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XV CONGRESS

Advantages and disadvantages of petrographic analyses of glacial sediments

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Petrographic studies are a helpful tool for glacial geomorphology, because they may supplement lithofacial analysis. They introduced information about dynamies and thermic conditions in a glacial sole, about different alimentary zones, and routes of an ice sheet and individual glaeial streams that deposited tills in central and western Wielkopolska, western Poland. Apart from advantages, the petrographic analyses have also disadvantages, e.g. ability to recognize 200 types of indicator erraties, which follows in pointing to respeetive souree areas. A sample volume must bc represented statistically, i.e. it should consist of not less than 1000 erratics from tills and not less than 300 pebbles from gravel.

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INTRODUCTION

Erratics present in the heterogeneous glacial material have aroused curiosity of nature scientists who attempted to reveal their origin based on macroscopic features and deposition location. A systematic petrographic analysis, both qualitative and quantitative, have been initiated (S. Konieczny, 1956; J. Nunberg, 1971). It was aimed to indicate correlation between the moraine layers and specific glaciations. Numerous and very diversified factors influencing the petrographic characteristics of tills (Fig. 1), did not allow presenting the same mineralogic-petrographic characteristics of glacial deposits representative for a larger study area, for example northwestern Poland. This difficulty results from the extremely dynamically diversified glacier margin, which advancing southward covered the morphologically diversified pre-Quaternary surfaces (R. Galon, 1967; E. Rühle, 1968). Thermics of a glacial sole was, however, responsible for a type and intensity of the basement destruction and incorporation of material, which was moved from its original position. A geologic structure of the area, over which a glacier was moving, thus both areas of Scandinavia and the Baltic Basin, as well as source areas and foreland of the maximum extent of an ice sheet, are considered the most important factor, however, which diversifies petrographic composition of clasts in tills. Studies currently conducted on the erratic composition of tills indicate (Fig. 1) that a petrographic spectrum results the most frequently from mixing of the Scandinavian material, transported directly from the alimentary area, with material transported from various parts of Scandinavia, e.g. drained by rivers and derived from tills of previous (G. Gillberg, 1977; P. U. Clark, 1987). A local material perhaps overlap this, already complex picture, which effectively changes the original content of Scandinavian rocks (A. Dreimanis, 1990; R. Puranen, 1990). Both issues were also approached in Poland (e.g. Z. Lamparski, 1970; J. Rzechowski, 1971, 1979; *cf.* M. Górska, 1998*b*).

REVIEW OF METHODS

Two methods, presented by V. Milthers (e.g. 1909, 1934) and J. Hesemann (e.g. 1931, 1935), are among the first quantitative studies on erratics, and index erratics are considered in both of them. This term introduced by J. Korn (1927) includes rocks from a single alimentary area, which is described by a latitude and a longitude of its central part. Correlation with appropriate outcrops is determined, based on macroscopic characteristics. Both methods exclusively analyse a crys-

