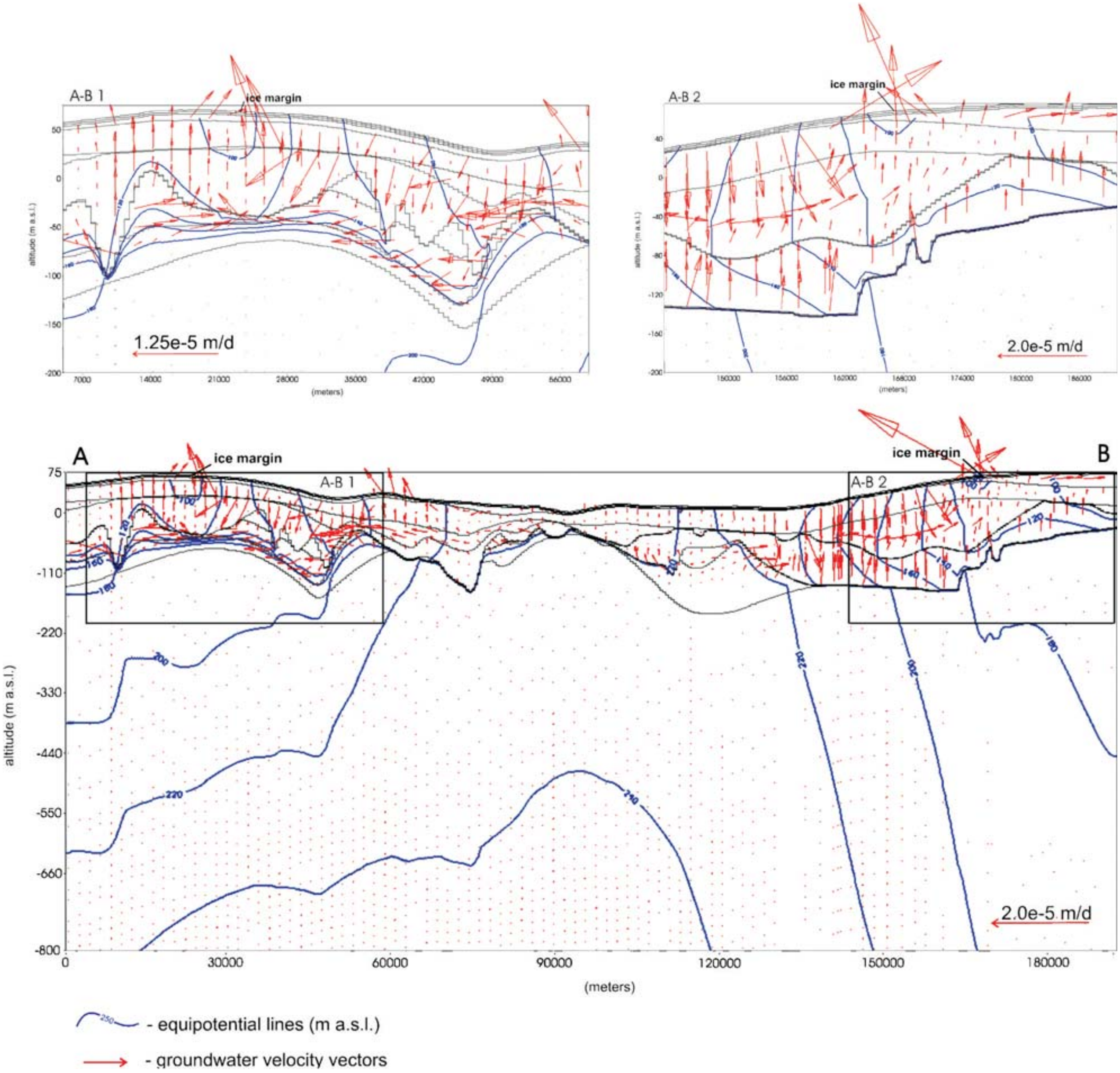


**Fig. 5.** Equipotential lines and flow velocity vectors along a W–E transect through the numerical model (location in Fig. 4)

that groundwater system is mainly recharged by water percolating from the ice/bed interface (Fig. 5). However, we can also distinguish areas where groundwater flows towards the ice/bed interface. In places vertical flow direction can be observed especially within aquitards. Calculated equipotential lines refer to the tangent flow line refraction law being result of conditions at the boundaries between materials of different hydraulic properties (Freeze & Witherspoon 1967). Close to the ice margin in both subglacial and periglacial zone upward direction of flow can be observed as a result of pressure gradient.

