

Petrographical analysis of Warthian fluvioglacial gravels as a tool to trace the source area – a case study from central Poland

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Abstract

The petrographical features of the medium- and coarse-grained gravels (4-10 mm and 20-60 mm, respectively) of weathered and fresh (unweathered) deposits indicate, in combination with so-called indicator and statistical erratics, that two glacial lobes joined in the borderland of the Polish Lowlands and Uplands. Lower Palaeozoic limestones become less frequent in the finer gravel fraction, whereas crystalline rocks and flints become more frequent. The petrographical analysis of the coarser gravel fraction indicates that the ice sheet advanced from the NE to NNW (the Widawka lobe) and from the NE to ENE (the Rawka, Pilica and Łuciąża lobes). The source areas of the gravel deposited by the Warthian ice sheet were magmatic and sedimentary areas of both the Baltic and the SE Sweden basins.

Keywords: gravel petrography, indicator erratics, fluvioglacial deposits, Warthian stadial, central Poland

1. Introduction

Quantitative analysis of the petrography of gravel fractions indicates how and in how far particular petrographical groups in glacial and fluvioglacial sediments change, in time and/or space. Such analyses have resulted in numerous often significantly different lithostratigraphic schemes (e.g. Lüttig, 1958, 1995, 1999; Cepek, 1962, 1973, 1975, 1981; Rühberg & Krienke, 1977; Böse, 1979, 1983, 1989, 1995; Meyer, 1994, 1998, 2000; Czerwonka & Krzyszkowski, 1994; Lisicki, 1998 a,b; Zabielski, 1996; Rühberg, 1999; Krienke, 2003). The results of petrographical analyses are usually aimed at helping to establish a lithostratigraphic correlation of deposits in a comparable stratigraphic succession (e.g. Czerwonka & Krzyszkowski, 1994), but in specific cases they may also be used for regional lithostratigraphic correlation.

Petrographical analysis in combination with identification of Scandinavian erratics tends to give an indication of the Scandinavian source areas and to suggest ice-sheet transgression route or individual zones of ice movement during its advance. This is obvious, for instance, the Warthian stadial of the Odranian glaciation in the border area between the lowlands and uplands of central Poland (Figs 1, 2).

The significance of petrographical analyses, of both medium- and coarse-gravel fractions, is therefore huge: they complement lithofacies analysis as applied by Kasprzak & Kozarski (1984) regarding Quaternary deposits. They confirm the hypothesis about the lithostratigraphy as determined earlier (e.g. Kozarski, 1988; Kasprzak, 1985, 1992, 1997; Böse, 1989, 1995; Böse & Górską, 1995; Pettersson, 1995, 1997, 2002).

The petrographical investigation of medium-sized gravel of glacial tills became a standard

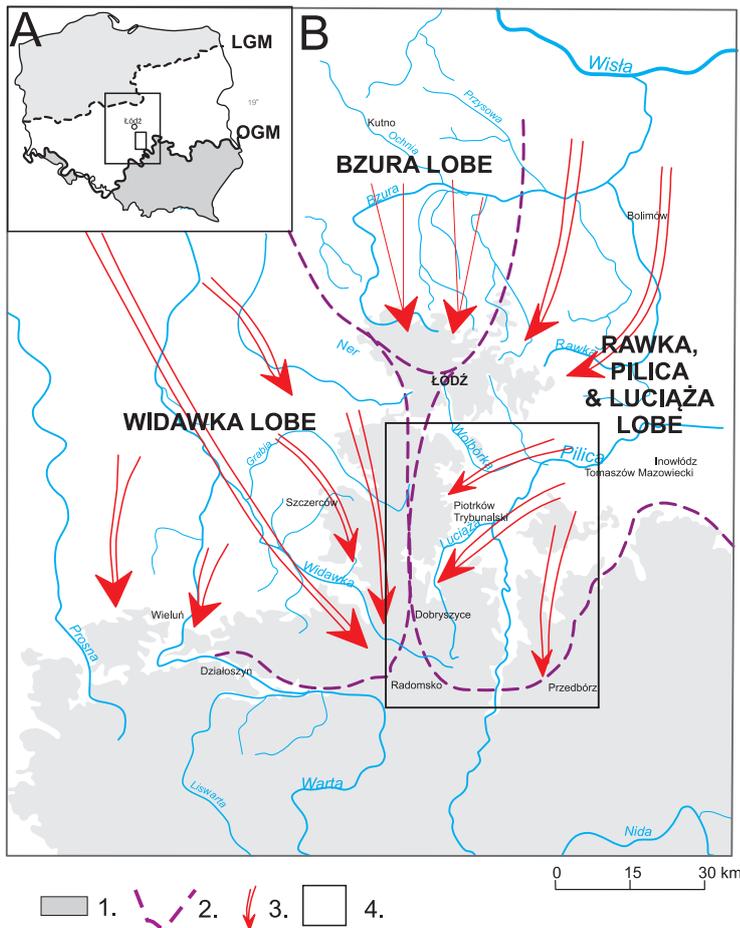


Fig. 1. Lobes of the ice-marginal zone during the Warthian stadial in central Poland. Slightly modified after Turkowska (2006)
A: Location of the study area in central Poland. OGM = Odra Glacial Maximum; LGM = Last Glacial Maximum; **B:** 1 = area over 200 m above sea level; 2 = ice-sheet extent; 3 = directions of the ice-sheet advance; 4 = study area

type of investigation when the Detailed Geological Map of Poland (DGMP) at scale 1:50 000 was prepared. This led to much more common use of this type of research. Yet, petrographical examination of gravel from fluvio-glacial deposits is still, regardless of the size fraction, carried out rarely: a missed chance.

The main cause of the relatively small attention for the gravel in fluvio-glacial deposits is, apart from the problem of painstaking, time-consuming analyses, the large influence of post-depositional processes on the final petrographical composition of these deposits.

It is remarkable in this context that fluvio-glacial deposits are in Poland considered hardly useful for petrographical analyses, whereas German investigators publish results of analyses of Scandinavian indicator erratics for many types of glacial deposits; they started doing so already in the beginning of the 1990s (e.g. Lüttig, 1991, 1997b, 1999, 2005). Lüttig based his stratigraphic interpretation even on such research of fluvio-glacial and periglacial deposits and even on the gravels from river terraces. Petrographical analyses of medium to coarse gravel from fluvial, limnic and other proglacial

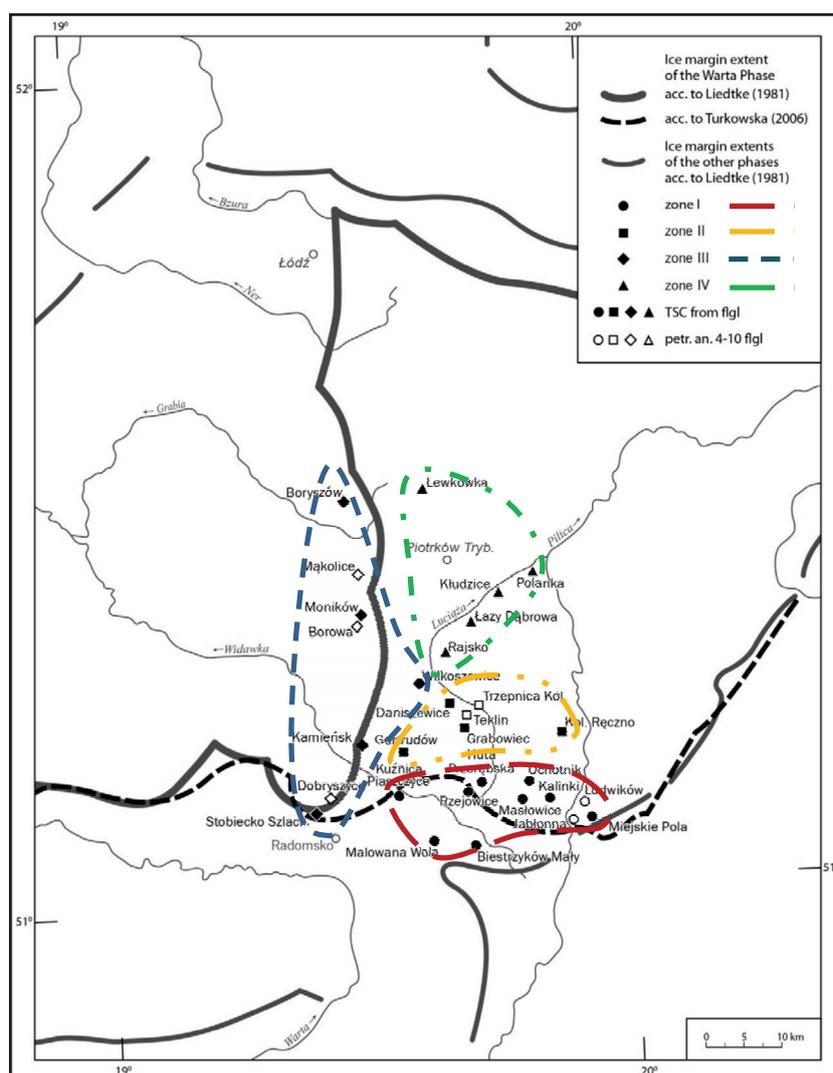
were also carried out by, among others, Badura et al. (1992), Czerwonka et al. (1997) and Meyer (2000). It should be clearly stressed, however, that the objective was first of all a lithostratigraphical division of the Pleistocene deposits.