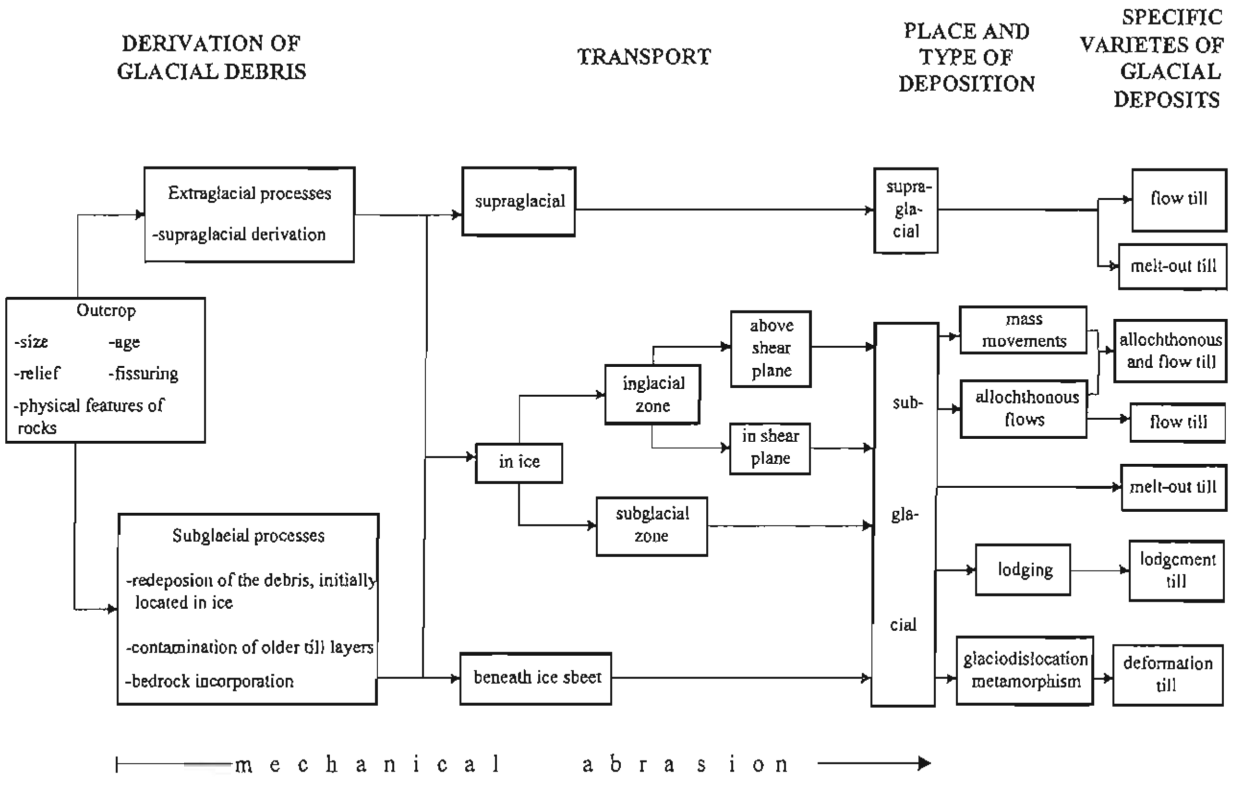

Fig. 1. Factors affecting genetic type and mineral composition of tills (modified after A. Dreimanis, 1982; P. U. Clark, 1987)

talline material, which is considered to be more resistant to weathering. P. Smed (1993) questions this thesis, however, saying that continental glaciers are able to transport less resistant rocks, such as limestones or Palaeozoic shales, even at significant distances without their entire destruction.

Roundness of surfaces and observed, very gradual decrease of their content in the entire population of erratics, are traces of indisputable mechanic destruction in the glacier interior (M. Górska, 1997).

V. Milthers (1909, 1934) suggests the analysis of only six, relatively easily recognizable index rocks, which originate from the three alimentary areas, varying in terms of area sizes. This causes, that P. Smed (1993) reproached him with neglect of majority of possible occurrences of Swedish erratics in tills, and causing subsequently a greater significance of the rombohedral porphyry from Oslo and rapakivi granites from the Åland Islands. V. Milthers (1909, 1934) did not distinguish a till, deposited by the ice sheet advancing from the north at all. It eventually resulted in incorrect conclusions of V. Milthers (1909, 1934) about predominance of the ice sheet advancing directions from the north-west and the Baltic Basin.

In order to avoid similar mistakes and in result to reconstruct, relatively precisely, directions of the ice sheet advance into the European Lowland, possibly numerous rock samples not limiting their size, for example, to few subjectively selected erratics, should be analysed.

In contrast to V. Milthers (1909, 1934), J. Hesemann (1931, 1935) saw additional information in every detail, thus extended a spectrum of analysed erratics to about 200 specimens, considering only 11 types (J. Nunberg, 1971), giving a secondary role to others. Analysing samples of varying sizes (50–100 specimens of index rocks), he obtained an initial material to introduce a four-digit index. Each of the digits represented, after rounding to nearest tens, a number of crystalline erratics within a one out of four (V. Milthers, 1909, 1934), varying in terms of sizes and alimentary areas.

These averaged twice values, thus affected by a large error, depart significantly from a real percentage content of index erratics, and it considerably decreases a quality of the method. Lack of information about a presence or absence of a specific rock type, which in many cases may have a significant importance, is the next disadvantage of the J. Hesemann's method. All types are included into a single alimentary area, knowing, however, that all samples associated with this area, could have not been transported together by the same ice sheet or its individual ice streams.

G. Lüttig (1958) introduced a new method of determination of the alimentary area of a rock debris in tills, and named it the theoretical erratic centre TGZ (in German: Teoretisches Geschiebe-Zentrum). Based on the analysis of 400 types of Scandinavian sedimentary and crystalline erratics from parent areas of known geographic coordinates, G. Lüttig (1958)

Table 1

Characteristc features of important Scandinavian crystalline indicator erratics after J. Hesemann (1975); sketch K.-D. Meyer (1980)

