since 1961

Baltica

BALTICA Volume 30 Number 1 June 2017: 1–14
http://dx.doi.org/10.5200/baltica.2017.30.01

Heavy-mineral derived provenance study of Quaternary sediments of the Mazovian Lowland, Central Poland

Edyta Kalińska-Nartiša, Māris Nartišs

Kalińska-Nartiša, E., Nartišs, M., 2017. Heavy-mineral derived provenance study of Quaternary sediments of the Mazovian Lowland, Central Poland. *Baltica, 30 (1), 1–14.* Vilnius. ISSN 0067–3064.
Manuscript submitted 7 January 2017 / Accepted 24 May 2017 / Published online 10 June 2017

Abstract This study makes an attempt to characterise Quaternary sediments in terms of their heavy minerals (HM) composition. Authors focus on the Mazovian Lowland, Central Poland, where a number of clastic sediments of different age and origin overlap. Five sedimentary settings, covering the Saalian-Holocene (MIS 1-6) time frame, have been studied to reveal whether these sediments have single or multiple source areas and to decipher sediment transformations. In the glacial setting either garnet- or amphibole-dominated sediments occur. This unequivocal mineral combination likely reflects a multi-sourcing resulting from multi-directional ice advance. The HM taken from fan-like forms and aeolian sediments are closely related; these sediments are largely multicyclic and likely derived from pre-existing recycling sediments. Similar mineral suite is also typical for long-lasting aeolian processes and is observed in dune sediments. Ultrastable components are less frequent in the coversand, which points at a shorter-lived aeolian process. Finally, the fluvial setting reveals multi-sourcing largely depending on local geological conditions.

Keywords • garnet • amphibole • fan-like forms • glacial • aeolian • fluvial • Saalian • Vistulian • Holocene

✉ *Edyta Kalińska- Nartiša (edyta.kalinska@gmail.com), SunGIS SIA, Pruuni, Rencēni Parish, Burtnieki region, LV-4232, Latvia, University of Tartu, Institute of Ecology and Earth Sciences, Department of Geology, Ravila 14A, EE-50411 Tartu, Estonia; Māris Nartišs (maris.nartiss@gmail.com), Faculty of Geography and Earth Sciences, University of Latvia, Jelgavas iela 1, LV-1004 Rīga, Latvia*

INTRODUCTION

Heavy minerals (=HM) are believed to be potentially useful in palaeoenvironmental and transport reconstructions, analyses of sediment provenance and related source rock or dynamics of the processes (Mange, Wright 2007). Indeed, their compilation can be tested towards the applicability in the numerous sedimentary environments, such as coastal (Dill *et al.* 2012; Järvelill *et al.* 2015), marine (Derkachev, Nikolaeva 2013), tsunami (Jagodziński *et al.* 2012), fluvial (Guedes *et al.* 2011; Nascimento *et al.* 2015; Weckwerth *et al.* 2013), aeolian (Hamdan *et al.* 2015; Kasper-Zubillaga, Zolezzi-Ruiz 2007; Kilibarda, Blockland, 2011; Ugolini *et al.* 2008), or glacial settings (Mahaney *et al.* 2011), where the HM proxies are commonly used. Consequently, this correlates with the Polish HM research, of which numerous approaches and applications have been widely tested in the peculiar sedimentary settings in different regions of Poland (Ludwikowska-Kędzia 2013; Marcinkowski, Mycielska-Dowgiałło 2013; Pisarska-Jamroży *et al.* 2015; Wachecka-Kotkowska, Ludwikowska-Kędzia 2013; Woronko *et al.* 2013). This is partially due to an extensive and long-lasting drilling program and detailed geological mapping at 1:50 000 scale (Ber 2005), but also due to a previous study, which addressed the HM composition of some of the surficial sediments. For example, in the Mazovian Lowland, Central Poland, dune sediments have been investigated in this context (Konecka-Betley, Janowska 2005; Dzierwa, Mycielska-Dowgiałło 2003).

This study also focus on the Mazovian Lowland, where a number of glacial, glaciofluvial, fluvial, periglacial and aeolian settings occur and most of them lack of HM information. Authors provide a new data about the HM composition of sediments in the selected settings and aim to decipher: (1) the HM characteristics of sediments, (2) sediment single or multiple sourcing, and (3) sediment provenance and the HM transformation by a particular setting. To be able to meet these objectives, the five sedimentary settings (glacial, fan-like forms, dunes, coversand and fluvial setting) covering the Saalian (MIS 6) to Holocene (MIS 1) time frame were investigated. Authors consider these settings as representative for the overall geological pattern of the Mazovian Lowland.

STUDY AREA

The study area is located in the Mazovian Lowland, Central Poland (Fig. 1A), and entirely outside of the last maximum extent of the Scandinavian Ice Sheet (Wysota *et al.* 2009) on a distance of 40 to 120 km from a distinct ice marginal zone of the Weichselian (MIS 2-5d; Vistulian) Glaciation date approximately at 19 to 20 ka (Marks 2012). The previous Saalian (MIS 6; Wartanian) ice sheet reached its respective maximum extent (Marks 2004, 2002), covering entirely the study area (Fig. 1A). Sediment of a different age and various origin, resulting in a wide variety of landforms, occur in the Mazovian Lowland (Table 1, Figs 1A-E). Five representative sedimentary settings were chosen for this study (Table 1, Fig. 2).

1. Glacial setting

A patchy mosaic of sands, gravels and tills build the higher-elevated Rawa (Fig. 1A, D) and the Kałuszyn moraine plateaus (Fig. 1A), south-west and north-east of Warsaw, respectively, and this is apparent from the numerous geological maps (Marks *et al.* 2006; Nowak 1984; Szalewicz 1994, 1987). Up to 12-m thick glacial till form these plateaus (Szalewicz 1994). Till continues also towards the north, directly under the sediments of the fan-like forms, and further partially forming the vast areas of denuded plains: Błonie (Figs 1A, B, D, 2) and Wołomin (Figs1A, E, 2).

2. Fan-like form setting

Vast quantities of sandy sediments resembling the fan-like forms borders the topographically higher-elevated plateaus and lower-elevated denuded plains, being partially a results of ice-dammed lake in this area (Marks 2005). The fan-like forms slope slightly north-eastwards (Figs 1C-E, 2) and form up a several-meter-thick sediment cover of massive medium-, fine- and occasionally coarse-grained sand (Kalińska 2008a; Kalińska-Nartiša, Nartišs 2016a), which was deposited in four stages between ~48 ka and ~12 ka (Kalińska-Nartiša, Nartišs, 2016a, b). Their origin has been widely discussed, however the latest study shows that aeolian factor largely dominated during their formation (Kalińska-Nartiša, Nartišs, 2016a, b). Because a field of fan-like forms reaches of ca. 100 km in length, and stretches along the northern margin of moraine plateaus, both west and east of Warsaw, its the westernmost, central and easternmost part were investigated (Figs 1A, C-E).

3. Coversand

It is well established, that numerous forms and sediments were produced due to aeolian activity between the Last Glacial and the Mid-Atlantic period (Kalińska-Nartiša *et al. 2016*; Kolstrup *et al.* 2007; Marks *et al.* 2016; Tolksdorf, Kaiser, 2012; Vandenberghe *et al.* 2013). The shapeless and thin coversands occur widely in the Mazovian Lowland (Marks *et al.* 2006). This is likely due to a numerous factors i.e. wind speed and/or material accessibility. In this study, the coversand located west of Warsaw at Plecewice site was investigated (Fig. 1A-B). The source of the sand is unknown, however, fluvial sands of the river terrace/s could significantly contribute in its formation. At the Plecewice site, the c. 2-m thick massive and mostly fine-grained coversand is directly underlain by the varved clays of the ice-damn lake in

Table 1 The main sedimentary settings and landforms of the Mazovian Lowland, Central Poland (*see* Study area for references)

Sedimentary setting	Landform/regional unit		Sediment/interpretation	Relative age
glacial*	morain plateau/Rawa and Kałuszyn		sand, gravel, glacial till/glacial accumulation	Saalian
fan-like forms*	fan-like form		sand/	Vistulian
glaciolacustrine	plain/Błonie and Wołomin		varved clays, denuded glacial till/deposition in ice-dammed lake, denudation	Vistulian
dunes*	dune	Warsaw Basin	sand/aeolian accumulation	Vistulian/Holocene
coversand*	coversand		sand/aeolian-fluvial accumulation	Vistulian/Holocene
fluvial*	fluvial terrace/ Warsaw Basin		sand/fluvial accumulation	Vistulian/Holocene

* settings investigated in this study

the Warsaw Basin (Kalińska 2012). The matter of debate is whether these coversands are fluvial or aeolian origin (Baraniecka, Konecka-Betley 1987; Kalińska 2012; Sarnacka 1982).

