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# THE MORPHOLOGY OF FOSSIL PEBBLES AS A TOOL FOR DETERMINING THEIR TRANSPORT PROCESSES (KOŹMIN SOUTH LIGNITE OPEN-CAST PIT, CENTRAL POLAND)

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**Abstract:** The Koźmin South lignite open-cast pit is the southernmost exposure of Palaeogene (lower Oligocene) deposits in central Poland. This study is focused on Palaeogene pebbles of the so-called Koźmin Gravels, redeposited in the Neogene sands. These pebbles are not known from the adjacent territory of central Poland and they vary in petrographic composition, shape and surface texture. The classification of the pebble-size particle form is determined as $D_I/D_L$ (elongation ratio) and $D_S/D_I$ (flatness ratio). A great number of pebbles are disc-shaped (oblate-shaped) and blade-shaped or they can be classified as platy, bladed and very bladed pebbles. The oblate–prolate index (OP) is less than –2 for 45% of the particles (typical of beach pebbles), the mean sphericity ($\psi_p$) is 0.56 (typical of beach pebbles), and the mean roundness ($R_{Wt}$) is 0.73 (typical of beach pebbles).

The data obtained from SEM analysis of quartz pebble surface micromorphology are characteristic of high mechanical energy of the littoral environment. The surface of some pebbles is excellently polished with v-shaped indentations and grooves. The average composition of the heavy mineral fraction occurring with these pebbles is marked by the predominance of zircon (exceeding 70%). All the above-mentioned data, in the light of extensive literature, indicate that more morphological features of the analysed pebbles have been inherited from the littoral/beach environment. Moreover, a detailed petrographic study was very useful for determining the provenance of these pebbles. The most characteristic rocks are greyish-blue quartzes. They are known only from the Sudetes Mts., situated on the NE slope of the Bohemian Massif. Thus, the rock fragments were transported at least 300 km by rivers from the Sudetes to the littoral/beach zone of the Palaeogene sea. Then, the residually-marine beach pebbles were redeposited into the Neogene debris flow and/or fluvial deposits. The present-day area of the Koźmin South lignite open-cast pit was tectonically active at that time.

**Key words:** pebble morphology, shape, surface texture, sediment provenance, transport processes, central Poland.

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## INTRODUCTION

The morphology of sedimentary particles is defined in various ways, sometimes incorrectly. That is the reason why I use the term “morphology” according to the meaning proposed by Blott and Pye (2008) in the present contribution. In their opinion, the term “morphology” includes two aspects of a particle, *i.e.* “shape” and “surface texture”. They describe the analysed object morphology at the macro- and micro-scales, respectively. Shape is used to determine the following features: form (length, width and thickness), roundness (relative rounding or angularity), and sphericity. Pebble-size particles are measured with a ruler or caliper and then the remaining form ratios and form factors can be quantified, as well as the form diagrams can be constructed (*e.g.*, Wentworth, 1922; Wadell, 1932, 1933; Zingg, 1935; Krumbein, 1941; Powers, 1953; Folk, 1954; Sneed & Folk, 1958; Dobkins & Folk, 1970; Blatt *et al.*, 1980; Illenberger, 1991; Howard, 1992; Blott & Pye, 2008). Conversely, the surface texture of the particle requires magnification of 200–3,000 (*e.g.*, Krinsley & Donahue, 1968; Krinsley & Doornkamp, 1973). Thus, scanning electron microscopy (SEM) must be used to study the micromorphology of pebble-size particles at the micro-scale.

Many authors consider that the shape and surface texture, *i.e.* morphology, are important properties of sedimentary particles. These external geometrical features of pebble-size particles provide information related to their provenance, transport processes and depositional environment. Such studies are often supported by investigations of the pebble petrology and the heavy mineral assemblage content. Therefore, the above-mentioned integrated research methods can help to resolve the geological problem of the transport history of the particles. To avoid or reduce a mis-

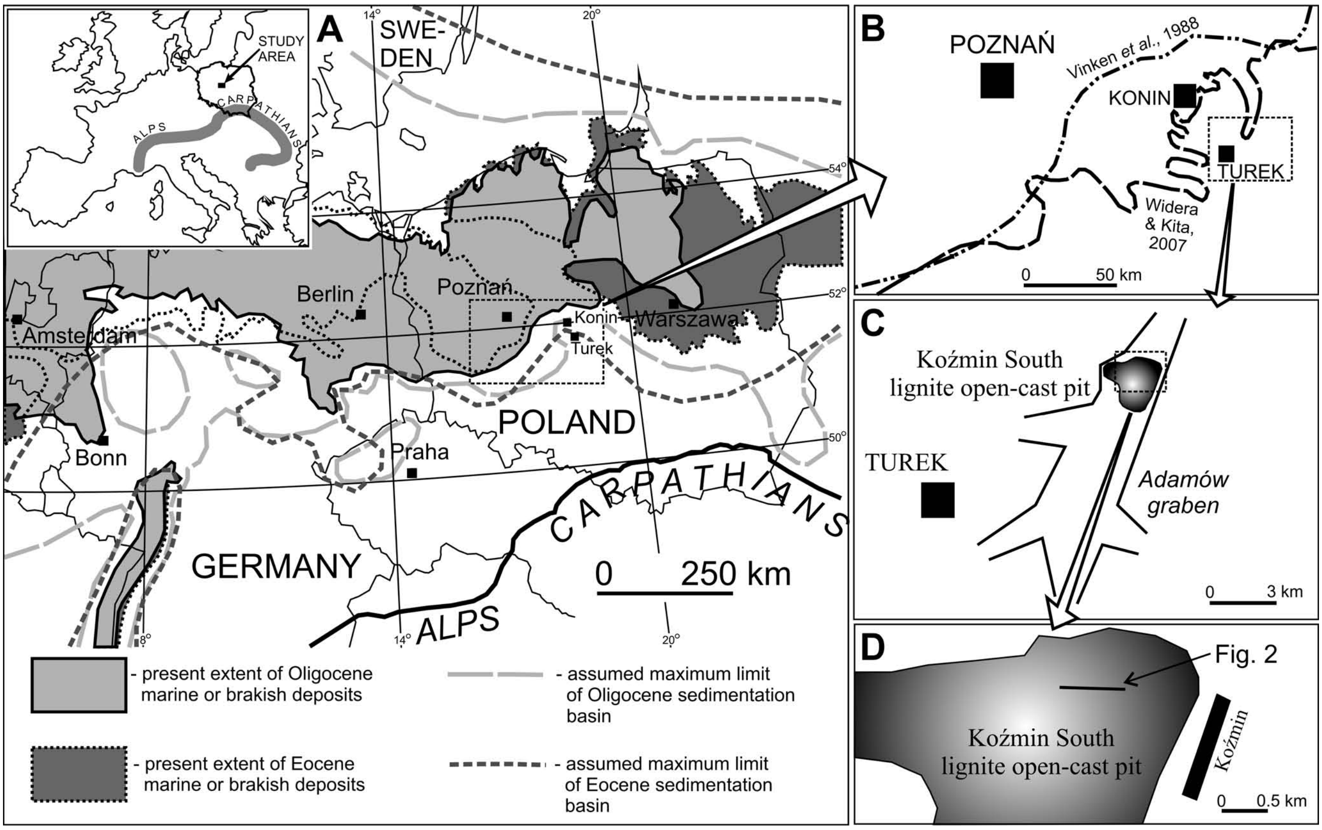


**Fig. 1.** Location map. **A** – study area in the background of the Northwest European Palaeogene and Neogene Basin in Eocene and Oligocene (modified after Vinken *et al.*, 1988); **B** – compilation of the southern extent of the Palaeogene marine deposits in central Poland (modified after Vinken *et al.*, 1988; Widera & Kita, 2007); **C** – location of the Koźmin South lignite open-cast pit in the Adamów graben; **D** – detailed location of investigated area with geological section in the Koźmin South lignite open-cast pit; for location see Figs 2, 3

