Faculty of Science

Sediment Sources and Transport Pathways, Lithuanian Coastal Zone

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Ph.D. thesis

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UNIVERSITY OF GOTHENBURG

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ABSTRACT

This thesis presents an investigation of recent sediments of the Lithuanian coastal zone, SE Baltic Sea. The main focus is upon the detailed documentation of grain size and mineralogy and the development of analytical methods using these essential and most common sediment parameters. Mineralogical composition of surface samples was determined by X-ray diffraction (XRD) and grain-size distribution was obtained by standard dry sieving and pipette techniques. The overall grain-size distribution and interrelations between grain-size statistical parameters of 712 sediment samples are used to interpret transport processes in the nearshore zone. Then, two different approaches to specify sedimentologic conditions and sediment transport pathways based on spatial trends in grain size data are applied: 1) a transport vector method focused upon successive changes along possible transport pathways, and 2) a population anomalies method based on comparison of the spatial deviations of the sample sites in comparison with local population statistics in order to estimate balance between erosion and deposition. Mineralogical analyses of the silt and clay fraction of sandy deposits of 37 surface samples is interpreted to identify sediment source types. Contributions from the identified sources are then derived by simultaneous equations for each specific mineral or group of minerals. "Pure" end-members are resolved using multiple samples and calculating the maximum contribution of each source type.

The sediments closest to the Lithuanian shoreline represent a balance between erosion and accumulation processes. Some areas of local shore erosion occur at Klaipėda, in the southernmost part of the study area, and north of Palanga. The influence of wave activity is predominant within the entire central part of the study area (Klaipėda – Palanga) and near the coast in the north and south. Increasing depth (1-5 m) correlates with the decreasing strength and variability of wave-induced turbulence, allowing accumulation within continuous shore-parallel zones along the entire coastline. Seaward of the accumulation zone exists a coast-parallel area (5-13 m) where sediment transport is predominant, with little erosion or accumulation. Longshore currents and occasional storm-wave turbulence rework these sediments. The greatest variability of all parameters, including the coarsest, most positively skewed and worst sorted deposit, is found at 13-20 m depth. These sediments are interpreted to be derived from till erosion in northern offshore areas. Deposits at more than 20 m water depth south of Klaipėda have the finest grain size and accumulate below normal wave base.

The main sources supplying sediment to the area are: 1) the Sambian Peninsula to the south (erosion of Pleistocene till and "Blue Earth" Paleogene sediments), supplying approximately 33% of the fine-grained fraction, 2) the Nemunas River, which discharges through Curonian Lagoon, and supplies an estimated 17% of the fine fraction, and 3) Pleistocene till, eroded on the sea floor in the north and at the Olando Kepurė shore cliff to contribute an average of 50% of the fine sediment.

Detailed grain-size distributions allow interpretations of transport pathways and site dynamics. Combining quantified source contributions with the identified transport pathways helps to complete the source to basin modelling that many sedimentological studies aim to achieve. Spatial trends in grain size complement mineralogical data for this purpose.

Keywords: Baltic Sea, Lithuanian coast, sandy deposits, sediment transport, grain size, quantitative provenance, mineralogy, fine-grained sediments

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Keywords: Baltic Sea, Lithuanian coast, sandy deposits, sediment transport, grain size, quantitative provenance, mineralogy, fine-grained sediments

PREFACE

This doctoral thesis consists of an introduction and four appended papers. In the introduction the papers are referred to using their Roman numerals.

I

Gaigalas, A., Kairytė, M., Gulbinskas, S., 1999. Lithodynamic interpretation of granulometric composition of the nearshore sediments between Klaipėda and Šventoji in Lithuania. In: K. Rotnicki (Editor), *Quaternary studies in Poland,* Szczecin, Poland, 95-103.

II

Kairytė, M., Stevens, R.L. Sediment transport pathways interpreted from spatial trends in grain size, the SE Baltic Sea, Lithuanian coast. Manuscript.

III

Kairytė, M., Stevens, R.L., Trimonis, E., 2005. Provenance of silt and clay within sandy deposits of the Lithuanian coastal zone (Baltic Sea). *Marine Geology* 218, 97-112.

IV

Kairytė, M., Stevens, R.L. Quantitative provenance of silt and clay within sandy deposits of the Lithuanian coastal zone (Baltic Sea). Manuscript.

Kairytė carried out all grain-size (712) and mineralogical (61) analyses and participated in the sampling expeditions. Logistics was managed by Gulbinskas together with project leader Trimonis, both at Institute of Geology and Geography, Vilnius. Kairytė carried out all statistical procedures and interpretations of the data and wrote all manuscripts with assistance by the co-authors.