Rock	Size	Colour	Feldspates	Quartz	Basic elements	Texture, other
Bredvad porphyry Dalarna	very fine	light red	few, in colour of matrix, 1–5 mm	–	very few, green spots, 1–2 mm	partly fluidal
Red Baltic porphyry	very fine	brick-red	few, in colour of matrix, 0.5–2 mm	numerous, angular, grey, 0.5–2 mm	very few, green spots, mm-cm	–
Brown Baltic porphyry	very fine	red-brown, grey-brown	many, reddish, 1–5 mm	many, 0.5–2 mm	few, green-black spots	often white clongated feldspates (weathered)
Grönklitt porphyrite Dalarna	very fine	reddish-brown, violet	many, red, brown, grey, 1–5 mm	–	amany, spots glitter (augite, hornblende)	–
Påscallavik porphyry Småland	very fine	grey-reddish-violet	many, up to 2 cm, round, white-red	very numerous, white-grey-blue, 1–3 mm	few, sometimes in form of clongated stripes or zones, up to 1 cm	fine-granite, sometimes fluidal, "mock brown" structure
Åland quartz porphyry	very fine	brick-red, red-brown	few reddish, up to 1 cm	numerous, up to 0.5 cm, round, grey	very few, green spots	sometimes "rapakivi" type: round potassium feldspates surrounded by 1 mm fringe of plagioclases
Åland Rapakivi	middle-coarse	red brownish-red to red-brown	many red orthoclases with greenish plagioclases, 1–2 cm	few, grey, round, 1–3 mm	spots of biotites, hornblendes, 1–10 mm	rapakivi structure!
Åland granite	middle-fine	red brownish-red	many red orthoclases, few plagioclases, up to 0.5 cm	few, grey, 1–3 mm	few hornblendes and biotites, small spots	sometimes hieroglyphic, granular
Red Växjö granite Småland	fine-middle-coarse	red-light red	many, red, up to 1 cm	numerous, grey-blue, 1–3 mm	few, partly spots	"Småland granite with blue quartzes"
Stockholm granite	fine	light grey, grey	grey-white to white	few, grey, 1–3 mm	many, glitter, brown-black	partly similar to gneiss
Uppsala granite	middle-coarse	light grey, grey	whitish, up to 1 cm, seldom reddish	grey, sometimes blue, 1–5 mm	hornblende, biotite in shape of spots	sometimes structure of lenses
Kinne diabase	middle-fine	greenish-grey	clusters of feldspates, up to 1 cm	–	augite, 1–5 mm	spots, sometimes glitter like silk
Scania basalt	very fine	black, dark grey	only in matrix	–	augite, olivine	rusty-brown grains, often hollows after weathered olivines
Rhomb porphyry Oslo	very fine	brown, grey, red-violet	rhomb in shape, many, pink-white, 1–2 cm	–	–	porphyrytic, feldspates in shape of rhombs

obtained two values, which are mathematically calculated averages of a geographic latitude and longitude of the alimentary area of the entire erratic spectrum. This method has been successfully applied till present time by K.-D. Meyer (1965, 1983, 1990, 1991, 1995). R. Vinx (1996, 1998) and T. Geisler (1996) introduced new rock types from southwestern Sweden, including all requirements which have to be filled by index erratics.

Diversification of a local accumulative sequence at Ujście, obtained earlier by S. Kozarski (1991, 1995) and S. Kozarski *et al.* (1985, 1987) was confirmed by petrographic examination of glacial sediments considering a theoretical erratic centre (M. Böse, M. Górska, 1995; M. Górska, 1995*b*, 1997, 1998*a*). First of all, changes of TGZ, calculated for specific lithostratigraphic layers in the studied location, proved a previously suggested distinct direction of the ice sheet advance during the Chodzież Phase (17.7 ka BP according to S. Kozarski, 1995).

A certain disadvantage of this method is the fact, that the value of TGZ does not correspond to a real past centre of

Table 2

Characteristic features of important Scandinavian sedimentary rocks after J. Hesemann (1975); sketch K.-D. Meyer (1980)

Rock	Age	Grain size	Colour	Significant features
Digerberg sandstone Dalarna	Precambrian	fine-middle-coarse	red-brown-grey-violet	sandstone with features of tuff and tuffite, very hard, arkose or aplit in character (typical of acid soil rocks)
Digerberg conglomerate Dalarna	Precambrian	up to coarse conglomerate	red-brown-grey-violet	as above and with big pebbles and fragments of Dala porphyry
Dala sandstone	Precambrian	fine-middle-coarse	light bricks- brown-red-violet	sometimes quartzitic, rarely conglomeratic, often spots, rarely carbonate
Kalmarsund sandstone "Chiasma", western coast of Öland, and the Kalmar Straits	Eocambrian (Lower Cambrian)	fine to middle	yellowish, light grey, violet-red-brown stripes	apart from cross-bedding also quasi-stratification (coloured belts, stripes), sometimes violet-red *Scolithos*
Scolithus sandstone Scania	Lower Cambrian	middle	light grey, yellowish	1–3 mm tubes perpendicular to bedding of transversal *Scolithos*
Hardeberga sandstone Scania	Lower Cambrian	fine to middle	light grey, white- grey	quartzitic, partly glassy, sometimes conglomeratic with quartz; variant with *Fucoidae*
Tessini sandstone, western coast of Öland	Middle Cambrian	fine sandy to coarse-grained silty shale	light grey, weathered — yellowish	flat, light carbonate, hard; undulated layer-top (ripplemarks), layer-bottom with traces of *Paradoxides paradoxissimus (tessini)*
"Ball" sandstone, bottom of the Baltic Sea, NE of Gotland	Devonian (Old Red)	fine-middle	light grey, yellowish, reddish, greenish	quasi spherical concretions, reflected fresh broken surface, glitter; fragments of fish
Conglomerate of rhomb porphyry S of Oslo	Lower Permian (New Red Sandstone)	fine to coarse	violet-red, brown, grey	with fragments and pebbles of rhomb porphyry, less hard
Palaeozoic limestone, between Öland and Gotland	Ordovician, Silurian	very fine, dense	grey, greenish, yellowish	sometimes visible algae *Palaeoporella* and crystallized fauna
Palaeozoic limestones Öland	Ordovician	fine	red	–

