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Heavy minerals as a tool to reconstruct river activity during the Weichselian glaciation (Toruń Basin, Poland)

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Abstract

The heavy-mineral composition of the Weichselian fluvial successions deposited by an ephemeral meandering river and by a sand-bed braided river in the Toruń Basin (central Poland) was analysed. On the basis of a lithofacies analysis, in combination with the composition of the heavy-mineral assemblages, the fluvial processes and river-channel morphology were reconstructed. This allows determining the provenance of the fluvial deposits and the rivers' discharge regimes. A model is proposed which can explain the changes in the amount of individual minerals in the fluvial sediments of different ages under the conditions of the oscillating Scandinavian ice sheet. The model assumes that, during the ice-sheet advances, the proglacial streams supplied large amounts of heavy minerals that were less resistant to mechanical abrasion. During the main phase of the ice-sheet retreat, the distance between the ice sheet and the Toruń Basin increased, and the amount of non-resistant minerals diminished as a result of sediment reworking in proglacial rivers. Due to the unique location of the Toruń Basin at the front of the Scandinavian ice sheet during the Weichselian glaciation, the heavy–mineral assemblages in the fluvial deposits form a valuable tool for the recognition of the ice-sheet extent.

Key words: heavy minerals, ice-marginal valley, river-discharge regime, channel-pattern transformation, Toruń Basin, Weichselian

1. Introduction

Fluvial successions from the Weichselian glaciation were deposited under changeable climatic conditions, which influenced the river-channel patterns (Kasse et al., 1995, 2007; Vandenberghe, 1995, 2001, 2002; Van Huissteden & Kasse, 2001; Van Huissteden et al., 2001; Zieliński, 2007). The transformation of these patterns was controlled mainly by the climatic warming or cooling, or by the intensity and seasonal distribution of the precipitation. These transformations took place in the form of changes between low- and high-energy braided rivers or ephemeral anastomosing and meandering rivers (Vandenberghe, 1995, 2002, 2003; Krzyszkowski, 1990, 1995, 1996; Huisink, 2000; Mol et al., 2000; Zieliński, 2007; Weckwerth, 2013). One of the direct causes of the river transformations was the expanding or diminishing permafrost. The permafrost extent affected the sediment supply to the fluvial systems by enhancing or reducing the surface runoff (changes in soil permeability), and controlled the river incision or aggradation rate (Vandenberghe, 1995, 2002, 2003; Kasse et al., 2003; Busschers et al., 2007).

This directly influenced the composition of the mineral assemblages in the fluvial deposits, which reflect the geological structure

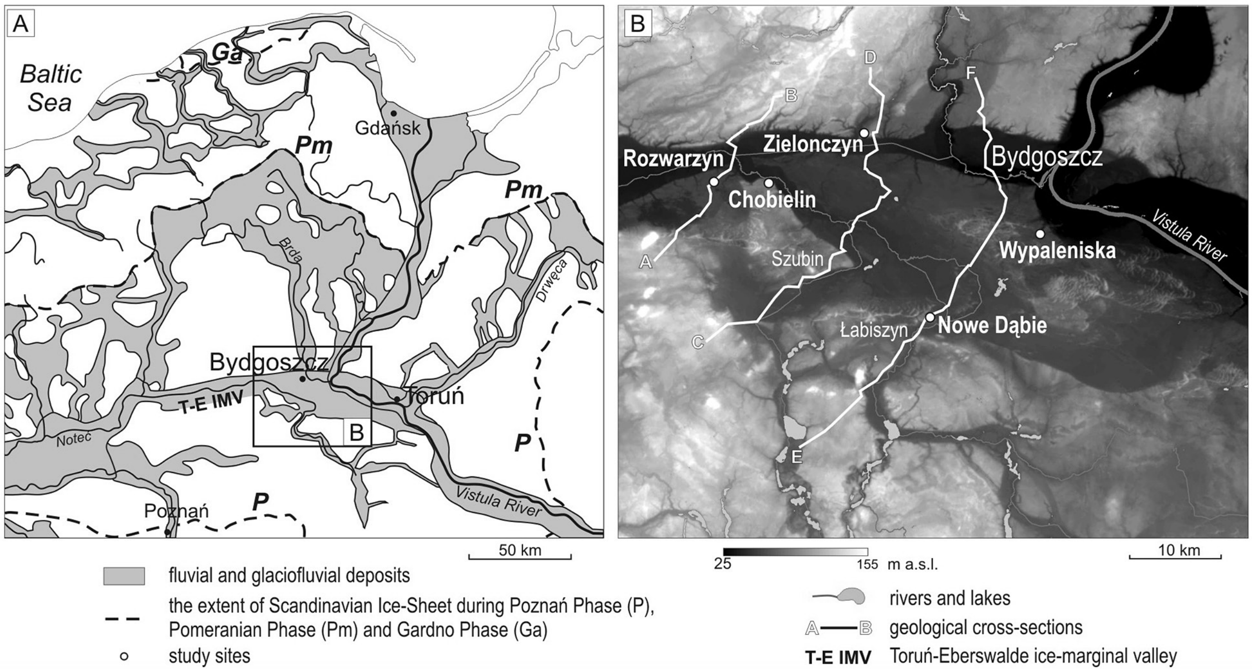

Fig. 1. Location map.
A: Position of the Toruń Basin in northern Poland, showing the extent of the Scandinavian ice sheet during several phases of the Weichselian glaciation.
B: Detailed map showing the locations of the study sites and the geological cross-sections.

of the catchment area undergoing weathering, river erosion and denudation (Mol, 1997; Morton & Hallsworth, 1999; Lee et al., 2004; Marcinkowski & Mycielska-Dowgiałło, 2013). Besides, the type of the river-channel pattern controlled the efficiency of fluvial transport and the transport mode; it also influenced the type of channel macroforms and river erosion. The nature of fluvial processes controlled by climatic factors consequently reflect the fluvial architecture and the petrographic composition of fluvial deposits as an effect of physical sorting and mechanical abrasion of heavy-mineral grains during transport (Lowright et al., 1972; Krzyszkowski, 1990, 1995, 1996; Fletcher et al., 1992; Morton & Hallsworth, 1999; Busschers et al., 2007; Komar, 2007; Ludwikowska-Kędzia, 2013; Wachecka-Kotkowska & Ludwikowska-Kędzia, 2013; Woronko et al., 2013).

The processes of fluvial deposition, transport and erosion (e.g. deep scouring), changed the composition of mineral assemblages in the fluvial deposits, modifying the original provenance signal that depends on the geological structure of the catchment area and the lithology of the basement of the river channel (cf. Van Huissteden, 1990; Morton & Hallsworth, 1999; Busschers et al., 2007; Popp et al., 2007; Morton et al. 2013). In the case of sedimentary basins, which may have been fed by meltwaters of proglacial streams during the Weichselian glaciation, the mineral composition of the fluvial deposits may have been modified by material from glacial sources. Due to the extent of the Scandinavian ice sheet, climatically controlled sediments – and thus source-related lithological variations – are to be expected in the fluvial deposits of the Weichselian glaciations (Church, 1988; Vandenberghe, 1995; Cordier et al., 2006). This means that the sediment supply to the sedimentary basins was dominated by proglacial rivers during the advance of the ice sheet, whereas it was dominated during ice retreat by the rivers of an arctic (subarctic) nival regime.

1.1. Objectives

Recognising one of these two types of river-discharge regimes in front of the ice sheet provides the possibility of identifying the sediments deposited within an ice-marginal valley during the Pleistocene (see Toucanne et al., 2009; Westaway & Bridgland, 2010; Weckwerth et al., 2011; Weckwerth, 2013). The present contribution is therefore aimed to relate the genesis of the various lithofacies of the channel environment during the Weichselian glaciation with the composition of the mineral assemblages in the fluvial deposits. For the purpose, we focus on the following questions: (1) how the composition of heavy-mineral assemblages reflects the variations in the river current energy; (2) whether (and if so: how) channel-pattern changes (including changes in channel bedforms and macroforms) correspond to the changes in the petrographical composition of fluvial deposits; and (3) whether the changes in the petrographical composition can be used for determining the river-discharge regimes controlled by climatic changes or by fluctuations in the extent of the ice sheet.

The stratigraphical position of the fluvial successions is discussed with respect to the revised architectural elements of the morphology of the river channels which existed during the Weichselian glaciations in the Toruń Basin (central Poland, Fig. 1). This was aimed to result, together with the distribution of heavy-mineral provenances, in an improved palaeogeographical concept of fluvial systems controlled by climate changes and oscillations of the Scandinavian ice sheet.

1.2. Geological setting

The Toruń Basin is the eastern part of the Toruń-Eberswalde ice-marginal valley where the lowest sections of the present-day river valleys, like those of the Vistula River, the Brda and the Drwęca, merge (Fig. 1A). The development of this basin was predestined by the earlier existing valleys and glacial basins which originated before the Leszno phase of the Weichselian glaciation, i.e. before 21 ka ago (Makowska, 1979, 1980; Weckwerth, 2010, 2013). These basins and fossil valleys are mainly filled up by Pleistocene glaciofluvial successions and by deposits of the Eemian and Mazovian (Holsteinian) interglacials, often reaching thicknesses of over 100 m and cutting the top of the Neogene and Palaeogene deposits down to 20–60 m below sea level (Fig. 2).