take, the obtained results should be compared with studies of modern sedimentological processes (*e.g.*, Kuenen, 1956, 1964; Sneed & Folk, 1958; Dobkins & Folk, 1970; Stratten, 1974; Boulton, 1978; Blatt *et al.*, 1980; Matthews, 1983; Dowdeswell *et al.*, 1985; Massari & Parea, 1988; Gale, 1990; Postma & Nemec, 1990; Gale & Hoare, 1991; Benn & Ballantyne, 1994; Sanders, 2000; Pontee *et al.*, 2004; Osborne, 2005).

Gravels within the Palaeogene and Neogene deposits were sporadically described from central Poland until the end of the 20$^{th}$ century. In the summer of 2004, an unexpected discovery was made in the Koźmin South lignite open-cast pit in the vicinity of Turek (Fig. 1). These coarse-grained deposits were termed “Koźmin Gravels” (Widera & Kita, 2007). On the other hand, the pebbles included in the gravels seemed to be much more interesting. It is, therefore, the aim of this paper to analyse the morphology of the above-mentioned fossil pebbles. Another objective of the present contribution is to indicate a source area for the pebbles from the Koźmin South lignite open-cast pit.

## GEOLOGICAL SETTING

The Koźmin South lignite open-cast pit is geologically located near the margin of the NW European Palaeogene and Neogene Basin (Fig. 1A; Vinken *et al.*, 1988). In the study area and in the adjacent territories of central Poland, Palaeogene deposits typical of marine (glauconitic sands, beach gravels) as well as of non-marine environments (fluviatile sands, lacustrine clays, lignites) have been discovered and documented over the last years (Widera, 2007; Widera & Kita, 2007; Dobosz & Widera, 2008). Therefore, the maximum Palaeogene shoreline was shifted by Widera and Kita (2007) at least a few kilometres south of the Koźmin South lignite open-cast pit (Fig. 1B).

It is one of seven open-cast pits in the Wielkopolska region (central Poland), where the Miocene lignites are exploited. The study area occurs in the northernmost fragment of the Adamów graben (Fig. 1C). This tectonic structure was active in the Palaeogene and Neogene times (Widera, 2004). The most interesting geological observations included in this paper were made in the NE part of the Koźmin South lignite open-cast pit (Fig. 1D).

The Palaeogene and Neogene lithostratigraphy in central Poland has not been established formally. It is caused by unfavourable facies conditions, often with noncalcareous shallow marine-brackish to terrestrial (lacustrine, fluviatile) sediments, in which microfossil groups are very rare. In places, the lithostratigraphical correlation is based on a comparison of facies, lithology and sequences of the Palaeogene and Neogene deposits. Only detailed palynological investigations of the lignite seam horizons are useful in interregional correlation in the parastratigraphic meaning (Schindewolf, 1960; Vinken *et al.*, 1988; Piwocki & Ziembińska-Tworzydło, 1997). Therefore, the lithostratigraphy

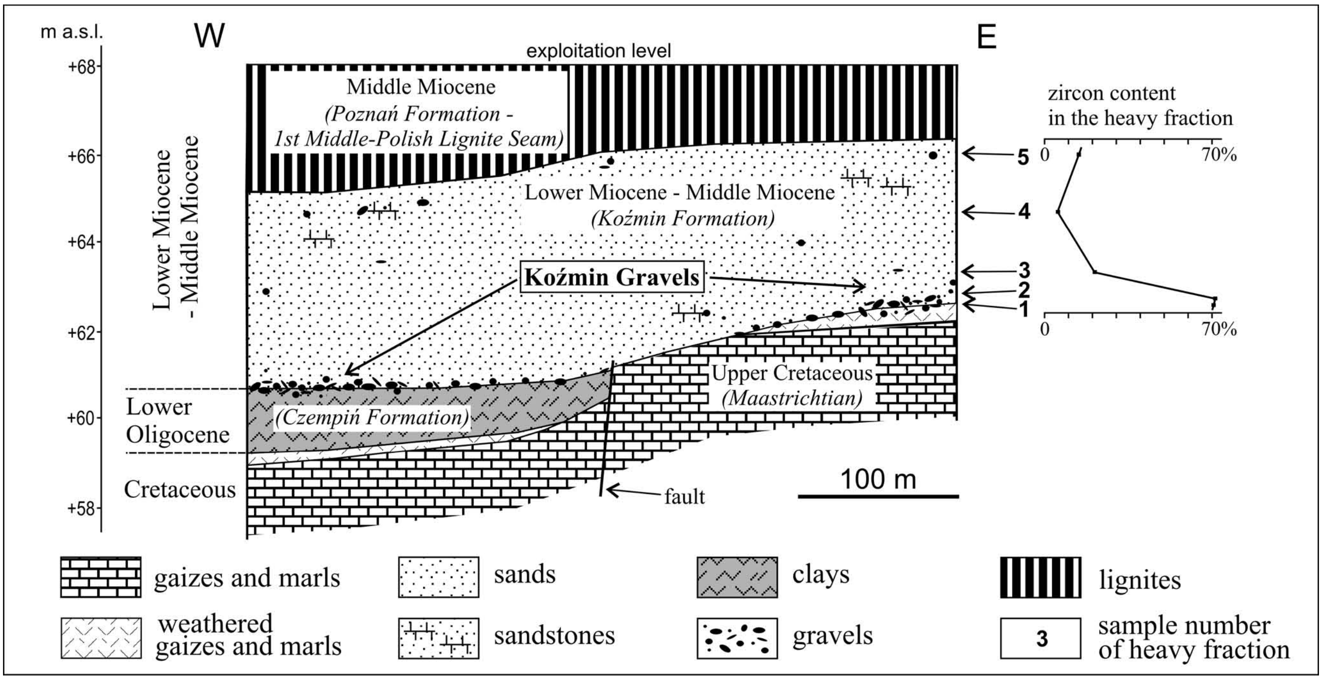


**Fig. 2.** Simplified geological section showing lithostratigraphic position of the Koźmin Gravels (modified after Dobosz & Widera, 2008). For location see Fig. 1D

of the study area in central Poland (Widera, 2007) may be easily correlated with that of other parts of the NW European Palaeogene and Neogene Basin (Vinken *et al.*, 1988), for instance, with the neighbouring territories of eastern Germany (Grimm *et al.*, 2002).