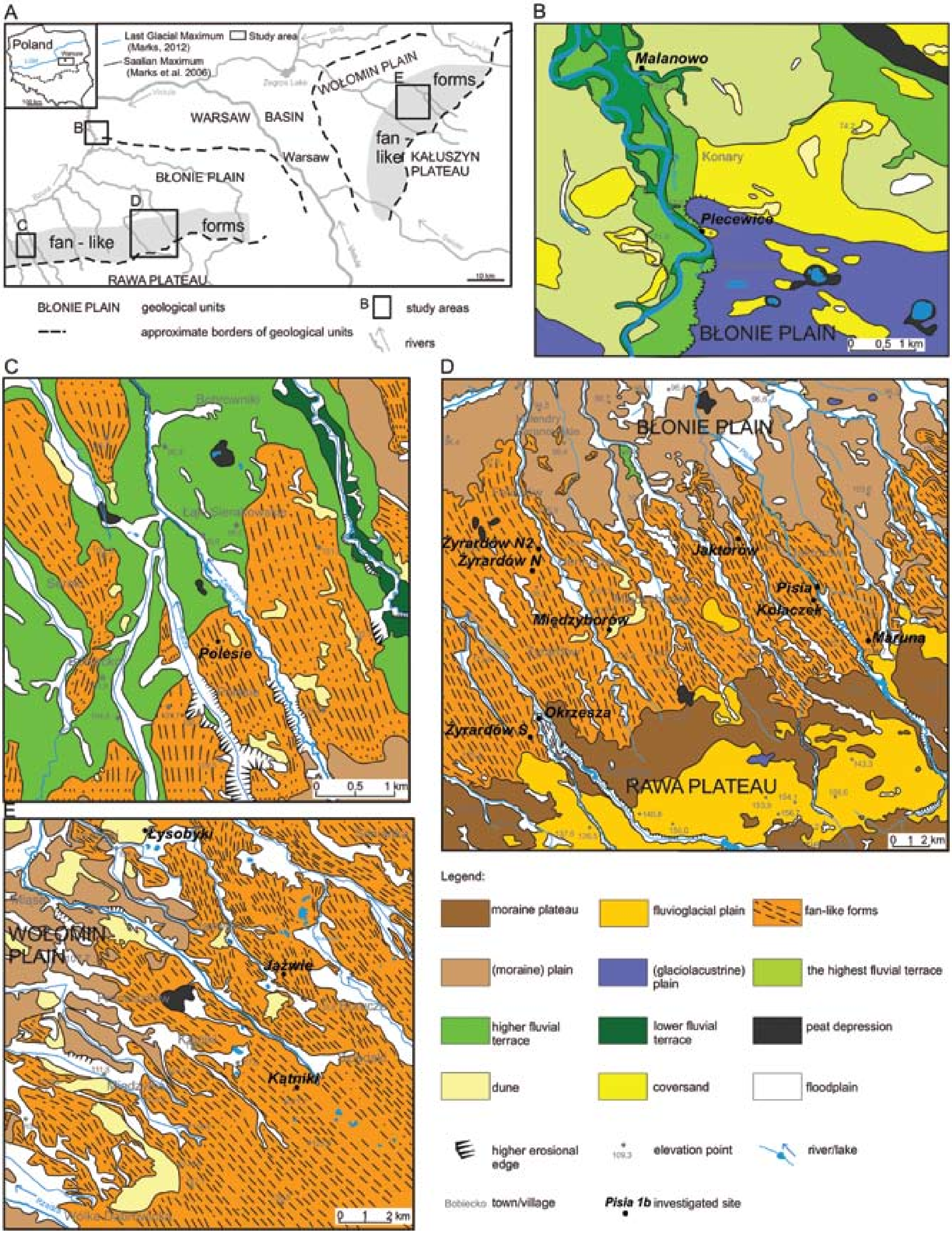

Fig. 1 Location of the investigated sites and their geological situation: A – a general location; B–E – geomorphological situation of the investigated sites and settings (after Nowak 1984; Szalewicz 1987, 1994, later modified and complied by Kalińska, 2008a; Kalińska-Nartiša and Nartišs, 2016a, b).

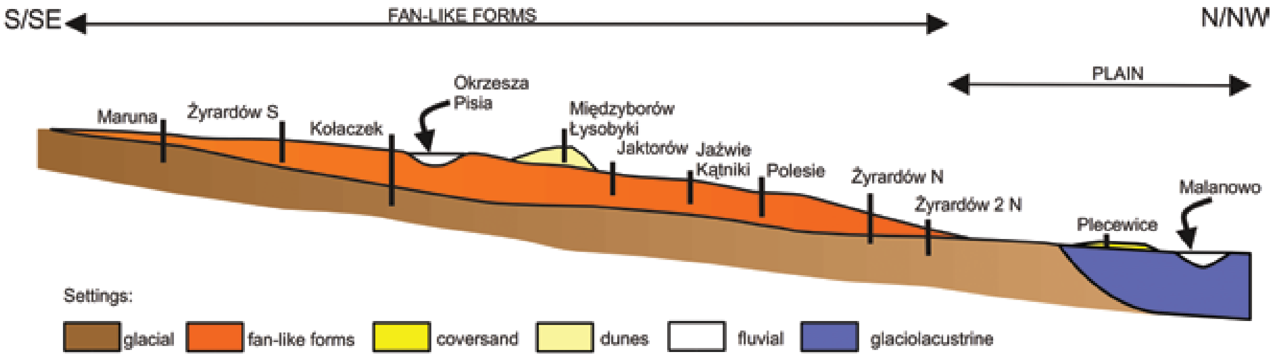

Fig. 2 An idealised cross-section showing a relation among the investigated settings in the Mazovian Lowland, Central Poland. Compiled by E. Kalińska-Nartiša, 2017.

4. Dunes

Throughout the Warsaw Basin, dune forms are rather limited to the particular areas i.e. fluvial terraces (Baraniecka, Konecka-Betley 1987; Konecka-Betley, Janowska, 2005; Marks *et al.* 2006), and east-west oriented dunes and dune complexes can be found; their deposition took place during the Late-Glacial – Holocene transition (Konecka-Betley, Janowska, 2005). In contrast, findings of the parabolic dunes atop of the plains, the fan-like forms and moraine plateaus are rather scarce. Situated in the central part of the fan-like forms, west of Warsaw and contacting directly with their sediments, the dune in Międzyborów seems to be exceptional (Fig. 1D). Reaching a maximum altitude of 123 m a.s.l. the dune of parabolic-like shape is the most distinctive morphological feature in the investigated area. As far, direct numerical age estimates are lacking. Surely, the aeolian accumulation postdates the deposition of the fan-like forms at ca. 14 ka in this area.

In contrast, the Łysobyki site, east of Warsaw, seems to represent one of the numerous dune setting in this area (Fig. 1E). Here, both parabolic and longitudinal dunes interplay with shapeless coversands and fan-like form sediments. A direct contact between the fan-like form and dune sediments enable to establish the minimum age of dune deposition to ca. 12 ka; this is the last moment where the fan-like form deposition took place east of Warsaw (Kalińska-Nartiša, Nartišs 2016b).

5. Fluvial setting

A successive episodes of fluvial erosion and accumulation took place in the Mazovian Lowland (Marks, 2004), and today this region is an important hydrographic junction of the Vistula River and its main tributaries (Fig 1A; Marks 2005; Starkel *et al.* 2007, 2015). The Okrzesza – Pisia – Bzura rivers represent the left-side tributary system of the Vistula river and their sediments were investigated in this study. A unique fluvial trend can be observed in the fan-like forms, where relatively narrow and parallel streams incised the sandy sediments; this is an example of the Okrzesza and the Pisia rivers, which follow this pattern (Fig. 1D). Here, the negligible alluvium displays along the rivers, of which most of them concentrate rather to the young sediments in the present-day rivers channel. The fluvial terraces, therefore, are mostly absent. Whereas the Okrzesza and the Pisia exhibit a narrow, subparallel channel pattern, the Bzura river emerges from confinement between valley-side slopes in the Plecewice area (Fig. 1B), meandering further to its mouth into the Vistula river. The wide spectra of distinct fluvial terraces can be identified, and correlated with the upper-Plenivistulian – Holocene transition (Andrzejewski 1991). The Malanowo site locates at the highest terrace level (Fig. 1B) and reveals an alternation of the sandy channel and organic-rich muddy flood deposits (*see* Fig. 2A in Kalińska 2008b).

MATERIAL AND METHODS

This study combines published material with a new data (*see* Table 2 for details). Altogether fifteen sites from five settings were taken as reference sites of the Mazovian Lowland (Fig. 2). Samples were collected with a hand auger, from the mechanically dug pits and outcrops. From these sites, 49 samples (7 from glacial setting, 4 from fluvial setting, 5 from dunes, 3 from coversand, and 30 from the fan-like forms) were analysed. Fluvial samples were taken directly from the present-day river bed. The studies of Marcinkowski and Mycielska-Dowgiałło (2013) indicated, that fraction in the range of the 0.1 to 0.2 mm is the best candidate for HM evaluation. Thus to separate specific grain size fraction all samples were sieved through a 0.1 and 0.125 mm sieve, washed and dried. Further, the 0.1-0.125 mm grain size fraction was treated with bromoform ($CHBr$) to separate HM fraction. The separated fraction were subsequently mounted in Canada balsam on glass slides, identified the mineral type and counted under a polarising microscope based on their optical properties. About 180 to 440 grains of the HM were identified per sample; the counting results obtained were converted to percentages. In the first stage, the HM were divided into carbonates, glauconite, opaque and transparent groups; the two latter allowed to calculate the T/O (transparent/opaque) mineral coefficient.