glacial erosion. It is only mathematically determined, centrally located relatively to other alimentation centres, from which basement deposits were incorporated.

Erratics the most commonly occurring in the European Lowland are these which are included in the Tables 1 and 2. Relatively recently P. Smed (1993, 1994) tried to determine paths of ice sheet advances using a new presentation with circle maps. Percentage content of index erratics corresponds to a circle diameter, which changes accordingly to a population size of the rocks determined. The circle centre is located in the centre of the alimentary area.

This new method of a graphic presentation (P. Smed, 1993, 1994) seems most thoroughly to include the corrected methodological errors of the previously applied methods, and represents a broad spectrum of information. A consideration of even individual rocks is a significant advantage of this method. Index erratics, which are not sufficiently abundant, and also these, which do not represent all adjacent types in a group, are not omitted. Moreover, placed on a map, they inform about possible contamination with older tills due to their incorporation during younger ice sheet advances (P. Smed, 1993). This last feature has not been considered in the earlier presented methods of V. Milthers (1909, 1934), J. Hesemann (1931, 1935) or TGZ. In the method of P. Smed (1993, 1994), the erratics having some index properties are considered (in German: statistische Leitgeschiebe). They are rocks which are numerous in a sample, possible for explicit identification, but having more than a single alimentary area. Although the Palaeozoic limestones have been taken under consideration in the earlier petrographic studies, they had no index significance. Because they are common, a significance of information which they contribute into the entire picture is indisputable. That is why including all erratics in a complex characteristics of a till layer is a great advantage in a petrographic analysis of a pebble fraction.

Table 3

Petrographic groups of gravel fraction and their diagnostic criteria (modified after G. Pettersson, 1995)

Symbols	Petrographic group	Diagnostic criteria
K	acid and basic crystalline	crystalline rocks consisting of more or less than 50% quartz respective and containing dark minerals; metamorphic rocks and mylonitic sedimentary rocks
S	sandstone, also Jothnian	sandstones, which break between the individual grains, multi-coloured; Jothnian: pink-reddish-violet quartzitic sandstone
	quartzitic sandstone	sandstones of dense, diagenetic texture, break through the crystals, white, pale, pinkish
TU	Palaeozoic silt, shale and other claystones	dark grey, very soft plates, possible to scratch with a nail
F	flint	grey, black, white, brownish, reddish, yellowish amorphous silica, with typical conchoidal fracture and sharp edges
KK	Cretaceous limestone	soft white limestone with loose texture composed of numerous fossils
PK	Palaeozoic limestone	grey, red limestones, sometimes with dense fracture, may contain fossil algae *Palaeoporella*, react strong to acid
D	dolomite	white, yellowish, pinkish sedimentary rocks, do not scratch glass, react weakly to acid, blue colour replaces violet in reaction with Magneson I
L	lydite	hard, brittle siliceous rock with laminae of chalcedony and quartz, break perpendicular to layers
Q	quartz	pure quartz with conchoidal or sugar-like fracture, hard (7 in the Mohs scale)
WQ	milk quartz	as above, and the quartz is distinctly not transparent, white

P. Smed (1993) also considers a problem of the sample size. He suggests that as little as 50 determined index rocks of 20–60 mm fraction may be sufficient to present a clear picture. Taking into consideration that only 10% erratics from till meets requirements for index properties (K.-D. Meyer, 1983), a sample should consist of at least 1000 specimens together with flints and limestones, and it is undoubtedly a disadvantage of this method. Such large population may be difficult to collect if a petrographic analysis is limited to a skeletal till material. R. Puranen (1990) indicated, however, that a basal, lodgment-type till provides the best information about the origin of erratics. Their record is not subjected to such large post-depositional changes, as for example a supraglacial material transported on icebergs in proglacial basins. Glaciofluvial deposits, transported at larger distances than the corresponding tills (M. Lilliesköld, 1990), are subjected to additional aqueous sorting, which also makes explicit identification of a parent area of a pebble fraction less possible. Petrographic studies of erratics of glaciofluvial facies and a till are conducted in Poland by J. Rutkowski (1995*a–c*).