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I AIM OF THE THESIS

The focus of this thesis is on the sedimentology of the Lithuanian coastal zone, SE Baltic Sea. The main goals are to interpret sedimentary processes and transport pathways based on spatial changes in grain-size distribution and to refine mineralogical methods for identifying and quantifying sediment sources.

Specific objectives that contribute to these goals are to:

1. Interpret transport processes and the balance between erosion and deposition using an analysis of spatial variations in grain-size distribution and the overall grain-size characteristics.
2. Discuss the advantages and restrictions of grain-size interpretation techniques for the evaluation of sedimentary conditions and depositional processes.
3. Identify and quantitatively partition sources for the fine-grained fraction (<0.01 mm) of the sediments in the Lithuanian coastal zone using mineralogical data.
4. Discuss the possibilities and limitations of the proposed new approaches using fine-grained fractions for provenance analyses of sandy deposits.

<u>Structure of the thesis</u>

In addition to summarizing the four separate papers, this thesis introduction proposes that combining mass-flux study with the identified transport pathways would help to complete the source to basin modeling that many sedimentological studies aim to achieve. Spatial trends in grain-size and mineralogical data complement each other for this purpose.

The environment of deposition and the processes of sediment transportation in the Lithuanian coastal zone are characterized using detailed grain-size data of the surface sediments from the shallowest part of the nearshore zone (0 - 10 m depth). The evaluation is presented in Paper I.

In paper II, two different methods used for interpretation of spatial changes in grain-size statistical parameters are compared, discussed and exemplified with the Lithuanian coast. These methods to interpret transport pathways and the balance between erosion and accumulation are applied to the deposits in the nearshore zone, an area of 45x6 km and 0 - 31 m of water depth.

Mineralogy of the medium-to-fine-silt and clay fraction is used to identify sediment sources in the Lithuanian coastal zone in Paper III. The identification of sources is indirectly based upon the mineralogical composition of the sediment deposits. The possibilities and limitations of sediment source identification using the fine-grained fraction for provenance interpretations of this small but important component of sandy deposits are discussed.

Contributions from identified source types are derived by simultaneous equations for each specific mineral association in Paper IV. In addition, "pure" end-members representing specific source mineralogy are resolved using sample suites and by calculating the maximum "activity" of each source type. Interpretation of the specific compositional character of sources and the changing balance of their contributions to the sediments of the Lithuanian coastal zone is used for exemplification.

II THEORETICAL BACKGROUND

The grain-size distribution of bottom sediments reflects the energy of the environment of deposition and the sizes available from the source. Mineralogical characteristics are often an inherited property, reflecting the provenance and transport history of the sediments. These two parameters in the field of sedimentological analysis are so closely related that if interpreted together, they give a better understanding about the environment, processes and sources involved in formation of the final deposit. If interpreted separately, especially mineralogical data, there is a major risk for error due to parameter interdependencies.

<u>Sedimentological conditions and depositional processes</u>

The interpretation of grain-size distributions has been, and still is, a fundamental goal of sedimentology (McLaren and Bowles, 1985). The idea that grain-size distributions may provide information on sediment provenance, transport and depositional environment has led toward development of a wide range of methods (Welje and Prins, 2007). The underlying assumption related to changes in grain-size distributions is that transport processes involved in sediment formation will affect the sediment in a predictable way (McLaren et al., 2007). Therefore, grain-size parameters are commonly used to characterize differing environmental energy levels reflected in deposits (McManus, 1988). Interrelationships between grain-size statistical parameters have been widely used to describe sedimentary processes and to identify transport behaviour in various depositional environments (Folk and Ward, 1957; Mason and Folk, 1958; Friedman, 1961; Shepard and Young, 1961; Passega, 1964; McManus, 1988; Sly, 1994).

Differences in sediment-hydraulic interactions in high and low energy regimes allow distinguishing erosional and depositional environments based on sediment characteristics (Sly, 1994). Sediment transport occurs within both, but coarse sediment transport is more-or-less limited to the high-energy regime. Sedimentary deposits of decreasing grain size commonly do reflect decreasing hydraulic energy, whereas coarser sediments usually indicate winnowing and more dynamic sedimentological environment. However, when interpreting sediment transport direction, uncertainties exist if a single grain-size parameter is used because, for instance, both fining and coarsening trends of material in the transport direction have been observed (McLaren, 1981; Le Roux and Rojas, 2007). Moreover, Griffiths (1951) argues that mean grain size and sorting are hydraulically controlled so that in most environments the best sorted sediments fall in the fine sand interval, others (Inman, 1949; Folk and Ward, 1957) conclude similarly that the sediments that usually fall within the "well-sorted" category are medium to fine sands, whereas all clays, silts and most gravels tend to be poorly to very poorly sorted. This makes it difficult to indicate the character of depositional environment or interpret grain-size trends in respect of transport processes based on mean grain size and sorting only. Therefore it has been suggested that also other grain-size statistical parameters, as skewness and in some cases kurtosis should be considered for interpretation of transport processes from grain-size trends.

