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Weichselian glaciations in the middle Noteć River region, northwest Poland

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Abstract

This thesis presents results of studies on the ice flow pattern and ice movement mechanism during the Weichselian glaciations in the middle Noteć River area, NW Poland. A new lithostratigraphy of the study area has been established, based on correlation of stratigraphical position, clast lithology, fabrics and grain size composition of till units. The lithostratigraphy covers two glacial advances of presumed Weichselian (Vistulian) age. The ice flow pattern during these glacial events was reconstructed using directional elements such as clast fabrics, striations and deformations. The first ice (Dziembowo ice advance), tentatively assigned to the Middle or Late Weichselian, initially moved towards the SE while creating large thrust ridges. The ice movement direction shifted towards the SW at the time of till deposition. The last glacial advance (Ujście ice advance), assumed to be Late Weichselian, has a twofold history with an initial advance towards the WSW and a final radial ice flow pattern towards the W. The occurrence of an ice readvance during the Chodzież subphase of the last deglaciation is rejected. The present results and information on the last ice flow direction in adjacent areas suggest that the western flank of a lobate ice front, centred in the Wisła Valley, covered the study area during the last deglaciation. The lobate ice front seems to have existed during the deglaciation from the Late Weichselian maximum ice marginal position in the Wisła Valley and probably back to the present Baltic Sea coastline. It is suggested that the lobate ice front represents the terrestrial termination of an ice stream following the Wisła Valley.

Key words:

Weichselian; Vistulian; Lithostratigraphy; Poland; Chodziez; Clast lithology; Clast fabrics; Deglaciation; Ice stream

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I: **Pettersson, G.** 1997: Unexpected ice movement directions during the last deglaciation in Ujście, NW Poland - Stratigraphical investigations. *Quaternary Studies in Poland 14*, 85-94.

II: **Pettersson, G.** Vistulian (Weichselian) lithostratigraphy of the middle Noteć River area, NW Poland. *Submitted to Geological Quarterly.*

III: **Pettersson, G.** Ice lobe formation during the Late Weichselian (Vistulian) deglaciation in NW Poland. *Submitted to Journal of Quaternary Science.*

Weichselian glaciations in the middle Noteć River region, northwest Poland

by

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This thesis is based on three papers listed below as appendices I-III and referred to in the text by their Roman numerals. Paper I is reprinted with the permission of the Polish Academy of Sciences, whereas paper II is submitted to Geological Quarterly and paper III is submitted to Journal of Quaternary Science.

App. I: **Pettersson, G. 1997:** Unexpected ice movement directions during the last deglaciation in Ujście, NW Poland - Stratigraphical investigations. *Quaternary Studies in Poland 14*, 85-94.

App. II: **Pettersson, G.** Vistulian (Weichselian) lithostratigraphy of the middle Noteć River area, NW Poland. Manuscript submitted to *Geological Quarterly.*

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Esker located in the center of a tunnel valley at Jastrowie. View towards the south.

Introduction

Better understanding of the Earth's climate system is an important issue for the scientific community, as there are indications that the human lifestyle is starting to impact the climate (Trenberth, 2001). This scientific interest involves studies of numerous aspects of the climate system in order to understand the processes involved. These processes are mimicked in General Circulation Models (GCM), which are computer models attempting to simulate the climate system. In theory, the GCM's should allow us to reconstruct past scenarios and predict natural and man-induced future changes of climate. Quaternary geology has a role in this work by providing climatic information from pre-historic time, information that can be used to calibrate and evaluate the GCM's.

One important factor in the climate system is the extent of the ice sheets (Clark *et al.*, 1999; Clark *et al.*, 2000). The ice sheets influences many climatic parameters, such as the albedo, humidity, precipitation, wind pattern etc. Reconstructions of the timing, extent, shape and dynamics of former ice sheets can be accomplished through geomorphological, sedimentological and stratigraphical investigations. These investigations may also help to improve understanding of the processes involved in the glacial environment. Reconstructions are continuously improved through more detailed studies of poorly understood areas or problematic observations.

Stefan Kozarski from Adam Mickiewicz University in Poznań made an observation of a problematic ice flow direction, in the middle Noteć River area (Fig. 1). Geomorphological mapping suggested that a major oscillation of the ice front had created large glaciotectonic ridges on the S side of the Noteć River Valley during the last deglaciation (Kozarski, 1962). The oscillation was named the Chodzież subphase (Kozarski, 1981; Figs. 1, 2). In stratigraphical investigations at Ujście (Fig. 1) a separate till bed was found to correspond with this oscillation (Kasprzak & Kozarski, 1985; Kozarski & Nowaczyk, 1985; Kozarski & Kasprzak, 1987). Clast fabrics and glaciotectonic deformations indicated an ice movement towards the W during till deposition. (Kozarski & Kasprzak, 1987). Kozarski (1992) noted that this ice movement direction during the oscillation was something new in the general deglaciation pattern in Poland and should be the subject of further study. In the 1980's, no ice movement mechanism was known that could explain an ice flow direction, deviating radically from the presumed regional ice flow direction (which was towards the SSW) in an area of low topographic relief.

A project was set up with the aim of explaining the ice dynamics behind the observed ice movement direction and reconstructing the ice flow pattern during the last glaciation and deglaciation of the area. To this end, two primary questions were formulated:

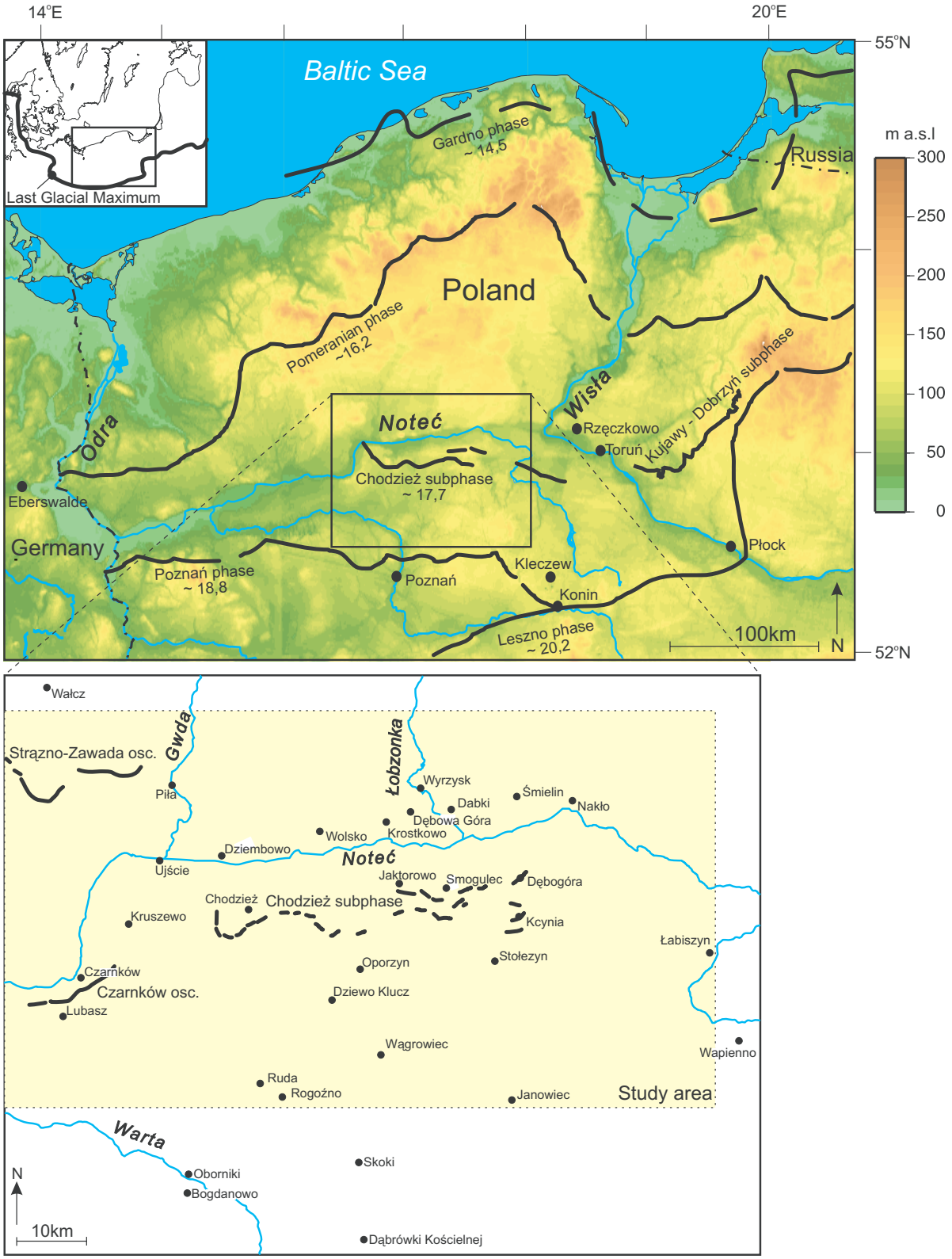
1. What was the extent and ice flow pattern of the uppermost till unit observed at Ujście?
2. What mechanism caused the observed ice movement pattern?