Successful petrographical analyses of fluvio-glacial deposits had been conducted also elsewhere, for instance in Lithuania and Latvia (Jurgaitis, 1969, 1984; Danilans, 1973; Mikalajskas, 1985). The usefulness of petrographical analysis of fluvio-glacial gravel has not been truly neglected by Saarnisto (1990) either.

Earlier research of glacial tills and the accompanying simultaneous fluvio-glacial deposits at Koczery in the area of Podlasie at Wardyń in Pojezierze Drawskie (the Drawskie Lakeland) (Górská, 2002b), and at Sobolewo in Suwalszczyzna (the Suwałki region) (Górská, 2006b) indicate that only small differences exist in the percentages of the various petrographical groups of the medium coarse gravel between glacial tills and fluvio-glacial deposits. Analyses of indicator erratics of the coarse-gravel fraction deposited during the same advance of the Scandinavian ice sheet, also showed largely similar results.

Fig. 2. Location of the sites in the four zones (I–IV) and extent of the ice-sheet lobes during the Warthian stadial

TSC from till = Theoretical Stone Centre calculated from glacial till; TSC from flgl = Theoretical Stone Centre calculated from fluvioglacial sediments, 4–10 petr. an. flgl = petrographical analysis conducted on 4–10 mm gravel derived from fluvioglacial sediments



More recently, Lipka (2011) has presented a detailed study of the spatial petrological differences of glacial deposits in the Wysoczyzna Lubuska area (Lubuska Upland). She proved that no statistically substantial differences exist between the components of the glacial deposits and the related fluvioglacial deposits. This implies the possibility of comparing the petrographical compositions of glacial tills and fluvioglacial deposits. This conclusion is of utmost importance if a statistically significant analysis must be carried out while it is difficult to take sufficiently large samples for petrographical analysis, with sufficient numbers of clasts, as shown by the studies of Czubla & Wachecka-Kotkowska (2009) and Wachecka-Kotkowska et al. (2012, 2013).

2. Objectives

The present study was carried out in order to get a better insight into the petrographical composition

of the medium- and coarse-grained gravels which form part of the fluvioglacial deposits in the area between Radomsko, Przedbórz and Piotrków Trybunalski (Fig. 2). For the first time, this study of the coarse gravel (20–60 mm) of the fluvioglacial deposits of this area includes a detailed analysis of indicator and statistical erratics. It is supplemented with the identification of the petrographical components of the medium-sized gravel (4–10 mm) of the same deposits.

The petrographical analysis was combined with structural and texture analyses of the glacial deposits, because these are important for a good understanding of the morphogenesis of the study area.

It was hypothesised that the fluvioglacial deposits within the marginal landforms related to the Rawka, Pilica and Luciąża Lobe (zone I and II), the Widawka Lobe (zone III) and the Piotrków till plain (zone IV), had different petrographical features (see Figs 1 and 2). The main purpose of the analyses described here is to accept or reject this hypothesis.

The results of the petrographical investigation are expected to help reconstructing the direction(s) of the ice-sheet advance (Fig. 1), taking into account the bedrock configuration.

3. Methods

3.1. Sampling

The method of sampling medium-sized (4–10 mm) and coarse-sized gravel (20–60 mm) fractions follows that of other authors (e.g. Górska, 2000, 2006; Górska-Zabielska, 2008; Górska-Zabielska & Zabielski, 2010, 2011). Only the main procedures will therefore be described below.

Samples were collected at 29 sites in both active and abandoned gravel and sand pits. The locations

and the number and type of the samples are presented in Table 1.

Indicator erratics were investigated following Lüttig (1958); other particles derived from recognizable rock units (so-called ‘statistical rocks’) were investigated according to Smed (1993); these to gravel categories were selected from seven samples of coarse-grained gravel. Each time a statistically representative sample was subjected to analysis.

The principles of statistics (Stanisz, 2001) imply that correct conclusions can be obtained on the basis of a sample consisting of only thirty elements. Taking into consideration the existing experience with petrographical analysis of indicator erratics, however, the population of the sample was arranged in compliance with the methodical recommendation by Smed (1993) who states that correct conclusions can be drawn only after analysis of fifty definite indicator erratics in the 20–60 mm fraction. Taking into account that barely 10% of the investigated er-

Table 1. Zones (I–IV) of the study area with sampling sites and number of samples of the medium (4–10 mm) and coarse (20–60 mm) fractions from the fluvioglacial gravel

Zones	Sites	4–10 mm (between brackets: number of samples of fresh gravel)	20–60 mm (between brackets: number of samples of fresh gravel)
I Radomsko Hills and Przed- bórz Upland	Jabłonna	1 (1)	1 (1)
	Ludwików	2 (2)	1 (1)
	Miejskie Pole	2 (2)	
	Masłowice	2 (1)	
	Kuźnica	2 (0)	
	Ochotnik	2 (2)	
	Kalinki	1 (1)	
	Biestrzyków Mały	1 (0)	
	Małowana Wola	1 (0)	
	Rzejowice	1 (0)	
	Wola Przerębska	1 (1)	
II Dobryczyce Hills, centre of the study area	Kol. Ręczno	1 (1)	
	Teklin	5 (5)	1 (1)
	Grabowiec	1 (0)	
	Trzepnica Kolonia	4 (0)	1
	Daniszewice	3 (3)	
	Gertrudów	1 (0)	
III Bełchatów Plateau, Widawka Lobe of the Wartanian ice sheet	Borowa	2 (1)	1 (1)
	Dobryczyce	3 (1)	1 (1)
	Mąkolice	6 (3)	1
	Stobiecko	3 (2)	
	Boryszów	1 (0)	
	Wilkoszewice	2 (2)	
	Kamieńsk	3 (1)	
Moników	1 (1)		
IV Piotrków Plain	Kłudzice	1 (0)	
	Lewkówka	6 (2)	
	Polanka	2 (0)	
	Rajsko Małe	1 (0)	
Total		62 (32)	7 (5)

erratics meet the requirements of an indicator erratic (Meyer, 1983), it was tried to ensure each sample was large enough. Such a sample should contain at least five hundred specimens, including sandstones, flints and carbonate rocks. When sampling the erratics of the coarse-gravel fraction, the present authors followed also their own experiences (Böse & Górska, 1995; Górska, 2000, 2002a, b, 2006).

With regard to both the advantages and disadvantages of petrographical analyses (Górska, 1999), the samples for analysis were supplemented by medium gravel (4–10 mm). This was done because, due to the frequent lack of coarse gravel, only medium-gravel fraction could sometimes be used for petrographical analysis.