The deposition of the fluvial successions during the Eemian and Mazovian interglacials was mainly a consequence of the development of the pre-Noteć, pre-Warta and pre-Vistula river systems (Lindner et al., 1982; Makowska, 1979, 1980; Brykczyński, 1986; Weckwerth, 2010). At the time of these interglacials, the main river valleys developed in the southern part of the Toruń Basin and ran parallel to its axis (Fig. 2). The river erosion which took place at the beginning of the Eemian almost totally removed the deposits of the Saalian glaciation and significantly reduced the thickness of the Mazovian fluvial deposits (Fig. 2). Due to this, the deposits of the Eemian rivers, which represent three sedimentation cycles of meandering rivers (Makowska, 1979), fill up most of the main fossil valleys along the southern part of the Toruń Basin (Fig. 2). The fluvial and glaciofluvial successions of the Weichselian glaciation that are located above the Eemian deposits build lithostratigraphic units which are separated by tills or by glaciolacustrine sediments.

During the early Weichselian, the first fluvial lithostratigraphic unit was deposited: the Lower Vistula Formation (Makowska, 1979, 1980; Wysota, 2002); the fluvial deposits of the Rzęczkowo Formation date from the middle Weichselian (Wysota, 2002; Wysota et al., 2009; Weckwerth et al., 2011), whereas the deposition of the fluvial Zielonczyn Formation took place 28–21 ka ago (Weckwerth et al., 2011; Weckwerth, 2013). The deposition of the Lower Vistula Formation was a continuation of the sedimentation by Eemian meandering rivers (Makowska, 1980; Wysota, 2002). The fluvial deposits of the Rzęczkowo and Zielonczyn Formations in the Toruń Basin represent rivers (with various channel patterns) which flowed towards the West (Wysota et al., 1996; Wysota, 2002; Molewski, 2007; Weckwerth et al., 2013; Weckwerth, 2013). The fluvial successions in the lower and middle section of each formation (Lower Members) were deposited mainly by ephemeral meandering rivers or by occasional sheetfloods, whereas their upper parts (Upper Members) are built of braided–river deposits

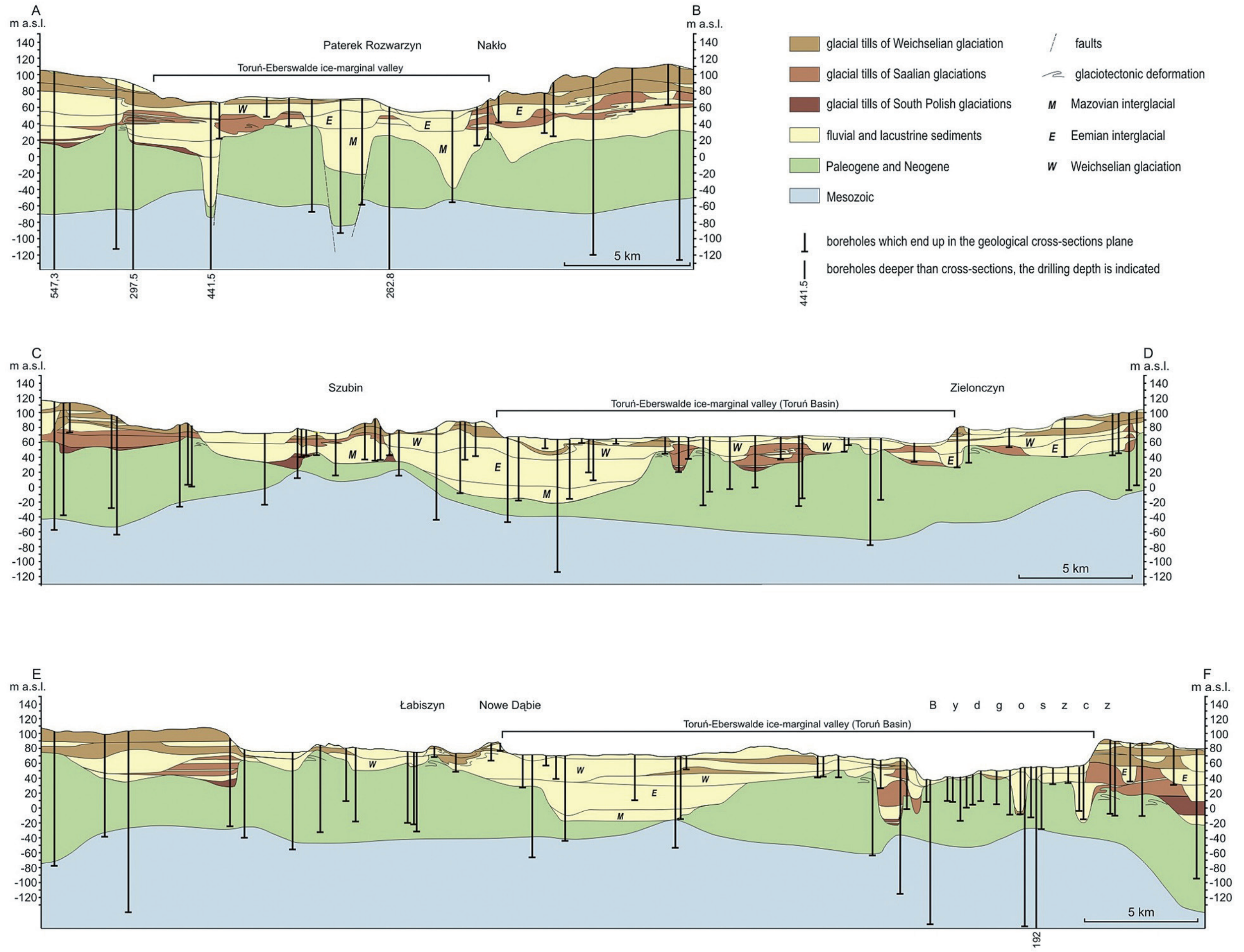

Fig. 2. Geological cross-sections in the western part of the Toruń Basin. Adapted from Weckwerth (2010).

with channels dominated by transverse bars (Wysota, 2002; Weckwerth, 2013).

During the retreat of the Weichselian ice sheet, from about 18 ka ago, the Toruń Basin was the initial section of the Toruń-Eberswalde ice-marginal valley (T-E IMV, Fig. 1). Meltwater streams, together with the water of the Vistula River and the Noteć, ran through this ice-marginal valley towards the West (Galon, 1968; Niewiarowski, 1969; Kozarski, 1988; Weckwerth, 2010). Consequently, fluvial deposits are present in the Toruń Basin as well as forms originated after the retreat of the Weichselian ice sheet, i.e. ice-marginal terraces built of sands and gravels deposited by braided rivers (the Noteć Formation). These rivers formed through merging of proglacial streams fed by the ice sheet and by nival regime rivers which came from the South.

2. Methods

The lithofacies characteristics of the fluvial sediments were analysed by identifying and describing their structural and textural properties. The lithofacies of the fluvial units were combined to lithofacies associations which genetically correspond with their depositional sub-environments and environments (Miall, 1978). This analysis applied lithofacies and lithogenetic codes (Table 1).

The grain-size distribution of the fluvial sediments was determined by sieving at 1-φ intervals, whereas the silt and mud fractions were measured with a laser particle-size analyser (Analysette 22), at 0.25-φ intervals. The grain-size classification follows the scale proposed by Udden and modified by Wentworth (1922). The statistical parameters of the grain-size dis-

Table 1. Symbols of lithofacies and codes for channel bedforms and macroforms (after Miall, 1978, 2006; Eyles et al., 1983; Zieliński, 1995, 1998; Zieliński & Pisarska-Jamroży, 2012, modified by the present author)

Lithofacies code		Lithogenetic code
Textural symbols	**Structural symbols**	
D – diamicton	m – massive	GL – glacial deposition
G – gravels	h – horizontal stratification, lamination	GB – gravelly bedforms and bars
S – sands	l – low-angle cross-stratification	SP – scour-pool infill, scouring channel
F – silt and/or mud	t – trough cross-stratification	CC – chute channel
D – diamicton	p – planar cross-stratification	UP – upper plane bed
	i – large-scale inclined stratification	SB – sandy bedforms
	r – ripple cross-lamination	FM – transverse bars
	w – wavy lamination	LM – side bars, point bars
	e – scour infill	OF – overbank forms: crevasse splays and sand sheets

tribution were determined on the basis of the formulas by Folk & Ward (1957).

The heavy minerals were analysed for 36 samples of sandy deposits. The samples were treated with HCl and HNO_3 to remove carbonates, iron oxides and organic components. From the 0.1–0.25 mm fraction, separated by sieving, at least 300 grains were prepared under gravity in a solution of sodium polytungstate (density 2.9 g cm^{-3}). The heavy-mineral samples were dried and subsequently rinsed with distilled water and a solution of acetic acid. The thus obtained heavy minerals were mounted under Canada balsam for optical identification with a polarising microscope. Non-transparent and transparent minerals were distinguished. The transparent minerals include amphibole (AMP), pyroxene (PYR), biotite (BIO), chlorite (CHL), epidote (EPI), garnet (GAR), tourmaline (TOU), zircon (ZIR), rutile (RUT), titanite (TIT), kyanite (KYA), staurolite (STA), andalusite (AND), sillimanite (SIL), apatite (APA), topaz (TOP), corundum (COR), glauconite (GLA) and unidentified minerals (UNM). The contents of the listed heavy minerals were determined in the group of transparent minerals. The identification of the minerals was based on their optical characteristics (Mange & Maurer, 1992). For a limited group of minerals the mineralogical coefficient, NR/R, was determined, which is the ratio between the total amount of minerals less resistant to physical abrasion and chemical weathering (AMP, PYR, CHL, BIO) to the sum of the minerals that are very and medium-resistant to weathering (EPI, GAR, TOU, CIR, RUT, TIT, KYA, STA, AND, SIL APA, TOP; Racinowski, 1995, 2000; Marcinkowski, 2007).

3. Lithofacies and heavy-mineral assemblages of the Weichselian fluvial sediments

3.1. Rzęczkowo Formation

The Rzęczkowo Formation is divided in a lower part (Lower Member) and an upper part (Upper Member). Both members have been investigated.