Recent interest in the dynamic behaviour of ice sheets adds a further dimension to this study. The increasing interest in the effect of fast flowing ice streams on ice sheet configurations (Stokes & Clark, 2001), and the attempts to model the behaviour of the last Scandinavian ice sheet (Kleman *et al.*, 1997; Boulton *et al.*, 2001), increases the need for more detailed data on glacial dynamics in the marginal areas of the former ice sheets.

Previous studies

An important early study in the area was made by Woldstedt (1932), about the outline of the ice marginal zones during the Weichselian deglaciation, and the creation of the Toruń-Eberswalde urstromtal. During the general deglaciation from the maximum Brandenburger (Leszno) ice marginal zone, the recession was halted and the Frankfurter (Poznań) ice marginal zone was formed (Figs. 1 and 2). Woldstedt considered the maximum ice extent in the Wisła valley to have formed during the Poznań phase. During the succeeding deglaciation, the ice front was separated into an Odra and a Wisła lobe, with the interlobate area migrating towards the north between Czarnków and Chodzież (Fig. 1). A major standstill occurred during the so-called Kolmarer phase, with an ice marginal zone running from an interlobate situation west of Wałcz towards SE, past Ujście, the Chodzież hills, Wągrowiecz and Janowiec (Fig. 1).

In drill cores around Śmielin (Fig. 1), Rühle (1954) and Środoń (1954) identified an Eemian pollen succession overlain by two till units. They



River

~ 20,2 Estimated age in ka BP (acc. to Kozarski, 1995)

Upper map: Major ice-marginal positions during the last deglaciation (acc. to Kozarski, 1986; Uścinowicz, 1999; Niewiarowski *et al.*, 1995)

Lower map: Marginal ridges (acc. to Kozarski, 1962)

Fig 1. Map of northern Poland with study area, ice-marginal positions during the last deglaciation and sites described in the text.

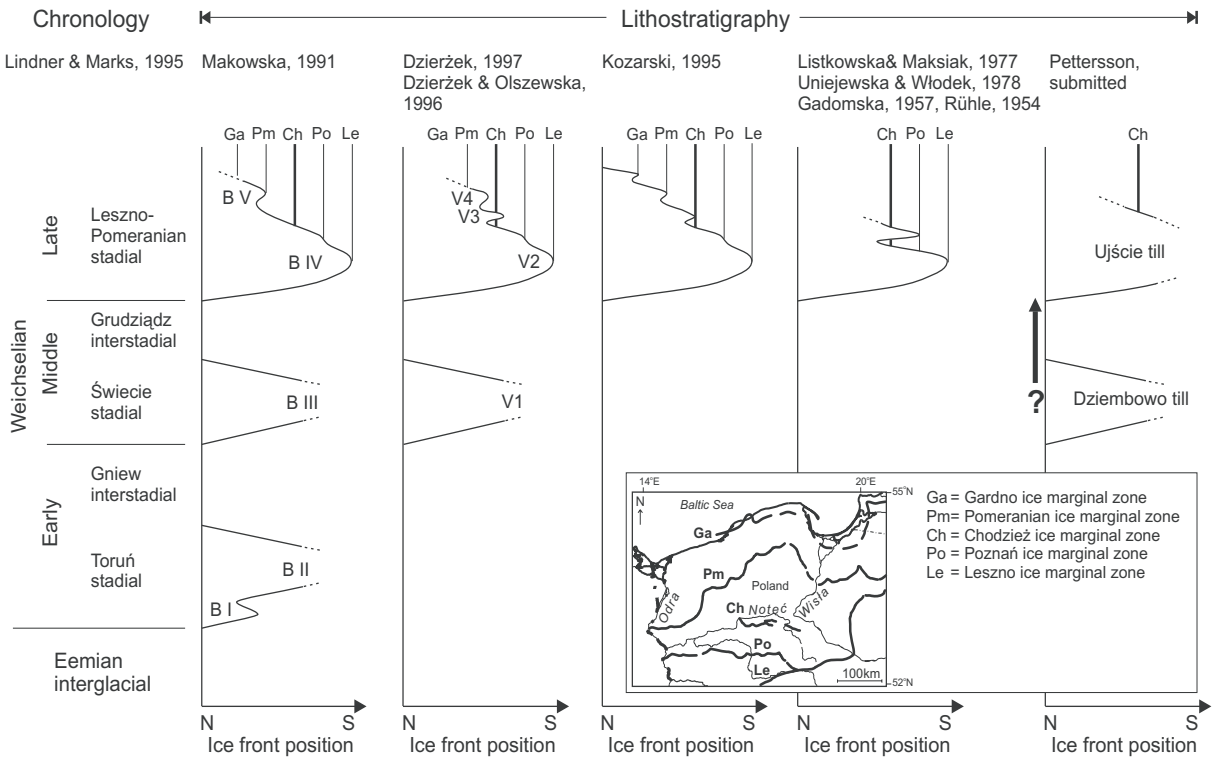


Fig 2. Time-distance diagram of ice margin positions in Poland during the Weichselian, according to different authors. Inset map after Kozarski, 1986 and Uścinowicz, 1999.

suggested that the till units were deposited during the Poznań and the Leszno phases (Fig. 2). Gadomska (1957), using drill cores, constructed two geological cross-sections across the Noteć River Valley south of Wyrzysk. The two upper till beds were suggested to be of Weichselian age. The uppermost till found north of Noteć was only found in one drill core south of Noteć and the conclusion was that this till unit is connected with the formation of the end moraines at Jaktorowo. The lower till unit was found on both sides of Noteć. Gadomska discussed signs of glaciotectonic dislocations in the large hills of Dębowa Gora and in a cross-section across Łobzonka River. Dębowa Gora was also studied by Szupryczyński (1958) who investigated the structure of the hills by using exposures and drill cores, and concluded that it consists of glaciotectonically displaced Pliocene clay and Quaternary sediments. The morphology of the minor ridges forming the Dębowa Gora massive mainly has its morphological axis trending E-W. The bedding planes in an exposure at the western side tilted towards the NW.