The samples of glacial deposits were taken from long profiles prepared in a cleaned wall of the outcrop, below the soil horizon. The laboratory analyses show, however, that a weathered horizon must have been sampled at some places as well. The volume of samples for petrographical analysis of medium- and coarse-gravel fractions was set in accordance with the methodological recommendations of Trembaczowski (1961) and Rutkowski (1995a, b), depending on the percentage of these fractions in the deposit.

For the petrographical analyses of the Fennoscandian erratics, a first segregation of the coarse-grained gravel was carried out in the field. All erratics of the 20–60 mm fraction were broken in order to study the fresh surface. The clasts were then provisionally identified, and the carbonate (Palaeozoic and the Mesozoic limestones and dolomites) and flint clasts were separated from the rest. This group constituted about half of the original sample, which consisted of petrographically strongly varied groups of effusive and hypogenic magmatic rocks as well as of other sedimentary rocks. These required further petrographical analysis in the laboratory.

3.2. Laboratory analyses

Laboratory analyses included segregation on the basis of their petrology of erratic material of the 4–10 mm and the 20–60 mm fractions. The analysis of the former fraction was made for clasts from both unweathered deposits and deposits showing post-depositional changes.

3.2.1. Petrographical analysis of the 4–10 mm fraction

The petrographical composition of 62 samples of medium-sized gravel was analysed for the 4–10

mm fraction; 32 samples came from unweathered deposits and 30 from weathered deposits (Table 1). This fraction is commonly investigated in Poland (e.g. Górska, 2000, 2002a, b; Lipka, 2011), which makes it possible to compare the outcome with previously obtained data. The analysis was carried out following Trembaczowski (1961) and Rutkowski (1995a).

Cepek (1969) and Böse (1989) suggest to exclude samples from weathered deposits, as their results may affect the original petrographical composition, but they restricted their investigations to glacial tills in areas where almost all gravel contain carbonates. In central Poland, however, where the present study was carried out, the fluvioglacial deposits contain fresh, weathered and even over-weathered gravel clasts.

Ten petrographical groups were from the samples of at least 300 clasts (Table 2). The identification of the clasts followed commonly used criteria (see Table 2.4 in Górska, 2000) using a geological magnifying glass, 10% HCl and a Magneson I indicator (Cepek, 1969). Samples from glacial deposits with a too numerous population of petrographical components were investigated applying the method of quartering (Rutkowski, 1995b).

The outcomes of the petrographical analyses are presented separately for the unweathered and the weathered deposits in order to prevent an incorrect impression because some petrographical components may, if weathered, have fallen in many fragments, thus seemingly being over-represented.

The petrographical analyses were carried out separately for each zone (I–IV) (Fig. 2). Cumulated histograms (Figs 4–11) compile the data from the various sites from the most northern sites in a given zone (upper part of the graph) to the southernmost sites (lower part of graph). The proportion of individual petrographical groups, as presented in figures and tables, is given as a percentage.

Table 2. Petrographical types of rock distinguished in the present study and their symbols

Symbol	Petrographical type of rock
Cr	crystallines
LPI1	grey Lower Palaeozoic limestones
LPI2	red Lower Palaeozoic limestones
Cl	Cretaceous limestones
D	dolomites
S	sandstones
Ps	Palaeozoic slates
F	flint
Q	quartz
mQ	milk quartz

3.2.2. Analysis of the indicator erratics

The petrographical analysis of the 20–60 mm clasts was carried out for seven samples from fluvioglacial deposits (Table 1). The erratics are subdivided into ten petrographical groups (Table 2) and the Fennoscandian indicator and statistical erratics were identified (Fig. 3). After a first petrographical segregation of the erratics in the field, the analysis was continued in the laboratory, where the whole range of Fennoscandian rocks was considered. The indicator erratics were identified following Lüttig (1958), Meyer (1983, 1985), Smed (1993), Zandstra (1999) and Smed & Ehlers (2002). Atlases of Scandinavian indicator erratics (Korn, 1927; Hesemann, 1975; Smed & Ehlers, 2002; Zandstra, 1999; Schulz, 2003; Rudolph, 2005; Svenson, 2005) were used for the identification. The collection of comparative rocks housed in the Institute of Geoecology and Geoinformation of Adam Mickiewicz University in Poznań was also used.

Figure 3 shows the location of the outcrops of the most common Scandinavian indicator rocks.

These points are marked with the numbers 1–24. The spatial spreading of the outcrops of the most common indicator sedimentary rocks is shown by different shades, along with symbols marking the centres of the source areas of selected, so-called 'statistical' (Vinx, 1993) erratics (letters A–E).

4. Results of the petrographical analysis of the 4–10 mm fraction

4.1. Zone I: Radomsko Hills

More than half of the gravels from fresh (unweathered) samples (51.6%; Fig. 4; Table 3) from the oldest glacial deposits in the area were identified as derived from Lower Palaeozoic limestones (LP11). These deposits may in principle be the ones that were affected most by post-depositional processes such as chemical decomposition of carbonates. Hence, they might be expected to be

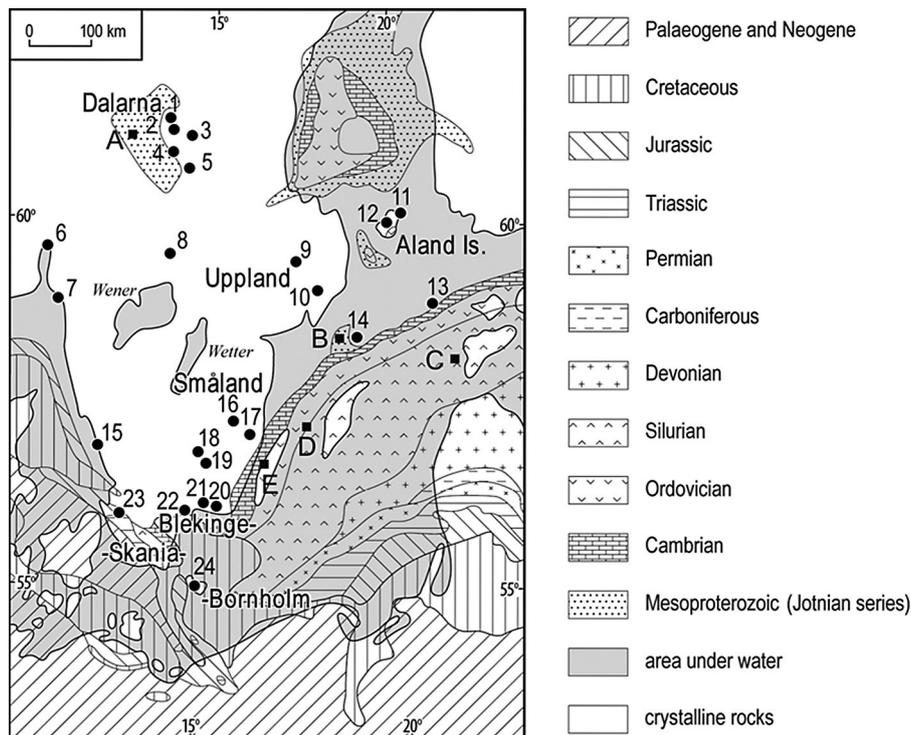


Fig. 3. Location of the source areas of the indicator erratics (●) and of the source areas of the statistical erratics (■)
Indicator erratics (●): 1 = Bredvad porphyry; 2 = Garberg granite; 3 = Grönklitt porphyry; 4 = Dalarna porphyry; 5 = Siljan granite; 6 = Oslo porphyry; 7 = Bohus granite; 8 = Filipstad granite; 9 = Uppsala granite; 10 = Stockholm granite; 11 = Åland granite and Åland rapakivi granite; 12 = Åland quartz porphyry; 13 = red Baltic porphyry; 14 = brown Baltic porphyry; 15 = charnockite; 16 = Småland granite; 17 = Påskallavik porphyry; 18 = grey Växjö granite; 19 = red Växjö granite; 20 = Karlshamn granite; 21 = Halen granite; 22 = Vånga granite; 23 = Scania basalt; 24 = granites and gneisses from Bornholm
Statistical erratics (■): A = Dalarna sandstone; B = Jotnian sandstone; C = east-Baltic limestone; D = *Palaeoporella* limestone; E = red Ordovician limestone

Table 3. Average percentages of some types of petrographical groups in fresh gravel from the four zones of the study area. For symbols of the petrographical types, see Table 2

Zone	Cr [%]	LPI1 [%]	S [%]	F [%]	Q [%]
I	37.6	51.6	7.4	0.3	1.4
II	43.0	42.9	8.4	1.0	2.4
III	41.4	41.1	8.3	1.6	3.5
IV	45.8	32.9	7.3	1.4	5.9

impoverished in carbonate clasts, but the opposite is true.