Seventeen types of transparent minerals were distinguished: amphiboles, pyroxenes, biotites, chlorites, epidotes, garnets, tourmalines, zircon, rutile, titanite, disten, staurolite, andalusite, sillimanite, apatites, topaz, and corundum. The emphasis was placed on two mineralogical coefficients (Marcinkowski, Mycielska-Dowgiałło 2013): (1) the A–coefficient (number of amphibole grains to garnet grains), (2) the B–coefficient (number of non–resistant minerals to resistant minerals). Additionally, the weathering index (W) was calculated and details on its equation can be found in Racinowski and Rzechowski (1969). These coefficients are believed to approximate the sedimentary environment (Woronko *et al.*, 2013). Finally, the ultrastable minerals (zircon, tourmaline and rutile), whose content is represented by the ZTR index (Hubert 1962) was calculated.

Table 2 Percentage of selected heavy minerals in the investigated settings. Transparent minerals are classified in the three "resistance" groups following a proposal of Marcinkowski and Mycielska-Dowgiałło (2013). Mineral symbols (following a proposal of Whitney and Evans, 2010): O – opaque minerals; And – andalusite; Zrn – zircon; St – staurolite; Tur – tourmaline; Tpz – topaz; Rt – rutile; Ep – epidotes; Grt – garnets; Amp – amphiboles; Px – pyroxene; A – A-coefficient; B – B-coefficient; W – weathering index; ZTW – maturity index (for coefficients and indexes see the text); [1] data partially after Kalińska-Nartiša and Nartišs (2016a); [2] data partially after Kalińska-Nartiša and Nartišs (2016b); [3] Kalińska (2008a)

Investigated settings	O	Transparent minerals										A	B	W	ZTR
		Most resistant						Less resistant		Non-resistant					
		And	Rt	St	Tpz	Tur	Zrn	Ep	Grt	Amp	Px				
Glacial setting															
Maruna 1.70[1]	16	0	0	5	0	2	4	1	50	29	4	0.6	0.5	169	6
Maruna 1.80[1]	17	0	1	3	1	3	5	3	57	17	4	0.3	0.3	108	9
Maruna 1.95[1]	11	0	0	7	1	3	4	4	49	24	4	0.5	0.4	101	7
Maruna 2.70[1]	12	0	0	3	0	0	2	1	45	37	6	0.8	0.8	329	3
Kołaczek 2.4[1]	25	1	0	6	1	6	6	4	63	6	2	0.1	0.1	30	12
Żyrardów N2 1.4[1]	4	1	0	1	0	2	1	1	17	64	3	3.8	2.9	295	3
Żyrardów N 2.4[1]	25	1	1	6	1	6	6	4	63	6	2	0.1	0.1	30	13
Fan-like forms															
Polesie 0.55	23	3	1	4	1	6	7	5	41	19	7	0.5	0.4	68	14
Polesie 0.95	29	0	1	6	1	3	5	1	56	15	5	0.3	0.3	74	9
Polesie 1.30	16	0	1	7	0	5	8	6	33	22	8	0.7	0.5	57	14
Polesie 1.65	18	1	2	8	0	2	8	2	36	22	9	0.6	0.5	62	12
Polesie 2.75	12	1	0	4	0	2	9	3	22	44	10	2.0	1.3	91	11
Polesie 3.05	13	0	0	6	1	3	3	3	61	12	4	0.2	0.2	82	6
Polesie 3.45	9	2	0	7	1	2	7	7	40	19	7	0.5	0.4	80	9
Żyrardów S[1] 0.4	16	0	2	10	1	2	8	4	61	9	0	0.2	0.01	33	12
Żyrardów S[1] 1.0	20	1	3	9	1	1	5	5	50	17	3	0.4	0.03	71	9
Żyrardów 2N[1] 1.2	19	0	1	6	0	3	5	2	46	29	2	0.6	0.04	130	9
Żyrardów 2N[1] 0.9	20	1	1	6	1	6	3	1	67	9	3	0.13	0.13	50	10
Maruna 0.6[1]	21	0	1	8	1	2	3	2	54	25	1	0.47	0.03	119	6
Maruna 0.8[1]	16	0	0	9	0	4	5	1	64	12	4	0.19	0.19	56	9
Maruna 0.9[1]	15	1	2	6	0	5	6	3	61	10	5	0.17	0.18	51	13
Kołaczek 0.6[1]	25	1	0	7	1	6	8	4	64	5	0	0.07	0.06	23	14
Kołaczek 1.6[1]	25	1	1	7	1	12	8	1	47	16	4	0.33	0.11	59	21
Kołaczek 1.8[1]	14	1	0	14	1	13	12	1	34	16	2	0.47	0.07	23	25
Kołaczek 1.95[1]	19	0	0	9	1	3	6	1	66	8	2	0.13	0.03	44	9
Kołaczek 2.2[1]	17	0	0	7	1	3	6	3	62	13	3	0.20	0.04	76	9
Jaktorów 0.6[1]	18	0	0	9	1	5	7	0	72	4	0	0.05	0.01	18	12
Jaktorów 0.7[1]	20	0	0	9	1	10	5	3	50	13	3	0.25	0.03	58	15

Investigated settings	O	Transparent minerals										A	B	W	ZTR
		Most resistant						Less resistant		Non-resistant					
		And	Rt	St	Tpz	Tur	Zrn	Ep	Grt	Amp	Px				
Jaktorów 0.8[1]	17	0	0	8	0	11	4	0	60	13	0	0.23	0.02	67	15
Jaktorów 1.1[1]	13	0	0	9	0	10	5	0	60	13	1	0.21	0.02	56	15
Jaktorów 1.2[1]	13	0	0	6	2	5	4	1	75	3	0	0.04	0.00	23	9
Jaźwie 0.7[2]	11	1	0	7	0	9	4	3	56	17	0	0.30	0.02	91	13
Jaźwie 0.8[2]	17	2	0	3	0	5	8	2	42	34	1	0.80	0.05	137	13
Jaźwie 1.1[2]	13	1	0	6	0	6	3	3	52	24	1	0.46	0.03	146	9
Jaźwie 1.8[2]	15	1	0	5	1	4	4	2	53	23	2	0.43	0.03	147	8
Kątniki 0.7[2]	20	2	3	8	0	6	9	1	45	8	6	0.17	0.16	29	18
Kątniki 0.8[2]	14	2	1	5	1	7	8	1	50	10	7	0.20	0.20	40	16
Kątniki 1.1[2]	15	0	1	6	1	5	15	1	48	9	5	0.18	0.16	24	21
Coversand															
Plecewice 1.1	20	2	1	8	0	2	2	1	64	15	4	0.23	0.23	98	5
Plecewice 1.2	16	2	2	5	1	2	1	2	55	17	8	0.31	0.35	149	5
Plecewice 1.3	19	0	2	6	1	3	5	2	68	8	3	0.11	0.13	51	10
Dune															
Międzyborów 1.0	10	0	0	6	1	4	12	1	53	8	5	0.16	0.16	34	16
Międzyborów 1.4	10	1	0	7	0	4	9	2	58	8	5	0.14	0.16	41	13
Międzyborów 2.2	13	1	1	5	0	1	5	1	65	9	6	0.14	0.18	86	7
Międzyborów 3.0	16	0	0	5	1	2	3	3	69	9	5	0.13	0.16	92	5
Łysobyki 1.0[2]	14	1	1	4	1	3	3	1	53	24	6	0.45	0.43	150	7
Fluvial setting															
Pisia	32	0	1	7	1	1	10	4	66	9	2	0.14	0.14	44	12
Okrzesza	25	2	0	6	3	7	1	4	16	8	1	2.90	1.40	89	8
Malanowo[3] 2.5	26	0	0	7	0	2	6	1	72	8	2	0.11	0.11	47	8
Malanowo[3] 3.0	19	1	1	4	1	2	4	1	63	15	4	0.24	0.23	108	7

RESULTS

The mineral coefficients, indices and percentage contents of the HM are shown in Table 2 along with their spatial distribution (Fig. 3), correlation between garnets and amphiboles (Fig. 4A), and between the most resistant and non-resistant minerals (Fig. 4B).

1. Glacial setting

The T/O mineral coefficient shows a high dominance of the transparent minerals over opaque. The analysed tills are either garnet- or amphibole-rich (45-63% and 64%, respectively). At the Kołaczek and Maruna garnet dominates in sediments over amphiboles, but at the Żyrardów N, a content of amphiboles is as high as 64%. Tills from this latter site reveal also a low value of the ZTR index, where only 3% of ultrastable minerals are noted. The value of the ZTR is, in contrast, the highest (3-19%) among all investigated sediment in the lowermost part of the Kołaczek profile. A significant differences in the distribution of the W (weathering) index were found among glacial sediments (between 30 at Kołaczek and 329 in the lowermost part of the Żyrardów N site).

2. Fan-like forms

A considerable variability exists between (1) the transparent and opaque mineral group, and (2) content of the garnet group derived from the fan-like forms deposits. The T/O value varies between 2.3 (the uppermost part of the Polesie site) to 11.0 (the lowermost part of the Polesie site). The garnet group ranges from 22% (Polesie site) to 75% (Jaktorów site), resulting in the value of the A-coefficient above 1.0 and close of zero, respectively. Consequently, a considerable mineral variability recorded by the B-coefficient can be observed. The values of the ZTR index is also high. For example, in the sediments taken from the Kątniki site the values are between 16 to 21. Only sediments at the Polesie site are undoubtedly influenced by the group of non-resistant assemblages.