An important paper by Kozarski (1962) presented results from geomorphological mapping and some structural investigations for the area between the Poznań marginal zone and the Noteć River. Woldstedt's Kolmarer phase was rejected due to problems with the drainage system outlined by Woldstedt. However, Kozarski recognised that there had been some important geomorphologic event, although it had a different outline than Woldstedt's Kolmarer phase. It was also suggested that the large glaciotectonic ridges south of Noteć (Figs. 3, 4) formed the margin of an ice readvance during the so-called Chodzież subphase. In addition to the geomorphological mapping, Kozarski presented measurements on deformational structures and used these to identify end moraines as push moraines and to interpret main stress directions. The western part of the Poznań moraines, which Woldstedt considered to be recessional, was considered by Kozarski to have been formed during an ice front oscillation. Kozarski (1962), referring to unpublished studies by Roszkówna, also found that the maximum ice extent in the Wisła valley was formed during the Leszno phase and not during the Poznań phase, as suggested by Woldstedt.

In 1961, Krygowski presented an extensive study on the geomorphology and the Quaternary lithostratigraphy of the Great Poland Lowland. Using drill cores he concluded that the deposits originated from three glaciations. The lithological characteristics (colour, grain size composition, clast

lithology, indicator boulders, and grain roundness) of the deposits were also described, and the conclusion was that only the clast lithology has differences large enough to have some stratigraphical importance. Krygowski discussed the problem of the outline of the Poznań and Leszno marginal zones in the region of Konin, but concluded that the outermost ice marginal position E of Konin was formed during the Leszno phase and that the Poznań ice marginal zone is present further north. It is also interesting to note that he discussed the age of glaciotectonic disturbances in end moraines and attributed the formation of structures in an end moraine near Poznań to an earlier glaciation, as the internal structures do not correspond with the morphology of the moraine. In a later paper, Krygowski (1974) expressed doubts about the age of the Chodzież hills. He noticed that several recessional moraines were formed during the deglaciation from the Poznań moraines and suggested that their orientation was linked to an Odra ice lobe in the west and a Wisła ice lobe in the east. In a more recent study by Pasierbski (1984), the structures of end moraines and their relation to the glaciation history of the glaciated area in Poland were studied. He did not consider the glaciotectonic ridges around Noteć to be remnants from an earlier glaciation, as proposed by Krygowski (1974), but argued that they were more likely to have formed during the last glaciation.

Karzewski (1963 and 1965) presented studies on morphology, structure and texture of the till in W Poland. Fractures, structures, clast fabrics, grain size composition and grain roundness, were studied in outcrops. One interesting discovery was that Karzewski found that the simplified grain size composition and clast lithology varies more within a till unit than between different till units. Clast fabrics from a greater depth were found to generally have a strong preferred orientation and were assumed to reflect ice movement direction. Samples from the uppermost 1-2 m in a till unit are more chaotic and their orientation generally reflects the surface slope. In studies considering the exposures at Ujście (Kasprzak & Kozarski, 1985; Kozarski & Nowaczyk, 1985; Kozarski & Kasprzak, 1987, Böse & Górska, 1995), the lithological and structural characteristics of the two presumed Weichselian till units are described. The till units have a clear difference in terms of grain size composition, calcium carbonate content and clast fabric (Kozarski & Kasprzak, 1987). The uppermost of the till units was found to have been deposited by ice moving towards the WSW and was suggested to have formed inside the ice marginal zone of the Chodzież subphase (Kasprzak & Kozarski, 1985; Kozarski & Kasprzak, 1987). The lower of the till units was assigned to the Leszno/Poznań phase of the Late Weichselian and had a clast fabric indicating ice movement towards the SSW during till deposition. Böse & Górska (1995) described the clast lithology of the two Weichselian till units and also two older till units presumed to be Elsterian and Saalian. They found that the till of the Chodzież subphase has a clast lithology of a more eastern provenance than the Leszno/Poznań till.

Fig 3. The village Kcynia (Fig. 1), located on a thrust moraine ridge. View towards the south.

Fig 4. View towards the south over the Noteć River Valley (Toruń-Eberswalde urstromtal) from Dziembowo towards Chodzież (Fig.1). The Chodzież hills can be seen at the horizon.

When considering the outline of the Poznań ice marginal zone, Kozarski (1988, referring to Mojski, 1984) accepted that the Late Weichselian maximum in the Wisła Valley was formed during the Poznań phase. It was concluded that the Poznań ice marginal zone in the vicinity of Poznań represents a period of ice front standstill (Kasprak and Kozarski, 1984; Kozarski & Kasprzak, 1987; Kozarski, 1992) during which the ice movement was balanced by the ablation. This event was succeeded by an ice front recession. Consequently, there is no separate Poznań till unit in the hinterland of the Poznań end moraines.

The lithostratigraphical correlations and chronology have presented a major problem in the middle Noteć River area. The geological maps of the Quaternary deposits of Piła and Nakło show the presence of two Weichselian till units, one of which is suggested to be from the Leszno phase and the other from the Poznań phase (Listkowska & Maksiak, 1977; Uniejewska & Włodek, 1978). Eemian pollen assemblages from drill cores in lacustrine deposits were found by Noryśkiewicz (1979) in the City of Nakło in the Noteć River Valley. However, the relationship between the deposits and surrounding till units was not clear. Włodek (1980) discussed the Eemian palaeo-valley and the stratigraphy of the area. He found that the Eemian lake sediments in the area are overlain by fluvial, glaciolacustrine and glaciofluvial sediments, covered by till from one glaciation. The till unit is, in turn, covered by glaciolacustrine sediment. He mentions the stratigraphy of the sites at Nakło and Wyrzysk. Dąbrowski *et al.* (1987) studied drill cores near Piła and found Eemian lake sediments. The Eemian sediments were proposed to be covered by till from the Leszno/Poznań phase and the Chodzież subphase. These conclusions were based on correlation between different drill cores as the Eemian sediments and the Weichselian till units were not present in the same core. The only observations of Eemian sediments and Weichselian till units in superposition are from drill cores studied by Rühle (1954) and Środoń (1954). More recent studies by Dzierżek & Olszewska (1996) have increased knowledge of the chronology through the use of TL dating. They examined an exposure near Wolsko and concluded that the observed till units were deposited during the Chodzież subphase, the Leszno/Poznań phase and the Middle Weichselian, Świecie stadial. However, the reliability of the dates is questioned as the chronology was based on TL dating of till and glaciofluvial sediments.

In an extensive study of both drill cores and exposures, Dzierżek (1997) presented the sub-Quaternary geology and Quaternary litho-stratigraphy of the middle Noteć River Valley. He found deposits of Quaternary age up to 220 m thick, representing 7 glaciations. The Weichselian stratigraphy consists of four till units, from the Świecie stadial, the Leszno/Poznań phase, the Chodzież subphase and a minor event succeeding the Chodzież subphase. The chronology was partly based on the study by Dzierżek & Olszewska (1996).

Magdalena Ratajczak has recently been studying the area although few of the results have been published as yet, except for one paper (Ratajczak, 1998) on an exposure at Krostkowo on the western slope of Dębowa Góra. Ratajczak describes the sedimentology, clast fabrics and clast lithology of one subglacial and one supraglacial diamict unit separated by glaciofluvial sediments. The age of the deposits was not clear.