The lithostratigraphy of the study area is not complete. The Cenozoic starts with a hiatus that represents a time interval from the lowermost Paleocene to the uppermost Eocene. In fact, the age of the Palaeogene deposits ranges from the uppermost Eocene until the end of the early Oligocene in the study area (Piwocki & Ziembińska-Tworzydło, 1997). The Palaeogene deposits lie unconformably on Upper Cretaceous rocks. Generally, the Palaeogene in the Adamów graben consists of the Lower Mosina, Czempiń and Upper Mosina formations. Unfortunately, the Czempiń Formation is exposed only in the Koźmin South lignite open-cast pit (Fig. 2). The Lower Mosina and Upper Mosina formations are known from boreholes located about 400–500 m from the above-mentioned exposures.

The Czempiń Formation is situated between the Lower Mosina and Upper Mosina formations in the lithostratigraphic scheme. It is composed of various non-marine sediments developed in lacustrine and fluvial facies, mainly clays with fragments of lignite. These lignites correspond to the Fifth Czempiń Lignite Group in central Poland (Piwocki & Ziembińska-Tworzydło, 1997) and the Fifth Lusatian Seam Horizon in eastern Germany (Grimm *et al.*, 2002). In contrast, the Lower and Upper Mosina formations are known from boreholes situated a few hundred metres north of the Koźmin South lignite open-cast pit. Both formations are composed of intensively green glauconitic sands and they are comparable with the Rupel-Basissand and the Rupelton of the Rupel Formation in eastern Germany, respectively (Grimm *et al.*, 2002). Then, a stratigraphical hiatus is present above the early Oligocene deposits. This hiatus represents a time interval of uplift and erosion in the late Oligocene (Widera, 2004).

The Neogene succession starts with a great number of gravels, the so-called Koźmin Gravels, at the base (Fig. 2). They are poorly-sorted and matrix-supported, without grading and stratification (Fig. 3). Their base is erosive and they form tabular as well as lens-like in shape pockets, up to 0.5 m thick. Deposits similar to those from the Adamów graben were described by Doktor (1983) in the Carpathian Foredeep. This author interpreted them as deposited by debris flows (Doktor, 1983).

Sands with gravels, including the pebbles investigated in this paper, are named the Koźmin Formation, the age of which ranges from the Early to Middle Miocene (Widera, 2004, 2007). During this time span, a few lithostratigraphic units, from the Rawicz to Adamów formations, were deposited in most of western Poland (Piwocki & Ziembińska-Tworzydło, 1997). The first Middle-Polish Lignite Seam, called the First Lusatian Seam Horizon in eastern Germany (Grimm *et al.*, 2002), is present at the top of the lower–middle Miocene deposits (Fig. 2). This lignite seam and a few metres of overlying clays, silts and sands belong to the Poznań Formation, which is referred to the Rauno Formation in the neighbouring territories of eastern Germany (Grimm *et al.*, 2002). On top of the Palaeogene and Neogene deposits rests a Quaternary cover.

## MATERIAL AND METHODS

The fieldwork was carried out in 2004–2006 when most of the important sedimentological and lithostratigraphic observations as well as sampling were carried out. The total

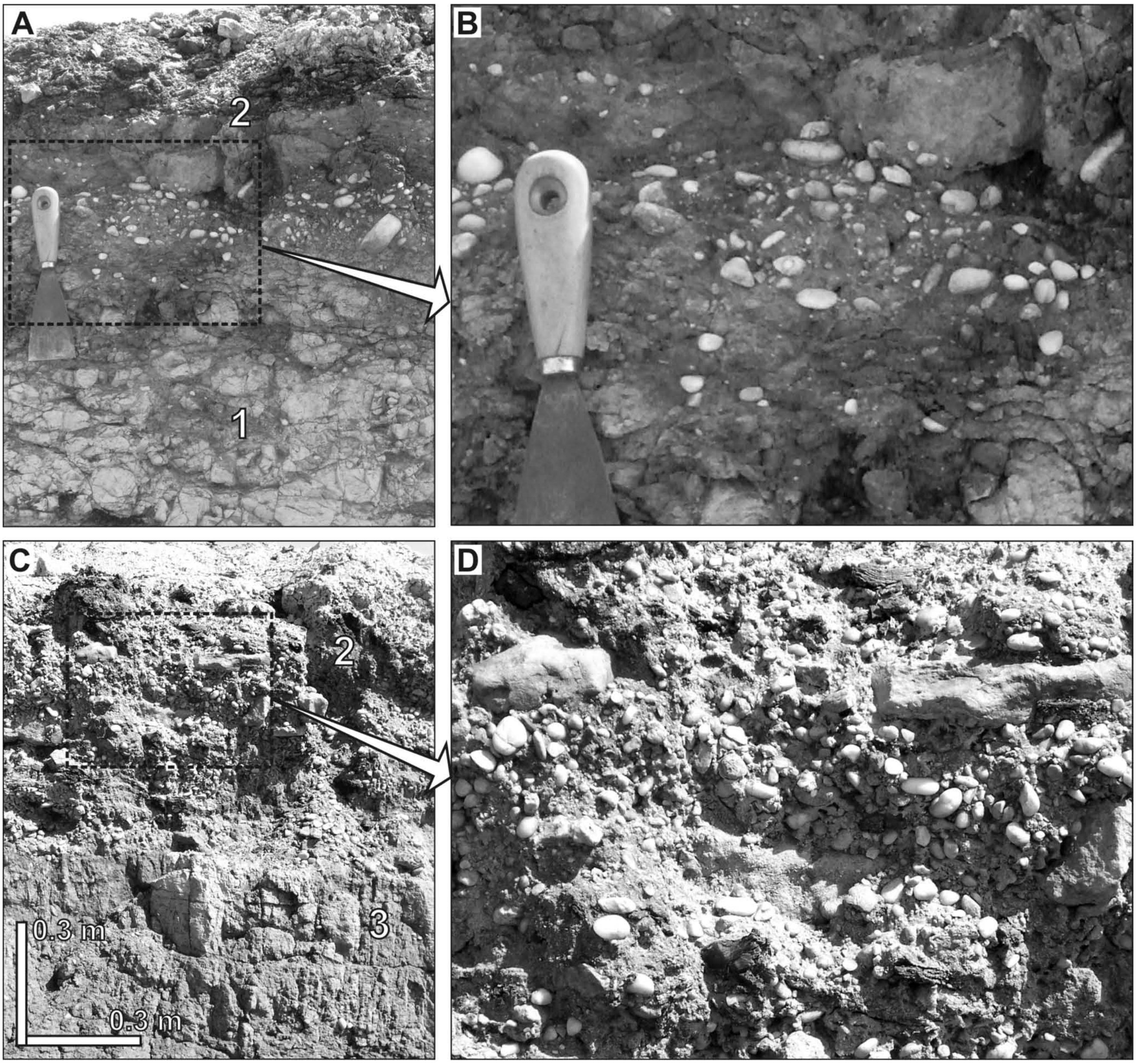


**Fig. 3.** Exposures of the Koźmin Gravels including the investigated pebbles. **A**, **B** – gravels situated at the top of the upper Cretaceous strata; **C**, **D** – gravels situated at the top of the lower Oligocene strata: 1 – weathered upper Cretaceous marls and gaizes, 2 – lower-middle Miocene sands of the Koźmin Formation, 3 – weathered lower Oligocene clays of the Czempiń Formation; for comparison see Fig. 2