3. Dunes

Relation between the transparent and non-transparent mineral groups seems to be the most homogeneous in dune sediments; it narrows to the range of 5.2 to 9.0. The sediments at the Międzyborów site seems more enriched into garnets (between 53% and 69%) than most of the localities. The value of the ZTR index

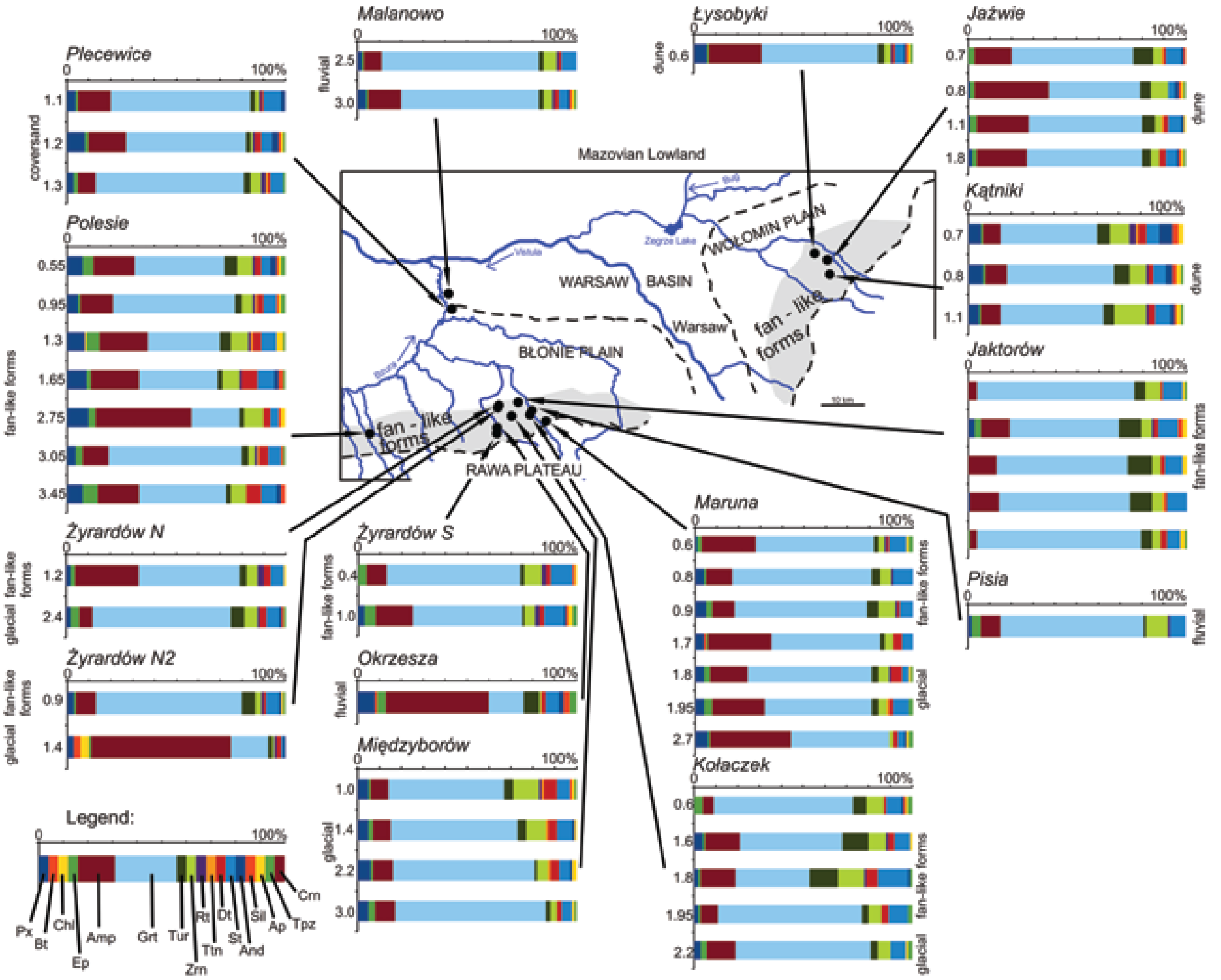

Fig. 3 Spatial distribution of the HM in sediments of the Mazovian Lowlan, Central Poland. Mineral symbols (following a proposal of Whitney and Evans, 2010): Px – pyroxenes; Bt – biotites; Chl – chlorites; Ep – epidotes; Amp – amphiboles; Grt – garnets; Tur – tourmaline; Zrn – zircon; Rt – rutile; Ttn – titanite; Dt – disten; St – staurolite; And – andalusite; Si – sillimanite; Ap – apatites; Tpz – topaz; Crn – corundum. Compiled by E. Kalińska-Nartiša, 2017.

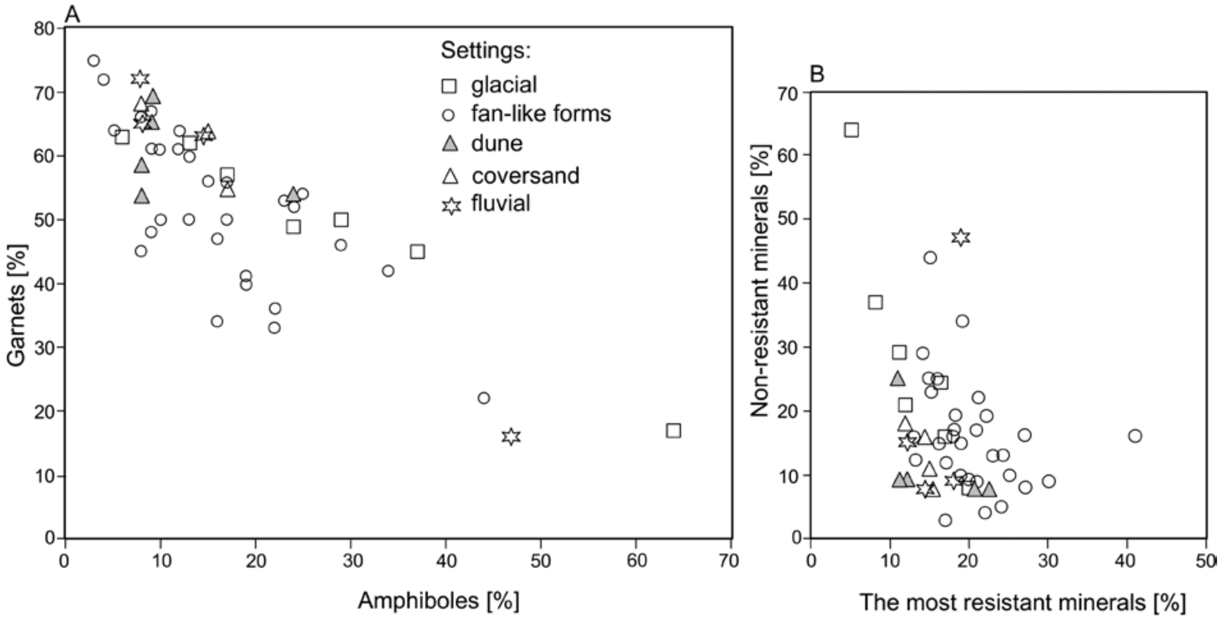

Fig. 4 Biplots of: A – percentage of garnets versus amphiboles and B – percentage of non-resistant minerals (amphiboles and pyroxenes) versus the most resistant minerals (andalusite, zircon, staurolite, tourmaline and topaz) in the investigated settings.

is also relatively high (between 13 and 16). This, however, is only true for the uppermost part of the profile. The value of this index seems decrease towards the bottom of the profile investigated, reaching value of 5 at the bottom. In contrast, value of the W coefficient increases toward the bottom of the profile and differs between 34 (at the topmost) to 92 (at the bottommost). At the Łysobyki, value of the A-coefficient equals of 0.45, thus pointing at an increase of amphiboles up to 24%. The value of the ZTR index seems smaller comparing with i.e. the Międzyborów site, and reaches only 7. Notably, the W index of 150 at Łysobyki is 3-5-times bigger than at Międzyborów, and resembles more i.e. the glacial settings studied here.

4. Coversand

Sediments taken from the coversands exhibit a relatively high percentage share of garnet (from 55 to 68%). The value of the ZTR index is lower than in dune setting, and makes up between 5 to 10. Traces of glauconite (1%) are recorded in the uppermost part of the coversand section. The values of W index are variable and range between 51 to 149.

5. Fluvial setting

A significant content of garnets (between 63 to 72%) is noted in the sediments at the Malanowo and Okrzesza sites. In contrast, only 16% of garnets and 47% of amphiboles are observed at the Pisia River. These give a variable correlation of the A-coefficient; values of 0.11 to 0.24 are typical for the Malanowo and Okrzesza setting and increase up to 2.9 is noted in the Pisia sample. The highest value (=12%) of the ZTR index is noted at the Pisia site, whereas both Okrzesza and Malanowo are lower (8, and 7-8 for Okrzesza and Malanowo, respectively). Values of the W index differs significantly between 44 (at the Pisia site) and 108 (in the lowermost part of the Malanowo profile).

DISCUSSION

Sedimentary processes re-shape the initial composition of HM assemblages (Garzanti *et al.* 2012; Morton, Hallsworth 1999), in a way that they should differ from their source rock (Sevastjanova *et al.* 2012). Following such assumption, the most liable to dissolution are i.e. amphiboles and pyroxenes, whereas tourmaline and zircon are the most stable (Morton, Hallsworth 2007; Sevastjanova *et al.* 2012). Abrasion and mechanical breakdown scarcely effect zircon, rutile, staurolite, tourmaline, apatite, epidote and finally garnet; these are, therefore, considered as the most mechanically resistant group (Chlebowski, Lindner 2004). Authors discuss the mineral characteristics, the sediment single or multiple sourcing and transformation paths in the following sections (Figs 5, 6).