Methods

Previous studies in the area mainly concerned the geomorphology and only a few studies dealt with the sediments. Therefore, most of the work in the present study was concentrated on detailed lithostratigraphical and sedimentological investigations in open exposures. A total of 12 sites were studied in terms of sedimentary structures, grain size composition, clast lithology, clast fabrics, clast striations, ventifacts, palaeocurrent directions and deformational structures. Calcium carbonate content was also measured initially but this method was later abandoned as its usefulness in sediments suffering from carbonate dissolution and precipitation is ambiguous. The methods used for clast fabric measurements, clast lithology analyses and sediment descriptions are outlined in detail in papers I and II.

Considerable effort was put into identifying suitable outcrops. These were found through local contacts and through studies of maps and satellite images, but mainly from reconnaissance of the entire area. Most information was derived from the excellent exposures in the slopes of the Noteć River Valley (Figs. 1, 5). On the till plains N and S of the Noteć River Valley, only minor, shallow exposures were present and their value was therefore limited.

Problem 1 was approached by identifying and mapping the two uppermost till units through lithostratigraphical correlation of stratigraphical position, clast lithology, clast fabrics and grain size composition of the till units at each site. The ice flow pattern was mainly derived from proxy data of ice flow direction, such as clast fabric, direction of deformations and striae at different lithostratigraphical levels. Geomorphological information was used when it could be correlated to a

Fig 5. The exposure at Dziembowo (Fig. 1). View towards the north. The ladder is c. 6 m high.

specific lithostratigraphic event.

Problem 2, the possible causes of the observed ice flow pattern, relies on interpretation of ice flow pattern along with interpretations of depositional processes and environment, based on observations of sedimentary and deformational structures at the different sites.

An attempt has been made to establish the chronology of the stratigraphy using Optically Stimulated Luminescence (OSL) dating but the results are not yet available. No organic material suitable for ^{14}C-dating or pollen analysis was found.

Results – summaries of papers

Paper I

Pettersson, G., 1997: Unexpected ice movement directions during the last deglaciation in Ujście, NW Poland – Stratigraphical investigations. *Quaternary Studies in Poland* 14: 85-94.

This paper presents the results of detailed sedimentological and lithostratigraphical studies of the exposures at Ujście (Fig. 1). Ujście is the key site for identifying the anomalous ice movement directions associated with the Chodzież subphase (Kozarski & Kasprzak, 1987). The main purpose of this study was to investigate the lithostratigraphical units in detail with the aim of finding criteria for identifying the different till units in other exposures.

Four different till units have been found at Ujście. The first may be of Saalian or Elsterian age, the second from the Wartha stage of the Saalian, the third from the Late Weichselian maximum phase (Leszno/Poznań) and the fourth from the Chodzież subphase (Böse & Górska, 1995; Fig. 2). The present study was restricted to the two upper till units, of presumed Weichselian age. The Weichselian till units have previously been examined in terms of grain size composition, calcium carbonate content, fabrics, deformations (Kozarski & Kasprzak, 1987), clast lithology and indicator boulders (Böse & Górska, 1995).

The lower of the presumed Weichselian till units is a 2-4 m thick, clayey and homogenous diamicton. Sandy and occasional clayey inclusions are present in some levels of the unit. The basal contact is erosive and the lower 30 cm of the unit contains inclusions of sand, silt and clay. The preferred a-axis orientations (V_1) in the five clast fabric measurements are between 2 and 22° with a strength of orientation (S_1/S_3) between 0.59/0.07 and 0.90/0.02. The clast lithology is relatively low in Palaeozoic limestone and dolomite, but high in crystalline lithologies. This unit was interpreted as a lodgement till deposited by a glacier moving towards the SSW.

The deposition of the lower Weichselian till was followed by a deglaciation, as indicated by wind polished clasts and glaciofluvial deposition. The glaciofluvial deposits are discontinuous and were not studied in this paper. However, they were studied by Kozarski & Kasprzak (1987) who reported glaciotectonic deformation of the glaciofluvium, with a main stress component towards the WSW.

The upper Weichselian till, termed Ujście till, is a 7 m thick, clayey and homogenous diamicton. The clay and silt content is higher than in the lower Weichselian till. The basal contact is erosive with some deformation and incorporation of the substratum. Preferred clast a-axis orientations (V_1) are between 48 and 75° with strengths of orientation (S_1/S_3) between 0.68/0.07 and 0.88/0.02. The clast lithology includes relatively high proportions of dolomite, upper Cretaceous glauconitic rocks and Palaeozoic limestone. The unit was interpreted as a lodgement till deposited by a glacier moving towards the WSW.

The present results confirmed and strengthened the results and conclusions of the previous studies from the site. The study also provided greater detail concerning the clast lithology and evidence in the form of ventifacts of ice-free conditions between the deposition of the two Weichselian till units.

Paper II

Pettersson, G. Vistulian (Weichselian) lithostratigraphy of the middle Noteć River area, NW Poland. Submitted to *Geological Quarterly*.

This paper presents a detailed lithostratigraphy for the middle Noteć River area covering the two last glacial advances. The results were based on studies of exposures at seven new sites: Dziembowo, Wyrzysk, Smogulec, Nakło, Dabki, Kcynia and Dziewo Klucz (Fig. 1). All sites were studied in detail and a lithostratigraphy for each site was constructed. Comparisons between the stratigraphies at the different sites led to the conclusion that all, except Dabki, could be

correlated. Correlation was also possible with the Wolsko site (Fig. 1), studied by Dzierżek & Olszewska (1996), who also dated the stratigraphy with thermoluminescence (TL). The TL dates from Wolsko provide the only indication of the chronology in any of the exposures.

The lower of the two uppermost till units was termed Dziembowo till (Fig. 2) and is present at Ujście, Dziembowo and Wolsko. Large-scale deformations are present below the till unit, formed by an ice push towards the SE. During till deposition, the ice movement direction had shifted towards the SW. The till has a characteristic clast lithology that is very low in dolomite, relatively low in Palaeozoic limestone and relatively high in crystalline lithologies. The till is sandier than the overlying Ujście till. It has a stratified appearance due to discontinuous layers and inclusions of sand and gravel. The till contains many deformational structures and it was interpreted as having formed through lodgement and deformation processes. The TL dates indicate that it was deposited between 84±12 ka and 65±10 ka BP, which may correspond to the Świecie stadial in the lower Wisła stratigraphy (Makowska, 1991; Fig 2). However, the uncertainty when using TL dating of glaciofluvial sediments, and new results from the Wisła Valley, suggests that the Dziembowo till may be much younger. The deposition of Dziembowo till was followed by an ice-free period with glaciofluvial deposition and development of ventifacts at Ujście and Dziembowo.

Deposition of the uppermost till, the Ujście till, was preceded by deformation of the substratum, indicating a main stress direction towards the WSW. The Ujście till is present in all the exposures studied, except Dabki. It was divided into a lower and an upper subunit. The upper subunit is massive, homogenous and has a clast lithology composition comparatively high in dolomite and Palaeozoic limestone and low in crystalline lithologies. It is very clayey and has a clast a-axis orientation generally oriented towards the W. The lower subunit is stratified, folded, sheared and has many intralayers and inclusions of sand and gravel, all indicating different degrees of deformation and mixing. The clast lithology and the grain size composition of the lower subunit is intermediate between the properties of the Dziembowo till and the upper subunit of the Ujście till, indicating some incorporation of the substratum during till formation. The ice movement direction during deposition of the lower subunit was towards WSW. The lower subunit is interpreted as a glaciotectonite grading into deformation till. In the upper subunits there are signs of both deformation and lodgement during till formation. The TL dates indicate deposition after 65±10 ka, which suggests a Late Weichselian age.