Focusing on the process effects of selective erosion and deposition, McLaren (1981) proposed a sediment trend analysis (STA) method for interpretation of sediment transport directions based on specific successive changes of grain-size parameters (mean, standard deviation and skewness) along possible paths. This approach does not differentiate transportation processes (i.e., traction, saltation, suspension) nor environments of deposition (i.e., dune, beach, lagoon). It determines if there is a sediment transport relationship between two samples. Factors such as shielding or cohesion of fines complicate interpretation of sediment transport pathways using grain-size changes because the sediment particles behave in a less predictable way. The theoretical arguments of McLaren model are that 1) sediment in transport must be finer, better sorted, and more negatively skewed than its source sediment (FB-), 2) a lag must become coarser, better sorted, and more positively skewed (CB+), and 3) succesive deposits may become finer or coarser, but the sorting must become better and skewness more positive (Mclaren and Bowles, 1985).

To reduce the subjectivity possibly introduced by selection of the sampling lines to delineate transport directions, Gao and Collins (1984) modified the method originally proposed by McLaren (1981) into two-dimensional. In this STA vector approach, each sample is compared with its nearest neighbours and a summed single trend vector is defined for one site whenever a trend is present. La Roux (1994) suggested equalizing the importance of grain-size parameters and comparison of groups of five samples at a time. Later, it was proposed to implement Gao and Collins (1992) approach into a GIS environment (Asselman, 1999). The GIS evaluation is less sensitive to irregularities of the sampling configurations because comparison is not limited to neighboring sampling sites. Each raster cell is compared with its near-by cells within a certain range determined by geostatistical analysis of semivariogram plots. The GIS gives smooth map patterns especially when a filtering operation in the form of moving-average technique is performed to reduce the remaining noise. However, filtering reduces the spatial resolution and can result in loss of valuable information, especially when the applied grid cells are large in comparison with the spatial variability in transport directions (Asselman, 1999). Each method has its advantages and drawbacks. An overview of methodological developments is presented by La Roux and Rojas (2007). Following the main assumptions of the STA, our data is treated within a GIS environment. Detailed method description is presented in appended Paper II. We refer to this modified approach as the Transport Vectors (TV) method.

Independently of this, but following similar assumptions regarding changes in grain-size statistical parameters relative to environmental energy, Baraniecki and Racinowski (1996) evaluated sedimentological processes based on deviations from the average values of mean, standard deviation, skewness and kurtosis in a particular area. This method aims to characterize the balance between erosion and deposition at each sampling site relative to average characteristics in the investigation area. The population anomalies take into account the entire data set or subsets of grain-size parameters from different coastal-morphological settings, and thereby reflect net effects of sedimentation processes in the region with a generalized and relatively long-term reference in comparison to the STA method. In this approach sediment that is finer, better sorted, more positively skewed and more platykurtic compared to the population average is characteristic of accumulative environment. The opposite textural features describe reworked sediment and a more dynamic sedimentary environment. As a result, the strength of the predominant process (deposition, accumulation, or equilibrium state) is classified and assigned a process intensity class at each station. We refer to this method as Population Anomalies (PA).

The TV and PA methods are similar in that that if environmental energy is sufficient to rework the sediment and is not limited by flocculation or shielding effects, then fine grains are more likely to be removed than coarser grains. This principal assumption broadens the applicability of these methods allowing using them in various sedimentological environments. The different perspectives of the TV and PA methods are largely related to their specific objectives. The TV method aims to interpret monotonic depositional processes along a pathway, whereas the PA approach analyses sedimentary effects in a more generalized view. We evaluate how the simultaneous comparison and combination of site specific and general trends suggested by these two approaches could provide an improved basis for distinguishing between transport direction alternatives and strengthen the reliability of the interpreted final trends (Paper II).

With complex coastal morphology, multiple sediment sources and variable hydrodynamic conditions, interpretation of grain size becomes more complicated (Anthony and Héquette, 2007; Bartholomä and Flemming, 2007). Many sediment deposits are not composed of one, unimodal grain-size population, but rather of a combination of sub-populations (McManus, 1988). Polymodal sediments indicate supply from more than one source or different processes acting simultaneously (Dias and Neal, 1990). Therefore, the variable distribution of grain-size modes is commonly evaluated as a complementary method to help define processes and sources.