length of exposures bearing pebbles reaches a few hundred metres, but their thickness is limited to 0.5 m in the Koźmin South open-cast pit. A total of 15 samples, including 686 pebbles, were collected and subjected to the petrographic (686 particles) and morphological (228 particles) study. First, all the samples were sieved to classify them according to the scheme presented by Folk (1954). Secondly, pebble-size particles were separated from each sample and sent for further research. The particle size of pebbles is described in this paper using the terminology of Wentworth (1922), modified by Friedman and Sanders (1978). It includes the major classes and their subdivisions, *e.g.* coarse pebble (16 to 32 mm), etc. However, it is more practical for statistical calculations and graphic presentations when phi ($\Phi$) diameters are used, *e.g.* coarse pebble (–4 to –5 $\Phi$), where the phi ($\Phi$) scale is computed by the following equation:

$$\Phi = -\log_2 (\text{grain size, mm}).$$

Here, according to Osborne's (2005) proposal, this equation may be written as: $\Phi = -\log_2 (D_I, \text{mm})$, where $D_I$ is the length of the intermediate axis of the pebble-size particle expressed in millimetres. Conversely, the following size classes of pebbles were distinguished by Matthews (1983): small (–2 to –3 $\Phi$), medium (–3 to –4 $\Phi$) and large (–4 to –5 $\Phi$). Both classifications are useful for a comparative study.

The basic methods used in the laboratory are measurements of the length ($D_L$), width ($D_I$) and thickness ($D_S$) of a pebble-size particle. In practice, three perpendicular (or-

thogonal) dimensions are measured: the longest ($D_L$), intermediate ($D_I$) and shortest diameter ($D_S$). All measurements presented in this article were made directly using a digital caliper. Then, on the basis of the obtained measurement results, a few form factors were calculated:
– $D_I/D_L$ (elongation ratio; Zingg, 1935),
– $D_S/D_I$ (flatness ratio; Zingg, 1935),
– $OP = \{10\{[(D_L–D_I)/(D_L–D_S)]–0.5\}\}/(D_S/D_L)$ (oblate–prolate index; Dobkins & Folk, 1970),
– $\psi_p = (D_S^2/D_LD_I)^{1/3}$ (sphericity – "maximum projection sphericity"; Sneed & Folk, 1958).

The roundness was preliminarily determined using the visual chart of Powers (1953). Then, a quantitative measurement of particle roundness ($R_{Wt}$) was obtained according to a modification of Wentworth's formula (1919; see also Dobkins & Folk, 1970). Here, roundness may be expressed as: $R_{Wt} = (D_k/D_i)$, where $D_k$ is the diameter of the inscribed circle in the sharpest corner and $D_i$ is the diameter of the largest inscribed circle on the maximum projection outline of the particle.

A combination of the elongation ratio ($D_I/D_L$) and the flatness ratio ($D_S/D_I$) is used to construct the Zingg diagram (1935), where four shape classes are defined. According to Blott and Pye (2008), these classes were renamed by a great number of scientists as well as being additionally modified by Blatt *et al.* (1980) as: disc (oblate), bladed, roller (prolate), and equant. In contrast, Sneed and Folk (1958) proposed a triangular plot for the classification of grain shape. The following form factors are on the triangle sides: $D_S/D_L$, $(D_L–D_I)/(D_L–D_S)$ and $\psi_p = (D_S^2/D_LD_I)^{1/3}$. The corners of the Sneed and Folk diagram (1958) are represented by: platy, elongated and compact form classes, respectively.

Other studies of pebble petrography, surface texture, heavy minerals and borehole data can be treated as complementary ones in this paper. However, they yielded information that supports the study of pebble morphology at the macro-scale.

Petrographic research was carried out for 686 pebble-size particles. The obtained results should include the source area (or areas) from where these pebbles were derived to the study area in central Poland.

The surface texture of pebble-size particles was examined with scanning electron microscopy (SEM). The methodology and interpretation of the obtained results followed the standard procedure suggested by Krinsley and Donahue (1968) as well as Krinsley and Doornkamp (1973). According to the above-mentioned authors, the SEM study is a tool differentiating ancient transport and deposition processes at the micro-scale.

The heavy mineral analysis of 5 samples was studied. The 0.1–0.25 mm fraction was separated in bromoform with a density of 2.8 g/cm$^3$ (Morton & Berge, 1995). Such heavy mineral fraction investigation is also recommended for preparing the *Detailed Geological Map of Poland* at the scale of 1:50,000. 200–300 grains were counted for each sample. The aim of this analysis was to show the difference in the relative content of heavy fraction in probably marine (2 of the lower samples – numbers 1 and 2; see Fig. 2) and fluvial sediments (3 of the upper samples – numbers 3, 4 and 5; see Fig. 2). The heavy mineral assemblage, together with the pebble shape and the quartz particle surface texture, can be helpful in the reconstruction of the transport process and depositional environment.

Additionally, more than a hundred borehole logs of the Palaeogene deposits were examined in the surrounding area of the Koźmin South lignite open-cast pit. These boreholes were drilled in the search for lignite deposits and their depth ranged from a few tens to more than 100 m and quite often ended in the Mesozoic substratum. The examination of the borehole logs yielded information about the position of the Koźmin Gravels in the lithostratigraphic scheme and their extent.

## RESULTS

### Sediment classification and petrography

The studied pebbles occur together with finer-grained and coarser-grained particles, which, according to Folk's (1954) sediment classification scheme, can be determined as gravelly sands (Widera & Kita, 2007). They consist of: sand (>75%), gravel (*ca.* 25%) and mud (<5%). The gravel fraction is composed mainly of pebbles and sporadically of cobbles, according to the nomenclature of Wentworth (1922). These cobbles, not taken into consideration in the present work, represent angular local Miocene sandstones and Cretaceous marls and/or gaizes. Here, an exception is one well-rounded flint particle ($D_L$ = 11 cm), which was found and documented in the Koźmin South lignite open-cast pit (Widera, 2007). In contrast, the rest of the gravels belonging to the pebble fraction were examined in detail.

The petrography and preliminary roundness, using the visual chart of Powers (1953), were analysed for all 686 pebbles (Fig. 4). They are predominantly composed of quartz particles – 94.6%. The lydite, flint, sandstone, marl and gaize particles comprise only the remaining 5.4% (Fig. 4A). Very important as well as interesting is the colour variety of the quartz pebbles: white, milky-white, honey-yellow, pink, greyish-blue and grey (see Widera & Kita, 2007).