3.1.1. Lower Member

The Lower Member of the Rzęczkowo Formation is represented by fine-grained sands at the Chobielin site. This member includes lithofacies associations dominated by low-angle cross-bedded sands (lithofacies Sl). This lithofacies is interbedded with ripple cross-laminated sands (lithofacies Sr), scour infillings (lithofacies Se) and by massive sands (lithofacies Sm).

The Lower Member of the Rzęczkowo Formation at the Chobielin site can be divided into two parts on the basis of the range of the median grain diameter (d_{50}). The lower part occurs at the depth of 9–5.6 m, while the upper part is present at a depth of 5.6 to 1.7 m (Fig. 3). The lower part consists of fine-grained and well (sporadically moderately well) sorted sands with an average median grain diameter d_{50} of 0.14 mm. The sands in the upper part of the Lower Member are

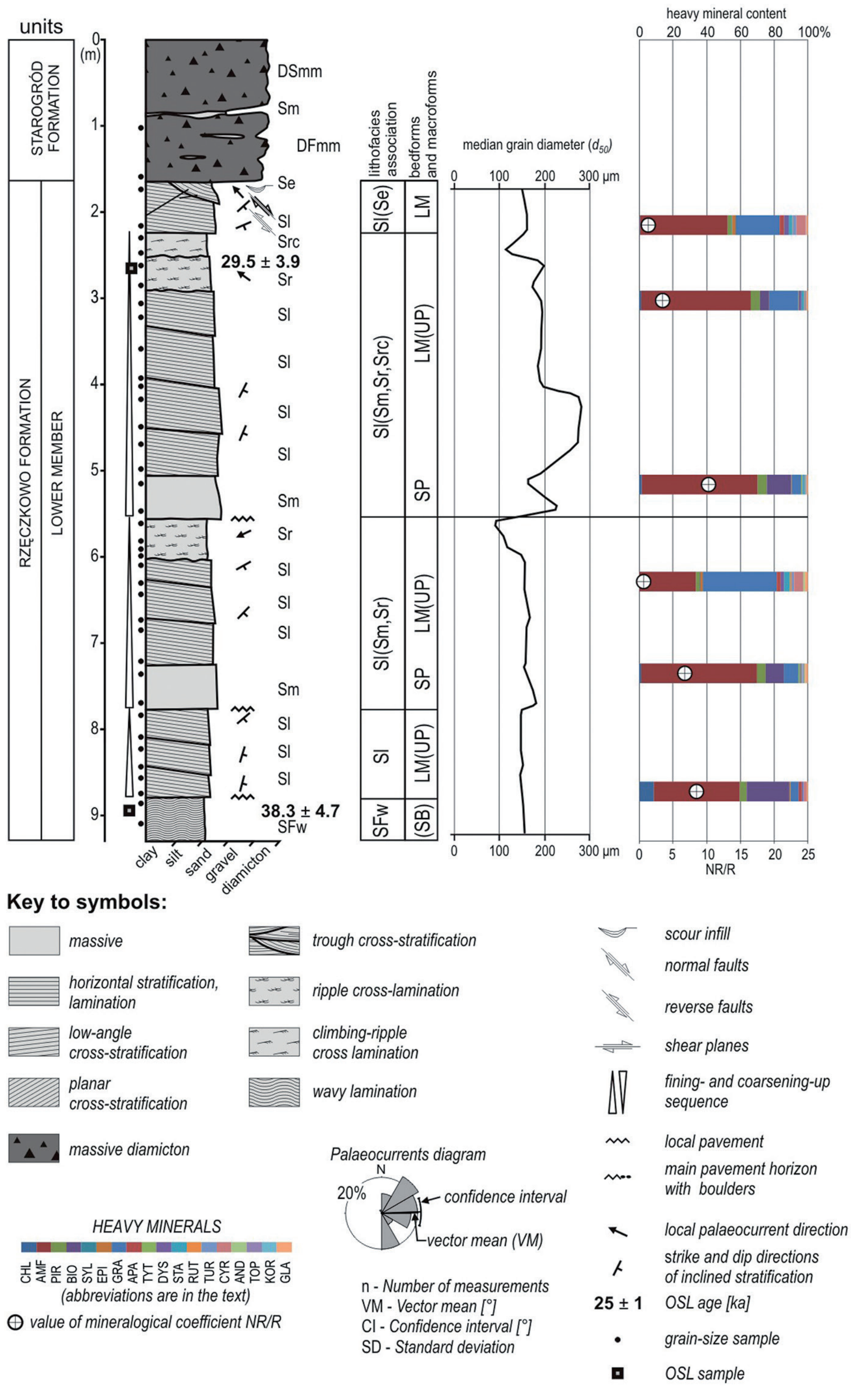

Fig. 3. Lithofacies log of the Chobielin site. The legend applies also to Figures 4–8.

coarser (with an average value of d_{50} of 0.19 mm), and they are only moderately sorted. Both parts are normally graded and are characterised by a decreasing percentage of amphibole in the lower and in upper parts (from 51% to 34% and from 69% to 52%, respectively), biotite (39%→25%→11%→0.3% and 15%→5%→0%, respectively) and pyroxene (from 5% to 2% and from 6% to 2%, respectively). Upwards in the lower and in the upper parts of this member the amount of garnet increases (2%→5%→8%→44% and 6%→17%→26%, respectively). These minerals do not show a significant diversity in their

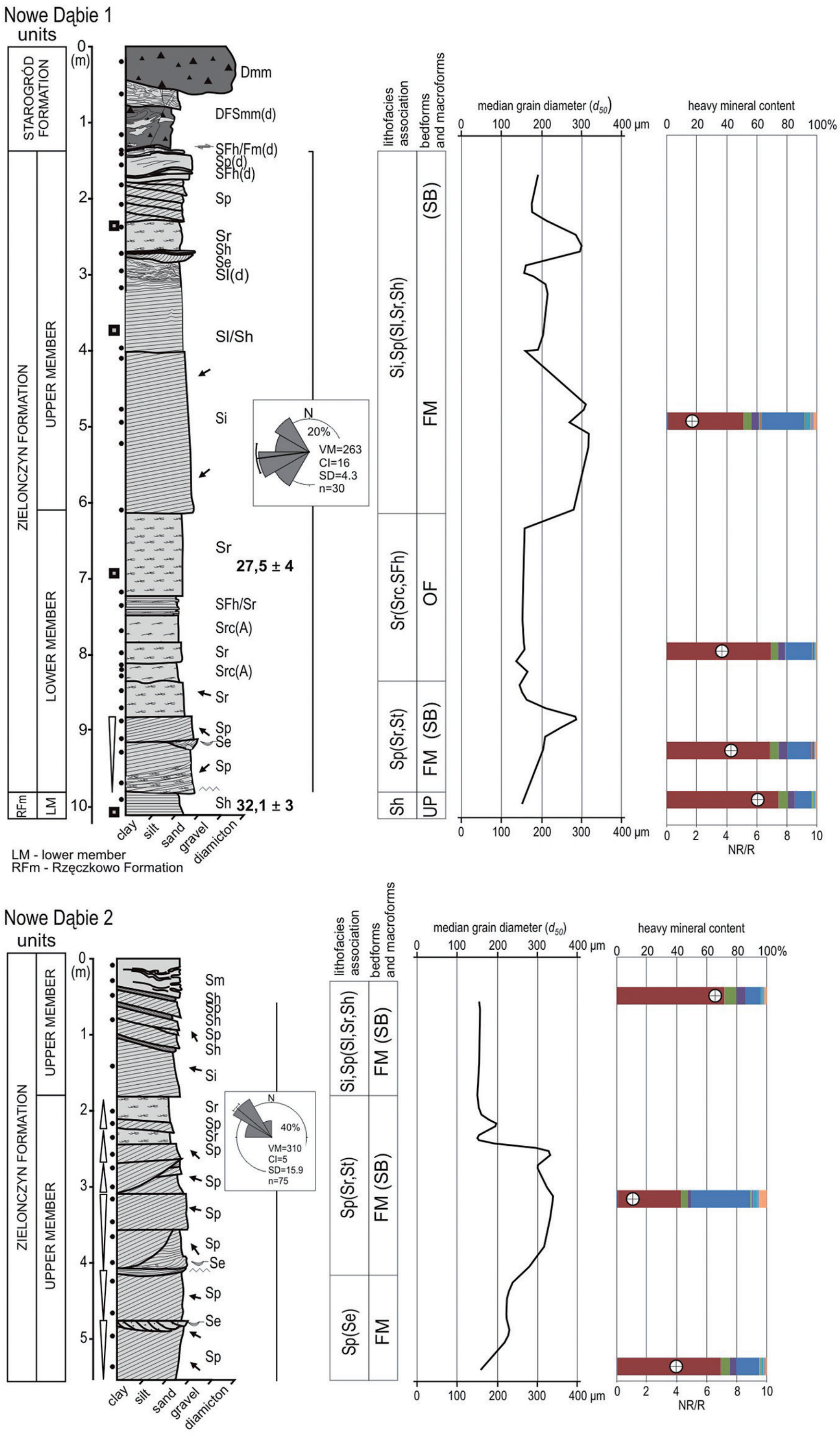

Fig. 4. Lithofacies log of the Nowe Dąbie site. For legend, see Figure 3.

grain sizes, but the minerals more resistant to weathering are poorly rounded. In the upper part of this member, the grains of the individual species of heavy minerals are smaller and more poorly rounded.

The Lower Member of the Rzęczkowo Formation was also found (at a depth of about 10 m) at the Nowe Dąbie site (Fig. 4). It consists of well-sorted, horizontally stratified fine-grained sands (lithofacies Sh), the median grain diameter of which is 0.15 mm (Fig. 4). These sediments are clearly dominated by amphibole (75%) over garnet (11%), pyrite (6%) and biotite (5%; Fig. 4). The amount of the remaining individual heavy-mineral species is less than 1%.