It is also suggested that the Chodzież subphase did not exist, as its marginal ridges are older than the last ice advance in the area, its presumed till bed is found outside its suggested marginal zone and the ice flow direction during till deposition was parallel to the presumed marginal ridges.

Paper III

Pettersson, G. Ice lobe formation during the Late Weichselian (Vistulian) deglaciation in NW Poland. Submitted to *Journal of Quaternary Science*.

The purpose of this paper was to describe the ice flow pattern during the advance and retreat of the two last glaciers in the middle Noteć River area. Special attention was paid to the last deglaciation.

The ice flow information was derived from proxy data such as clast fabrics, glaciotectonic deformations and striations, published in papers I and II and by other authors (Szupryczyński, 1958; Kozarski, 1959, 1962; Karczewski, 1963, 1965; Pasierbski, 1977, 1995, 1996; Dzierżek & Olszewska, 1996; Górska, 1999, 2000). This data was supplemented with lithostratigraphical investigations at the Stołezyn, Oporzyn, Kruszewo and Ruda sites (Fig. 1). Supplementary information in the form of orientation of former subglacial meltwater channels (tunnel valleys) terminating in sandur surfaces (Kozarski, 1962) was also used.

The first glacial advance, the Dziembowo advance, was assumed to have taken place during the Middle or Late Weichselian. The ice flow was directed towards the SE during the advance. Large-scale deformations in the large end moraine ridges in the area indicate an ice push towards the SSE during deformation, and it was assumed that these ridges were formed during the Dziembowo advance. The ice movement direction during the deposition of the Dziembowo till was towards the SW. The Dziembowo till corresponds to the lower part of the V1 till described by Dzierżek (1997). According to Dzierżek (1997), the V1 till may have covered the entire study area. However, immediately SW of the study area, no till unit with a similar clast lithology to the

Dziembowo till can be found in the expected stratigraphical position.

During the second ice advance, the Ujście advance, the ice movement direction was towards the SW with a radial shape of the ice front. The Ujście ice advance deposited the uppermost till, the Ujście till, at all the studied sites (except Dabki). A possible correlation of the clast lithology of the Ujście till with the Maliniec till, described in studies of areas further to the SW (Czerwonka & Krzyszkowski, 1994), was suggested. The Maliniec till directly overlies Eemian organic deposits at Bogdanowo (Czerwonka & Krzyszkowski, 1994; Fig 1). Czerwonka & Krzyszkowski (1994) proposed that the Maliniec till is present to the maximum extent of the Late Weichselian glaciation in Poland. The conclusion is that the Ujście till was deposited during the Late Weichselian.

During the last deglaciation, the ice movement pattern was strongly radial with ice flow towards the W in the northern parts and towards the SW in the southern parts of the study area. This pattern was maintained throughout the deglaciation of the area. When extrapolating this picture to the adjacent areas, a lobate pattern appears with its centre in the Wisła Valley. It is suggested that this lobate ice front reflects an ice stream, active during the deglaciation from the maximum ice position and possibly back to the Baltic Coast.

The argumentation around the Chodzież subphase, initiated in paper II, is elaborated further. The large glaciotectonic ridges in the area, previously suggested to be the marginal ridges of the Chodzież subphase, reveal similar deformation patterns in their internal structure. They seem to have been deformed by proglacial glaciotectonic deformation by ice moving towards the S-SE. The last glacial event in the lithostratigraphy with an ice movement in that direction is the Dziembowo ice advance and the conclusion is that the large ridges were formed during the Dziembowo ice advance. No separate till bed was found inside the ridges. Instead, the Ujście till forms the uppermost till, both N and S of the ridges. In the sites located close to the ridges, ice flow was found to be parallel to the ridges. The conclusion is that the Chodzież subphase did not exist.

Discussion

Extent and timing of Ujście till

The first subject of the research project was the extent and ice flow pattern of the uppermost till unit at Ujście. Information about this has improved considerably although the question is not yet solved. The till unit clearly extends far beyond the marginal zone of the Chodzież subphase and also outside the study area. There are some observations that may provide information about the extent of the advance towards the W and the SW:

Kozarski (1962) describes a tunnel valley consisting of WSW oriented lakes W of Wałcz (Fig. 1), ending at a gate in the end moraines of the Strązno-Zawada oscillation (Kozarski, 1962) at the head of a large sandur plain. Dzierżek (1997) found a separate till bed inside the extent of the Strązno-Zawada oscillation, although he considers this till bed to be younger than the till of the Chodzież subphase. Around Czarnków (Fig. 1), Dzierżek (1997) found till from what he assumes is the Chodzież subphase, which would be equivalent to Ujście till. An esker, oriented towards the WSW, is identified SW of Lubasz on the soil map (Listkowska & Maksiak, 1977; Fig. 1).

Another esker, oriented towards the SSW on the soil map (Uniejewska & Włodek, 1978), stretches from NE of Wągrowiec to Skoki (Fig. 2). This orientation is similar to the fabrics in the Ujście till at the nearby Ruda site (Górska, 2000; paper III) and possibly also Rogoźno (Karczewski, 1963, 1965). S of Skoki, the esker ends at a suggested tunnel valley (Kozarski, 1962) oriented towards the S. The tunnel valley ends at Dąbrówki Kościelnej (Fig. 1) at the head of a large sandur in an interlobate situation (Kozarski, 1962). The western lobe is suggested to have had an ice flow towards SE. This assertion is supported by the orientation of tunnel valleys and end moraines. The eastern lobe is suggested to have had an ice flow towards the SW. This is also supported by the orientation of tunnel valleys and end moraines. Measurements of glaciotectonic dislocations also indicate that the eastern ice lobe, pushed towards the SW (Kozarski, 1962). However, the orientation of tunnel valleys, eskers, marginal moraines and sandar in the region SW of Oborniki (Fig. 1) implies a last ice flow towards the SE (Skompski, 1994). It is therefore suggested that the marginal zone of

the Ujście ice advance may be found somewhere between Rogoźno and Oborniki and that it extends SE to the area of Dąbrówki Kościelnej.

Correlation with the stratigraphy in the Wisła Valley is problematic. A similar stratigraphy to the middle Noteć River area has been noted at Wapienno (Sokołowski, 2001; Sokołowski, pers. com., 2002), with two till units, the upper unit being bipartitioned. The upper bed of the two Late Weichselian till beds described from the southern part of the lower Wisła Valley (Wysota *et al.*, 2002) is assumed to correspond to the Ujście till. In the Konin area (Fig. 1), just inside the maximum extent of the Last Weichselian ice advance, Stankowski *et al.* (1995) reports a thin biparted till deposited after 21 ka ^{14}C BP. The authors found no older Weichselian till unit in the area. Widera (2000) cites discussions about whether one or two Weichselian till beds exist in the Kleczew area but concludes that there is only one.

The Kujawy - Dobrzyń advance (Niewiarowski *et al.*, 1995; Fig. 1) recognised east of the Wisła Valley has earlier been correlated with the Chodzież subphase. The present results indicate difficulties in drawing conclusions on how the Kujawy - Dobrzyń advance manifested itself in the middle Noteć River area. However, it is clear that the formation of the glaciotectonic ridges assigned to the Chodzież subphase is not synchronous with the formation of the Kujawy – Dobrzyń ice marginal zone.