Differences in groundwater flow velocities emphasize role of aquifers due to relatively high hydraulic conductivity there. Within aquifers (layers III, V and VIII) maximal flow velocities are order of magnitude higher then within aquitards (layers II, IV, VI, VII and IX). The highest flow velocity in the model layer III is $5.2\times10^{-5}$ m/s while the lowest one in layer IX is $2.3\times10^{-7}$ m/s. Significant increase of groundwater flow velocity within the model layers from II to IX can be noticed in marginal 10 km wide zone up-ice in contrast to relatively low velocity values in central part of the lobe what express low hydraulic gradient that refers to the estimated ice thickness. In front of the ice margin groundwater velocities significantly decreases.

Water budget calculation for the whole model area shows that groundwater outflow from the all model layers is ca. 19 $m^3/s$ (Fig. 6). Groundwater inflow through the north model boundary is ca. 13 $m^3/s$. To balance groundwater inflow and outflow is required ca. 6 $m^3/s$ that could be given as effective recharge of groundwater from the basal ice melting, and this value represents how much water could percolate into substratum. In calculations, annual melt-

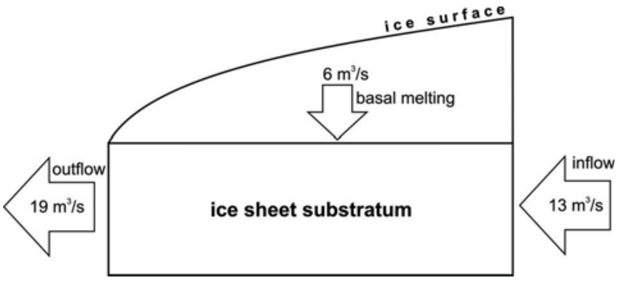


**Fig. 6.** Subglacial water budget for the maximum ice extent during the Pomeranian phase

ing rate was assumed equal 36 mm after Piotrowski (1997), even if this value is to high it do not assume possible recharge of surface ice ablation water that could be transmitted to the ice sole as it was concluded by Zwally et al. (2002). Based on this assumption total melting rate for the whole area is ca. 26 $m^3/s$ what means that is about four times higher than calculated effective recharge from the ice sole.

In this paper major importance was given to location of areas where water flows upward (to the ice sole) and downward (inward and outward flowing water, Fig. 4 and 5). For the maximum of the ice sheet extent during the Pomeranian phase areas of water flowing downward (inward flow vectors in Fig. 4) from the ice/bed interface – water is percolating to the ice substratum – is observed between the Stargard-Recz and Barlinek tunnel valleys, and in about 300 m wide zone along the ice margin between the Odra and Barlinek tunnel valley. Areas of water flowing upwards to the ice/bed interface (outward flow vectors in Fig. 4) are along the ice sheet margin where water is discharged to the ice forefield and additionally in the area of the highest density of eskers close to Pasewalk and Prenzlau, and in southern part of the Stargard drumlin field. Different location of both kind of areas were observed in maps presenting previous positions of the advancing ice margin.

## Model validation and discussion

To check if any hydrogeological model is a valid representation of groundwater system it is necessary to carry out verification test, for example simulating groundwater table for a different time period that it was previously done, and for which hydrogeological response is known. However, it is impossible to validate palaeo-models in this way. Simple but only superficial method of validation palaeo-glaciological model is to compare obtained results with contemporary glaciated regions. Additionally, in this case as a validation procedure it was decided to refer specific hydrogeological conditions obtained as the model output to geomorphological analysis.

Water budget calculation suggests that only about 24% of the ice basal meltwater could drained through the bed as groundwater, so due to low permeability of the ice bed thin water layer at the ice/bed interface was likely created. Such conditions cause significant decrease in shear stresses, and strongly influence ice motion since likely initiate basal sliding (Alley 1989, Iverson et al. 1995).

Recharged of the ice/bed interface by groundwater upwelling is an evidence for higher groundwater pressure under the ice then the ice pressure. Groundwater upwelling from the substratum to the ice/bed interface connected with intensive basal melting leads to pore pressure increase and sediment strength decrease what might influenced ductile deformations. Such conditions are registered in Pasewalk-Prenzlau region, and in the Stargard drumlin field where Rachlewicz (2001b) described typical example of ductile deformations in the core of drumlin which correspond there to pervasive deformations. Water discharge from the ice/bed interface could lead to increase in basal coupling and in the same way increase of shear stresses what may create thrust deformations. Location of such conditions is to the southwest of the Szczecin lagoon in German part of the lobe where large scale thrust structures are well documented (Börner et al. 2004). However, such conditions not always initiate glaciotectonic deformations, because even if water is intensively percolating into substratum water balance could be still positive due to intensive ice melting.