3.1.2. Upper Member

The Upper Member of the Rzęczkowo Formation is exposed at the Wypaleniska and Zielonczyn sites (Figs 5 and 6).

At the Wypaleniska site, it consists of thick lithofacies of fine- and medium-grained planar cross-stratified sands (Sp, SGp) with an admixture of fine gravel ($0.17<d_{50}<0.40$ mm; Fig. 5). These deposits are moderately to well sorted. The garnet content significantly decreases above the Lower Member of the Rzęczkowo Formation, from 50% to 15%; the amphibole percentage increases from 34% to 75% and that of biotite from 3% to 13% (Fig. 5). The amount of pyroxene increases from 1% to 6%. The content of the other individual heavy-minerals species does not exceed 2.8%.

At the Zielonczyn site, only the uppermost part of the Upper Member is present (Fig. 6). It is represented by well and moderately sorted fine-grained sands (d_{50} = 0.15 mm) with horizontal stratification (lithofacies Sh), at a depth of 22–23 m below the present-day surface. These sediments are overlain by fine-grained (d_{50} = 0.26 mm) and moderately sorted cross-stratified sands (lithofacies Sp) in which the heavy minerals are predominately angular. These are dominated by large grains of species less resistant to mechanical abrasion (amphibole 65–73%, pyroxene 3–7%, biotite 1–6%). These minerals, especially the amphiboles, are strongly weathered. The garnet content is 7–10%, epidote constitutes up to 4%, while the content of kyanite, tourmaline, zircon and andalusite is about 2% each.

3.2. Zielonczyn Formation

The Zielonczyn Formation is also subdivided in a Lower Member and an Upper Member, which both have been investigated.

3.2.1. Lower Member

At the Zielonczyn site, the Lower Member of the Zielonczyn Formation is 19.5 m thick (Fig. 6). Its basal part is built of planar cross-stratified and poorly sorted sandy gravel (lithofacies GSp; d_{50} = 1.77 mm), and overlie the pavement which was left after the top of a diamicton layer (the Zielonczyn till) had been eroded (Weckwerth et al., 2011). Above the GSp lithofacies ripple cross-laminated fine-grained sands occur (lithofacies Sr; d_{50} = 0.15 mm). These deposits are overlain by fine- and medium-grained sands and form fining-upward lithofacies associations, Sl,Sm(Se), Sl(Sr) and Sl(Sr,Se) (with d_{50} decreasing from 0.17 to 0.15 mm). Their basal parts are built of massive and fine-grained sands (lithofacies Sm, $0.15<d_{50}<0.16$ mm). The low-angle cross-stratified and well or moderately sorted fine-grained sands (Sl) occupy the middle part of each lithofacies association. These deposits are overlain by ripple cross-laminated sands (lithofacies Sr) or by sandy scour infillings (lithofacies Se) (Fig. 6).

The lithofacies Sl and Sr at the Zielonczyn site are time-equivalent with the deposits of the Lower Member of the Zielonczyn Formation at the Rozwarzyn site (Fig. 7) (Weckwerth, 2013). They are represented by horizontally stratified sands (lithofacies Sh) and ripple cross-laminated sands (lithofacies Sr). The median grain diameter (d_{50}) ranges from 0.15 to 0.16 mm.

The upper section of the Lower Member is built of lithofacies associations Sr,Sh(Sm) and Sl(Sh,Sr) (Zielonczyn site; Fig. 6). The first association is dominated by fine-grained and ripple cross-laminated sands (lithofacies Sr) with a thickness of about 2 m. These sediments are overlain by massive sands (lithofacies Sm) or by horizontally stratified sands (lithofacies Sh). Lithofacies association Sl(Sh,Sr) consists of fine-grained and low-angle cross-stratified sands (lithofacies Sl) interbedded with ripple cross-laminated sands (lithofacies Sr) or with horizontally stratified sands (lithofacies Sh).

The heavy–mineral grains in the Lower Member are well-sorted and poorly rounded. In the basal part of the Lower Member at Zielonczyn dominate amphibole (43%) and garnet (34%) over kyanite (5%), zircon (4%), pyrite

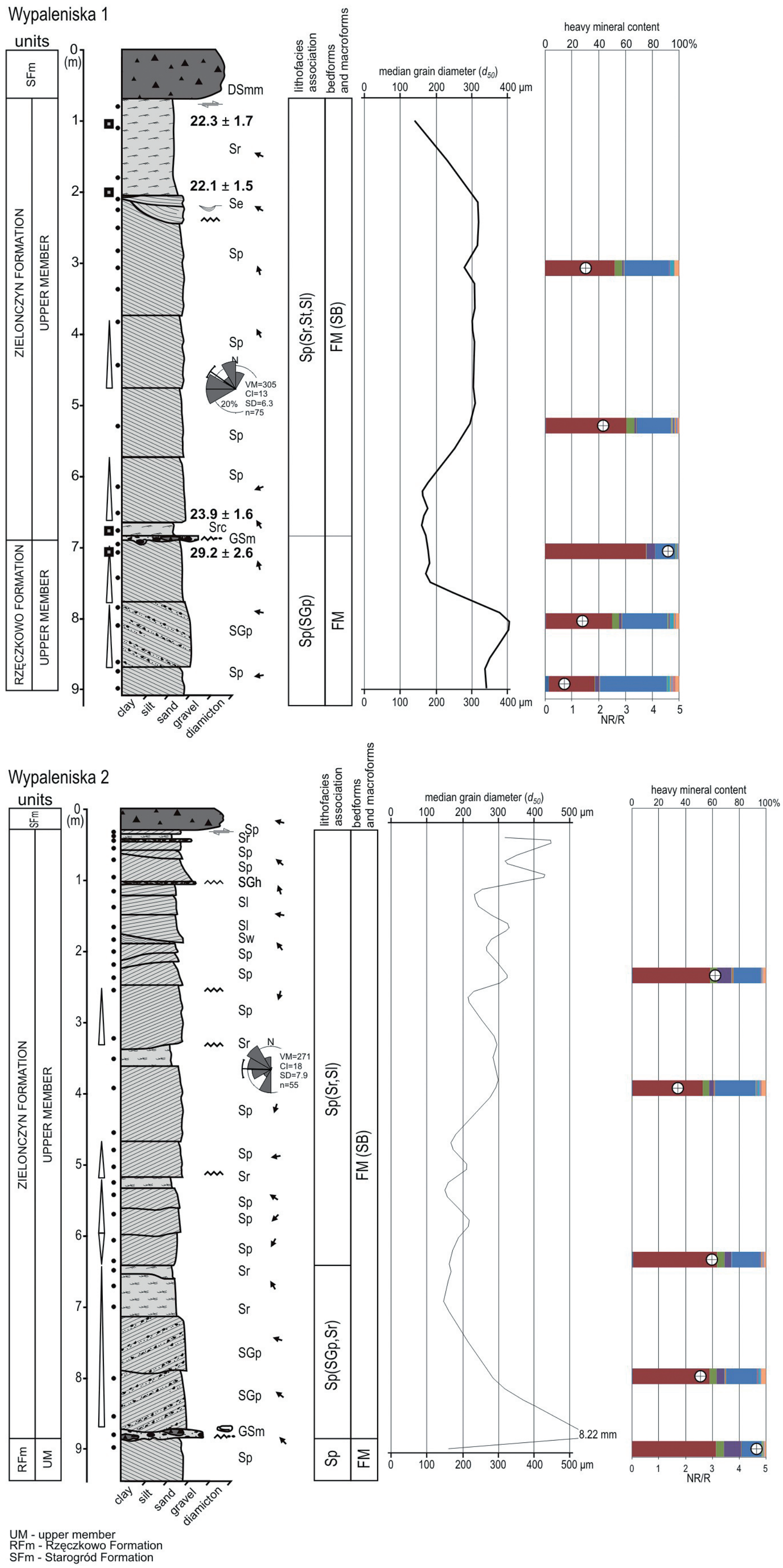

Fig. 5. Lithofacies log of the Wypaleniska site. For legend, see Figure 3.