The Ujście ice advance seems to represent the Late Weichselian main stadial in the study area, and as such we would expect it to reach the outermost margin of the Weichselian glaciation. This may be true in central Poland around the Wisła Valley, but the situation seems more complicated in western Poland.

A speculative scenario would be a separate, and probably earlier, ice advance shaping the landscape SW of Poznań. This advance would then have extended to the Leszno ice marginal zone (Fig. 6a) in western Poland. During a second phase the margin of the ice would have retreated to the western part of the Poznań ice marginal zone (Kozarski & Kasprzak, 1987; Fig. 6b). Simultaneously or later, the ice flow along Wisła Valley would have moved its front further S to the maximum extent of the Weichselian ice sheets. At this point the ice would override the marginal zone from the first and second phase and have an outline as shown in Fig. 6c. Neither the Leszno nor the Poznań ice marginal zone (Kozarski, 1988) would thus be synchronous.

Assuming the cause of events outlined above, the clast lithology of the deposits from the first advance would be expected to differ from Ujście till. However, this does not seem to be the case,

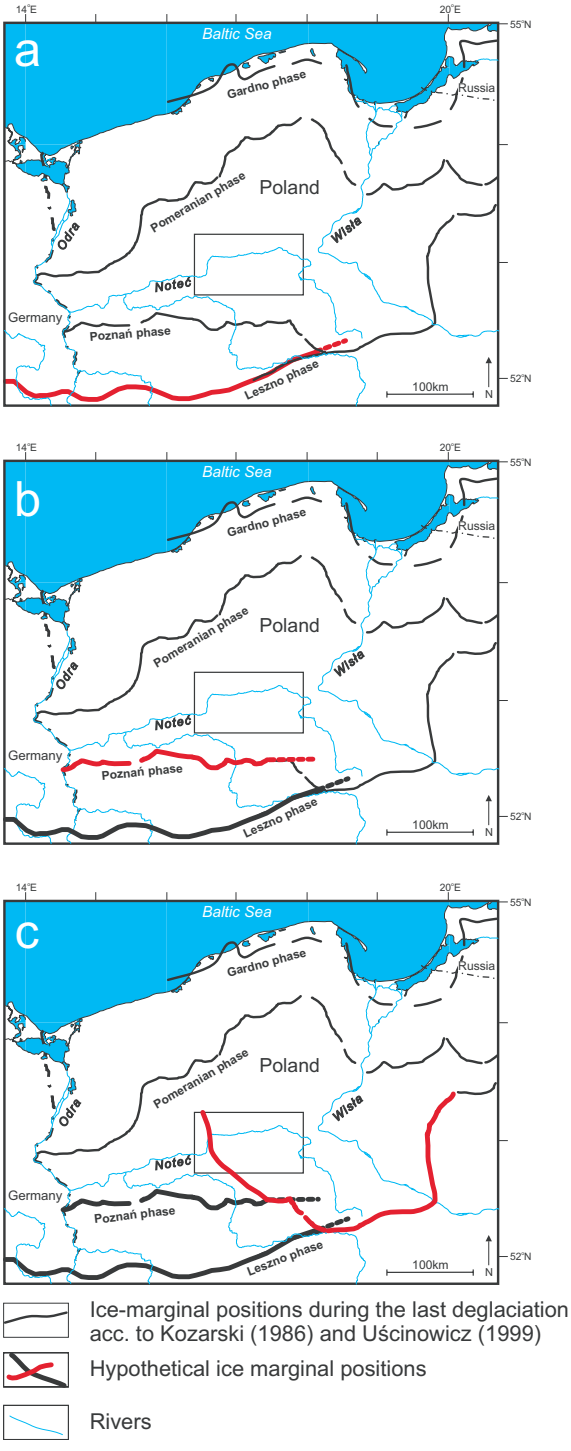


Fig 6. Speculations around the extent of, and time relations between, different ice flow events during the Late Weichselian. a) Maximum ice extent in western Poland. b) Ice marginal position after retreat to the Poznań marginal zone in western Poland. c) Ujście ice advance, representing the Late Weichselian maximum ice extent in the Wisła Valley area.

as Czerwonka & Krzyszkowski (1994) find a till similar to the Ujście till in drill cores at Bogdanowo (Fig. 1) and all the way out to the Leszno ice marginal zone (Fig. 6a) in western Poland. Consequently, the question of the extent of Ujście till is certainly far from solved.

Mechanism behind the observed ice flow pattern during the Ujście ice advance

The second aim of the research project, i.e. to find the cause of the observed ice movement pattern during deposition of Ujście till, is discussed in paper III. Ujście till seems to have been deposited by the western flank of a lobate ice front, centred in the present Wisła Valley (Fig. 7). The configuration of the ice lobe suggests that it was sensitive to the low relief topography in the region, implying a thin ice. Variations in the hydrological conductivity of the Quaternary substrate may also have influenced the ice flow pattern. The ice sheet seems to have had a lobate ice front during the deglaciation of the Wisła Valley from its maximum extent around Płock and possibly to the present Baltic Sea coast. It is suggested that the lobate ice front may represent the terrestrial termination of an ice stream following the present Wisła Valley.

Extent and timing of Dziembowo till

Knowledge of the extent and ice flow history of the Dziembowo ice advance is still fragmentary. No exposure deep enough to reach through the cover of Ujście till down into the Dziembowo till has been found S of the Noteć River Valley in the study area. In drill cores examined by Dzierżek (1997), the V1 till covers the entire study area. The lower part of the V1 till at Wolsko (Dzierżek & Olszewska, 1996) corresponds to the Dziembowo till and the upper part of the V1 till corresponds to the lower subunit of the Ujście till (Paper II).Therefore, using the extent of the V1 till as an indication of the extent of the Dziembowo till is problematic. No till unit with similar clast lithology composition has been found in drill cores further SW (Czerwonka & Krzyszkowski, 1994). However, this may be caused by the spatial variations occurring in the clast lithology composition in the till units over the distance of 50 km between Dziembowo and the closest drill core at Oborniki. The same problem would probably also occur in an attempt to use only clast lithology for correlation with the stratigraphy in the Wisła Valley (Wysota *et al.*, 2000, 2002; Makowska, 1991; Kenig, 1976) and at Wapienno (Sokołowski, 2001; Sokołowski, pers. com., 2002). At Wapienno the presence of an upper bipartate till and a lower till of presumed Weichselian age indicates that the lower till unit may correspond to Dziembowo till. The Weichselian glacial events in the southern part of the lower Wisła Valley (in the area northwest of Rzęczkowo, Fig. 1) are represented by glaciolacustrine and fluvial deposits of assumed Middle Weichselian age overlain by two till beds of Late Weichselian age (Wysota *et al.*, 2002). The upper till bed may correspond to the Ujście till and the lower till to the Dziembowo till. This would imply that the Dziembowo till is of Late Weichselian age. Another possible correlation would be to correlate the Middle Weichselian glaciolacustrine deposits to the Dziembowo till. This has some support in the TL dating in Wolsko. However, constructing an ice configuration that leaves glaciolacustrine sediments in the lower Wisła Valley and a till deposited from north-east in Wolsko would be difficult. The quality of TL dating is also difficult to assess and the Dziembowo till may well be younger than is indicated by the TL dating.