The interpretations of sedimentary processes within the Lithuanian coastal zone have most commonly been done using grain-size characteristics, distribution maps of sediment types and geomorphologic features of the area (Janukonis, 1994-1995; Bitinas et al., 2005). The complex combination of sources and processes acting in the coastal zone of the eastern Baltic Sea suggests that a more advanced analysis than simply mapping distributions will be necessary for detailed interpretations. We present combined results of various grain-size interpretation techniques for evaluation of sedimentary environment, as applied on sediments of the Lithuanian coastal zone (Papers I and II).

Quantitative Provenance

Provenance (source) identification is a traditional geologic task for basin analysis and a central issue in the field of environmental sedimentology. Sedimentary provenance studies aim to reconstruct the place of origin and composition of rocks from which the constituent materials are derived (Glossary of Geology, 1972). This is usually achieved by deducing the characteristics of source areas from measurements of compositional and textural properties of sediment deposits (Pettijohn et al., 1987).

A principal limitation of methods using sediment composition is the strong dependency of both mineralogy and geochemistry upon grain size, which is usually dealt with by selecting narrow size intervals for analysis. In petrographic studies, ascribing particular minerals to specific sources can be complicated by similar minerals supplied from different sources and compositional and textural modifications along the pathway from source to basin.

The heavy minerals commonly used in provenance studies are vulnerable to compositional changes due to mineral instability in sedimentary environments and hydraulic sorting during transport (Rittenhouse, 1943; Briggs, 1965; Luepke, 1980; Morton, 1984; Blatt, 1985). The disadvantage of single-grain techniques, which focus on variability within a certain mineral component (e.g., the chemical composition of rutile), is that the parent-rock mass corresponding to a single grain must be known. In other words, they can be utilized only if their results can be firmly connected to the bulk mass transfer from source to basin (Weltje and Eynatten, 2004).

Despite the fact that sediments from many depositional environments do not contain enough sand to make statistically significant petrographic determinations (Poppe et al., 1991), most of provenance studies have been focused on the sand fractions or bulk sediment samples. Pelitic rocks are predominant in many sedimentary basins. Whereas the modal sizes of feldspar and quartz in detrital rocks ranges from very fine sand to coarse silt size, the modal size of accessory minerals in detrital sediments is coarse silt (Blatt at al., 1972). Mineralogy of mudrocks is believed to be more representative than mineral calculations of sandstones because of dissolution of feldspars and loss of chemically unstable accessory minerals is generally greater in sand size sediments (Blatt, 1985). The efficiency of mixing during suspension transport of fine-grained sediments suggests that mud-derived provenance signals are likely more representative than sand-based provenance signals (Weltje and von Eynatten, 2004).

The environmental importance of fine sediments is partly that fine –grained sediments tend to have relatively high metal contents, largely due to the high specific surface area of the smaller particles and ionic attraction (Hochella and White, 1990). The provenance and transport history, reflected in the mineralogical characteristics of fine-grained sediment or the fine-grained part of coarse sediment, can be used to evaluate the source and pathways of pollution.

The strong trend toward quantitative modeling throughout the earth sciences (e.g. Griffen, 1999; Parks et al., 2000; Willis and White, 2000; Weltje and von Eynatten, 2004) and recent advances in analytical and interpretative techniques have considerably increased the interest for quantitative provenance. Although relatively few, attempts to partition sediment source contributions and budget the total fluxes have been done using composition information from deposits within either modern or ancient environments (Di Giulio, 1999; Bengtsson, 2000; Brack et al., 2001; Eittreim et al., 2002; Su and Huh, 2002; Audry et al., 2004; von Eynatten, 2004; Vezzoli et al., 2004; Zack et al., 2004).

However, quantitative source partitioning for individual sites of accumulation is seldom achieved because of the complex variability within most natural environments regarding on-going processes, which are often difficult to measure and nearly impossible to reliably integrate over time, largely due to the natural variations in process intensity and effectiveness. In addition, most biological and geochemical parameters are highly vulnerable to degradation and diagenesis. On the either hand, the stable components of the "sediment archive" offer a time-integrated, net-effect reflection of the combined processes of an entire environmental system, recorded for each individual site of accumulation.

The previous lack of attention to the fine-grained part of the sediment can be partially explained by analytical limitations. For instance, sources for the sediment in the Lithuanian coastal zone of the Baltic Sea have only been previously interpreted using the mapped distribution of heavy minerals (Stauskaitė, 1962; Linchius and Uginchius, 1970; Apanavičiūtė and Šimkevičius, 2001) and other mineral components within fine-sand and coarse-silt fractions and in bulk samples of bottom sediments (Blashchichin and Usonis, 1970; Blashchishin and Lukashev, 1981; Emelyanov and Trimonis, 1981; Trimonis, 1987). Recent instrumental developments now permit real quantitative modeling for fine-grained sediments, i.e. those most sensitive to change and most reactive with other environmental components (Ward et al., 1999).