### Macromorphology

The roundness was determined visually for each group of the quartz particles. Most of the quartz pebbles are generally rounded or well rounded. 270 of the milky quartz particles, *i.e.* more than 84% of the greatest group, belong to rounded or well-rounded particles. The value of rounded or well-rounded particles ranges between 64% and 84% in the other groups. In contrast, the angular and very angular quartz pebbles comprise 0–16% (Fig. 4B). The sub-angular and sub-rounded particles dominate among the white quartzes only, *i.e.* 6 particles (67%) are sub-angular or sub-rounded, and 3 particles (33%) are rounded or well rounded. In general, the quartz, lydite and occasionally flint pebbles are rounded and well rounded (Fig. 4B). It is noteworthy that their surface is often polished and excellently smoothed (see Widera & Kita, 2007). On the other hand, the sandstone, marl and gaize particles are quite often angular and very angular with generally frosted surface.

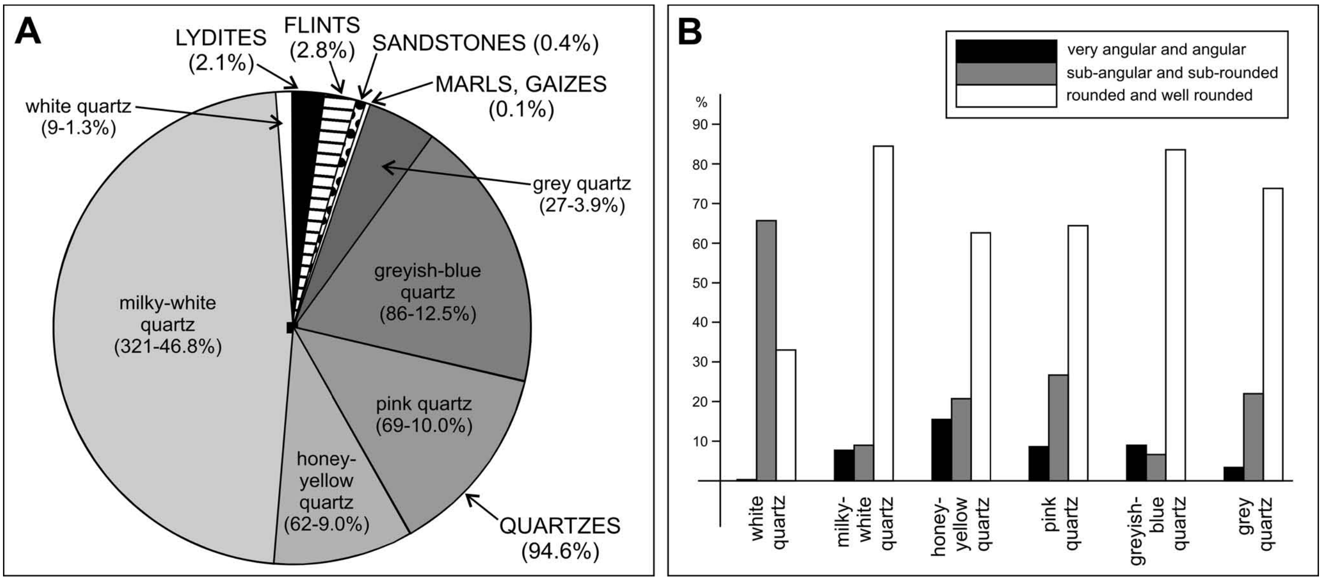


**Fig. 4.** Petrography and roundness of the pebbles: **A** – petrographic composition of 686 particles with subdivision of the quartz pebbles (modified after Dobosz & Widera, 2008); **B** – roundness of the quartz pebbles using the visual chart of Powers (1953)

The form factors of 228 quartz and sporadically lydite pebbles from the Koźmin South lignite open-cast pit were calculated and presented graphically (Figs 5, 6). According to the terminology of Wentworth (1922), modified by Friedman and Sanders (1978), all 228 pebbles belong to three classes. They include: very coarse (13%), coarse (58%) and medium (29%) pebbles. However, in the nomenclature of Matthews (1983), these pebbles can be named as: very large, large and medium, respectively. In both classifications, the length of the intermediate axis of the pebble-size particle – $D_I$ – is a fundamental criterion. In this case, $D_I$ varies from 8.95 to 38.29 mm, but $D_L$ ranges from 11.81 to 58.56 mm and the values of $D_S$ are between 4.54 and 17.02 mm.

Additionally, the same factors were determined for some representative non-quartz, *i.e.* flint, marl and gaize pebbles of beach origin (10 particles) from the Koźmin South lignite open-cast pit. The results achieved are set together for easy interpretation in the form of diagrams and plots (Figs 5, 6). For flint, marl and gaize pebbles, $D_L$ ranges from 41.43 to 84.19 mm, $D_I$ varies from 35.81 to 57.18 mm and the values of $D_S$ are between 23.73 and 35.90 mm.

More than half (63%) of the predominantly quartz pebbles are disc-shaped on the Zingg diagram (Fig. 5A). The particles of bladed shape comprise 34% and roller particles 3%. In contrast, non-quartz pebbles have higher values of the elongation ratio ($D_I/D_L$) and the flatness ratio ($D_S/D_I$) than the quartz pebbles. These non-quartz, *i.e.* flint, marl and gaize pebbles are concentrated in the upper-right corner on the Zingg diagram, indicating that the particles are more equant (Fig. 5A). The same data plotted on the Sneed and Folk diagram provide partially different results because of the large number of fields referring to form classes. In this case, the quartz pebbles are situated in the centre of a triangular diagram (Fig. 5B). They are blade-shaped (53%), very bladed (18%), platy (18%), elongated (5%), as well as very platy (3%) and compact elongated (3%). The Sneed and Folk diagram also separates the non-quartz pebbles quite well. These pebbles are pushed towards very bladed particles and are situated closer to the centre of the triangular diagram (Fig. 5B).

A compilation of the other quantifying form factors such as: sphericity ($\psi_p$, *i.e.* "maximum projection sphericity" calculated according to Sneed and Folk's formula, 1958) versus the intermediate axis of a pebble-size particle ($D_I$), roundness ($R_{Wt}$, calculated according to a modification of Wentworth's formula, 1919) versus the intermediate axis of a pebble-size particle ($D_I$), as well as sphericity ($\psi_p$) versus the oblate–prolate index (OP index, calculated according to Dobkins and Folk's formula, 1970) are very useful in pala- eoevironmental interpretation (Fig. 6). Thus, the sphericity ($\psi_p$) values range from 0.42 to 0.82 (Figs 6A, 6C) and the roundness ($R_{Wt}$) values are between 0.32 and 0.92 (Fig. 6B). The OP index values vary from –8.73 to +8.33 (Fig. 6C). For these indexes, the average values are: $\psi_p = 0.56$, $R_{Wt} = 0.73$ and OP = –1.46.