There are thus two possibilities: Dziembowo till is either Late Weichselian or Middle Weichselian. A Middle Weichselian age may correspond to the glaciations during the Świecie stadial suggested in the northern part of the lower Wisła Valley (Makowska, 1991; Wysota *et al.*, 2002) and the Middle Weichselian Ristinge stadial recognised in Denmark (Houmark-Nielsen, 1999). A Late Weichselian age could correspond to the first phase in the scenario outlined above (Fig. 6a).

The problem of dating

The chronology of the glacial deposits and landforms is a major problem in the area. No organic material suitable for radiocarbon dating has been found. The organic deposits with an Eemian flora, reported from the study area, have mostly been found in locations with no clear lithostratigraphic situation (Noryśkiewicz, 1979; Dąbrowski *et al.*, 1987; Rühle, 1954; Środoń, 1954). Organic deposits from the Weichselian glaciations are rare in the Great Poland Lowland, and are not found at all in the study area. Thermoluminescence dating (TL) has been

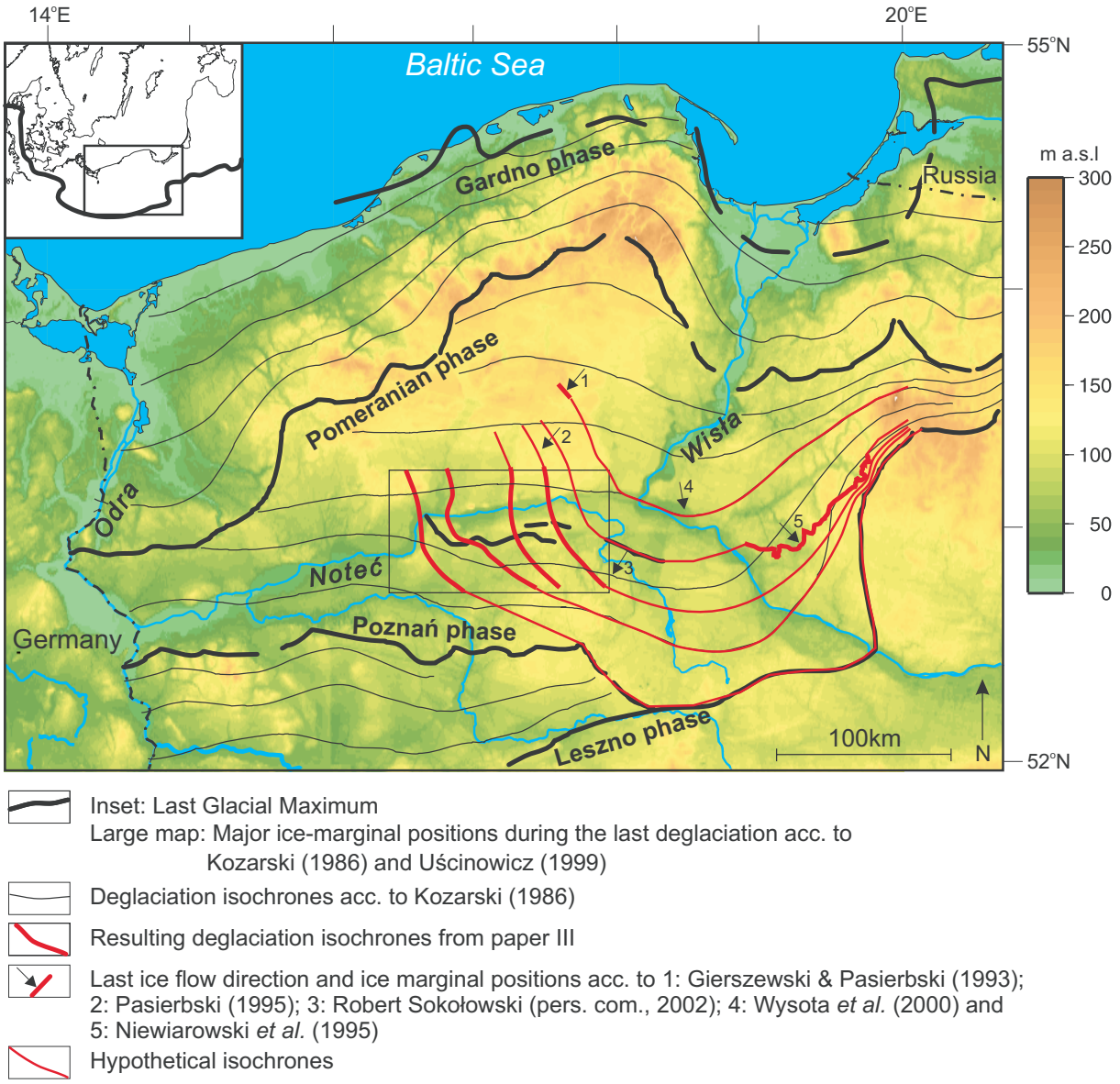


Fig 7. Map of north Poland showing the revised deglaciation pattern in the middle Notec River area and suggested correlations to the Wisła Valley region. Suggested ice marginal positions are marked with red lines and the traditional ice recession lines are marked with black. Note the discrepancy between the two reconstructions in the study area and also in surrounding areas.

attempted in the area (Dzierzek & Olszewska, 1996; Dzierzek, 1997) but the results are difficult to assess. The method relies on the bleaching of the luminescence signal at the time of deposition. It has been suggested that the signal may be reset by subglacial comminution although the validity of this process has not been confirmed (Lamothe, 1988; Forman, 1989). In spite of this, the method of dating till with TL has been extensively used in Poland (e.g. Drozdowski & Fedorowicz, 1987; Mojski, 1995; Dzierzek & Olszewska, 1996). Dating of fluvial deposits by TL relies on the bleaching of the luminescence signal by exposure to sunlight. This is problematic in glaciofluvial settings where the exposure to sunlight due to turbid water, short transport distances and fast depositional rates, may be insufficient to bleach the luminescence signal (Gemmel 1994, 1999). Insufficient bleaching would lead to an overestimation of time since deposition. Optically Stimulated Luminescence (OSL) dating may be more reliable as this requires less exposure to sunlight for the signal to reset. An attempt to improve the chronology in the area through OSL dating has been made but the results are not ready at the time of writing.

Interpretation of landforms

The use of landforms may be of great value when reconstructing the glacial history of an area. However, there are some important issues that must be considered when using landforms to interpret ice flow directions. First of all, the origin of the landform must be known. For example, an elongated ridge may be interpreted as an end moraine, oriented transverse to ice flow, or an esker or spindle shaped drumlin, oriented parallel to ice flow. There are examples in the area where opinions differ as to whether an elongated ridge is an end moraine or an esker (Kozarski, 1962, p42; Uniejewska & Włodek, 1978). Studies of the internal structures and sediments of the landforms may solve this kind of problems. This is especially important where we have a situation, as in the study area, of two approximately perpendicular ice advances shaping the landscape.

The second major issue is the time of formation of the landform. As can be seen in the example of the large ridges of the Chodzież subphase, landforms shaped by earlier events are also present in the landscape. This superposition of land systems has also been described in recent environments on Iceland and suggested for formerly glaciated areas in Denmark (Krüger, 1994). Some earlier studies in the study area consider that the push moraines were formed by readvances during the last deglaciation, but this should not be taken for granted.

The strict use of landforms in glacial reconstructions is associated with problems of landform origin, crosscutting lineations, time-relationships and chronology. Many of these problems can be solved by lithostratigraphic or kinetostratigraphic studies of the sediments and their structures. The use of lithostratigraphy and sediment studies may therefore be the way to solve problems encountered in studies of large-scale morphology with remote sensing (Boulton *et al.*, 2001, Kjær *et al.*, in press.).