The fine-silt and clay fractions primarily used in our study are largely transported together in suspension, presumably in aggregate form, and are not believed to be extensively effected by hydraulic sorting, which otherwise might result in size separation and mineral enrichment (Bengtsson and Stevens, 1996). Although the medium-to-fine-silt and clay fraction represents only a minor fraction of the total grain-size distribution of the sandy deposits, this fraction contains greater mineralogical variability than coarser fractions or bulk sediments and thereby provides alternative components to distinguish the anticipated sources (Stauskaitė, 1962; Blatt et al., 1972; Blatt, 1985; Buckley and Cranston, 1991).

We present a method for identifying sediment sources and quantitatively partitioning their contributions for individual sites using quantitative mineralogy data of grain-size specific (<0.01 mm) mineral composition and entire grain-size frequency distribution of sandy sediments (Papers III and IV).

III SEDIMENTOLOGICAL SETTING

The Baltic Sea is a relatively shallow sea (average depth of 55-60 m) and is the world's largest brackish water body (average salinity 3.5‰). It is a non-tidal inland sea with several small and large sub-basins naturally divided by straits, sills, archipelagos, and open sea areas. The general water circulation in the Baltic Sea is counter-clockwise with a positive water balance and restricted exchange through narrow and shallow connections (the Öresund, the Belt Sea and the Kattegat) to the Skagerrak.

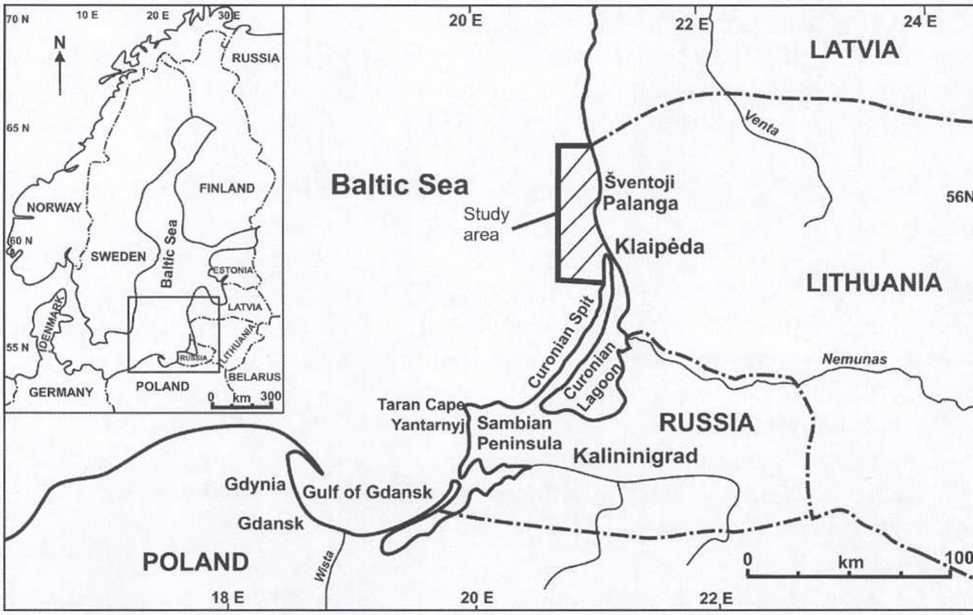

Fig. 1. Map of the SE Baltic Sea (modified from Ūsaitytė, 2000) with the study area indicated.

The pre-Quaternary geology of the Baltic basin consists predominantly of Precambrian crystalline bedrock, although in the south, Paleozoic (Cambro-Silurian) and Mezozoic (Createceous-Tertiary) bedrock types are most common (Winterhalter et al., 1981). Deposits in the southeastern part of the Baltic Sea are predominantly of glacial and glaciofluvial origin. These deposits have formed during several glacial cycles in the Pleistocene. Re-eroded sediments from earlier periods as well as first-cycle erosion of crystalline rocks of Fenoscandian origin were transported by glaciers from the north. Till deposits of the last glaciation are exposed on the sea bed in the northern part of the Lithuanian coastal zone at 9-10 meters water depth. They are usually covered by Weichselian and Holocene sediments. The investigated Klaipėda-Šventoji area belongs to part of Klaipėda – Ventspils plateau.

Westerly winds predominating in the SE Baltic Sea, together with the general counter-clockwise circulation, induce the general sediment transport direction north-northeast. Current speeds of 3-4 cm/s are common, strongest near the coast (Žaromskis, 1996). Sediment transport along the coast was earlier referred to as the East-Baltic nearshore current, begining near the Sambian Peninsula (Fig. 1) and reaching as far as 200-300 km to the north. The flux has been estimated to vary between 0.1 to 1 million m^3 of fine sand and silt sediment per year (Knaps, 1966; Blashchichin and Usonis, 1970). This is somewhat less now since the Sambian Peninsula has been artificially protected (Žaromskis, 2007-06-19).