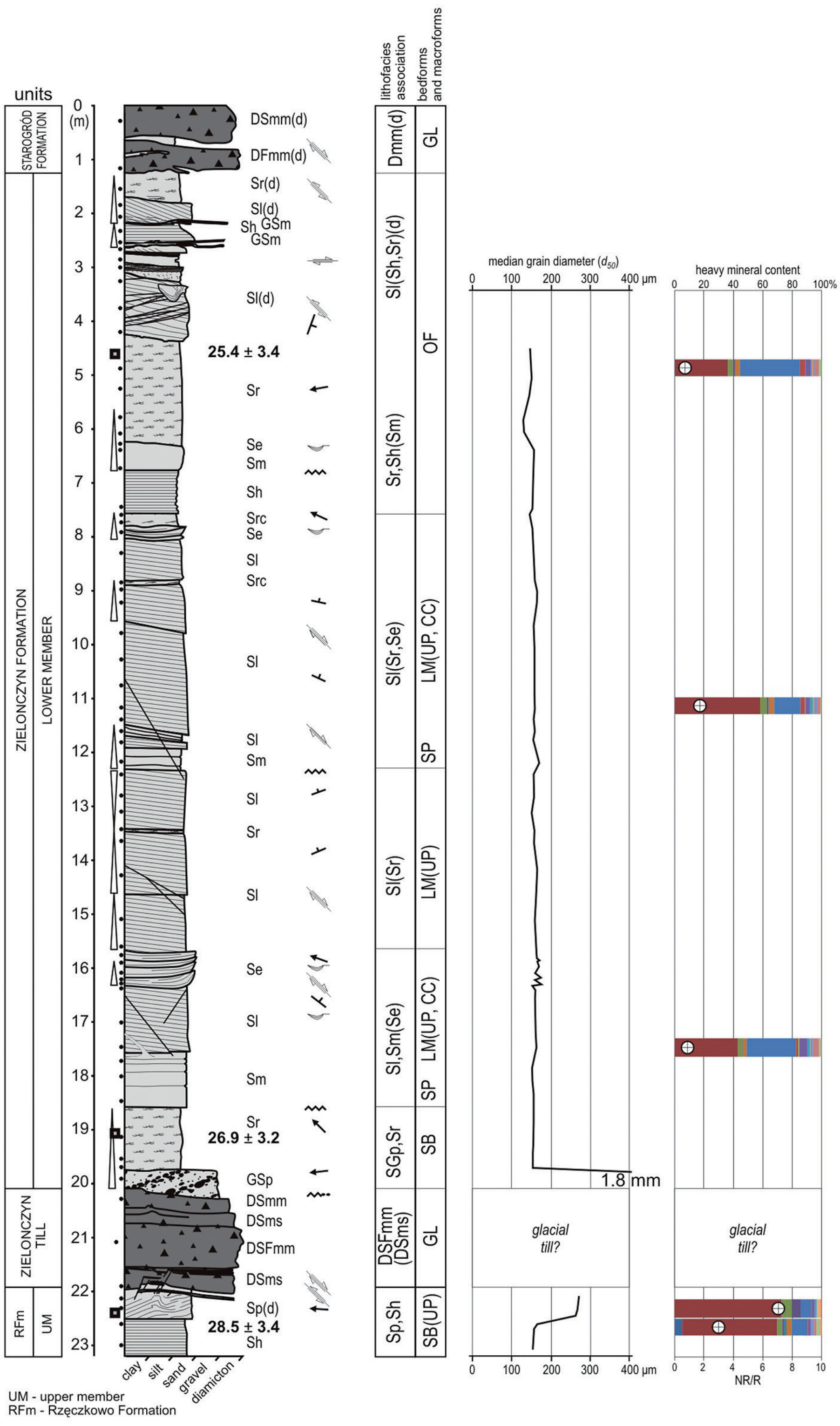

Fig. 6. Lithofacies log of the Zielonczyn site. For legend, see Figure 3.

and epidote (about 3% each), apatite and staurolite (about 2% each), tourmaline (1.5%) and andalusite (1.2%). The amount of the remaining individual mineral species does not exceed 1% (Fig. 6).

In the middle part of the Lower Member, the content of amphibole, pyroxene and biotite increases (58%, 4% and 1.3%, respectively) whereas that of garnet decreases (up to 18%). A similar strong dominance of amphibole

(73%) over garnet (13%) is present at the Rozwarzyn site. There, the content of pyroxene (6%), kyanite (3%) and biotite (2%) is also insignificant. The amount of the individual other heavy-mineral species does not exceed 1%.

In the upper part of the Lower Member at Zielonczyn, a significant decrease in the content of amphibole (36%) and garnet (41%) occurs. The amount of kyanite is 4%; apatite and pyroxene constitute 3.5% each, zircon and epidote 3% each, and biotite and tourmaline approx. 1% each.

3.2.2. Upper Member

The deposits of the Upper Member of the Zielonczyn Formation are exposed at Nowe Dąbie (Fig. 4), Wypaleniska (Fig. 5), Rozwarzyn (Fig. 7) and Paterek (Fig. 8). They are dominated by planar cross-stratified sands (lithofacies Sp) (Figs 5, 7 & 8) and sands with inclined stratification (lithofacies Si) the thickness of which may exceed 2 m (Figs 4 and 7).

At the Nowe Dąbie site they form lithofacies association Sp(Sr,St) built of fine- and medium-grained sands ($0.15<d_{50}<0.29$ mm). They are interbedded with scours infillings (lithofacies Se) or with ripple cross-laminated sands (lithofacies Sr). These sediments are overlain by lithofacies association Sr(Src,SFh), which consists of fine-grained sands ($0.14<d_{50}<0.17$ mm) that are interbedded with lithofacies association Sp(Sr,St) which has a thickness of 2.2 m (profile Nowe Dąbie 2, Fig. 4), and which is built of medium-grained sands ($0.29<d_{50}<0.34$ mm) turning at the top into fine-grained sands ($0.15<d_{50}<0.19$ mm).

The Upper Member at the Nowe Dąbie site also includes lithofacies association Si,Sp(Sl,Sr,Sh) (Fig. 4). Its main part consists of a fine- and medium-grained sandy lithofacies with inclined stratification (Si); it has a thickness of over 2 m (profile Nowe Dąbie 1: $0.16<d_{50}<0.31$ mm; profile Nowe Dąbie 2: $0.15<d_{50}<0.16$ mm). These deposits are overlain by planar and low-angle cross-stratified sands (lithofacies Sp, Sl), which are interbedded with sands with horizontal stratification (lithofacies Sh).

The heavy-mineral composition of the lower part of the Upper Member at the Nowe Dąbie site is dominated by amphibole (69%; Fig. 4). The other mineral species have lower contents (garnet 15–18%, pyroxene and biotite 5–6% each). In the middle part of the Upper Member, amphibole decreases to 42–51%, while garnet increases to 29–39%. The sands building the top part of the Upper Member again include more amphibole (72%) and contain less garnet (10%; profile Nowe Dąbie 2, Fig. 4). The amount of pyroxene (8%) and biotite (6%) increases here as well.

The lithofacies of the Upper Member at the Wypaleniska site are dominated by fine- and medium-grained planar cross-stratified sands ($0.17<d_{50}<0.39$ mm, lithofacies Sp; Fig. 5). A second lithofacies consist of ripple cross-laminated sands (lithofacies Sr) and wavy laminated fine-grained sands (lithofacies Sw), or trough and low-angle cross-stratified sands (lithofacies St and Sl, respectively). The heavy-mineral composition of lithofacies Sp is dominated by amphibole, the content of which in the basal and middle parts of this member at Wypaleniska is higher than in its upper part (58–63% and 52–58%, respectively; Fig. 5). Garnet ranges from 21% to 31%. This upper part contains low pyroxene and biotite percentages (1–10%). The other individual heavy-mineral species do not exceed 1.5%.

At the Rozwarzyn site, the Upper Member is represented by medium- and fine-grained sands with planar cross-stratification and inclined stratification (lithofacies Sp and Si, respectively) (Fig. 7). These sediments form coarsening-upward sequences which show an upward increase in the content of amphibole (from 47% to 71%), pyroxene (from 5% to 6%) and biotite (from 3% to 12%). The garnet percentage, in contrast, decreases from 38% to 8%. The kyanite amount slightly increases (up to 2%), while the remaining individual heavy-mineral species do not exceed 1%.

At the Paterek site, the deposits of the Upper Member are dominated by medium-grained planar cross-stratified sands ($0.40<d_{50}<0.54$ mm, lithofacies Sp; Fig. 8). Locally, they are interbedded with fine-grained sands ($0.15<d_{50}<0.40$ mm) with ripple cross-lamination (lithofacies Sr) or by sands of scours infillings (lithofacies Se). The heavy-mineral composition in lithofacies Sp is dominated by

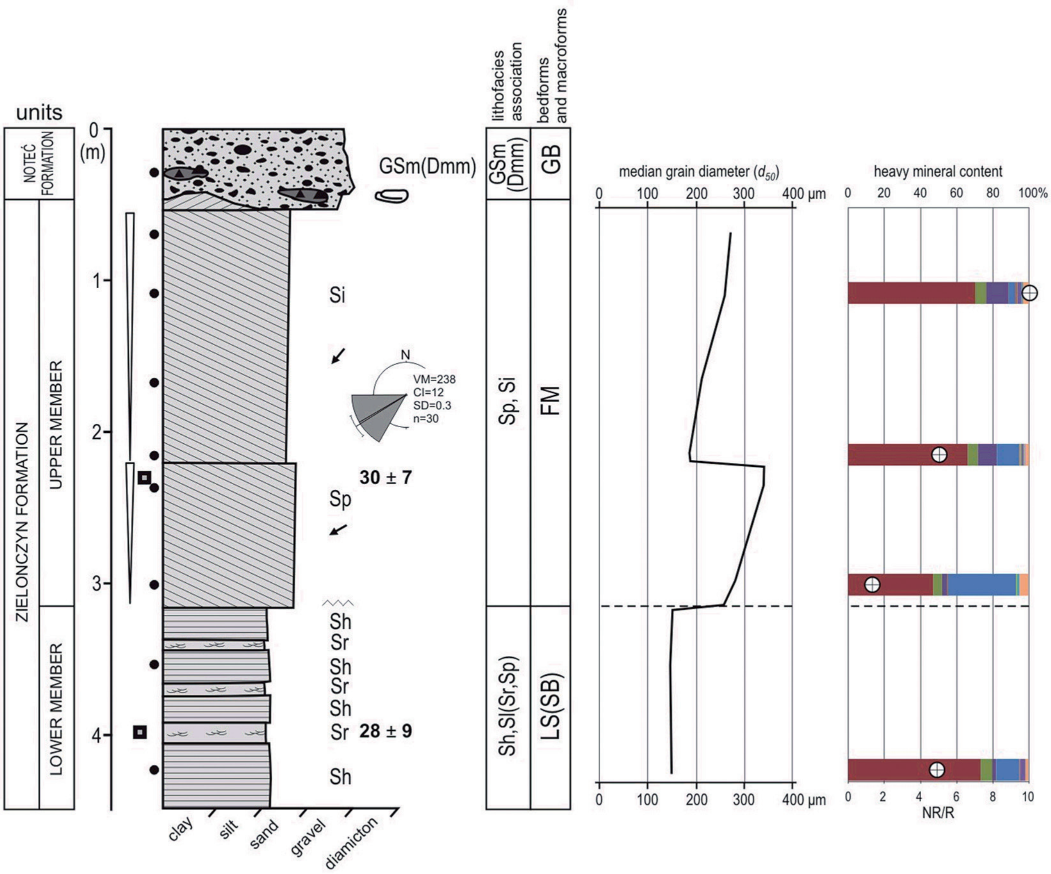

Fig. 7. Lithofacies log of the Rozwarzyn site. For legend, see Figure 3.

amphibole (50–60%), while the garnet constitutes only 21–35%. Above the Sp lithofacies, a gradual increase of the amphibole content occurs at the expense of garnet. A similar increase is shown by biotite (from 2% to 6%) and pyroxene (from 5% to 6%). The amount of the remaining individual heavy minerals species is lower than 1.5%. Lithofacies Sp is overlain by fine-grained sands with horizontal stratification ($0.17<d_{50}<0.24$ mm, lithofacies Sh). These deposits are dominated by amphibole (61%) and garnet (22%; Fig. 8). Pyroxene and biotite have similar contents (5% each). The percentages of zircon and titanite are low (1% each). Other heavy-mineral species do not exceed 1%.