Conclusions

- A detailed regional lithostratigraphy is established, encompassing the two last glacial events.
- Both glacial events probably took place during the Weichselian (Vistulian).
- The first event, the Dziembowo advance, is characterised by an initial ice advance towards the SE accompanied by glacial tectonics. Ice movement shifted towards the SW during till deposition. TL dating by Dzierżek & Olszewska (1996) places this ice advance between 84 ± 12 ka and 65 ± 10 ka BP, which could correspond to the Świecie stadial in the stratigraphy of the lower Wisła Valley (Dzierżek, 1997; Makowska, 1991). However, considering the uncertainty of TL dates on glaciofluvium, and new results in the southern part of the lower Wisła Valley (Wysota *et al.*, 2002), a Late Weichselian age is also possible.
- An ice-free period follows the Dziembowo advance as indicated by glaciofluvial deposition and windpolished clasts.
- The second and last glacial advance (the Ujście ice advance) started with an ice advance towards the WSW. The deposits (Ujście till) of the last glacial event are divided into a lower and an upper subunit.
- The lower subunit of Ujście till has a grain size composition and clast lithology that is intermediate between the underlying Dziembowo till and the overlying upper subunit of Ujście till. During till deposition, ice movement was directed towards the WSW with intense deformation and mixing with earlier deposits.
- The upper subunit of Ujście till is a homogenous, clayey, massive diamicton with a clast lithology that has a central/eastern Baltic Sea Basin signature. The ice moved directly towards W along the Noteć River Valley during deposition of the upper subunit.
- The Ujście till is the uppermost till unit of the area, present above an uncertain TL date of 65 ± 10 ka BP. Being the uppermost till unit, this till was probably deposited during the Late Weichselian.
- A lobate ice front existed continuously in the Wisła Valley during the last deglaciation from the maximum ice margin position in the Wisła Valley and probably back to the Baltic coast.
- The lobate ice front is suggested to represent the terrestrial termination of an ice stream.
- The Chodzież subphase did not exist. The glaciotectonic ridges supposed to mark its outer extent were formed during an earlier ice advance, the Dziembowo advance. The till bed assigned to the Chodzież subphase is also found outside the ridges of the presumed marginal position. In the sites located close to the ridges, ice flow was found to be parallel to the supposed ice margin.

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Svensk populärvetenskaplig sammanfattning

Nedisningar under Weichsel-istiden kring floden Noteć i nordvästra Polen

Inlandsisar är en viktig komponent i jordens klimatsystem. Deras utbredning och rörelsemekanismer styrs till stor del av klimatet samtidigt som isarna i sin tur också påverkar klimatsystemet. Genom kunskap om hur inlandsisarna växte till och smälte av under den senaste istiden kan man utvärdera och utveckla de modeller vi har över hur jordens klimat fungerar.

Denna avhandling behandlar de nedisningar som har förekommit i området runt floden Noteć i nordvästra Polen under den senaste istiden (Weichsel-istiden, 115.000-10.000 år sedan). Noteć-området ligger centralt i den del av norra Polen som blev nedisad under den senaste istiden. Det är viktigt att förstå nedisningsförloppet i detta område när man försöker rekonstruera hur hela den Skandinaviska inlandsisen fungerade. De rekonstruktioner som har gjorts för Noteć-området har dock varit motsägande och innehållit en del problem. Enligt olika teorier har det varit mellan en och fyra isframstötar i området under den senaste istiden. Det finns också olika uppfattningar om utbredningen av dessa framstötar. Ett annat svårförklarat fenomen var att den senaste isframstöten i området rörde sig mot väst. Detta avviker från den normala isrörelseriktningen som har varit mot sydsydväst. En så pass avvikande isrörelseriktning var svår att förklara med äldre teorier för hur inlandsisar rör sig.

Min forskningsuppgift har varit att undersöka utbredning och isrörelsemönster för den senaste nedisningen, d.v.s. isframstöten med det avvikande isrörelsemönstret. Ytterligare en frågeställning har varit varför isen har haft en så avvikande isrörelseriktning.

Metoden för att lösa problemet bygger till stor del på undersökningar av de moränbäddar som bildats när inlandsisarna har rört sig över området. Det man undersöker är sedimentstrukturer,

deformationsstrukturer, bergartssammansättning, partikelorientering, kornstorlekssammansättning, räfflade stenar och block m.m. Genom att studera de olika egenskaperna hos moränbäddarna kan man se hur de är avsatta, dvs om de är avsatta under isen, och i så fall hur, om de är avsatta vid kanten av isen eller om de har avsatts från efterlämnade isblock vid isens tillbakaryckning från området. Det går också att se åt vilket håll isen har rört sig. En annan viktig sak är att de olika isframstötarna efterlämnade moränbäddar med lite olika egenskaper. Det gör att det går att känna igen en viss moränbädd även på andra platser i närheten. Genom att undersöka ett antal olika platser i området kan man då se dels vilka platser en viss isframstöt har avsatt morän på och dels åt vilket håll isen har rört sig. För att komma åt att studera sedimenten måste de vara blottade, som t ex i grustag, dagbrott och vägarbeten. Totalt har jag gjort undersökningar på 12 olika platser.

Resultaten visar att det har varit två isframstötar i området under den senaste istiden. Den första isframstöten, Dziembowo-framstöten, har lämnat spår efter sig på tre av de undersökta platserna. Övriga blottningar var inte tillräckligt djupa för att det skulle gå att nå ner till den aktuella moränbädden. Isen rörde sig i ett första skede mot sydost. Under framstöten deformerade den sitt underlag och bildade höga ryggar vid iskanten. Dessa sticker nu upp mellan 15 och 70 m över omgivande terräng. I ett senare skede hade isrörelsen vridit mot sydväst varefter isen smälte bort från området.

Nästa isframstöt, Ujście-framstöten, var den sista i området och rörde sig in över området mot väst-sydväst. Yttergränsen för denna isframstöt ligger utanför undersökningsområdet, vilket innebär att utbredningen av isen, under detta skede, var mycket större än man tidigare har trott. Det är sannolikt så att denna isframstöt utgör den yttersta gränsen för den senaste istidens isframstötar i Wisła-dalen. Isrörelsemönstret under avsmältningen av den senaste inlandsisen har visat sig vara väldigt styrt av topografin i området. Isen har rört sig mot väster längs Noteć:s dalgång och mot sydväst på platåerna lite längre söderut. När man kombinerar dessa resultat med resultat från undersökningar i kringliggande områden så visar det sig att Noteć-området sannolikt har varit täckt av den västra flanken av en lobformad utbuktning från inlandsisen. Denna islob har haft sitt centrum i Wisła-dalen, ca 50 km öster om undersökningsområdet. Troligen har denna islob bildats på grund av snabbt strömmande is, en s.k. isström, som har följt Wisła-dalen. Isströmmen verkar ha varit aktiv under hela perioden för den senaste inlandsisens avsmältning från Polen, från den maximala utbredningen i Wisladalen, upp till den polska Östersjökusten. Denna nya rekonstruktion av isrörelsemönstret under isavsmältningen från området är väsentligt annorlunda mot de tidigare rekonstruktionerna från området. Dessa nya resultat kan användas till att förbättra modeller över hur den Skandinaviska inlandsisen fungerade under slutet av den senaste istiden, vilket i sin tur är viktigt när man försöker förstå sambanden mellan jordens klimat och dynamiken hos de stora inlandsisarna.

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