A number of coastline settings are linked along the transport pathways, and each area exerts a certain influence on the composition of the coastal sediments (Figs. 1, 2). The sediment environments of particular importance are: a) Sambian Peninsula coast in the south, including shore erosion, b) Curonian lagoon, including the Nemunas River discharge of predominantly fine-grained sediments, c) linear shorelines, characterized by prevailing north-northeast long-shore sediment transport and both depositional and erosional areas, d) areas of sea-floor erosion of exposed late Pleistocene till deposits, and e) fine-sediment accumulation areas (e.g. offshore deeps).

IV ANALYTICAL METHODS

Seafloor sediment samples from the coast of Lithuania were taken along 92 transects oriented perpendicular to the shoreline and spaced 500 m apart. Samples were taken from the shoreline to a depth of about 31 m. Surface sediments (0-5 cm) were sampled at 712 stations during four years (1993, 1994, 1995, 1997; Fig. 3).

Grain-size composition was determined using standard pipette methodology (0.005 to 0.5 mm) and dry sieving analyses with a set of 22 sieves (1/4φ interval) for the coarse-grained fractions (0.05 to 10.0 mm). Statistical parameters of the grain-size data were calculated according to the graphic method of Folk and Ward (1957).

Thirty-seven samples for mineralogical analyses were selected from the data set (Fig. 4). The samples included those from sites situated closest to the shoreline and those farthest offshore along 15 cross-shelf transects. Addition samples were taken to provide good areal coverage and enable statistical procedures. These samples were dispersed with sodium diphosphate and ultrasound. Fractions less than 0.01 mm and 0.01-0.063 mm were separated from the coarser sediment by wet sieving and centrifuge.

Mineralogical composition was determined for powdered, non-oriented samples using a Siemens D5005 diffractometer for specific grain-size intervals: 37 analyses of the <0.01 mm fraction and 17 analyses of the 0.01 – 0.063 mm fraction. Bulk-sample mineralogy was documented for 7 sites. Samples were scanned with Ni-filtered and Cu-Kα radiation between 2 – 65° 2Θ at 40 kV and 40 mA effect and with a scanning speed of one degree 2Θ per minute. The *Siroquant* program (Ward et al., 1999), based upon the Rietveld methodology for diffractogram simulation, was used for quantification of the identified minerals.

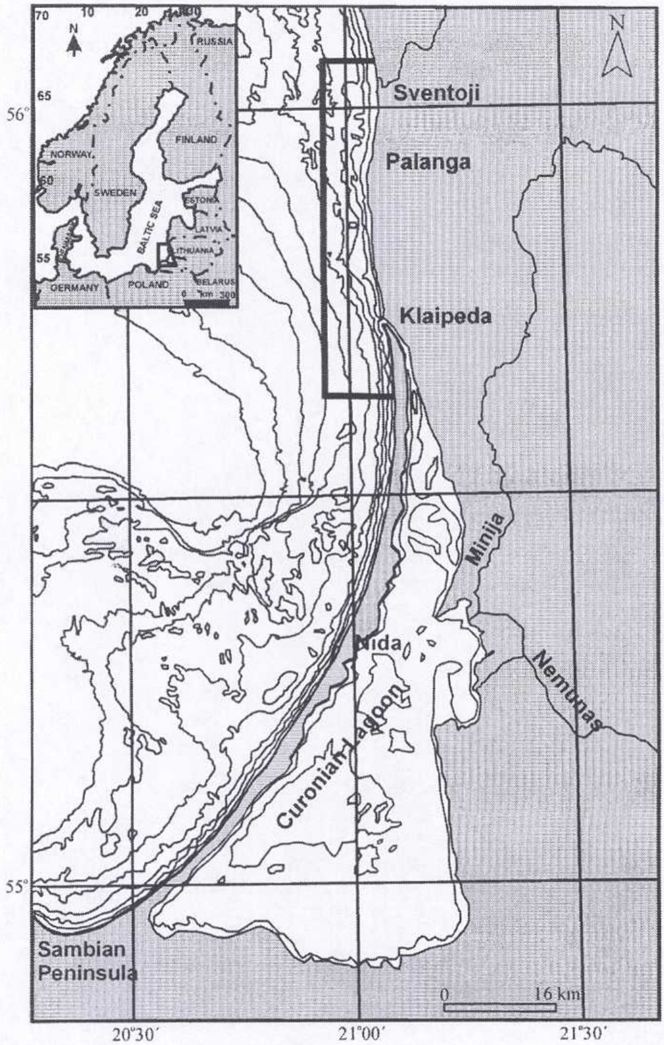

Fig. 2. Bathymetric map of the Lithuanian Baltic Sea nearshore area (from Gelumbauskaitė et al., 1998). Isobaths are drawn at every 5 m, and in the Curonian Lagoon at 2 and 5 m. Part of Sambian Peninsula is seen at SW corner of the map. The boarders of the study area are marked in thick black.