In the north-eastern part of the zone (sites: Jabłonna, Miejskie Pola, Ludwików, Kalinki, Masłowice, Ochotnik and Kolonia Przerębska), grey Silurian limestones, accompanied by red Ordovician limestones, form the largest group. The second petrographical group consists of crystalline rocks (37.6% on average). The third petrographical group consists of sandstones (7.4%). Flints, which are fairly resistant to weathering, make up only a negligible amount (0.3%). Quartz clasts, highly resistance to destruction, reach only 1.4%.

In the western part of zone I (sites: Kuźnica Piaszcyce, Rzejowice, Malowana Woda and Biestrzyków Mały), the 4–10 mm fraction is devoid of grey and red Lower Palaeozoic limestones. The dominant petrographical group in these weathered sediments consists of crystalline rocks (67.7%; Table 4; Fig. 5); more than three times less frequent is the group of sandstones (18.3%). Quartz amounts to 8.4%, and flints to 3.4% of all gravel clasts from the six samples.

4.2. Zone II: Dobryrzyce Hills

The clasts from unweathered deposits were examined for nine samples from three sites; they have comparable amounts of carbonate rocks (LPI1 42.9% + LPI2 0.8% + CI 0.4%) and crystalline rocks (Cr almost 43%; Table 3; Fig. 6). None of the petrographical groups dominates. It is worth noting that the grey Silurian limestones are always accompanied by the red Ordovician limestones. The sandstones make up 8.4% of the gravel. In comparison with zone I, the gravel of zone II has a higher percentage of quartz (2.4%) and flint (1.0%).

In the group of six samples without carbonate rocks (Table 4, Fig. 7), crystalline rocks dominate (57.5%); sandstones make up a little more than 20%. Quartz makes up as much as 14.4%. This is remarkable because zones III and IV, as far as

Table 4. Average percentages of some types of petrographical groups in weathered gravel from the four zones of the study area. For symbols of the petrographical types, see Table 2

Zone	Cr [%]	S [%]	F [%]	Q [%]
I	67.7	18.3	3.4	8.4
II	57.5	20.5	5.8	14.4
III	71.9	16.8	1.9	7.5
IV	76.0	12.8	1.8	6.7

weathered sediments are concerned, contain only about half of this amount of quartz (Table 4). The percentage of flint is also the highest in zone II (5.8%).

4.3. Zone III: Bełchatów Plateau, Widawka River lobe of the Warthian ice sheet

The eight sites of this zone, from which 21 samples were collected, are located on the Bełchatów Plateau. Eleven samples come from fresh deposits (Fig. 8), and ten from weathered deposits (Fig. 9).

The samples from the fresh deposits show comparable percentages of carbonate rocks (LPI1 41.1% + LPI2 1.1% + CI 1.2%) and crystalline rocks (41.4%) (Table 3). The red Ordovician limestones always accompany the grey Silurian limestones, apart from at the Moników site. The percentage of sandstones among the gravel clasts is comparable to that in the other zones. The content of flints is higher in zone III (1.6%) than in the other zones. The gravel contains 3.5% of quartz grains; quartz systematically increases from zone I to zone IV.

The percentage of fragile Cretaceous limestones is twice as high (CI 1.2%) as in the neighbouring zones; they occur at three sites in the central part of zone III: Borowa, Moników and Dobryrzyce (Fig. 8); in the other zones they occur only rarely, in amounts not exceeding 0.6%.

The weathered gravels are distinctly dominated by crystalline rocks (Cr 71.9%), with a secondary role for sandstones (S 16.8%; Table 4). The percentage of sandstone clasts ranges from 8.0 to 14.7%, except for two samples from Kamieńsk, where they show an exceptional value of some 48% (Fig. 9): the largest percentage of sandstone of all 62 samples collected from the entire study area.

The high percentage of crystalline rocks in the weathered deposits was expected to be accompanied by a large amount of quartz, as this mineral is resistant to diagenetic weathering, but its value does not exceed 7.5% (Table 4). This is only half the

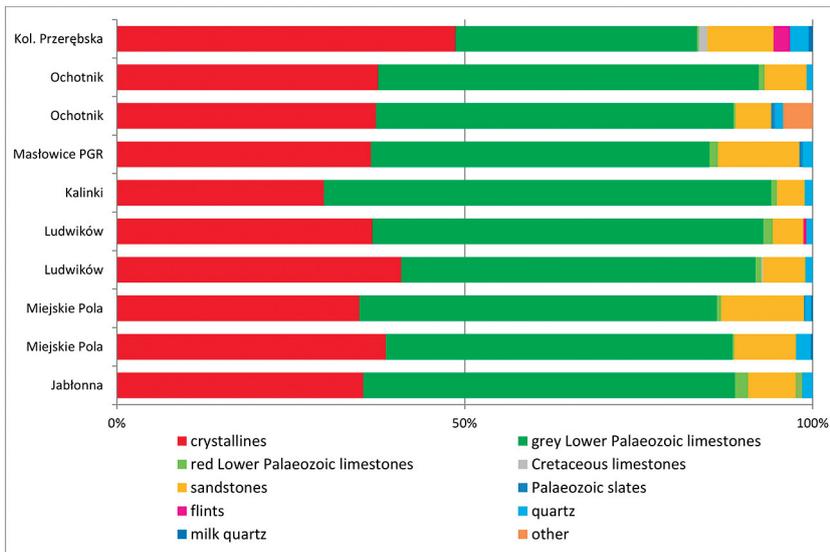


Fig. 4. Percentages of the various petrographical groups of the Warthian fluvioglacial fresh gravel (4–10 mm fraction) in zone I (Radomsko Hills) (for legend see Table 2)

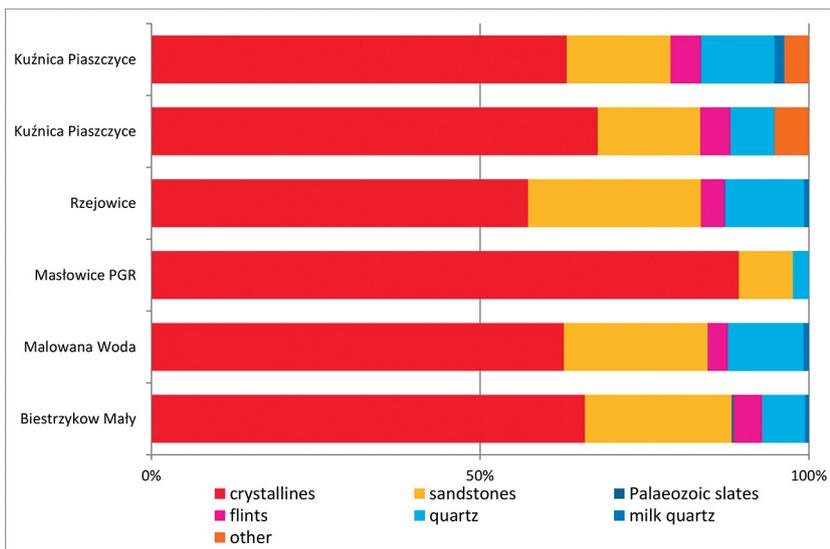


Fig. 5. Percentages of the various petrographical groups of the Warthian fluvioglacial weathered gravel (4–10 mm fraction) in zone I (Radomsko Hills) (for legend see Table 2).