1. Glacial setting

The final HM composition in the glacial setting closely depends on (1) the composition of the parent sediments, which are resistant to the mechanical damage, and (2) subjection to the chemical weathering (Passchier 2007). If so, most HM are restricted to spe-

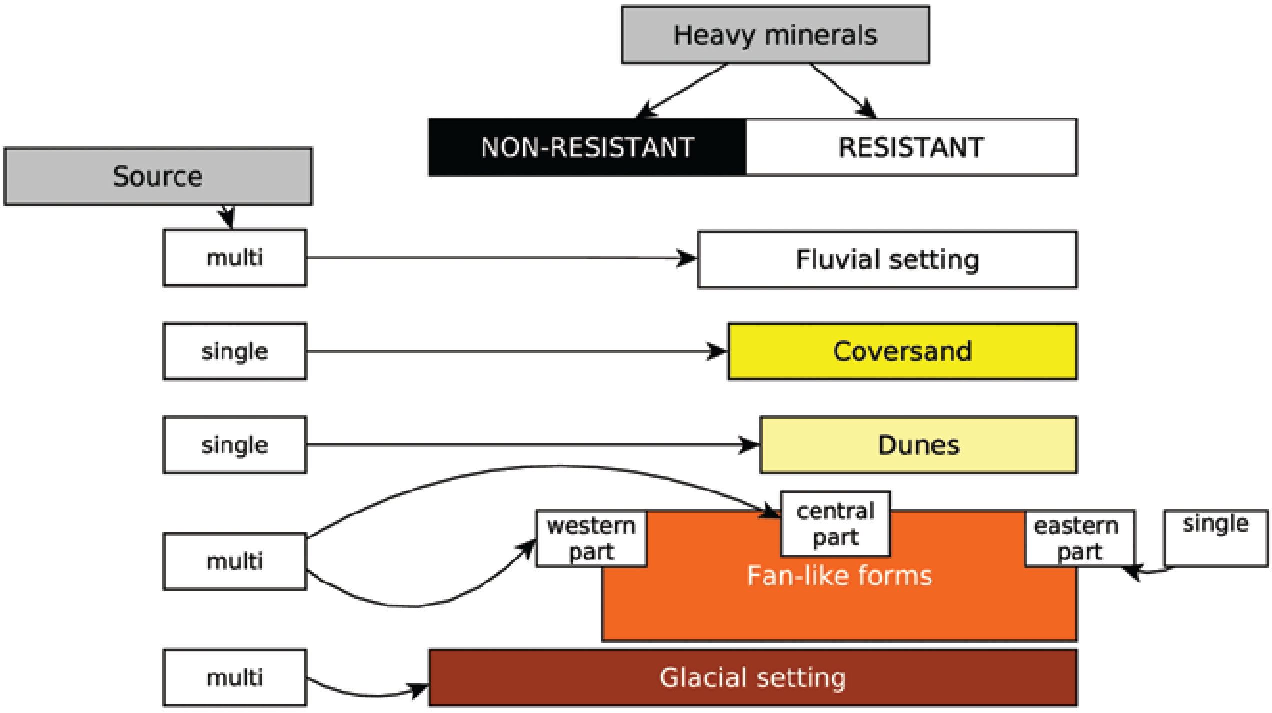

Fig. 5 Type of sediment source of the investigated settings. Compiled by E. Kalińska-Nartiša, 2017.

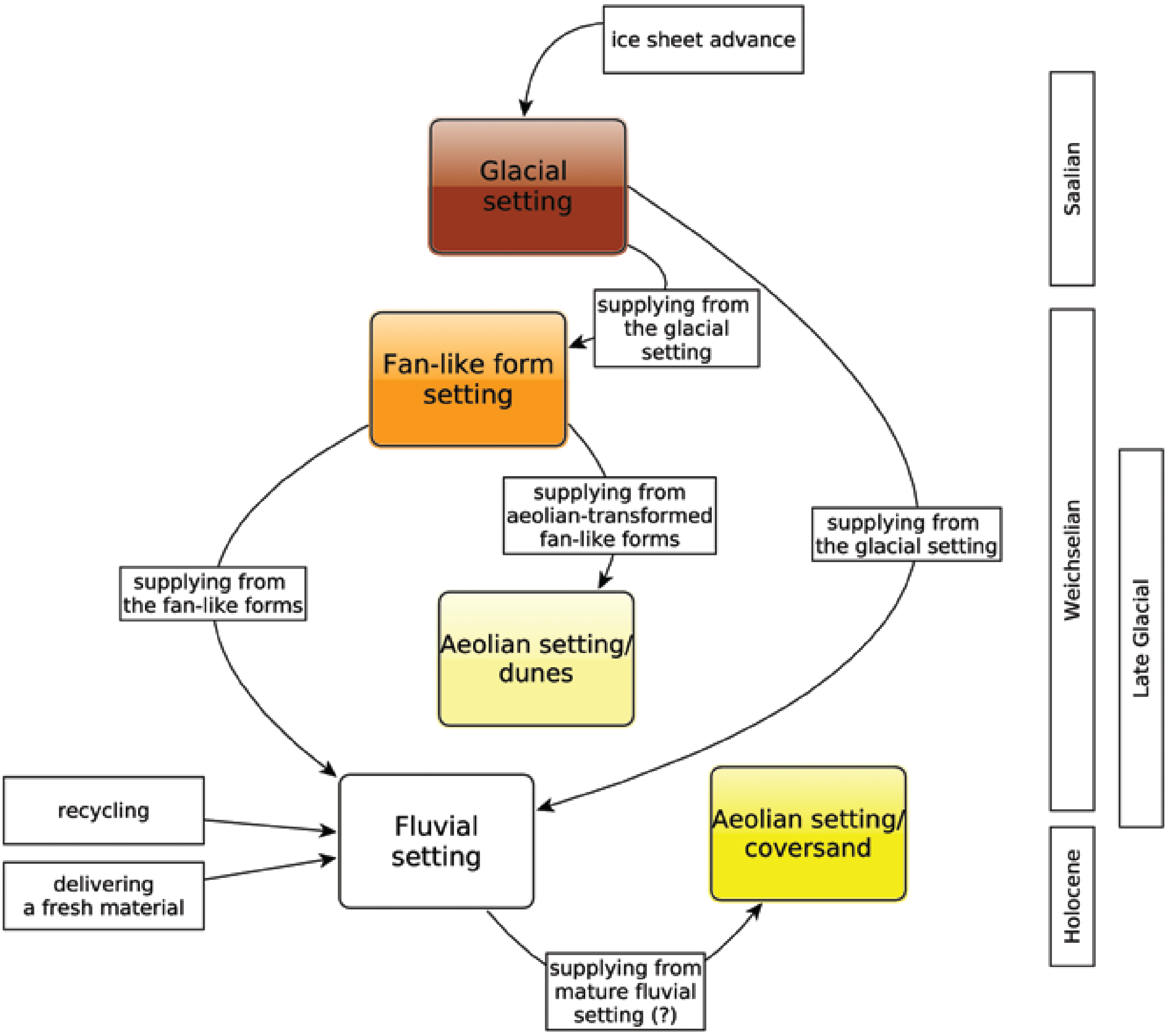

Fig. 6 Sediment pathways and transformation in the investigated settings. Compiled by E. Kalińska-Nartiša, 2017.

cific source rocks, which can provide distinguishable differences among sediment source area (Sevastjanova *et al.* 2012). In our study, garnets and amphiboles occur in significant abundances in the glacial setting (Figs 3, 4A) represented by the Kołaczek, Maruna and Żyrardów N sites. These tills are either enriched in garnets followed by resistant group or, conversely, in amphiboles, and further followed by the less-resistant assemblages (Table 2, Figs 3, 4A,B), which may be the methodological problem. On the other hand, these results support findings of Marcinkowski (2007), who stated, that no unequivocal pattern can be established for glacial sediments. These sediments have multiple sourcing, because the delivery system by the ice sheet might have been complex and multidirectional (Woźniak, Czubla 2015). The garnet-amphibole enhancement has been observed in the numerous Saalian glacial sediments (Czerwonka *et al.* 1997; Ludwikowska-Kędzia 2013; Rappol, Stoltenberg 1985; Woronko *et al.* 2013), which likely supports their Fennoscandian origin resulting from the ice advance (*cf.* Woronko *et al.* 2013).