Adverse slope of the ice bed especially in the marginal zone could hamper water drainage form the ice/bed interface and lead to subglacial water accumulation as subglacial lakes (Clarke 2005) or in pores of dilated till (Hooke & Jannings 2006). Subglacial water storage was also noticed under the Antarctic ice sheet (Peters et al. 2007). Discharge from subglacial lakes could occurred as spontaneous outburst events as it was also suggested for the other areas covered by the Pleistocene ice sheets (Piotrowski 1994, Beaney & Show 2000, Cutler et al. 2002, Jørgensen & Sandersen 2006), and currently glaciated regions (Rushmer 2006). Storage and sudden discharge of subglacial water is of primary importance for basal processes and ice motion (Peters et al. 2007), it also proves insufficiency of ice substratum to drain all basal melting water and can initiate creation of channelized drainage system. As an evidence of subglacial water outburst in the Odra lobe area are deposits localized in front of the Banie tunnel valley with large density of well rounded boulders (Fig. 7) which were likely transmitted during spontaneous outburst. Similar mechanism was suggested for the Des Moines lobe of Laurentide ice sheet (Patterson 1997).

Despite the fact that the origin of some subglacial landforms is currently a matter of debate studying their spatial distribution and relationships provide not only records of ice flow direction but also reflects time-dependant conditions at the ice/bed interface. Occurrence of drumlins and flutings is usually connected with fast flowing ice bodies like ice streams (Colgan & Mickelson 1997, Stokes & Clark 2001, Smith et al. 2007), areas where ice surge occurred (Christoffersen et al. 2005, Larsen et al. 2006) or with areas of fast flowing ice lobes (Clark 1993, Hart 1999, Rattas & Piotrowski 2003). Stokes & Clark (1999) presented criteria for identification of former ice streams. In their model one of the diagnostic criteria is location of drumlins which occur behind ice stagnation landforms, thus similarly to the Stargard drumlin field position. Another examples of similar drumlins position in relation to ice margin were observed within Saginaw Lobe (Fisher et al. 2005), Green Bay Lobe (Colgan & Mickelson 1997), in Alberta in western Canada (Evans et al. 2008) and also in some other areas described as palaeo-ice lobes. It was also concluded that drumlins are typically formed under relatively thin and fast flowing ice (e.g. Clark et al. 2003, Evans et al. 2008). However, referring to the criteria specified by Stokes & Clark (1999), in the Odra lobe area there is a lack of one important component which are mega-scale glacial lineations. One possible explanation why there are no indicators of strongly elongated ridges or furrows is that morphology were strongly reshaped during the following ice recession mainly by strong subglacial and proglacial erosion due to intensive water discharge or used in this study DTED model is not enough detailed. Occurrence of eskers in the Pasewalk-Prenzlau region and lack of drumlins in this area suggests efficient drainage system in that area.

Additional important factor for the subglacial conditions could be occurrence of permafrost beneath the ice fringe (Piotrowski & Tulaczyk 1999) but its thickness and extent in the Odra lobe area is still a matter of debate (Šafanda et al. 2004, Szewczyk et al. 2007). If in front and below the ice margin thick permafrost had occurred as it was suggested for north-western Germany (Fränzle 1988, Piotrowski 1994) and north-eastern Poland (Šafanda et al. 2004, Szewczyk et al. 2007) then it would removed possibility of steady channelized drainage that is why water may had been stored subglacially until it was released during abrupt events initiating formation of the channels. Well developed subglacial discharge pattern controlled water pressure at the ice/bed interface and in consequence led to the ice flow deceleration and subsequently efficiently forced stoppage of the ice advance.

**Fig. 7.** Boulders deposited in front of the Banie tunnel valley

## Conclusions

The ice sheet loading in the Odra lobe area produced significant increase of the hydraulic head in subglacial and periglacial zone, and totally reorganized regional groundwater flow in terms of velocities and directions. Even though, water budget calculations for the whole Odra lobe area show that only small fraction of basal meltwater could drain through the bed spots of different hydraulic conditions occurred under the ice giving rise to specific geological processes and formation of subglacial landforms. Due to insufficient subglacial drainage system water likely accumulated at the ice/bed interface and subsequently was drained in outburst events. Intensive water discharge contributed to the stabilization of the ice sheet by evacuating large volumes of water from the ice/bed interface. Dense network of N-type subglacial channels which bed is deeply cut into hummocky moraine and cross cut end moraines as well as all other subglacial landforms gives evidence that subglacial drainage system was triggered at the late stage of ice streaming.

In contrast to the eastern part of the lobe there are no evidences of fast ice flow in central nor western part of the lobe or it is necessary to use detailed, with high mesh resolution DTED or the Landsat image which could be very useful since can reveal previously unsuspected large-scale pattern of streamlining (Clark 1993). Another scenario is that in this area the ice advance was moderated by more efficient subglacial drainage or basal melting rate was significantly smaller.

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