A progressing examination of the Scandinavian erratics made that more frequently, an attention was diverted to methodologic errors. The following ones are listed among them:

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— certain and unquestionable identification of the average pebble spectrum of 10% only (K.-D. Meyer, 1983).

These disadvantages caused that since then, a spectrum of the analysed petrographic material was extended to the entire rock inventory included in a gravel fraction.

Despite several years of experience in a petrographic segregation of gravel, unfortunately it was not possible to determine a uniform fraetion, characteristic for this skeletal material. In Germany, where petrographic analyses belong to standard methods used for examination of tills, A. G. Cepek (1962, 1967, 1969) defined a fraction 4–10 mm as the most representative one. The same till fraction was analysed by G. Lüttig (1957, 1958, 1995) and W.-A. Panzig (1989, 1992). However, K.-D. Meyer (1983) and M. Böse (1979, 1989, 1995) suggest a broader fractional spectrum of analysis, dividing it into 4–6.3 and 6.3–12.5 mm intervals, respectively. Similarly J. Ehlers (1979, 1980, 1983) and G. Lüttig (1995) postulate that a larger fractional interval of a skeletal material should be analysed, i.e. 2–3.15 and 3.15–5 mm (J. Ehlers, 1979), or 2–3.5, 3.5–5, 5–8 and 8–13 mm (G. Lüttig, 1995).

In Sweden petrographic analyses are conducted in various fractions. K. Malmberg-Persson, E. Lagerlund (1994), and E. Lagerlund *et al.* (1995) selected a fraction 3–8 mm, G. Petterson (1995, 1997, 1998) and S. Eriksson (1998) a fraction 2.8–4, 4–5.6 and 5.6–8 mm. The most recent petrographic analysis of a till is limited to the fraction 4–10 mm (J. Albrecht, 1995).

W. Schultz (1996) summarized, in terms of a historic view, selected fractions included in a study on till petrography in Western Europe, referring to a corresponding author and the area.

Great contribution to methodology of petrographic studies in Poland was made by J. Trembaczowski (1961, 1967), who tried to standardize a sample population size and its fraction subjected to a detailed analysis. He proposed an analysis of till of a volume at least 0.015 m^3 in a fraction 4–10 mm. He suggested that a smaller fraction, e.g. 2–3 mm, obtained from geologic drillings (J. Gołąb, 1933; A. Dreimanis, 1939; T. Bartkowski, 1950, 1956; J. Trembaczowski, 1967; A. Linden, 1975) does not represent fine rock fragments, but only their compositional components, mainly quartz.

The Polish Geological Institute advises to use the fraction 5–10 mm, which is selected from a till, collected mostly from drillings. This method is used in Poland commonly (e.g. K. Choma-Moryl *et al.*, 1991; S. Lisicki, 1993, 1998*a*, *b*; K. Kenig, 1998).

Taking into consideration a petrographic analysis introduced by A. Jaroszewicz-Kłyszyńska (1938), R. Błachowski (1938), and later applied successfully by J. Ehlers (1978, 1979, 1980, 1982) and M. Böse (1979, 1989), 10 groups of rock material in a till are distinguished (M. Górska, 1992, 1995*a*, *b*, 1997, 1998*a*; *cf.* Table 3).

Different types of petrographic analyses of gravel fraction applied are aimed at computing the so-called pebble indexes, that are relationships between specific rock groups. Petrographic composition of glacial deposits is characterized best by ratio of crystalline rocks (K) to Palaeozoic limestones (PK), because both of these components are of Scandinavian derivation and occur in similar quantities. This type of assumption was brought out by Z. Lamparski (1971), who questioned, in terms of methodology, an application of indexes based on the Scandinavian and local material, and on specific rock groups occurring in different quantities.

Considering geology of the northern Europe, it is easier to correlate the entire erratic material of tills occurring in the European Lowland with their source areas in Scandinavia and the Baltic Basin. Subsequently, alimentary centres of tills may be indicated and direction of a long-distance transport, glacier advance paths and/or its individualized ice streams determined.

In the process of segregation of erratic material in gravel and pebble fractions, errors resulting from subjective assessment of macroscopic erratic features may occur. Facial variability of the same rock type, observed in an alimentary area even at a short distance, may influence decisively a different classification of the same erratic, which has been transported several hundred kilometres apart. According to P. Smed (1994, and pers. inform.), however, the problem does not focus on identification of a single or two erratics. It is important, which is indicated by R. Vinx (1993), to determine in case of index rocks a presence of possibly the largest number of rocks from the same alimentary area (so-called series, suite or index sequence), features of which are easily identifiable. As the alimentary centre is recognized more thoroughly by correlation with appropriate erratics, information about a parent area of rocks and their transport path becomes more convincing than a presence of individual erratics from the entire Scandinavia.