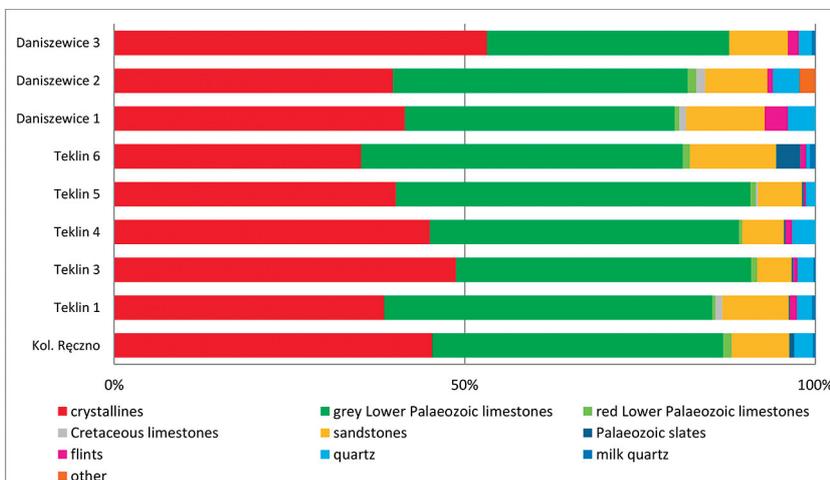


Fig. 6. Percentages of the various petrographical groups of the Warthian fluvioglacial fresh gravel (4–10 mm fraction) in zone II (Dobryczyce Hills) (for legend see Table 2)

Fig. 7. Percentages of the various petrographical groups of the Warthian fluvioglacial weathered gravel (4–10 mm fraction) in zone II (Dobryrzyce Hills and Radomsko Hills) (for legend see Table 2)

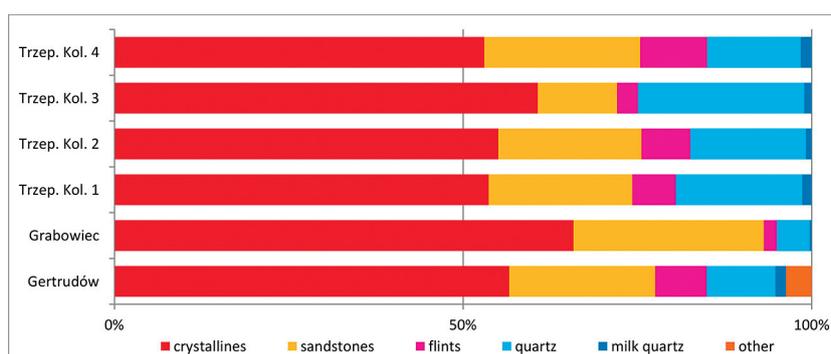


Fig. 8. Percentages of the various petrographical groups of the Warthian fluvioglacial fresh gravel (4–10 mm fraction) in zone III (Bełchatów Plateau) (for legend see Table 2)

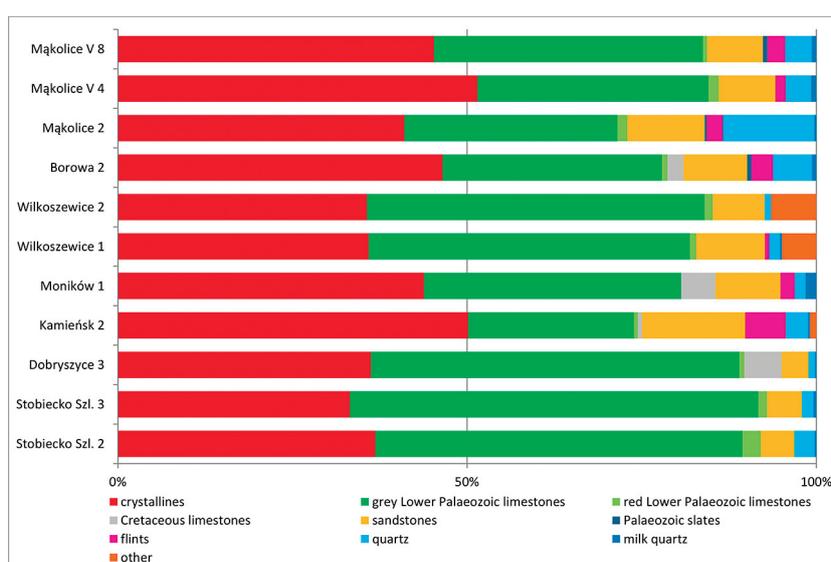
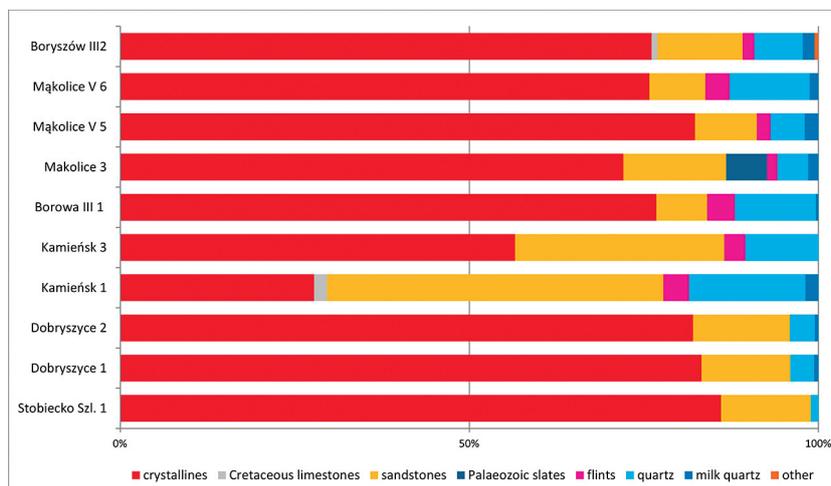


Fig. 9. Percentages of the various petrographical groups of the Warthian fluvioglacial weathered gravel (4–10 mm fraction) in zone III (the Bełchatów Plateau) (for legend see Table 2)



value of quartz in zone II. Flint does not occur in large numbers either (1.9%).

The gravels from Mąkolice show much variation. This is because the samples were collected from various parts of an end-morainic hummock.

4.4. Zone IV: the Piotrków Plain

The ten samples from zone IV lack carbonate rocks except for two samples from Lewkówka (Fig. 10), where the gravel composition is unusual due to

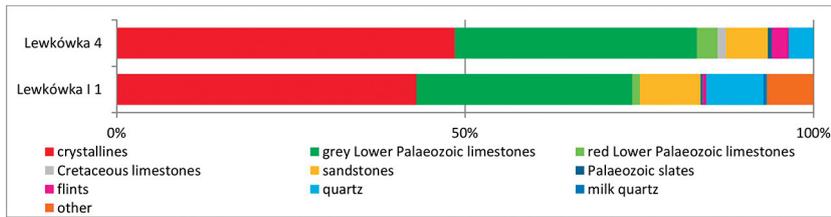


Fig. 10. Percentages of the various petrographical groups of the Warthian fluvioglacial fresh gravel (4–10 mm fraction) in zone IV (Piotrków Plain) (for legend see Table 2)

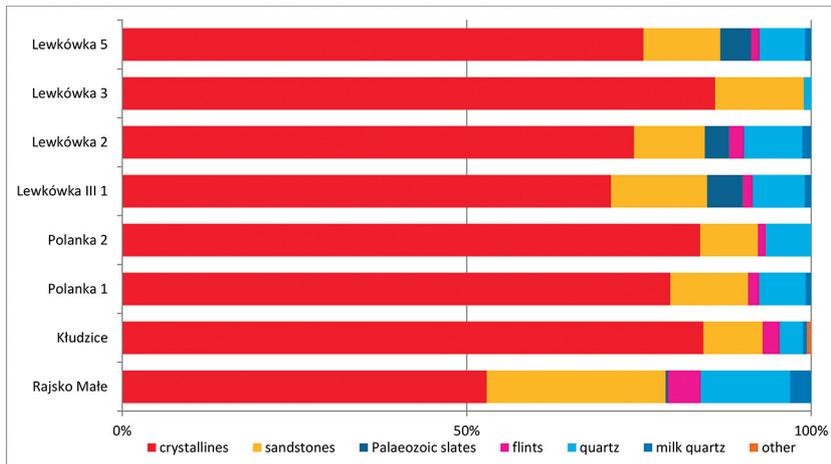


Fig. 11. Percentages of the various petrographical groups of the Warthian fluvioglacial weathered gravel (4–10 mm fraction) in zone IV (Piotrków Plain) (for legend see Table 2)

the presence of fragile Palaeozoic slates five out of the six samples (Ps 0.4–5.2%; Fig. 10, 11).