The first plot, *i.e.* $\psi_p$ versus $D_I$, seems to be the best to distinguish quartz from non-quartz particles of a marine origin (Fig. 6A). In this case, the non-quartz (flint, marl and gaize) pebbles are characterized by higher values of sphericity for the same intermediate axis length – the average sphericity value is 0.73. These particles are located in the upper-right corner of the plot. Conversely, most of the study quartz pebbles are situated in the lower-left corner of the plot (Fig. 6A). The second plot, *i.e.* $R_{Wt}$ versus $D_I$, does not show a correlation between these two form factors. Considering the same intermediate axis length of the particles, the roundness values are similar for all pebbles of variable petrography (Fig. 6B). Moreover, the average roundness values for the flint, marl and gaize pebbles ($R_{Wt} = 0.65$) are a little less than those yielded for the above-mentioned and studied in detail quartz pebbles. Here, for comparison, are drawn the average roundness values that were used as indi-

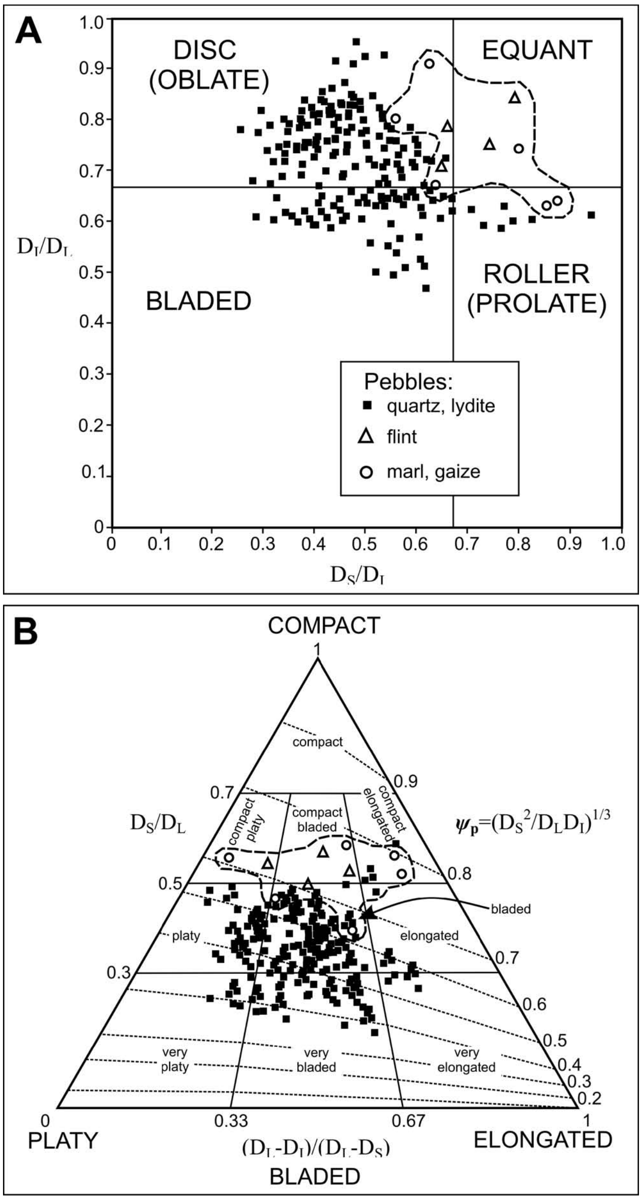


**Fig. 5.** Classification of the Koźmin Gravels form: **A** – using the diagram of Zingg (1935) with modification after Blatt *et al.* (1980); **B** – using the diagram of Sneed and Folk (1958)

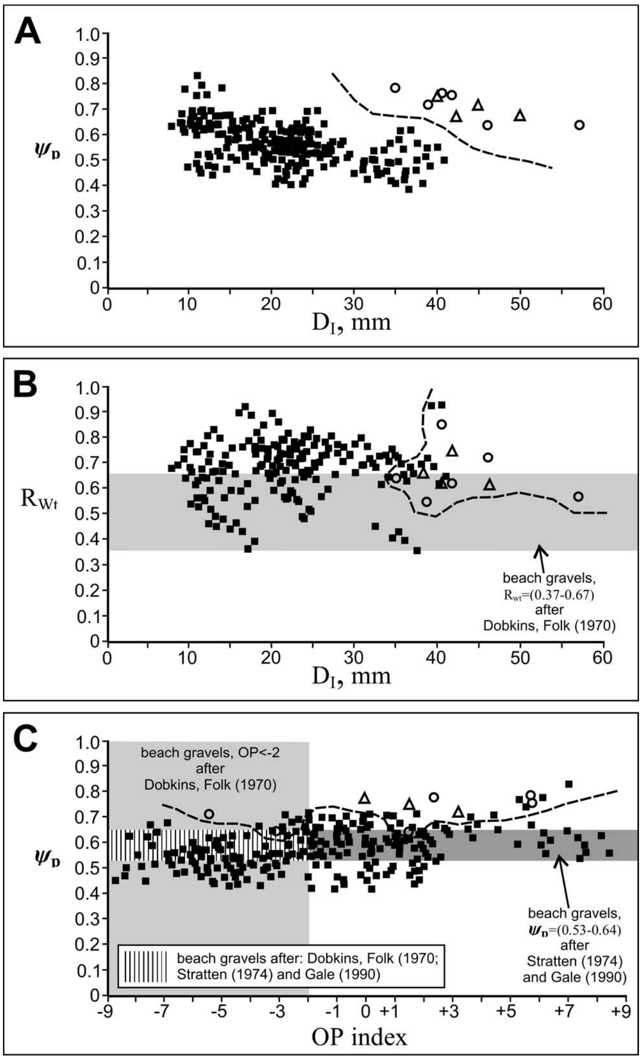


**Fig. 6.** Plots of major particle parameters. **A** – sphericity ($\psi_p$) versus intermediate axial length ($D_I$); **B** – roundness ($R_{Wt}$) versus intermediate axial length ($D_I$); **C** – sphericity ($\psi_p$) versus oblate-prolate index (OP index); for other explanations see Fig. 5

cators of the beach environment by Dobkins and Folk (1970). According to Dobkins and Folk's criterion, the average roundness of all pebbles, *i.e.* quartz and non-quartz, refers only to the beach pebbles (Fig. 6B). The third plot reflects $\psi_p$ versus the OP index (Fig. 6C), where the beach environment is distinguished by criteria suggested by Dobkins and Folk (1970) as well as Straten (1974) and Gale (1990). Using Dobkins and Folk's (1970) criterion, 45% of the analysed quartz particles represent the beach environment, but according to Stratten's (1974) and Gale's (1990) criteria, 50% of them may be regarded as beach pebbles. Moreover, 80% of the flint, marl and gaize pebbles are not characteristic of the beach environment, according to the meaning of Dobkins and Folk (1970), Stratten (1974), and Gale (1990).