The least amount of problems in terms of classification among erratics of pebble fraction are caused by porphyries, because of their characteristic fabric; however, sandstones are the most difficult (M. Górska *et al.*, 1998). Index erratics are classified, based on the present knowledge (R. Vinx, 1996, 1998; T. Geisler, 1996; P. Smed, pers. inform.). A possible derivation of a specific index erratic from another outcrop than the known one is not taken into account. Also different than present locations of alimentary areas as well as larger outcrops are rarely taken into consideration, however, it is known (J. E. Mojski, 1995) that sediments 25–150 m thick were removed from a bottom of the Baltic Basin and the Baltic Sea itself. There are still the areas in Scandinavia which have not been studied thoroughly and in detail, or their geology is not widely distributed because of political-economic reasons, e.g. the Baltic Sea, is an area of navy manoeuvres and prospective for resources of natural oil and gas (*cf.* W. K. Gudelis, J. M. Jemielianov, 1982).

CONCLUSIONS

All who undertake carrying out a petrographic analysis of glacial deposits have to be still open to face its numerous shortcomings.

Varying transport environments influence a final mineral-petrographic composition of a till, thus an appropriate selection of a lithofacies is necessary.

A sample population has to be statistically representative. In case of gravel fraction about 300 specimen (B. Krygowski, 1955; A. Gaigalas, 1963; J. Nunberg, 1971; M. Böse, 1989), and in case of pebble fraction at least 1000 specimen (K.-D. Meyer, 1983) are needed. Moreover, the area of occurrence should be appropriately sampled.

Determination of zones, where glacial erosion occurs, depends mostly on a proper classification of the index erratic to one of the four source areas in Scandinavia and the Baltic Basin, and its reference to the appropriate term.

Studies are laborious and long-lasting. Large samples should be analysed only in the field where water is available to allow an appropriate classification after they have been flushed.

Petrographic analyses of gravels, because of a smaller volume of samples, can be successfully conducted in a laboratory, especially as a fresh rock fracture can be observed with a use o microscope or a magnifying glass. Selection of limestones has to be confirmed by a visible reaction to hydrochloric acid. Similarly alteration of colour from violet to blue, triggered by reaction with the Magneson I indicator (A. G. Cepek, 1969), allows to distinguish dolomites.

Despite the listed disadvantages, a study of petrographic composition of tills have been accepted among standard research methods of these deposits in Western Europe (G. Lüttig, 1958, 1995; M. Houmark-Nielsen, 1987; W.-A. Panzig, 1989, 1992; M. Böse, 1995). Increase of interest in petrographic analysis has been observed lately also in Poland (Z. Siliwończuk, 1985; D. Krzyszkowski, 1988, 1990, 1994; W. Stankowski, D. Krzyszkowski, 1991; K. Choma-Moryl *et al.*, 1991; W. Gogołek, 1991*a*, *b*, 1994; K. Kenig, 1991, 1998; R. Racinowski, 1991; H. Klatkowa, 1993; S. Dobrzyński, 1995; C. Seul, 1995; P. Kłysz, 1995; S. Lisicki, 1993, 1997, 1998*a*–*c*; P. Czubla, 1998).

Petrography of the erratic material in gravel fraction 4–12.5 mm (K.-D. Meyer, 1983; M. Böse, 1979, 1989) and index erratics 20–60 mm (K.-D. Meyer, 1983) are the ideal exten-

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In Sweden petrographic analyses are conducted in various fractions. K. Malmberg-Persson, E. Lagerlund (1994), and E. Lagerlund *et al.* (1995) selected a fraction 3–8 mm, G. Petterson (1995, 1997, 1998) and S. Eriksson (1998) a fraction 2.8–4, 4–5.6 and 5.6–8 mm. The most recent petrographic analysis of a till is limited to the fraction 4–10 mm (J. Albrecht, 1995).

W. Schultz (1996) summarized, in terms of a historic view, selected fractions included in a study on till petrography in Western Europe, referring to a corresponding author and the area.

Great contribution to methodology of petrographic studies in Poland was made by J. Trembaczowski (1961, 1967), who tried to standardize a sample population size and its fraction subjected to a detailed analysis. He proposed an analysis of till of a volume at least 0.015 m^3 in a fraction 4–10 mm. He suggested that a smaller fraction, e.g. 2–3 mm, obtained from geologic drillings (J. Gołąb, 1933; A. Dreimanis, 1939; T. Bartkowski, 1950, 1956; J. Trembaczowski, 1967; A. Linden, 1975) does not represent fine rock fragments, but only their compositional components, mainly quartz.

The Polish Geological Institute advises to use the fraction 5–10 mm, which is selected from a till, collected mostly from drillings. This method is used in Poland commonly (e.g. K. Choma-Moryl *et al.*, 1991; S. Lisicki, 1993, 1998*a, b*; K. Kenig, 1998).

Taking into consideration a petrographic analysis introduced by A. Jaroszewicz-Kłyszyńska (1938), R. Błachowski (1938), and later applied successfully by J. Ehlers (1978, 1979, 1980, 1982) and M. Böse (1979, 1989), 10 groups of rock material in a till are distinguished (M. Górska, 1992, 1995*a, b*, 1997, 1998*a*; *cf.* Table 3).