2. Fan-like forms

Sand mineralogy of primary glacial sediment generally records the composition of rocks eroded up to the several hundreds of kilometers upstream from the glacial terminus (Gwyn, Dreimanis 1979). Under this conditions only mechanically ultrastable minerals, such as i.e. zircon, are potentially able to survive long-term glacial transport in the sandy fraction (Hauptvogel, Passchier 2012). This study shows the highest value of the ZTR index in the easternmost part (Kątniki) and the central part (Jaźwie and Kołaczek) of the fan-like forms (Table 2, Fig. 3) along with the mechanically resistant and well-rounded garnet, tourmaline and staurolite as recorded previously (Kalińska-Nartiša, Nartišs 2016a,b). Sediments at these sites must be, therefore, multicyclic and derived from one source with pre-existing recycling sediments (Fig. 5), and closely related to i.e. dune sands (Hamdan *et al.* 2015; Muhs 2004). This statement agrees with our previous study, where the fan-like forms were attributed to cold and windy conditions in periglacial climate with additional contribution of snow/ice and fluvial signal (Kalińska-Nartiša, Nartišs 2016a,b). The HM study shows that presumably dry pre- and post-Weichselian climatic conditions during the fan-like forms deposition are plausible reason for a very similar heavy mineral record between the fan-like forms and dune sediments. Considering, that either external sorting or aeolian sorting contributed, the labile components were destructed. Sediments of the fan-like forms may have experienced a high number of burial-erosion cycles. But another equally valid scenario might be due to occurrence of already mineralogically mature sediments, that served as a potential source. This is especially valid, while assuming (1) the patchy amphibole-garnet (less-more resistant) of the underlain tills, so that the more resistant parts had already diminished into the labile components, and (2) that the initial mixture of the fan-like form sediment grain originates partially/fully from this glacial setting (Fig. 6).

It is well established, that samples representing the older sediments, that have been buried to greater depths and for a longer time tend to have a high ZTR value (Nie *et al.* 2013). To some extent, this may be supported by the sediments of the fan-like form, where (1) the oldest (ca. 48 ka onwards) sequence reveals an alternation of both the more- and less-resistant horizons, (2) the pre-LGM (ca. 31-25 ka) part is enriched into garnets and some ultra-resistant staurolite and tourmaline, (3) the post-LGM (ca. 16-14 ka) sequence shows either enrichment into garnets (topmost of the Kołaczek profile; Table 1) or into the most resistant species (Jaźwie site), and lastly, (4) the youngest (ca. 12 ka) phase gradually depletes into amphiboles and reveals one of the lowest B-coefficient. This chronological-HM-based grouping supports somewhat an idea on repeatable sedimentary cycles.

Sediments at the Polesie site show both the A- and B-coefficients higher than elsewhere (Table 2, Fig. 3), thus resembling i.e. the glacial settings from some profiles (*see* above). Twice more of amphiboles is found in the middle part of the Polesie profile (Table 2, Fig. 3). The lowermost part of the Polesie profile (depths of 3.05 and 3.45 m) again resembles multicyclic, where garnet with some ultrastable components prevail. Such resistant-less-resistant mineral alternations might be similar with the oldest part of the Kołaczek profile. This latter has been defined as a dry-humid environmental interactions (Kalińska-Nartiša, Nartišs 2016a), and resulted from multi-sourcing (Fig. 5).

3. Dunes

In aeolian environment, deflation process and source deposits are strongly responsible for the HM transformation (Marcinkowski, Mycielska-Dowgiałło 2013; Mycielska-Dowgiałło 1993). This means, that some particles tend to be winnowed, but some of them have a very high stability and resistance (Scheib *et al.* 2013).

The HM can be found in dune flanks due to wind turbulences (Garzanti *et al.* 2012) and stoss side of dune, where flow velocity increases (Komar 2007). Authors found dense minerals in dune flank at the Międzyborów site, but also in the sediments of the coversand, where garnets, zircon, tourmaline, disten and staurolite prevail (Table 1; Figs 3, 4A-B). These sediments are thus mineralogically mature (Fig. 5), and this results from the long-lived aeolian processes or/and their source had already undergone a preliminary enrichment into a resistant mineral suite. For example, at the Międzyborów site, dune sediments originate from an already aeolian-transformed fan-like form sands. A general western wind direction may have prevailed during dune formation (Bokhorst *et al.* 2011; Brauer *et al.* 2008; Renssen *et al.* 2007), and thus sediment was delivered from the surroundings of the Żyrardów N site. Considering this scenario, more mechanically durable garnet and the most durable zircon, disten and staurolite occur in a dune sediments than in their source. This also means, that less durable minerals were depleted from dune sediments in deflation process. The ultrastable HM seem concentrate in the uppermost part of the profile at the Międzyborów, which may be due to reworking of the lower-located sediments.

At Łysobyki, dune sediments reveal: (1) the A- and B-coefficients a few-times higher than in other aeolian settings, (2) the highest (among aeolian settings) W coefficient, and (3) relatively low the ZTR index. Authors interpret, that the relative differences of this dune sediments must result from (1) diminishing of garnet, (2) removal of heavy minerals with a lower resistance to chemical weathering, and (3) depletion into an ultrastable assemblages. Assuming that not only active phases but also stabilization events interplay in aeolian environment (Navarro *et al.* 2011; Tsoar 2005), the Łysobyki site may represent cessation of aeolian activity. Similar HM record, displaying relatively high content of amphiboles (up to 36%) and comparable ZTR index, was observed in dune sediments east of Warsaw and assigned with soil processes (Konecka-Betley, Janowska 2005).

Coversand

Coversands generally cover the pre-existing morphology (Kasse 1997), and are considered of fluvial-aeolian origin (Bateman, Van Huissteden 1999; Zieliński *et al.* 2016), and brief deposition (Kasse 2002, 1997). The mineral composition of their sediments is, therefore, expected to differ from typical dune sediments, for example by revealing a lower maturity of sediments (Marcinkowski, Mycielska-Dowgiałło 2013). At the Plecewice site, sediments reveal a similar number of garnets, as these noted in dune sediments (Table 1; Fig. 3, 4A). The contribution of amphiboles is, however, higher, and consequently, the ultrastable components are depleted. Assuming this, only a stable wind-proxy (garnet) prevail in the coversand sediments, indicating, therefore, a shorter-lived aeolian transformation than in dunes. Fluvial sediments, similar to these at the Malanowo site (*see* in Results and below), might have been a potential coversand source. Assuming this, coversand sediments carry a signal of single sourcing by an already mature material with only minor aeolian transformation (Fig. 5).

4. Fluvial setting

Fluvial and fan-like form sediments seem strongly correlated in terms of their HM characteristic, thus supporting a statement, that HM are largely source-dependent (Jagodziński *et al.* 2012). For example, in sediment of the Pisia River occurrence of garnet and other mechanically durable assemblages (Table 2) is very similar to the sands of the fan-like forms (Fig. 3). This is because this site locates in the central part of the fan-like forms. At the Okrzesza site, in contrast, mineral outline of the sediments remains rather an amphibole-rich combination, and over 2-times more amphiboles than garnets (Table 2; Figs 3, 4A), together with unstable amphiboles, biotite and chlorite. Amphiboles are non-resistant to both mechanical abrasion and weathering (Marcinkowski, Mycielska-Dowgiałło 2013), and may be deliver to the sedimentary system i.e. by fluvial incision into the lower-located glacial tills as observed by Weckwerth *et al.* (2013). This is a case at the Okrzesza site, sediments of which originate from the glacial sediments. Preservation of the commonly regarded as less durable and unstable pyroxenes and amphiboles suggests high erosion rates, rapid transport and short grain residence time in the river (Sevastjanova *et al.* 2012). Assuming a very close location of the Saalian glacial sediments of the Rawa plateau, the Okrzesza river incised into these glacial sediments without remarkable fluvial reworking. Both the sediments taken from the Okrzesza and Pisia sites may disagree with a general statement, that the processes of fluvial deposition, transport and erosion are expected to modify the original provenance signal (Weckwerth *et al.* 2013).

In contrast, the sands of the higher terrace of the Bzura reveal one of the highest percentage of garnets (72%) in this study (Table 2; Figs 3, 4A). This seems be strongly correlated with the transitional regime, where sediments underwent a repeatedly reworking and eroding, as observed i.e. in sandur settings in NW Poland (Pisarska-Jamroży *et al.* 2015). In the second sand sample the content of stable garnets slightly decreases and is replaced by non-resistant amphiboles. The cause of this can be explained by seasonal increasing of fluvial erosion rates and denudation as observed by Weckwerth *et al.* (2013). Additionally, these sediments, by revealing the W index almost twice higher than elsewhere and, thus, diminishing of the chemically low-resistant minerals, point at an abrupt erosion and delivering a fresh material to the fluvial system (Fig. 6). Similar pattern has been observed in central Poland (Wachecka-Kotkowska, Ludwikowska-Kędzia, 2013). The mineral differences among fluvial sediments likely indicate their multiple sourcing, which may be similar to this observed in i.e. large rivers (Nascimento *et al.* 2015).

CONCLUSIONS

The HM record of five sedimentary settings in the Mazovian Lowland, Central Poland as expounded upon allows us to reach the following conclusions.

In the glacial setting either the most durable garnets or less-resistant amphiboles prevail, and this combination has been already subjected to the numerous Saalian glacial settings in Poland. Certainly, there is no unequivocal mineral pattern for glacial sediments, since they reveal either a multiple sourcing or the methodological problems may be addressed.

Fan-like form and aeolian settings seem greatly connected; these sediments are multicyclic and largely derived from pre-existing recycling sediments (tills-fan-like forms-dune sediments). Locally, deeper buried, and thus, longer-time-standing sediments of these settings, tend to have a high maturity ZTR coefficient. In contrast, the westernmost part of the fan-like forms reveals the highest amount of amphiboles and non-resistant minerals, resembling the glacial setting. Work at higher resolution is needed for better understanding this.