Crystalline rocks dominate the gravels collected from weathered deposits (Cr 76.0%; Table 4). Such a large percentage was not found in any of the other zones. On the other hand, sandstones have the lowest percentage of all zones, with merely 12.8%. Crystalline rocks being so numerous, a high percentage of flint – which is equally resistant to damage – is to be expected. Flint, however, constitutes only 1.8% of the gravel from weathered deposits in this zone, which is the lowest percentage from all zones. Also quartz is not well represented, reaching only 6.7%, the lowest percentage of all zones.

5. Results of the petrographical analysis of the 20–60 mm fraction

A petrographical analysis of the coarse-grained gravel (20–60 mm) was carried out for seven samples from zones I, II and III (Table 1, Fig. 12). Five samples were collected from fresh sediments, two from weathered deposits.

5.1. Zone I: Radomsko Hills and Przedbórz Upland

The gravels from zone I have similar compositions and percentages of petrographical types (Figs

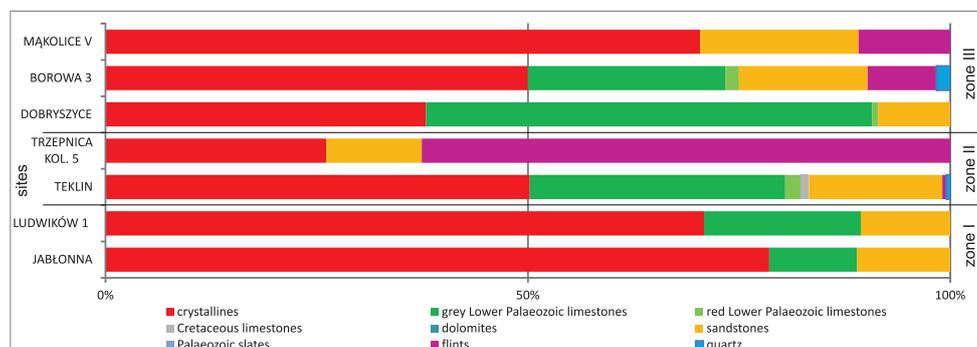


Fig. 12. Percentages of the various petrographical groups of the Warthian fluvioglacial gravel (20–60 mm fraction)

12, 13). More than 70% of each sample consists of crystalline rocks, and the percentage of the Lower Palaeozoic limestones falls within the range of approx. 10–18%; sandstones are less numerous, but have in both samples almost the same value (approx. 11%).

The group of indicator erratics, which constitutes up to 17.5% is dominated by rocks from Småland (Fig. 13): Småland granites and grey and red Väjö granites. Åland quartz porphyries come from outcrops on the Åland Islands. Some rocks originated in Dalarna. In the sample from Jablonna, two specimens of Stockholm granite from Uppland occur. The theoretical centres of the source areas for both samples are located close to each other (Figs 13 and 16): TSC J: 58.4°N, 17°E; and TSC L: 58.7°N, 16.8°E.

5.2. Zone II: Dobryczyce Hills

The petrographical composition of the coarse-grained gravel of this zone varies (Fig. 12). The sample from Teklin represents a typical composition and percentage of petrographical types, but the sample from nearby Trzeznica Kolonia lacks carbonate rocks. As carbonate rocks are not present in the medium-grained gravel of this site either, from the gravel of the samples probably was derived from a decalcified zone, presumably the Palaeogene substratum, which is built of rock debris and weathered clays. The highest percentage in the sample from this site is taken by flint (approx. 63%). Further, slightly over 26% of crystalline rocks and approx. 11% of sandstones are present. The sample from Teklin consists for half of crystalline rocks, whereas Lower Palaeozoic limestones amount to 30%, and sandstones to 16%. Trace amounts occur of red Ordovician limestones and Cretaceous limestones – fragile and only rarely present – as well as flint and quartz.

The two sites of zone II thus differ in the quantity of flint (F). Taking into account that flint occurs in the 4–10 mm fraction in an above-average quantity, it must be assumed that the deposits in Trzeznica Kolonia were enriched in this rock type by erosion of local outcrops of a deeper bed. The aforementioned weathered Palaeogene substratum, lacking carbonate rocks, may have been enriched in flint.

In both samples erratics from outcrops in south-eastern Sweden are present; they concern crystalline Småland and Väjö granites and also Västervik quartzites and Tessini and Kalmarsund sandstones (Fig. 14). Erratics from the Åland Is-

lands are also present as well as a few specimens of erratics from Dalarna in central Sweden. Also crystalline and sedimentary erratics from Skåne and Bornholm, so from the southern Scandinavian outcrops, are present.

The theoretical centres of the source areas of the erratics are all positioned at the same longitude, i.e. 16.6°E (Figs 14, 16). The difference in the latitude of both TSC amounts only to 0.6°: T is positioned at 57.6°N, TK at 58.2°N (Fig. 14). The indicator erratics constitute 12% (TK) and 22% (T), respectively.

The deposit from which the sample from Trzeznica Kolonia was taken was enriched in local flint stones. The lack of limestones may indicate that the sample was collected from a weathered level.

5.3. Zone III: Bełchatów Plateau, Widawka River lobe of the Warthian ice sheet

The petrographical analysis shows that the three samples differ from one another by the presence of the Lower Palaeozoic limestones and flint (Figs 12, 15). The sample from Dobryczyce is dominated (more than 50%) by grey Silurian and red Ordovician limestones. Around 38% consists of crystalline rocks and the rest (8.5%) are sandstones. At Borowa also other petrographical groups are present. Apart from the crystalline rocks (50%), the Lower Palaeozoic limestones (25%, including red Ordovician) and sandstones (15%), flint and quartz are present. In contrast, the sample from Małolice contains only three petrographical types: crystalline rocks (over 70%), sandstones (approx. 19%) and flints (approx. 11%). The results indicate a tendency from south to north: the percentage of the Lower Palaeozoic limestones decreases while the crystalline rocks and flint increase.

Rocks from south-eastern Sweden are the most common (Fig. 15). It is the source area of crystalline rocks like Småland and Väjö granites as well as of Västervik quartzites and Tessini sandstones. Erratics from the Åland Islands are present in each sample; they are mainly granites, including Åland rapakivi. At Dobryczyce and Borowa, where the Lower Palaeozoic limestones occur, single specimens from Bornholm are present; at Dobryczyce and Małolice specimens from Dalarna occur.

The geographical co-ordinates of the theoretical centres of the source areas of the erratics differ; they are for TSC D 58°N, and 16.9°E; for TSC B 57.5°N, 16.4°E; and for TSC M 58.2°N, 16.6°E (Figs 15 and 16). The percentage of indicator erratics in the samples fluctuates between 13% and 17%.