Different types of petrographic analyses of gravel fraction applied are aimed at computing the so-called pebble indexes, that are relationships between specific rock groups. Petrographic composition of glacial deposits is characterized best by ratio of crystalline rocks (K) to Palaeozoic limestones (PK), because both of these components are of Scandinavian derivation and occur in similar quantities. This type of assumption was brought out by Z. Lamparski (1971), who questioned, in terms of methodology, an application of indexes based on the Scandinavian and local material, and on specific rock groups occurring in different quantities.

Considering geology of the northern Europe, it is easier to correlate the entire erratic material of tills occurring in the European Lowland with their source areas in Scandinavia and the Baltic Basin. Subsequently, alimentary centres of tills may be indicated and direction of a long-distance transport, glacier advance paths and/or its individualized ice streams determined.

In the process of segregation of erratic material in gravel and pebble fractions, errors resulting from subjective assessment of macroscopic erratic features may occur. Facial variability of the same rock type, observed in an alimentary area even at a short distance, may influence decisively a different classification of the same erratic, which has been transported several hundred kilometres apart. According to P. Smed (1994, and pers. inform.), however, the problem does not focus on identification of a single or two erratics. It is important, which is indicated by R. Vinx (1993), to determine in case of index rocks a presence of possibly the largest number of rocks from the same alimentary area (so-called series, suite or index sequence), features of which are easily identifiable. As the alimentary centre is recognized more thoroughly by correlation with appropriate erratics, information about a parent area of rocks and their transport path becomes more convincing than a presence of individual erratics from the entire Scandinavia.

The least amount of problems in terms of classification among erratics of pebble fraction are caused by porphyries, because of their characteristic fabric; however, sandstones are the most difficult (M. Górska *et al.*, 1998). Index erratics are classified, based on the present knowledge (R. Vinx, 1996, 1998; T. Geisler, 1996; P. Smed, pers. inform.). A possible derivation of a specific index erratic from another outcrop than the known one is not taken into account. Also different than present locations of alimentary areas as well as larger outcrops are rarely taken into consideration, however, it is known (J. E. Mojski, 1995) that sediments 25–150 m thick were removed from a bottom of the Baltic Basin and the Baltic Sea itself. There are still the areas in Scandinavia which have not been studied thoroughly and in detail, or their geology is not widely distributed because of political-economic reasons, e.g. the Baltic Sea, is an area of navy manoeuvres and prospective for resources of natural oil and gas (*cf.* W. K. Gudelis, J. M. Jemielianov, 1982).

CONCLUSIONS

All who undertake carrying out a petrographic analysis of glacial deposits have to be still open to face its numerous shortcomings.

Varying transport environments influence a final mineral-petrographic composition of a till, thus an appropriate selection of a lithofacies is necessary.

A sample population has to be statistically representative. In case of gravel fraction about 300 specimen (B. Krygowski, 1955; A. Gaigalas, 1963; J. Nunberg, 1971; M. Böse, 1989), and in case of pebble fraction at least 1000 specimen (K.-D. Meyer, 1983) are needed. Moreover, the area of occurrence should be appropriately sampled.

Determination of zones, where glacial erosion occurs, depends mostly on a proper classification of the index erratic to one of the four source areas in Scandinavia and the Baltic Basin, and its reference to the appropriate term.

Studies are laborious and long-lasting. Large samples should be analysed only in the field where water is available to allow an appropriate classification after they have been flushed.

Petrographic analyses of gravels, because of a smaller volume of samples, can be successfully conducted in a laboratory, especially as a fresh rock fracture can be observed with a use o microscope or a magnifying glass. Selection of limestones has to be confirmed by a visible reaction to hydrochloric acid. Similarly alteration of colour from violet to blue, triggered by reaction with the Magneson I indicator (A. G. Cepek, 1969), allows to distinguish dolomites.

Despite the listed disadvantages, a study of petrographic composition of tills have been accepted among standard research methods of these deposits in Western Europe (G. Lüttig, 1958, 1995; M. Houmark-Nielsen, 1987; W.-A. Panzig, 1989, 1992; M. Böse, 1995). Increase of interest in petrographic analysis has been observed lately also in Poland (Z. Siliwończuk, 1985; D. Krzyszkowski, 1988, 1990, 1994; W. Stankowski, D. Krzyszkowski, 1991; K. Choma-Moryl *et al.*, 1991; W. Gogołek, 1991*a, b*, 1994; K. Kenig, 1991, 1998; R. Racinowski, 1991; H. Klatkowa, 1993; S. Dobrzyński, 1995; C. Seul, 1995; P. Kłysz, 1995; S. Lisicki, 1993, 1997, 1998*a–c*; P. Czubla, 1998).