Dunes and coversand are enriched in resistive minerals such as garnets, zircon, tourmaline, disten and staurolite, which either result from the long-lived aeolian processes or/and from an already enriched into a resistant mineral suite sediment source (fan-like forms). Occasionally, depletion in an ultrastable assemblages is noted, which may represent aeolian cessation. In the sediments of the coversand the contribution of amphiboles is higher, and consequently, the ultrastable components are depleted, which indicate a shorter-lived aeolian transformation.

Mineral composition of fluvial sediments indicates their multiple sourcing, and strongly correlates either with sediments of the fan-like forms or glacial sediments.

ACKNOWLEDGMENTS

Comments from journal reviewers are appreciated. The research was financed by the Ministry of Science and Higher Education of Poland, grant no. N N307 2731 33 “Age and correlation of sand deposits of the southern and eastern margin of the Middle Mazovian Lowland” in years 2007–2009, the Institute of Geology, Faculty of Geology, University of Warsaw (statutory funding no. 1241/2; BW funding no. 1686/2, 1726/3, 1761/3, 1797/3) in years 2005–2008, Mazovian Stipend for the best PhD students in year 2009, SIA SunGIS in years 2015–2017 (to E. Kalińska-Nartiša), and by research funding of University of Latvia (to M. Naritšs).

REFERENCES

Andrzejewski, L., 1991. The course of fluvial processes in the lower Bzura river valley during the last 15 000 years. *Geographical Studies Special Issue 6*, 147–154.

Baraniecka, M.D., Konecka-Betley, K., 1987. Fluvial sediments of the Vistulian and Holocene in the Warsaw Basin. *In* Starkel, L. (Ed.), *Evolution of the Vistula River Valley during the Last 15000 Years*. Zakład Narodowy im. Ossolińskich, Wrocław, 151–170.

Bateman, M.D., Van Huissteden, J., 1999. The timing of last-glacial periglacial and aeolian events, Twente, eastern Netherlands. *Journal of Quaternary Sciences 14,* 277–283.

Ber, A., 2005. The Detailed Geological Map of Poland 1:50,000: the history, present and future. *Przegląd Geologiczny 53*, 903–906.

Bokhorst, M.P., Vandenberghe, J., Sümegi, P., Łanczont, M., Gerasimenko, N.P., Matviishina, Z.N., Marković, S.B., Frechen, M., 2011. Atmospheric circulation patterns in central and eastern Europe during the Weichselian Pleniglacial inferred from loess grain-size records. *Quaternary International 234,* 62–74.

Brauer, A., Haug, G.H., Dulski, P., Sigman, D.M., Negendank, J.F.W., 2008. An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period. *Nature Geoscience 1*, 520–523.

Chlebowski, R., Lindner, L., 2004. Aspekty mineralogiczne w metodyce badań lessów na przykładzie lessów polskich i ukraińskich (Mineralogical issues in the methodology of loess analysis with examples from the loesses of Poland and Ukraine). *In* Kostrzewski, A. (Ed.), *Geneza, Litologia i Stratygrafia Utworów Czwartorzędowych.* Adam Mickiewicz University, Poznań, 17–36. [In Polish].

Czerwonka, J.A., Dobosz, T., Krzyszkowski, D., 1997. Till stratigraphy and petrography of the northern part of Silesia (southwestern Poland). *Geological Quarterly 41,* 209–242.

Derkachev, A.N., Nikolaeva, N.A., 2013. Possibilities and restrictions of heavy-mineral analysis for the reconstruction of sedimentary environments and source areas. *Geologos 19,* 147–158.

Dill, H.G., Kaufhold, S., Lindenmaier, F., Dohrmann, R., Ludwig, R., Botz, R., 2012. Joint clay–heavy–light mineral analysis: a tool to investigate the hydrographic–hydraulic regime of Late Cenozoic deltaic inland fans under changing climatic conditions (Cuvelai-Etosha Basin, Namibia). *International Journal of Earth Sciences 102,* 265–304.

Dzierwa, K, Mycielska-Dowgiałło, E. 2003. Rekonstrukcja dynamiki procesów eolicznych i czasu ich trwania na podstawie wybranych cech teksturalnych osadów wydmy w Cięciwie (Reconstruction of the dynamics of aeolian processes and of their duration on the basis of selected textural features of the deposits within the dune at Cięciwa, eastern Poland). *Przegląd Geologiczny 51,* 163–167. [In Polish].

Garzanti, E., Andò, S., Vezzoli, G., Lustrino, M., Boni, M., Vermeesch, P., 2012. Petrology of the Namib Sand Sea: Long-distance transport and compositional variability in the wind-displaced Orange Delta. *Earth-Science Reviews 112,* 173–189.

Guedes, C.C.F., Giannini, P.C.F., Nascimento, D.R., Sawakuchi, A.O., Tanaka, A.P.B., Rossi, M.G., 2011. Controls of heavy minerals and grain size in a holocene regressive barrier (Ilha Comprida, southeastern Brazil). *Journal of South American Earth Sciences 31,* 110–123.

Gwyn, Q.H.J., Dreimanis, A., 1979. Heavy mineral assemblages in tills and their use in distinguishing glacial lobes in the Great Lakes region. *Canadian Journal of Earth Sciences 16,* 2219–2235.

Hamdan, M.A., Refaat, A.A., Anwar, E.A., Shallaly, N.A., 2015. Source of the aeolian dune sand of Toshka area , southeastern Western Desert , Egypt. *Aeolian Research 17,* 275–289.

Hauptvogel, D.W., Passchier, S., 2012. Early–Middle Miocene (17–14 Ma) Antarctic ice dynamics reconstructed from the heavy mineral provenance in the AND-2A drill core, Ross Sea, Antarctica. *Global and Planetary Change 82–83,* 38–50.

Hubert, J. F., 1962. A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. *Journal of Sedimentary Research 32,* 440–450.

Jagodziński, R., Sternal, B., Szczuciński, W., Chagué-Goff, C., Sugawara, D., 2012. Heavy minerals in the 2011 Tohoku-oki tsunami deposits—insights into sediment sources and hydrodynamics. *Sedimentary Geology 282*, 57–64.

Järvelill, J.-I., Kleesment, A., Raukas A., 2015. Accumulation of heavy minerals in the eastern coast of the Gulf of Riga, south-western Estonia. *Bulletin of the Geological Society of Finland 87,* 67–78.

Kalińska-Nartiša, E., Dzierżek, J., Bińka, K., Borkowski, A., Rydelek, P., Zawrzykraj, P., 2016. Upper Pleistocene palaeoenvironmental changes at the Zwierzyniec site, central Poland. *Geological Quaterly 60(3),* 610–623.

Kalińska-Nartiša, E., Nartišs, M., 2016a. The fan-like forms in the southern margin of the Mazovian Lowland area (Central Poland): a new high-resolution textural-timing study. *International Journal of Earth Sciences 105,* 885–903.

Kalińska-Nartiša, E., Nartišs, M., 2016b. Sandy fan-like forms in the central-eastern Mazovian Lowland (Central Poland): textural record and chronology. *Geografiska Annaler Series A, Physical Geography 98,* 111–127.

Kalińska-Nartiša, E., Thiel, C., Nartišs, M., Buylaert, J.P., Murray, A.S., 2016. The north-eastern aeolian 'European Sand Belt'as potential record of environmental changes: A case study from Eastern Latvia and Southern Estonia. *Aeolian Research 22*, 59-72.

Kalińska, E., 2012. Geological setting and sedimentary characteristics of the coversands distributed in the western part of the Blonie glaciolacustrine basin (Central Poland) – preliminary results. *Bulletin of the Geological Society of Finland 84,* 33–44.

Kalińska, E., 2008a. Zmienność cech teksturalnych osadów południowego obrzeżenia Równiny Łowicko-Błońskiej między Jaktorowem i Żyrardowem (Sediments of the south Łowicz-Błonie Plain between Jaktorów and Żyrardów – textural variability). *Landform Analysis 9,* 151–154. [In Polish].

Kalińska, E., 2008b. Piaszczyste osady poziomu chodakowskiego i doliny dolnej Bzury w świetle wybranych cech sedymentologicznych (Sandy sediments of the Chodaków Level and the lower Bzura valley – sedimentary features). *Landform Analysis 9*, 88–90. [In Polish].

Kasper-Zubillaga, J.J., Zolezzi-Ruiz, H., 2007. Grain size, mineralogical and geochemical studies of coastal and inland dune sands from El Vizcaíno Desert, Baja California Peninsula, Mexico. *Revista Mexicana de Ciencias Geologicas 24,* 423–438.

Kasse, C., 2002. Sandy aeolian deposits and environments and their relation to climate during the Last Glacial Maximum and Lateglacial in northwest and central Europe. *Progress in Physical Geography, 26* 507–532.

Kasse, C., 1997. Cold-climate aeolian sand-sheet formation in North-Western Europe (c. 14-12.4 ka); a response to permafrost degradation and increased aridity. *Permafrost and Periglacial Processes 8,* 295–311.

Kilibarda, Z., Blockland, J., 2011. Morphology and origin of the Fair Oaks Dunes in NW Indiana, USA. *Geomorphology 125,* 305–318.

Kolstrup, E., Murray, A., Possnert, G., 2007. Luminescence and radiocarbon ages from laminated Lateglacial aeolian sediments in western Jutland, Denmark. *Boreas 36,* 314–325.