Statistical procedures

The weight percentage of minerals identified in the <0.01 mm fraction, statistical parameters of the grain-size data (mean, sorting and skewness), and water depth were used to build the correlation matrix. Factor analysis, by means of principal component extraction and Varimax rotation, was performed on the same set of variables to support interpretation of parameter relationships and simplify the complex data by identifying a relatively small number of controlling factors that represent relationships among sets of interrelated variables. Factor analysis was performed on the set of 17 variables and 37 samples.

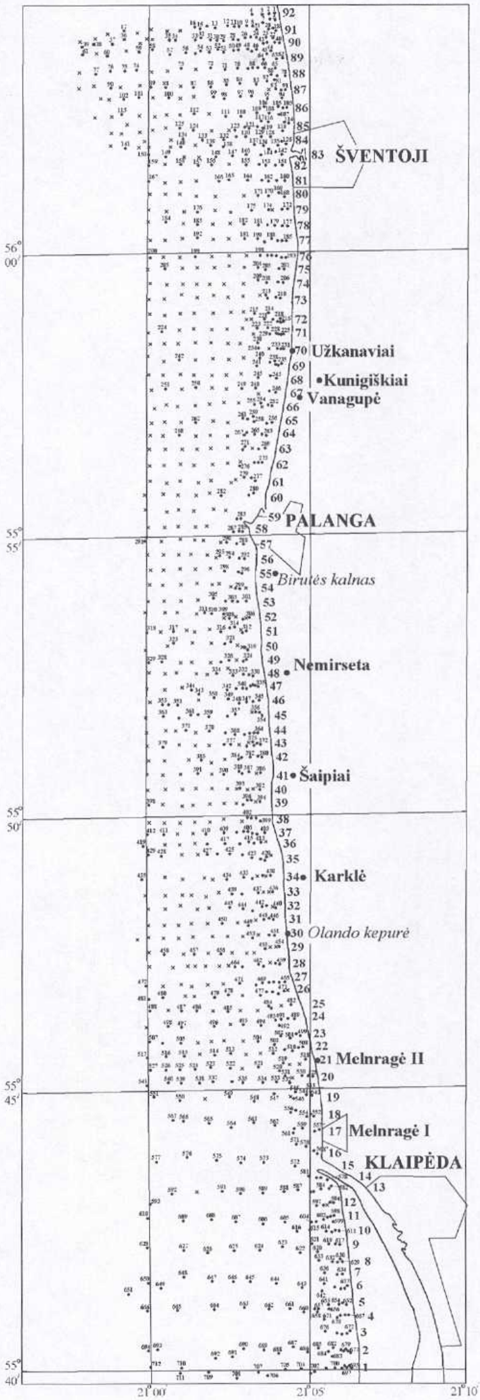

Fig. 3. Sampling sites (1-712) for surficial sediments along the Lithuanian coast (circles). Profile numbers (1-92) are indicated on the right. Eroded surfaces covered with boulders and coarse-grained deposits (x) were not possible to sample.