Petrography of the erratic material in gravel fraction 4–12.5 mm (K.-D. Meyer, 1983; M. Böse, 1979, 1989) and index erratics 20–60 mm (K.-D. Meyer, 1983) are the ideal extension of a lithofacial analysis (M. Górska, 1997) which is its significant advantage, because:

— they complement data on dynamics and thermics of a glacier sole, alimentary area and a path of ice sheet advance;

— basing on pebble indexes, they support conclusions about diversified alimentary centres of tills;

— they confirm a long-distance transport, determine routes of ice sheets and/or their individual ice streams.

It should be clearly emphasized and very well remembered, what has been many a time underlined in the subject literature (G. Lüttig, 1995; and others) that the petrographic analyses are a sedimentologic-petrographic complement. Therefore, it may set in order a stratigraphic classification only in conjunction with the other complementary lithologic-stratigraphic methods.

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ZALETY I WADY ANALIZ PETROGRAFICZNYCH OSADÓW LODOWCOWYCH

Streszczenie

Pierwsze systematyczne i metodologicznie przygotowane analizy składu petrograficznego glin lodowcowych pochodzą z początku XX wieku. V. Milthers (1909, 1934), J. Hesemann (1931, 1935) i później G. Lüttig (1958) próbowali znaleźć najlepszy sposób na wskazanie skandynawskich obszarów egzaracji eratyków przewodnich (20–60 mm), które występują w glinach lodowcowych Niemiec, Danii i Polski. Na podstawie 200 znanych eratyków przewodnich P. Smed (1993) zaproponował nowy sposób prezentacji graficznej torów wędrówki odrębnych strumieni lodowych, począwszy od ich ośrodków alimentacyjnych w Skandynawii aż po Niż Europejski.

Frakcja żwirowa 4–12,5 mm występująca w heterogenicznej glinie (M. Böse, 1989) jest separowana na 10 grup petrograficznych (tab. 3), które z kolei służą wyliczeniu tzw. wskaźników głazowych. Frakcja kamienista 20–60 mm (K.-D. Meyer, 1983) analizowana jest pod względem liczebności eratyków przewodnich (tab. 1, 2), co prowadzi do wyliczenia teoretycznego centrum głazowego TGZ.

Studia nad petrografią w obu frakcjach mają zarówno wady, jak i zalety. Wśród słabych punktów metody wymienia się konieczność umiejętnego wyboru litofacji, od której zależy ostateczny skład mineralno-petrograficzny glin morenowych. Dużą niedogodnością metody jest analizowanie statystycznie reprezentatywnej frakcji żwirowej — co najmniej 300 sztuk (B. Krygowski, 1955; A. Gaigalas, 1963; por. J. Nunberg, 1971; M. Böse, 1989) i frakcji kamienistej — co najmniej 1000 okazów (K.-D. Meyer, 1983), wobec czego badania są żmudne i długotrwałe. Wyznaczenie stref, w których przebiegała egzaracja, zależy w dużej mierze od poprawnego zaklasyfikowania eratyku przewodniego do jednego z czterech obszarów źródłowych Skandynawii i niecki Bałtyku i przyporządkowanie mu właściwej nazwy.

Mimo wymienionych wad, studia nad składem petrograficznym glin morenowych weszły na stałe do standardowych metod badawczych tych osadów w Europie Zachodniej (np. G. Lüttig, 1958, 1995; M. Houmark-Nielsen, 1987; W.-A. Panzig, 1989, 1992; M. Böse, 1996). Również w Polsce zauważa się od kilku lat wzrost zainteresowania analizami petrograficznymi (np. D. Krzyszkowski, 1988, 1990, 1994; K. Choma-Moryl i in., 1991; W. Gogołek, 1991*a*, *b*, 1994; K. Kenig, 1991, 1989; R. Racinowski, 1991; H. Klatkowa, 1993; M. Górska, 1995*a*, *b*, 1997; S. Dobrzyński, 1995; C. Seul, 1995; S. Lisicki, 1997, 1998*a–c*).

Analizy petrograficzne są doskonałą metodą wspierającą analizy litofacjalne osadów (M. Górska, 1997) w geomorfologii glacjalnej; uzupełniają dane dotyczące dynamiki, termiki stopy lądolodu, obszaru alimentacji i toru wędrówki lądolodu. Studia nad petrografią wspierają wyznaczone, na podstawie wskaźników głazowych, wnioski o zróżnicowanych ośrodkach alimentacyjnych glin morenowych.

Należy przy tym wyraźnie stwierdzić i bezwzględnie pamiętać, co było wielokrotnie podnoszone w literaturze przedmiotu (m.in. G. Lüttig, 1995), że analizy petrograficzne, będące uzupełnieniem sedymentologiczno-petrograficznym, mogą uporządkować klasyfikację stratygraficzną jedynie w połączeniu z innymi, komplementarnymi metodami litologiczno-stratygraficznymi.