3.3. Noteć Formation

The thickness of the Noteć Formation at the Paterek site is 4 m (Fig. 8). This unit consists of lithofacies association SGp,GSp(GSm), in which sands (d_{50} = 0.19 mm) and gravelly sands ($0.52<d_{50}<1.00$ mm) dominate. The lower part of the formation is built by medium-scale sandy and sandy/gravelly lithofacies with planar cross-stratification (lithofacies Sp, SGp). Locally they are interbedded with a layer of fine-grained sands with ripple cross-lamination (lithofacies Sr).

The Upper Member of the Noteć Formation consists of sandy gravels with tabular cross-stratification (lithofacies GSp) and massive sandy gravels (GSm). Regarding the heavy minerals, the Noteć Formation is dominated by amphibole; its amount in lithofacies Sp is lower (42%) than in the overlying sandy gravel lithofacies GSm (64%; Fig. 8). In upward direction the percentages of biotite and glauconite increase (from 8% to 13%, and up to 3%, respectively), while pyroxene remains stable (about 4%). However, garnet decreases from 38% to 12%, and staurolite from 4% to about 1%. The individual other heavy minerals do not exceed 1%.

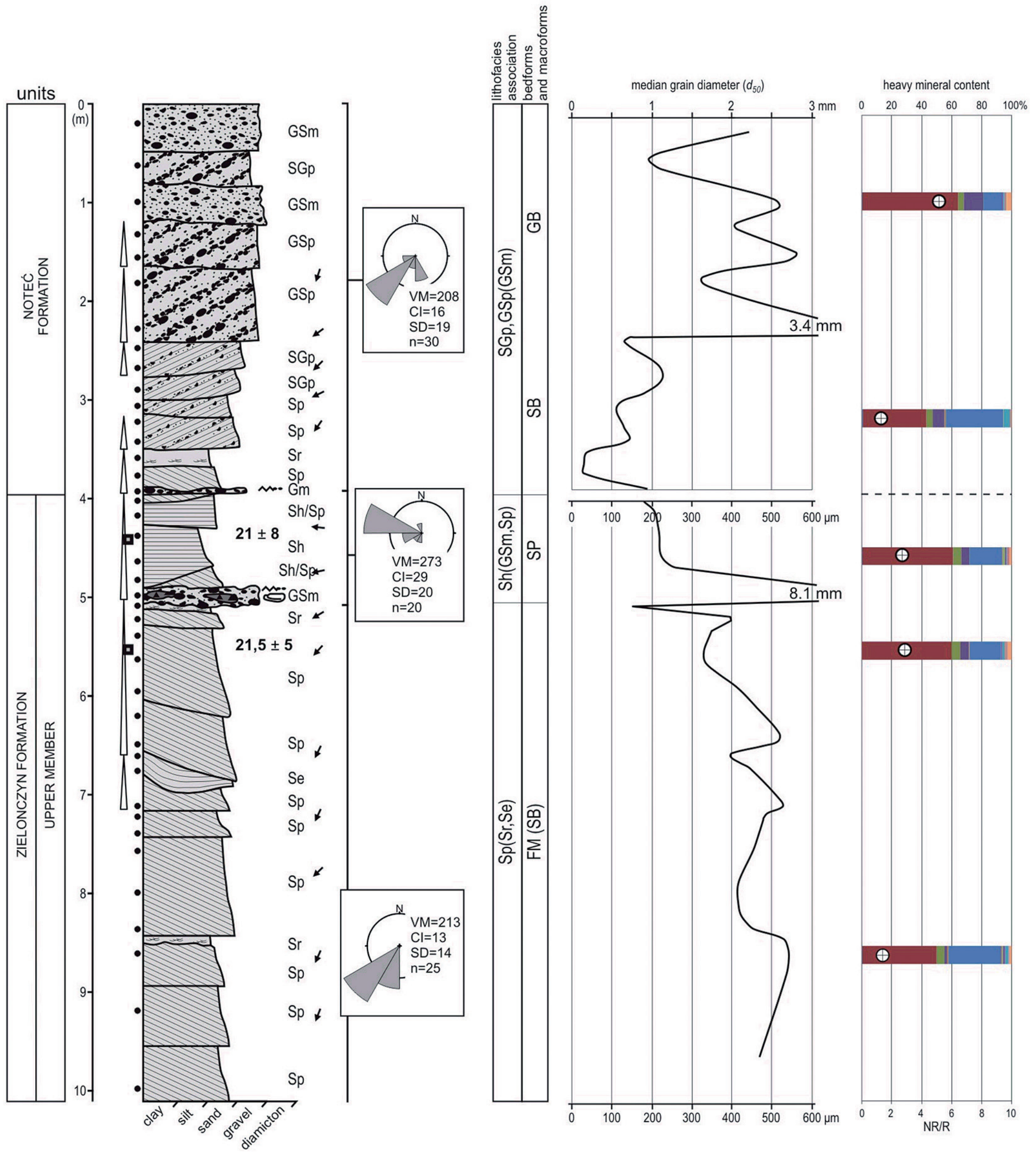

Fig. 8. Lithofacies log of the Paterek site. For legend, see Figure 3.

4. Discussion

4.1. Channel forms and processes in relation to the heavy-mineral composition

The sediments of the Lower Members of the Rzęczkowo and Zielonczyn Formations were deposited in river channels with two types of pattern. The first one is characterised by a sinuous thalweg and side bars with a flat surface (Chobielin and Zielonczyn sites). This surface was formed under conditions of a supercritical flow in an ephemeral, sandy, meandering river (cf. Miall, 2006; Weckwerth et al., 2011; Weckwerth, 2013). At the Chobielin site, the sediments of the side bars were deposited during two cycles of channel sedimentation, during which sequences Sm→Sl→Se/Sr were developed. These cycles are characterised by different median grain diameters (Fig. 3). During each cycle, the basal part consists of massive fine-grained sands (lithofacies Sm), formed in a shallow and supercritical current (see Alexander et al., 2001), as scour-pool infillings (see Gorrell & Shaw, 1991; Russell et al., 2007). Lithofacies Sl was deposited at the surface of side bars; it is inclined to the thalweg, as a result of sheetfloods. The sands were incised by shallow chute channels (lithofacies Se) or covered by ripples during slowing down of the current. The cyclicity in the composition of the heavy minerals corresponds with the two depositional cycles of the ephemeral, sandy, meandering river.

Above both fluvial cycles, the content of heavy minerals less resistant to mechanical abrasion, such as amphibole, pyroxene and biotite, decreases. At the same time, the amount of garnet increases. These changes in the heavy-mineral assemblages at the Chobielin site are reflected by a decreasing NR/R index in the first depositional cycle from 8.6→6.7→0.6, and in the second cycle from 10.2→3.5→1.2 (Figs 3 and 9). A concentration of heavy minerals with a relatively low resistance to mechanical abrasion is present at the beginning of each cycle; the concentration took place during the development of wide and shallow scours and pools, as a result of sudden, occasional floodings. The mineralogical coefficient NR/R ranged then from 8 to 10. The decreasing amount of amphibole, pyroxene and biotite in the overlying deposits (building the middle and upper parts of the side bars) influences the decrease of the NR/R ratio to below 2 (Figs 3 and 9). A comparable insignificant total content of amphibole, pyroxene and biotite occurs in the side-bar deposits of the Lower Member of the Zielonczyn Formation at the Zielonczyn site (Fig. 6). These deposits are represented by three sedimentation cycles Sl/Sm→Se/Sr. The low content of amphibole, pyroxene, biotite and chlorite (46–67% in total) and the high garnet percentage (18–34%) cause a low NR/R ratio, which does not exceed 2 (Figs 6 and 9).

Similar changes in the composition of the heavy minerals occur in the deposits of the sand-bed braided rivers of the Lower Member of the Zielonczyn Formation (the Nowe Dąbie and Rozwarzyn sites; Figs 4 and 7). At the Nowe Dąbie site, above the main pavement horizon, the sandy lithofacies Sp is present, which was deposited as a result of the downstream migration of transverse bars. Their surface was locally incised by shallow chute channels (lithofacies *Se*). The side bars show an upward decrease of the total content of amphibole, pyroxene, biotite and chlorite from 81% to 62%, while the garnet percentage increases from 15% to 29% (Fig. 4). This is reflected by a decrease in the NR/R value from 4.3 to 1.7 (Figs 4 and 9). The floodplain deposits have an NR/R value of 3.8 (Fig. 4). The high proportion of heavy minerals less resistant to mechanical abrasion is also recorded in lithofacies Sh, which was deposited at the Rozwarzyn site under conditions of a supercritical flow (Fig. 7).