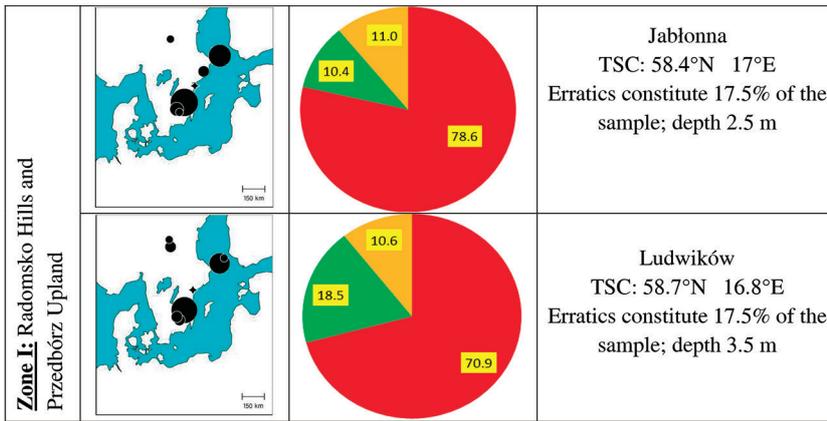


Fig. 13. Extended petrographical analysis of the coarse gravel (20–60 mm fraction) from zone I. **A:** Source areas of the indicator erratics with locations of the TSC (theoretical stone centre); **B:** Percentages of the various petrographical types of the coarse (20–60 mm) gravel; **C:** Additional information.

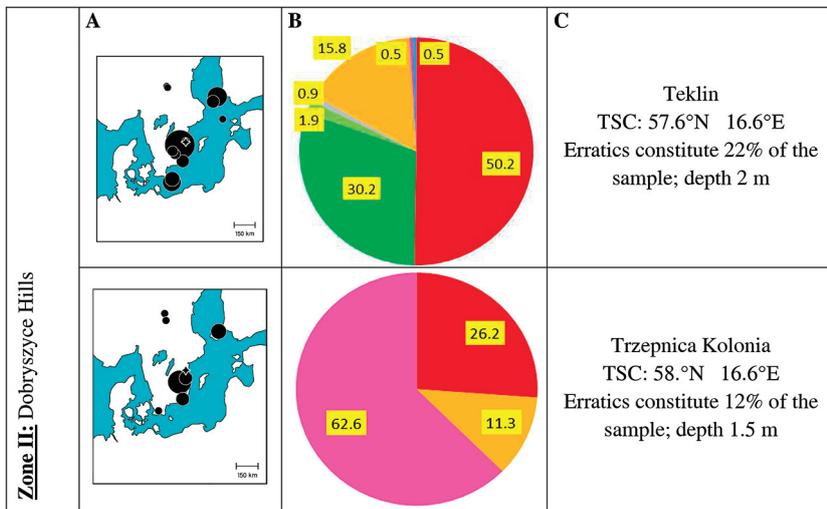


Fig. 14. Extended petrographical analysis of the coarse gravel (20–60 mm fraction) from zone II **A:** Source areas of the indicator erratics with locations of the TSC (theoretical stone centre); **B:** Percentages of the various petrographical types of the coarse (20–60 mm) gravel; **C:** Additional information

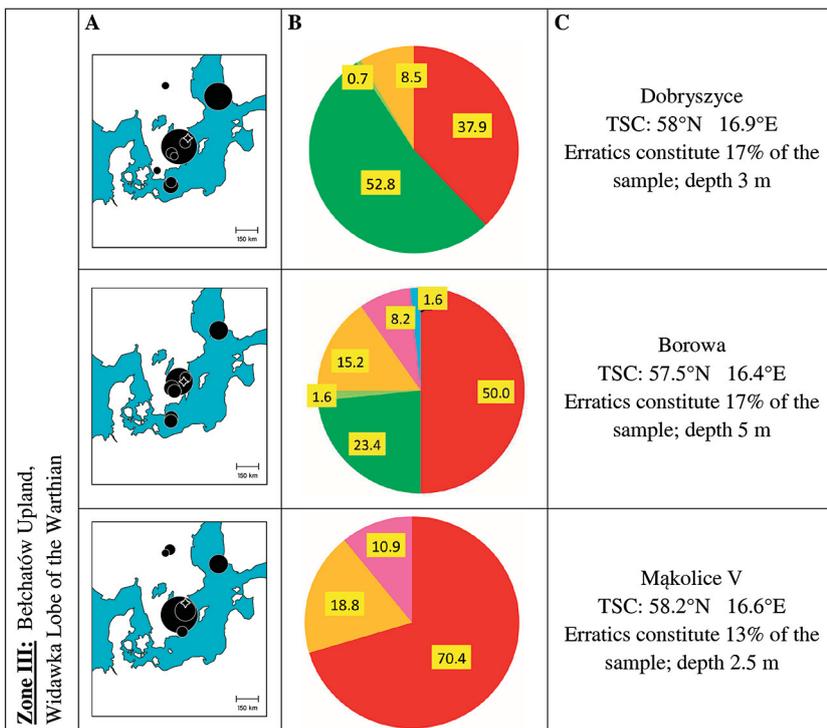


Fig. 15. Extended petrographical analysis of the coarse (20–60 mm) gravel from zone III **A:** Source areas of the indicator erratics with locations of the TSC (theoretical stone centre); **B:** Percentages of the various petrographical types of the coarse (20–60 mm) gravel; **C:** Additional information.

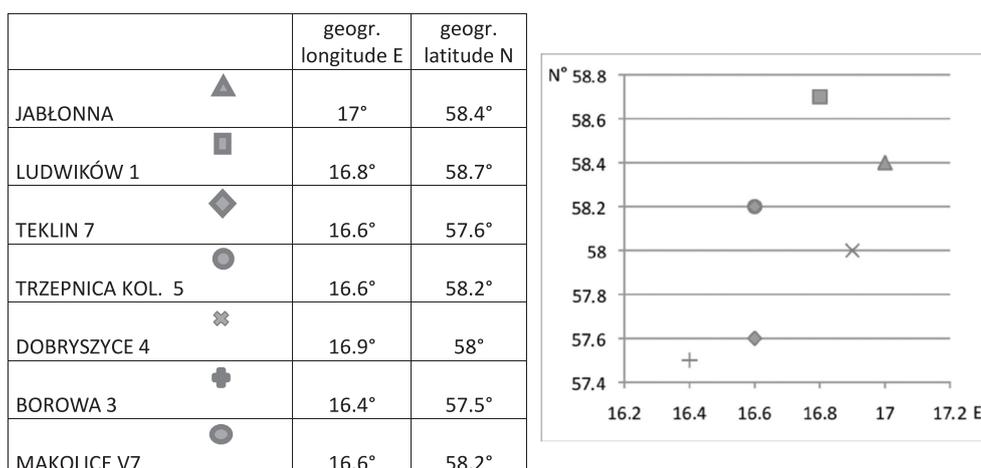


Fig. 16. Geographical co-ordinates and location of the theoretical erratic centres (TSC) of the samples of the coarse (20–60 mm) gravel from the study area

6. Discussion

6.1. Causes the changes in petrography of the fluvioglacial deposits

6.1.1. The 4–10 mm fraction

The petrographical composition of fluvioglacial gravel of 4–10 mm deposited changed during the decline of the ice sheet decline in central Poland. The main petrographical types are crystalline rocks and, for fresh (unweathered) deposits, Lower Palaeozoic limestones. These two rock types show, for samples from fresh deposits, an opposite trend: the percentage of crystalline rocks increases from south to north, whereas that of the Lower Palaeozoic limestones (which are highly susceptible to weathering, are the most frequent in the southern parts of the study area, decreasing systematically northwards. The deposits in the southern part of the study area, which had been subjected to diagenetic processes longer than the northern ones (because they were the earliest to be set free from the ice sheet), might be expected to contain the most resistant components, but the opposite is found. Hence, the hypothesis repeatedly brought up in literature about the influence of weathering on the petrographical composition (e.g. Lisicki, 1998c; Woźniak, 2004) must be considered erroneous for the sediments under study here, particularly because the non-resistant clasts become more frequent with increasing time of being outside the ice sheet. A similar trend is shown by the average percentage of quartz (Table 3). Theoretically, the quartz frequency should increase from north to south because the more southern deposits were deposited by the ice sheet earlier than the deposits representing later phases of deglaciation (i.e.

fluvioglacial gravels in the northern region). Our study shows, however, that the frequency of quartz decreases from the north to the south.