## Micromorphology

The morphology of the quartz pebbles at the microscale reflects a high mechanically energetic environment. All the particles analysed by SEM are rounded and they sometimes have an excellently polished surface (Fig. 7). Such excellently polished surfaces of fine pebbles are also known from the Palaeogene marine deposits in south-western Poland (Kosmowska-Ceranowicz & Bühmann, 1982; Dobosz & Widera, 2008). The surface polishing may have been produced by chemical processes (Kuenen, 1956, 1964) and physical abrasion (Dobkins & Folk, 1970). In general, polished particle surfaces are much more common on beaches than in rivers (Krinsley & Donahue, 1968). More characteristic features corresponding to a littoral environment can be observed at a higher magnification (Figs 7B, 7C). The first example shows the v-shaped indentations that were produced in high-energy syn-sedimentary conditions,

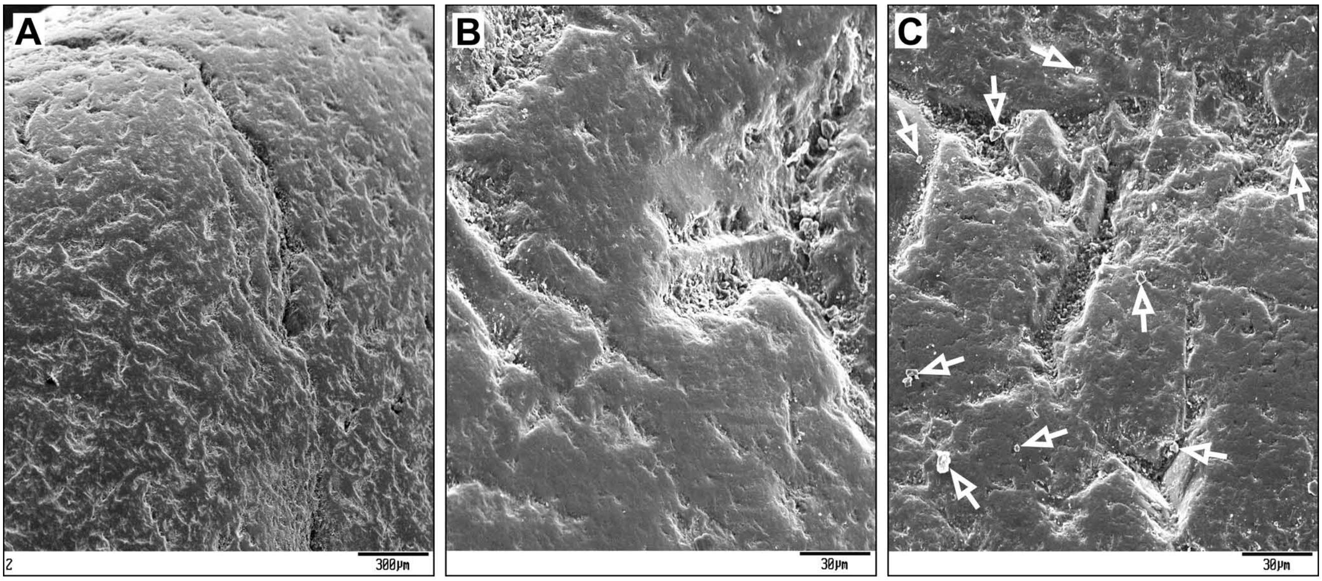


**Fig. 7.** Quartz pebble surface micromorphology (SEM – scanning electron microphotographs). **A** – general view of excellently polished quartz surface of probably beach origin; **B** – quartz surface showing the v-shaped indentations; **C** – quartz surface showing the v-shaped indentations, grooves and silica globules; note the silica globules are indicated with white arrows

**Table 1**

Composition of the heavy mineral fraction of different origin (*analysed by T. Dobosz*)

| Sample no. | Am (%) | Py (%) | Bi (%) | Ch (%) | Ep (%) | Ga (%) | Tu (%) | Zi (%) | Ru (%) | Ky (%) | St (%) | An (%) | Si (%) | Ap (%) | Other (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6.3 | 1.3 | 0.3 | 0 | 1.7 | 2.7 | 0 | **72.0** | 4.0 | 3.7 | 1.0 | 1.0 | 0 | 1.0 | 5.0 |
| 2 | 2.0 | 0.3 | 2.3 | 0 | 0.3 | 2.0 | 0 | **73.0** | 4.7 | 8.0 | 0.3 | 1.0 | 0 | 0.3 | 5.2 |
| 3 | 0 | 0 | 12.0 | 2.4 | 14.4 | 0 | 12.0 | **21.0** | 0 | 14.5 | 2.4 | 12.0 | 1.2 | 2.5 | 5.6 |
| 4 | 0 | 0 | 0 | 2.4 | 14.0 | 20.4 | 7.2 | **7.0** | 1.0 | 16.8 | 8.4 | 0 | 1.2 | 9.6 | 4.0 |
| 5 | 0 | 0 | 6.0 | 0 | 13.2 | 10.8 | 9.6 | **14.0** | 0.5 | 9.6 | 4.8 | 6.0 | 4.8 | 14.4 | 5.3 |

Samples 1 and 2 represent probably reworked marine deposits; samples 3, 4 and 5 correspond to fluvial deposits; Am - amphibole, Py - pyroxene, Bi - biotite, Ch - chlorite, Ep - epidote, Ga - garnet, Tu - tourmaline, Zi - zircon, Ru - rutile, Ky - kyanite, St - staurolite, An - andalusite, Si - sillimanite, Ap - apatite; note that the zircon content is typed in bold. For samples location see Fig. 2

during which the pebble surface was polished. In the second example described, in spite of the above-mentioned v-shaped indentations and grooves, a few silica globules are visible (Fig. 9C). Their origin can be linked with the Miocene post-sedimentary processes when sandstones and conglomerates were produced (Widera, 2007). The present features of the quartz surfaces refer to those regarded by Krinsley and Doornkamp (1973) as typical of high mechanical energy environments, *e.g*. the littoral zone of the sea.

### Heavy minerals

The results of the preliminary heavy mineral analysis quite clearly indicate differences between sediments of various origin and ages (Table 1). The most characteristic is a relatively equal and high content of zircon (72–73%) in two of the lowermost samples corresponding to the pebble-bearing horizon (see Fig. 2). These deposits probably originated initially from the Palaeogene beach and finally from the Neogene debris flow. On the other hand, there is a relatively small content of zircon (7–21%) in the upper 3 samples representing the Miocene river sands or sandstones (Table 1; *cf.* Fig. 2).

### Source area

Most of the local pebbles are not useful in the determination of their source area because they were derived from the Cretaceous and Miocene strata also occurring in the vicinity of the Koźmin South lignite open-cast pit. On the other hand, the lydite and greyish-blue quartz source areas are located relatively far from the study area (Fig. 8). The lydite is known from the Holy Cross Mountains and from the Sudetes, which form an integral part of the Bohemian Massif. However, the greyish-blue quartz is documented in the western Sudetes only (Fig. 8). Taking into consideration the transport directions, the greyish-blue quartz grains can only be regarded as the most useful in the pebble provenance investigations (Kosmowska-Ceranowicz & Bühmann, 1982). They were derived from gneiss and granite-gneiss rocks of Precambrian age that are exposed close to the localities of Wądroże Wielkie, Wigancice Złotoryjskie and Bogatynia (Grodzicki, 1998; Dobosz & Widera, 2008). Thus, the most probable source area for the studied pebbles is in the Sudetes Mts., located in the NE part of the Bohemian Massif (Fig. 8).