Komar, P.D., 2007. The entrainment, transport and sorting of heavy minerals by waves and currents. *Developments in Sedimentology 58,* 3–48.

Konecka-Betley K., Janowska, E., 2005. Late Glacial and Holocene stratotype profile of palaeosoils in the Warsaw Basin. *Studia Quaternaria 22,* 3–16.

Ludwikowska-Kędzia, M., 2013. The assemblages of transparent heavy minerals in Quaternary sediments of the Kielce-Łagów Valley (Holy Cross Mountains, Poland). *Geologos 19 (1-2),* 95–129.

Mahaney, W.C., Hancock, R.G.V., Melville, H., 2011. Late glacial retreat and Neoglacial advance sequences in the Zillertal Alps, Austria. *Geomorphology 130,* 312–326.

Mange, M.A., Wright, D.T., 2007. *Heavy minerals in use: Developments in Sedimentology*, 58. Elsevier, Amsterdam. 1283 pp.

Marcinkowski, B., 2007. Wykorzystanie składu mineralnego i morfologii ziaren minerałów ciężkich do określania środowiska sedymentacyjnego (Application of mineral composite and morphologic grain minerals in designation of sedimentary environment). *Przegląd Geologiczny 55,* 207. [In Polish].

Marcinkowski, B., Mycielska-Dowgiałło, E., 2013. Heavy-mineral analysis in Polish investigations of Quaternary deposits: a review. *Geologos 19,* 5–23.

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. *Quaternary Science Reviews 44,* 81–88.

Marks, L., 2005. Pleistocene river systems in the southern peribaltic area as indication of interglacial sea level changes in the Baltic Basin. *Quaternary International 130,* 43–48.

Marks, L., 2004. Middle and Late Pleistocene fluvial systems in central Poland. *Proceedings of the Geologists' Association115*, 174–182.

Marks, L., 2002. Last Glacial Maximum in Poland. *Quaternary Science Reviews 21,* 103–110.

Marks, L., Gałązka, D., Woronko, B., 2016. Climate, environment and stratigraphy of the last Pleistocene glacial stage in Poland. *Quaternary International 420*, 259–271.

Marks, L., Gogołek, W., Piotrowska, K., 2006. *Geological Map of Poland 1 : 500000, with Explanatory Text.* Państwowy Instytut Geologiczny, Warszawa. [In Polish].

Morton, A.C., Hallsworth, C.R., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology 124 (1),* 3–29.

Morton, A.C., Hallsworth, C.R., 2007. Stability of detrital heavy minerals during burial diagenesis. *Developments in Sedimentology 58,* 215–245.

Muhs, D.R., 2004. Mineralogical maturity in dunefields of North America, Africa and Australia. *Geomorphology 59,* 247–269.

Mycielska-Dowgiałło, E., 1993. Estimates of Late Glacial and Holocene aeolian activity in Belgium, Poland and Sweden. *Boreas 22,* 165–170.

Nascimento, D.R., Sawakuchi, A.O., Guedes, C.C.F., Giannini, P.C.F., Grohmann, C.H., Ferreira, M.P., 2015. Provenance of sands from the confluence of the Amazon and Madeira rivers based on detrital heavy minerals and luminescence of quartz and feldspar. *Sedimentary Geology 316,* 1–12.

Navarro, M., Muñoz-Pérez, J.J., Román-Sierra, J., Tsoar, H., Rodríguez, I., Gómez-Pina, G., 2011. Assessment of highly active dune mobility in the medium, short and very short term. *Geomorphology 129*, 14–28.

Nie, J., Peng, W., Pfaff, K., Möller, A., Garzanti, E., Andò, S., Stevens, T., Bird, A., Chang, H., Song, Y., Liu, S., Ji, S., 2013. Controlling factors on heavy mineral assemblages in Chinese loess and Red Clay. *Palaeogeography, Palaeoclimatology, Palaeoecology 381–382,* 110–118.

Nowak, J., 1984. *Szczegółowa Mapa Geologiczna Polski 1:50 000, arkusz Tłuszcz (489) (Detailed Geological Map of Poland 1:50 000, Tłuszcz sheet).* Państwowy Instytut Geologiczny, Warszawa. [In Polish].

Passchier, S., 2007. The use of heavy minerals in the reconstruction of ice-sheet drainage patterns: an example from the edge of the East Antarctic ice sheet. *Developments in Sedimentology 58,* 677–699.

Pisarska-Jamroży, M., van Loon, A. J. (Tom), Woronko, B., 2015. Sorting of heavy minerals in sediments deposited at a high accumulation rate, with examples from sandurs and an ice-marginal valley in NW Poland. *GFF 137 (2),* 126–140.

Racinowski, R., Rzechowski, J., 1969. Minerały ciężkie w glinach zwałowych Polski środkowej (Heavy minerals in boulder clays of central Poland). *Geological Quarterly 13,* 479–490. [In Polish]

Rappol, M., Stoltenberg, H.M.P., 1985. Compositional variability of Saalian till in The Netherlands and its origi*n. Boreas 14,* 33–50.

Renssen, H., Kasse, C., Vandenberghe, J., Lorenz, S.J., 2007. Weichselian Late Pleniglacial surface winds over northwest and central Europe: A model-data comparison. *Journal of Quaternary Science 22,* 281–293.

Sarnacka, Z., 1982. Age revision of the Warsaw proglacial lake in the Warsaw region. *Biuletyn Instytutu Geologicznego 343,* 59–70.

Scheib, A.J., Birke, M., Dinelli, E., 2013. Geochemical evidence of aeolian deposits in European soils. *Boreas 43 (1),* 175–192.

Sevastjanova, I., Hall, R., Alderton, D., 2012. A detrital heavy mineral viewpoint on sediment provenance and tropical weathering in SE Asia. *Sedimentary Geology 280,* 179–194.

Starkel, L., Gębica, P., Superson, J., 2007. Last Glacial–Interglacial cycle in the evolution of river valleys in southern and central Poland. *Quaternary Science Reviews 26,* 2924–2936.

Starkel, L., Michczyńska, D.J., Gębica, P., Kiss, T., Panin, A., Perşoiu, I., 2015. Climatic fluctuations reflected in the evolution of fluvial systems of Central-Eastern Europe (60–8 ka cal BP). *Quaternary International 388,* 97–118.

Starkel, L., Soja, R., Michczyńska, D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. *Catena 66*, 24–33.

Szalewicz, H., 1994. *Szczegółowa Mapa Geologiczna Polski 1:50 000, arkusz Żyrardów (557) (Detailed Geological Map of Poland 1:50 000, Żyrardów sheet).* Państwowy Instytut Geologiczny, Warszawa. [In Polish]

Szalewicz, H., 1987. *Szczegółowa Mapa Geologiczna Polski 1:50 000, arkusz Grodzisk Mazowiecki (558) (Detailed Geological Map of Poland 1:50 000, Grodzisk Mazowiecki sheet).* Państwowy Instytut Geologiczny, Warszawa. [In Polish].

Tolksdorf, J.F., Kaiser, K., 2012. Holocene aeolian dynamics in the European sand-belt as indicated by geochronological data. *Boreas 41,* 408–421.

Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. *Physica A Statistical Mechanics and its Applications 357,* 50–56.

Ugolini, F.C., Hillier, S., Certini, G., Wilson, M.J., 2008. The contribution of aeolian material to an Aridisol from southern Jordan as revealed by mineralogical analysis. *Journal of Arid Environments 72,* 1431–1447.

Vandenberghe, D.A.G., Derese, C., Kasse, C., Van den Haute, P., 2013. Late Weichselian (fluvio-) aeolian sediments and Holocene drift-sands of the classic type locality in Twente (E Netherlands): a high-resolution dating study using optically stimulated luminescence. *Quaternary Science Reviews 68,* 96–113.

Wachecka-Kotkowska, L., Ludwikowska-Kędzia, M., 2013. Heavy – mineral assemblages from fluvial Pleniglacial deposits of the Piotrków Plateau and the Holy Cross Mountains – a comparative study. *Geologos 19 (1-2),* 131–146.

Weckwerth, P., Chabowski, M., 2013. Heavy minerals as a tool to reconstruct river activity during the Weichselian glaciation. *Geologos 19 (1-2),* 25–46.

Whitney, D., Evans, B., 2010. Abbreviation for names of rock-forming minerals. *American Mineralogist 95 (1),* 185–187.

Woronko, B., Rychel, J., Karasiewicz, M.T., Ber, A., Krzywicki, T., Marks, L., Pochocka-Szwarc, K., 2013. Heavy and light minerals as a tool for reconstructing depositional environments: an example from the Jałówka site (northern Podlasie region, NE Poland). *Geologos 19 (1-2),* 47–66.

Woźniak, P.P., Czubla, P., 2015. The Late Weichselian glacial record in northern Poland: A new look at debris transport routes by the Fennoscandian Ice Sheet. *Quaternary International 386,* 3–17.

Wysota, W., Molewski, P., Sokołowski, R.J., 2009. Record of the Vistula ice lobe advances in the Late Weichselian glacial sequence in north-central Poland. *Quaternary International 207,* 26–41.

Zieliński, P., Sokołowski, R.J., Woronko, B., Fedorowicz, S., Jankowski, M., Standzikowski, K., 2016. Sandy deposition in a small dry valley in the periglacial zone of the Last Glacial Maxiumum: A case study from the Józefów site, SE Poland. *Quaternary International 399,* 58–71.