The average percentage of sandstones in the samples from fresh gravel is stable (Table 3), whereas it is highly variable in the samples from weathered sediments (Table 4). For example, a sample from Kamieńsk in zone III is characterised by a sandstone percentage of 48.1%, which is higher than the average (Fig. 9). In our opinion, these gravels were derived from older glacial sediments and were deposited again in Warthian sediments.

The less frequent rocks (up to 5%) also deserve attention, particularly the flints and the Palaeozoic slates (Tables 3, 4). The presence of flint is a characteristic feature of tills and fluvioglacial deposits (Haldorsen, 1982; Böse, 1989). Flint occurs in all four zones, but most frequently (5.8%) in the decalcified gravels of zone II (Dobryszyce Hills; Table 4). In other zones, the average flint percentage does not exceed 3.4%. Soft and fragile Palaeozoic slates are characteristic for all four studied zones, but only in unweathered deposits. Their average percentage varies (Table 3), but most often fluctuates around 0.5%. The highest percentage of Palaeozoic slates occurs in zone II (Dobryszyce Hills); their frequency there is three times higher than in the other zones (Table 3). Their presence in central Poland cannot be explained by glacial transport from Scandinavia as non-resistant rocks should have been destroyed during the long englacial transport. The Palaeozoic slates undergo complete destruction even during the relatively short (from a few to something like a dozen kilometres) glacial transport (e.g. Lilliesköld, 1990). The erosion of these rocks was more intense in a fluvioglacial environment. Thus, the

presence of the slates must be connected with other factors, such as a local outcrop of ice-rafted rocks in the near vicinity of the research area, especially in zone IV (Piotrków Plain). A possible glacial transport from the NNE or NE within an ice stream along the pre-Luciąża valley can, however, is not neglected.

6.1.2. The 20–60 mm fraction

The coarse-grained (20–60 mm) gravels contain less limestones and more crystalline rocks than the medium-grained (4–10 mm) gravels. This trend seems characteristic for fluvio-glacial deposits (Górska, 2000).

Sandstones are the third petrographical group in the coarse fraction. Their frequency is relatively constant (10–15%). Palaeozoic slates are absent, but flint is present in four samples of this fraction. Their frequent presence at the Trzepnica Kolonia site might be connected with the existence of a nearby local outcrop.

Quartz is distinctly less frequent than in the medium-grained gravel, which is characteristic of this petrographical group (e.g. Schulz, 1996, 1999). It is connected with the crystallographic structure of quartz and the geological setting of Scandinavian outcrops (e.g. a vein-rich rock).

6.2. Directions of the Warthian ice-sheet advance

The analysis of the indicator and statistical erratics suggests that the main stream of the Warthian ice sheet, which deposited glaciofluvial sediments in the southern part of the study area, started from the vicinity of Åland Islands and advanced through the western part of the Baltic Basin. The Warthian ice-sheet transgression along the eastern coast of southern Sweden is supported by the high percentage of crystalline rocks and the low amount of carbonate rocks in the samples from zone I (Radomsko Hills and Przedbórz Upland). The limestones and sandstones in this zone may have been transported incorporated in the ice sheet after having been eroded from the basement of the western part of the central Baltic, in the vicinities of Öland and the Gotland islands. Most probably the ice mass bypassed Skåne (Scania), Blekinge and Bornholm: rocks from these areas are lacking.

The deposits of the Dobryrzyce Hills (zone II) were transported by the same glacial stream, which can be deduced from the indicator erratics from around Teklin, representing mainly rocks derived from south-eastern Sweden: crystalline Småland

and Västergötland granites along with Tessini and Kalmar sandstones. Crystalline and sedimentary indicator erratics from Skåne and Bornholm are also present. Some statistical erratics (Jotnian Baltic sandstones, Silurian and Ordovician limestones) were found. It indicates that the ice sheet advanced through the Baltic trough and the eastern parts of southern Sweden.

The Warthian ice sheet that left sediments in zone III (Bełchatów Plateau, Widawka River basin) must have moved through the Baltic area with Ordovician and Silurian limestones and the area of crystalline rocks of SE Sweden, the Åland Islands and Bornholm. The high percentage of crystalline rocks suggests that the ice sheet travelled along Svekofenids and the Trans-Scandinavian Igneous Belt (cf. Górską-Zabielska, 2008).

The petrographical differences between the two size fractions support the hypothesis that two glacial lobes came together in the study area: the lobe of the Widawka and Rawka rivers and the lobe of the Pilica and Luciąża rivers. The petrographical analyses point out that the ice masses advanced from the NE to NNW (the Widawka lobe) and from the NE to ENE (the Rawka, Pilica and Luciąża lobe).

7. Conclusions

Petrographical investigations were conducted with respect to: (1) fraction (medium- and coarse-grained gravels, i.e. 4–10 mm and 20–60 mm, respectively), (2) state of the deposits (fresh: 32 samples; weathered: 30 samples), and (3) zones (I: Radomsko Hills and Przedbórz Upland; II: Dobryrzyce Hills; III: Bełchatów Plateau – Widawka Lobe; IV: Piotrków Plain).

The two main petrographical groups in the medium-grained gravels consist of Lower Palaeozoic limestones and crystalline rocks. From the south to the north of the study area, the medium-grained gravels show systematically decreasing amounts of Lower Palaeozoic limestones and increasing amounts of crystalline rocks and flint. No such tendency was found for the coarse-grained gravel, most probably because of an insufficient number of samples.

The percentage of sandstones is more or less constant in all samples, in both the fresh and the weathered deposits.

A remarkable feature is a large amount of quartz clasts in the medium-gravel fraction of unweathered deposits (Table 3). Their amount increases from zone I to zone IV, i.e. from south to north. In

weathered gravel, their amount in zone II is twice as high as in the neighbouring zones (Table 4).

Also in the 4–10 mm fraction, fragile Palaeozoic slates make up approx. 0.2%, apart from in samples from fresh sediment in zone II (Table 3), where their amount is three times higher. Flint is more frequent in samples from weathered deposits of zone II. The source areas of the flint and Palaeozoic slates are presumably small outcrops not far away from the final depositional site.

The indicator and statistical erratics indicate that the main stream of the Warthian ice sheet, which left deposits in the southern part of the study area, started in the vicinity of the Åland Islands, the travelled across the western part of the Baltic Basin and along the eastern coast of southern Sweden.

The clasts in the deposits of the Dobryrzyce Hills (zone II) were transported by the same glacial stream, as evidenced both by the indicator erratics from the Teklin site: mainly rocks derived from the Baltic Basin (red Baltic porphyry, Bornholm granites, Tessini sandstones), and by the statistical erratics (Jotnian Baltic sandstones, Silurian and Ordovician limestones).

The ice sheet which left deposits in zone III advanced through the Baltic area with Palaeozoic limestones and through the area with crystalline rocks in SE Sweden. In the region of Borowa and Małolice, the glacial stream advanced across a local area with flint. The indicator and statistical erratics thus suggest that the source areas of the Warthian ice sheet were magmatic and sedimentary areas in both the Baltic and south-eastern Sweden. The theoretical centre of the area from where the coarse-grained gravel have come, is a narrow area situated between 16.4°E and 17.0°E and between 57.5°N and 58.7°N.

The petrographical characteristics of the fluvioglacial gravel supports the hypothesis that the study area is a zone where two glacial lobes joined: the lobe of the Widawka and the lobe of the Rawka, Pilica and Luciąża rivers. The present study proves that the Warthian ice masses advanced from the NNW (the Widawka lobe) and from the NE to ENE (the Rawka, Pilica and Luciąża lobe).

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