Deposition of the sediments building the Upper Members of the Rzęczkowo and Zielonczyn Formations took place each time 1.5–3 ka before the advance of the Scandinavian ice sheet: this happened 28 ka ago (the 'Zielonczyn advance'?) and 21 ka ago (the Leszno phase) (Fig. 9; Weckwerth et al., 2011; Weckwerth, 2013). These lithostratigraphic units represent aggrading braided rivers (Weckwerth et al., 2011; Weckwerth, 2013). Their channels were dominated by foreset macroforms, predominantly compound bars, forming mid-channel sand shoals (cf. Cant & Walker, 1978; Bridge, 1993, 2003; Sambrook Smith et al., 2006; Ashworth et al., 2000, 2011). The compound bars show an upward increase in the total amount of amphibole, pyroxene, biotite and chlorite, and a decrease of the garnet content. For the Upper Member of the Rzęczkowo Formation, their total amount at the Wypaleniska 1 site increases from 40.6% to 82.1%, while the garnet percentage decreases from 50.1% to 15% (Fig. 5). These changes in the composition of the heavy-mineral assemblage are reflected by the increase in the NR/R value from 0.7 to 4.6. A similar NR/R increase, for the lithostratigraphic unit of the same age, is recorded at the Zielonczyn site (Fig. 6). Additionally, enriching of angular grains of heavy minerals in the Upper Member of the Rzęczkowo Formation occurs as a result of watering due to climate cooling before ice-sheet advance.

The transverse bars deposited by braided rivers shortly before the ice advance of the Leszno phase show also a tendency of an increasing NR/R index at both the Rozwarzyn site (from 1.4 to 10.4, Figs 7 and 9) and the Nowe Dąbie site (from 1.7 to 6.6; Figs 4 and 9). The increase of the amphibole content in the transverse bars in the Nowe Dąbie 1 profile from

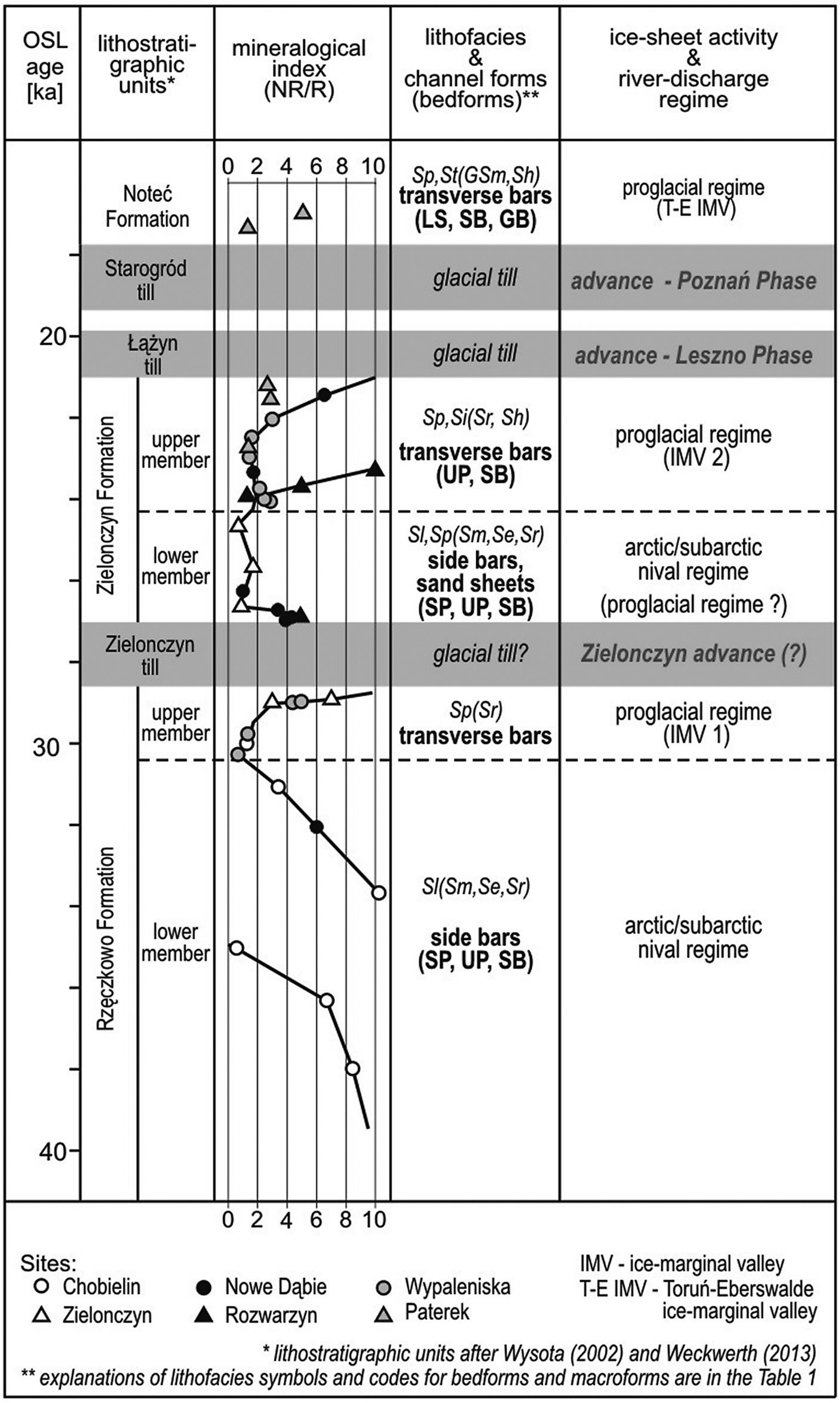

Fig. 9. Values of the NR/R index in relation to the main lithostratigraphic units, river-channel morphology and river-discharge regimes during the Weichselian glaciation. Adapted from Weckwerth (2013).

50.5% (Si lithofacies) to 71.7% (Sh/Sp lithofacies) in the Nowe Dąbie 2 profile, and the decrease of the garnet percentage from 28.9% to 10.1% (Fig. 4) coincide with the increased current velocity during the development of compound bars (see Weckwerth, 2009, 2011). The increase of the amphibole content (amphiboles easily undergo transportation) by currents with increased energy indicates a significant supply of sediments from glacial sources to the river system. Physical sorting during transport thus has a relatively small modifying effect on the relative frequencies of heavy minerals (cf. Bateman & Cat, 2007; Komar, 2007). At the Wypaleniska and Paterek sites, a smaller increase of amphibole occurs at the expense of the garnet content in the transverse bars that were deposited shortly before the ice advance of the Leszno phase, (Figs 5, 8 and 9).

The deposition of the Noteć Formation took place after the ice retreat of the Poznań phase (Fig. 9). The sandy gravels of the ice-marginal valley terrace at the Paterek site accumulated in a braided-river channel environment. Initially, low sandy gravel and sandy straight-crested dunes developed under a lower flow regime. During the next stage of deposition, the current energy increased and longitudinal bars developed within the channel of the braided river (lithofacies GSm, GSp). These two stages of fluvial sedimentation are reflected by the changes in the heavy-mineral composition. During the first phase (development of straight-crested dunes), the total amount of amphibole, pyroxene, biotite and chlorite was 55.3%, while this increased during the second phase (development of longitudinal bars) to 81.2%. This was accompanied by a drop in the garnet percentage from 38.2% to 12%. Thus, the changes in the morphology of the braided riverbed coincide with the increase of the NR/R value from 1.2 to 5.2 (Fig. 8).

4.2. Potential provenance of the Weichselian fluvial sediments

The deposition of Weichselian fluvial and glaciofluvial successions was associated with river erosion, which enriched the channel deposits with basement-sourced material. The presence of epidote and pyroxene in these fluvial deposits means that the garnet and amphibole that are also present, are not derived from Neogene and Palaeogene sediments (Krzyszkowski, 1996; Wysota, 2002). Such erosion during the Weichselian was limited, due to the considerable thickness of the Pleistocene between the top of the Neogene and the Weichselian sediments (Fig. 2). The deposits of the Weichselian rivers may have been derived from eroded tills or glaciofluvial sands which contained heavy-mineral assemblages from weathered Scandinavian crystalline and sedimentary rocks, or from the local Quaternary basement in northern Poland or in the South Baltic region. The heavy-mineral assemblage of the tills consists commonly of garnet (15–35%), amphibole (5–25%) and biotite (up to 30%), whereas amphibole (10–35%) dominates over garnet (15–30%; Racinowski, 2010) in the glaciofluvial sands. A similar high amount of amphibole and garnet derived from Palaeozoic and Precambrian rocks in the eastern central Baltic was found in Saalian tills in The Netherlands and in Weichselian tills in north-eastern Germany (Rappol & Stoltenberg, 1985; Haldorsen et al., 1989; Górska, 2006). The deposits of the rivers which were not fed by meltwater are characterised by the domination of garnet (30–45%) and in most cases an insignificant amphibole and biotite content (less than 10%: Racinowski, 2010).

In the case of the Toruń Basin and its surroundings, small divergences occur from the above general mineralogical characteristics of the main types of Pleistocene deposits in Poland. The parent material of the Weichselian fluvial deposits in the area of the Toruń Basin (derived from river incision and erosion) might have been Mazovian sediments (Fig. 2). In the north-eastern vicinity of the Toruń Basin, these deposits contain up to 66% of garnet and up to 35% of amphibole (Kenig et al., 2006). The fluvioglacial sands and gravels of the Saalian might also have undergone river erosion during the Weichselian. In the Saalian fluvioglacial deposits to the north-east and east of the Toruń Basin, heavy minerals less resistant to mechanical abrasion dominate (amphibole 40–69%, pyroxene 5–6%, biotite 3–4%), while the percentage of garnet is low (15–27%) (Kenig et al., 2006; Weckwerth, 2013). The deposits potentially undergoing river erosion during the Weichselian might have also been the Eemian, which contains a high amount of garnet (76–82%) in the surroundings of the Toruń Basin, while the content of amphibole (8%) and zircon is low (8% and 6–10%, respectively) (Kenig et al., 2006).