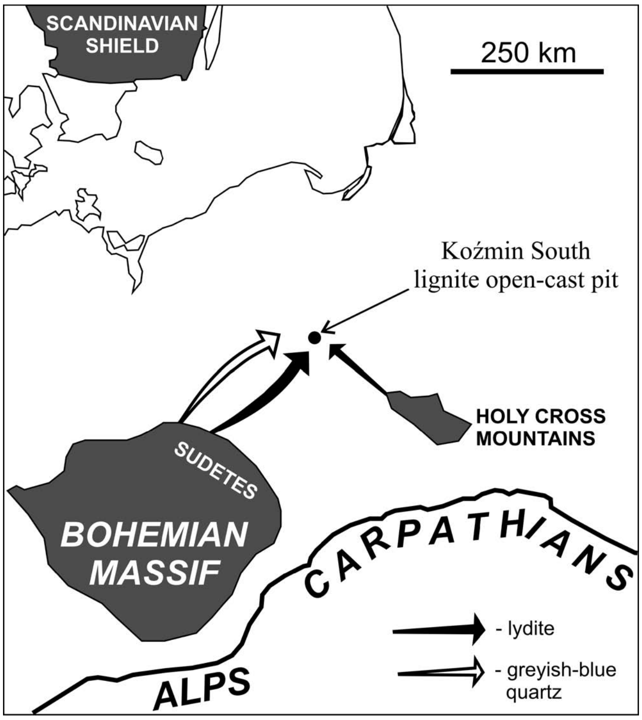


**Fig. 8.** Possible transport direction and a source area for pebbles from the Koźmin South lignite open-cast pit

## DISCUSSION

The predominance of quartz pebbles provides information on the environmental conditions during transport. One of the most important features is the resistance of quartz and occasionally lydite particles to physical and chemical weathering as well as to abrasive processes. In places, the lack of less resistant rocks, derived from the same territory, indicates a long distance between the source and deposition area, *i.e.* between the Koźmin South lignite open-cast pit and the Sudetes in the Bohemian Massif. Thus, the entire distance of river transport is over 300 km (see Fig. 8). Note that the soft and angular sandstones, marls and gaizes were carried by rivers for a relatively short distance, probably not more than a few kilometres. On the other hand, quite hard and rounded flint particles could have been derived even from rocks located some tens of kilometres from the study area (Dobosz & Widera, 2008; Widera & Dobosz, 2009). Generally, the flint pebbles are bigger than the quartz ones. That is the reason why the distance of flints' transport was much more shorter than that of quartzes.

Both Zingg (1935) and Sneed and Folk (1958) diagrams are most popular for visual presentation of the shape of sedimentary particles, including pebbles. The authors indicate the advantages and disadvantages of these diagrams (*e.g.*, Dobkins & Folk, 1970; Benn & Ballantyne, 1992; Blott & Pye, 2008). Therefore, the pebble shape is presented on both the above-mentioned diagrams for a comparative study (see Fig. 5). In my opinion, these diagrams are useful for distinguishing the particles of variable petrography and origin. However, they do not define the sedimentary environment of the pebble-size particles on the basis of their position on the diagram only. Because of an important shape property that can be expressed visually, I recommend the use both the Zingg (1935) and Sneed and Folk (1958) diagrams.

The results of the preliminary heavy mineral analysis provide some information. In the case of the basal pebble-rich horizon, there is an unexpectedly high zircon content, averaging around 72.5% (see Fig. 2 and Table 1). As this is in contrast to both the younger alluvial deposits and the above-mentioned older source rocks located in the Sudetes, where an average zircon content is about two, three or more times lower (Grodzicki, 1998), this phenomenon should be discussed here. In places, it is suggested that the original heavy mineral assemblage fraction composition was successively reworked and selected during river transport. Then, one of the most resistant minerals, *i.e.* zircon, was sorted in a high-energy littoral environment. The enrichment of the heavy mineral fraction in the modern and ancient littoral/beach environments was also observed and summarized by Komar and Wang (1984) and Paine (2005). Moreover, these authors recognized the littoral/beach environment, especially that formed in J-shaped bays, as the most effective in heavy mineral concentration. Finally, beach deposits including the study pebble-size particles as well as those with a very elevated zircon content were probably deposited by debris flows as poorly sorted deposits in conditions referring to the tectonic activity of the Adamów graben during the transition between the Palaeogene and Neogene (Widera, 2007).

On the basis of sedimentary features it is possible to indicate similarity between deposition of gravelly sequences in the area of rapid tectonic subsidence, *e.g*. the Adamów graben and in the foredeep of accelerated uplift, like for instance close to the Carpathian margin. In both cases a significant role in deposition and/or redeposition of the Miocene coarse-sized rocks was played by debris flows. It is noteworthy that the gravels occurring in the Carpathian Foredeep are much more varied in thickness and lithofacies features (Doktor, 1983) than those in the study area.

There seems to be a very interesting problem regarding the beach type where the above-presented characteristic morphology of the pebbles was produced. It is important to establish whether the pebbles were formed on more gravelly or on more sandy beaches. Studied in detail pebbles are more spherical and their shape is quite similar to the pebble-size particles that are observed on gravelly beaches elsewhere in the world (*e.g.*, Dobkins & Folk, 1970; Matthews, 1983; Massari & Parea, 1988; Gale, 1990; Postma & Nemec, 1990; Sanders, 2000; Pontee *et al.*, 2004). Similar results were also obtained by experimental studies (*cf.* Kuenen, 1956, 1964; Matthews, 1983; Osborne, 2005).

## CONCLUSIONS

1. The fine-grained Neogene deposits in the Koźmin South lignite open-cast pit (central Poland) include gravels, which are named the Koźmin Gravels. Among them, the most interesting are extraordinary pebbles. The genesis of these pebbles was inferred from detailed study of their morphology, *i.e*. "shape" and "surface texture". Additionally, other complimentary investigations were carried out: petrographic examination of the pebble-size particles, SEM and heavy mineral analysis.

2. The yielded results of shape factors and surface micromorphology are considered conclusive evidence that the quartz pebbles are of beach/littoral origin. They include a high percentage of disc-shaped, rounded and excellently polished clasts as well as a dominant zircon content. Conversely, their sphericity is usually lower than in the case of the non-quartz pebbles. Thus, they are characteristic of a high energy environment, *i.e*. they are typical of wave-dominated gravelly beaches.

3. The age of these pebbles could not be determined directly because of the lack of shell fragments, microfauna, dinocysts, glauconite, etc. On the basis of a probable beach origin and position in the lithostratigraphic sections, with respect to the palaeogeography of central Poland during the Cenozoic, the age of these pebbles can be estimated as the early Oligocene. This age corresponds loosely to that of he Upper Mosina Formation, the sediments of which have been eroded in the Koźmin South lignite open-cast pit. During the transition between the Oligocene and Miocene, in accelerated tectonic activity, the beach pebbles were redeposited as debris flows and then buried beneath the Neogene fluvial deposits.

4. The most probable source area for pebbles from the Koźmin South lignite open-cast pit seems to be the Sudetes Mts., located on the NE slope of the Bohemian Massif. This opinion is supported by the presence of greyish-blue quartz that is known only from the Sudetes.

5. In summary, I conclude that the morphology of pebbles is a very useful tool for determining their transport processes. It is especially important when neither palaeontological nor sedimentological evidence is provided, like in the discussed example.

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