The fluvial sediments in the Toruń Basin may have been enriched with material supplied by proglacial meltwater streams during the advance or retreat of the ice sheet. Among the heavy minerals in the (glacio)fluvial deposits with a glacial source, the amphibole content is high in the proximal parts of the fossil proglacial valleys (32–49%), while their percentage is lower in the distal parts of outwash plains (22–29%: Wysota, 2002). The content of garnet is the reverse and amounts to 14–29% in the proximal part and 33–36% in the distal part.

4.3. River-discharge regime and provenance of the fluvial sediments in the Toruń Basin

The changes in the composition of the heavy-mineral assemblages in the fluvial deposits of the Rzęczkowo and Zielonczyn Formations indicate two different supplies to the Toruń Basin during the middle and late Weichselian. The high values of the NR/R index (over 2) in the Lower Members of the Rzęczkowo and Zielonczyn Formations are characteristic of the lithofacies of their lower parts. This is mainly caused by the high amphibole content and the low garnet percentage in (1) the lithofacies above the main pavement and erosive horizons, (2) the lithofacies in the incised channel, and (3) the lower parts of the transverse bars. The NR/R index decreases to below 2 in upward direction in both the side and the transverse bars (Fig. 9).

The deposits of both the Rzęczkowo and the Zielonczyn Formation must have been reworked a couple of times, as indicated by the high percentage of very well rounded grains with a shiny and smooth surface (Weckwerth et al., 2011). The fluvial reworking caused a decrease in the amount of minerals that are less resistant to mechanical abrasion, as well as an increase in the garnet percentage (cf. Clemens & Komar, 1988; Krzyszkowski, 1990, 1998; Komar, 2007). It follows that the cyclical increases in the total amounts of amphibole, pyroxene, chlorite and biotite in the channel-lag deposits of the ephemeral, sandy, meandering rivers (Lower Member of the Rzęczkowo Formation) was caused by seasonally increased fluvial erosion rates and denudation of the catchment area built of glacial deposits, which is characteristic of nival flood regime rivers (Fig. 9). Such developments took place during the warm-to-cold transitions, when also the streams fed by melting snow came into existence (cf. Church, 1988; Vandenberghe, 1995; Cordier et al., 2006). The large seasonal water supply of rivers flowing from the South (Fig. 10) occurred during climate cooling, as indicated by the poorer sorting and larger grain diameters of fluvial deposits of the second depositional cycle at the Chobielin site (Fig. 3). A seasonal, large stream fed by molten snow coincided with a reduced sediment load due to the temporarily persisting vegetation (Vandenberghe, 1995, 2003).

The main reason for the high amphibole content and the low garnet percentage in the lower lithofacies of both the braided and the meandering river systems of the Lower Member of the Zielonczyn Formation was the increase in sediment supply, due to the incision of the river into the Zielonczyn till (Fig. 9). However, it cannot be excluded that the increase of the NR/R index in the lower part of the Lower Member resulted from the initially large sediment supply by proglacial streams. The decreased amount of amphibole and the increased amount of garnet in the younger deposits might indicate increasing transport distances from the ice-sheet front to the sedimentary basin (cf. Krzyszkowski, 1990; Wysota, 2002). Such a relationship was found at the Paterek site (Figs 8 and 10). Despite the sediment supply to the Toruń-Eberswalde ice-marginal valley by material eroded from glacial deposits and transported by meltwater (cf. Galon, 1961; Niewiarowski, 1968; Weckwerth, 2010), the sediments reveal a low amphibole content and an NR/R index below 2, due to the long distance of fluvial transport between the Toruń-Eberswalde ice-marginal valley and the ice-sheet front during the Pomeranian phase (Fig. 1). Yet, the proportions of these minerals are higher for the gravelly and gravelly/sandy channel-lag deposits, due to sediment supply as a result of the local river incision into the Weichselian till layer (cross-section A–B, Fig. 2).

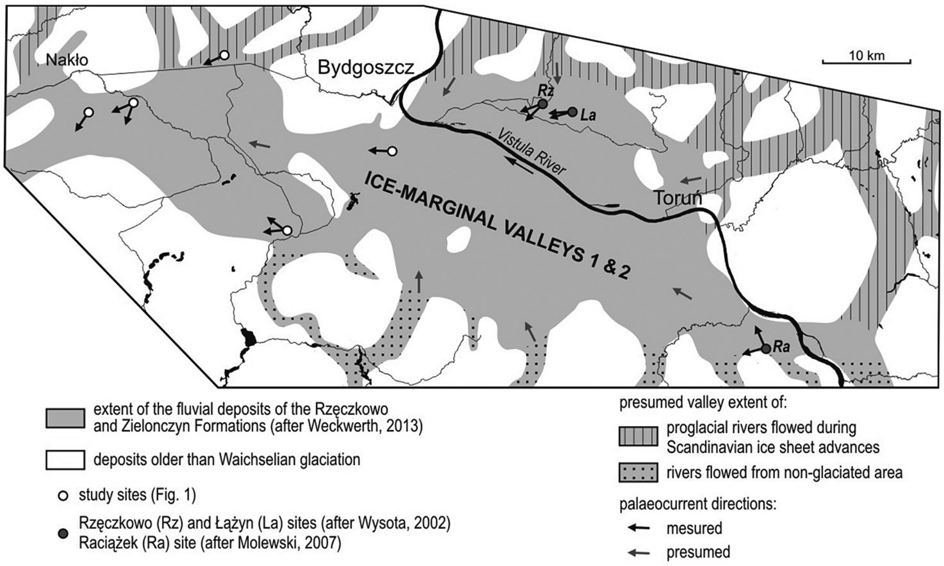

Fig. 10. Palaeogeographical reconstruction of the fluvial systems during the deposition of the Rzęczkowo and Zielonczyn Formations.

The deposition of the Upper Members of the Rzęczkowo and Zielonczyn Formations by braided rivers with a high aggradation rate coincided with an increasing content of minerals with less resistance to mechanical abrasion. Thus, the composition of heavy minerals in the channel deposits changed and the NR/R index increased to above 2 during 1.5–3 ka before the 'Zielonczyn advance' and the advance of the Leszno phase (Fig. 9). This tendency of the changes in the heavy-mineral composition of the fluvial deposits cannot have been caused by a basement-sourced sediment supply due to the river erosion and incision into the older glacial deposits, as the lithofacies characteristics of the Upper Members of the Rzęczkowo and Zielonczyn Formations do not indicate so. This must be ascribed to the glacial provenance of the fluvial deposits which were transported by proglacial rivers into the sedimentary basin just before the two ice advances of, respectively, 28 ka and 21 ka ago (Fig. 10). This also implies that, before these ice advances in the Toruń Basin, two ice-marginal valleys (IMV 1 and IMV 2, Figs 9 & 10) may have functioned. These ice-marginal valleys were fed by meltwater streams from the North, which merged with the rivers coming from the South (Fig. 10).

5. Conclusions

On the basis of the above analyses and reasoning, the following conclusions can be drawn.

1) The parent material for the fluvial sediments deposited during the Weichselian glaciation in the Toruń Basin were older glacial or interglacial sediments as well as material transported by proglacial streams from the Scandinavian ice sheet during the Weichselian. Thanks to the differences in the content of amphibole, pyroxene, biotite and garnet in the different parent materials and due to the transport distance of the material by proglacial streams, the NR/R index enables recognition of the provenance of the fluvial deposits on the basis of the relationship between minerals that are less resistant to mechanical abrasion and the remaining minerals, which are dominated by garnet.
2) The changes in the composition of the heavy-mineral assemblages in the Weichselian fluvial deposits indicate changes of the channel patterns from catchment- and basement-sourced ephemeral meandering rivers or flashy ephemeral sheetfloods (rivers of arctic/subarctic nival regime) to glacially sourced braided rivers with a high aggradation rate under the con-

ditions of a polar desert just before ice-sheet advances (proglacial regime). The input by ice-sheet-sourced minerals coincides with the climatically controlled transformation of the channel patterns.

3) The cyclical increase in the amphibole content in relation to garnet in fluvial sequences corresponds to the cyclical development of side-bars in ephemeral meandering rivers, and indicates a sediment supply by fluvial erosion of older glacial sediments (tills and glaciofluvial sands).
4) An increased content of heavy minerals less resistant to physical abrasion (amphibole, pyroxene, chlorite, biotite) occurs in the overbank sediments of the braided rivers as well as on the surface of transverse bars in a channel subenvironment. These changes occur irrespective of the physical sorting of the heavy minerals that is caused by the increase of the current velocity during high-discharge floods. Such floods took place shortly before the ice-sheet advance and may have depended on the ablation cycle.
5) The gravelly and gravelly/sandy lithofacies as well as the main pavement horizons indicate basement-sourced fluvial sediments, irrespective of the river regime. The amphibole content in relation to garnet in the sandy lithofacies of the side bars and transverse bars can be used to assess the distance between sedimentary basins and an ice sheet, although the decreased amphibole amount might be an effect of a temporal lack of sediment supply by proglacial streams.
6) The high garnet content within deposits of the scoured channel resulted from the deposition under conditions of the upper flow regime, in contrast to the sediments of the transverse bars, which were in most cases deposited under conditions of the lower flow regime, where a larger amount of heavy minerals less resistant to physical abrasion (amphibole, pyroxene, chlorite, biotite) is recorded.

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