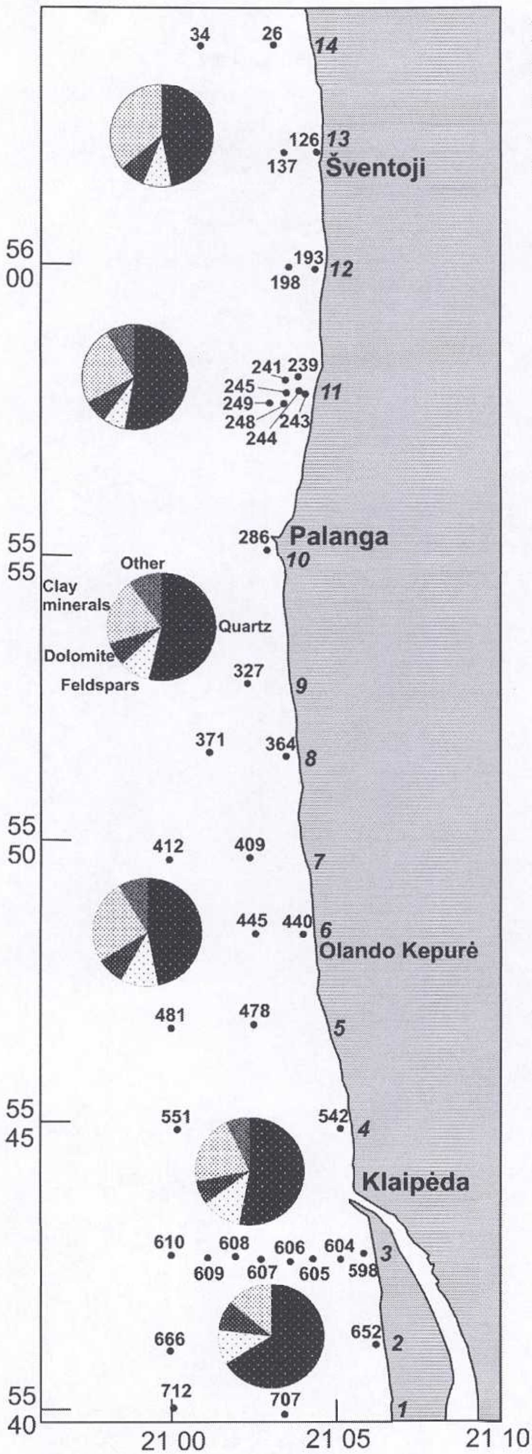

Fig. 4. Sampling sites for mineralogy. The circle diagrams show average mineral compositions of six different sectors of the study area.

V RESULTS AND DISCUSSION

Transport processes

Sediments in the Lithuanian nearshore zone are predominately very well sorted (σ <0.35 φ), fine to medium sands (1.5-2.5 φ) with near-symmetrical, normal grain-size distributions ($S_k = 0.02$, $K_G=0$). The sediments vary from poorly to very well sorted (1.23 - 0.345 φ), very coarse to very fine (-0.69 - 3.76 φ) sand, with coarse to very fine-skewed (-0.43 - +0.44), extremely leptokurtic to very platykurtic (0.33 - 6.82) distribution curves (Fig. 5).

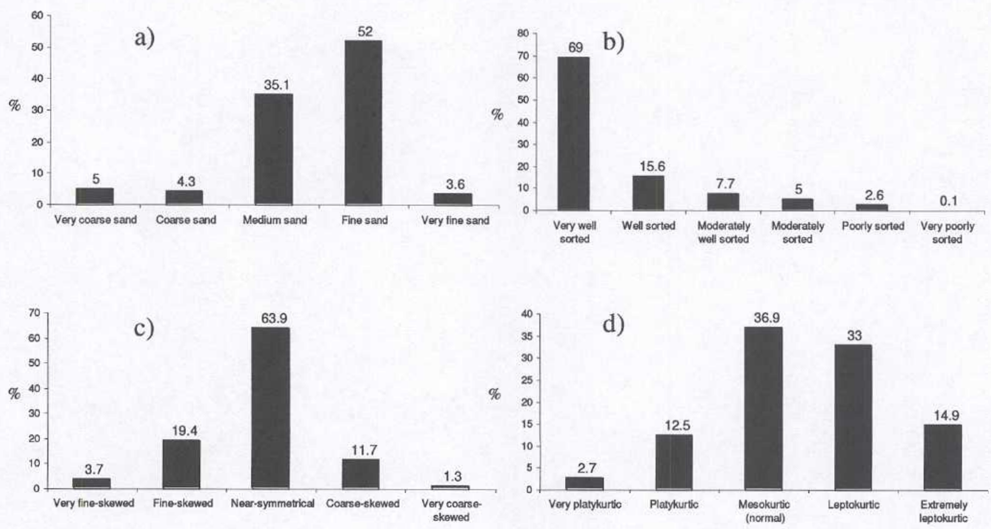

Fig. 5. Distribution of grain-size parameters of 712 samlples in the nearshore zone (0-31 m of depth): a) mean grain size, b) standard deviation (sorting), c) skewness, d) kurtosis; (classifications of Wentworth, 1922; Folk and Ward, 1957).

Grain-size parameters along the sampling lines associate largely with five depth zones (Fig. 6, 7, 8). Sediment closest to the shoreline (up to ca. 1 m depth), where the wave influence is the most pronounced, is predominantly very well sorted medium sand with coarse-skewed to near-symmetrical grain-size distribution curves and kurtosis values ranging from platykurtic till very leptokurtic. Increasing depth (1-5 m) correlates with finer mean grain size, better sorting and more positive skewness of the medium to fine sand deposits. Deeper (5-13 m) areas are dominated by fine sand with greater sorting variability and near-symmetrical skewness. The greatest variability of all parameters, including the coarsest, most positively skewed and worst sorted deposit, is found at 13-20 m depth. These sediments are interpreted to be derived from till erosion in northern offshore areas. Deeper than 20 m, fine to very fine-grained sand, with more negative skewness, wide range of sorting and kurtosis values is present. These southern deposits have the finest grain size and accumulate below normal wave base.

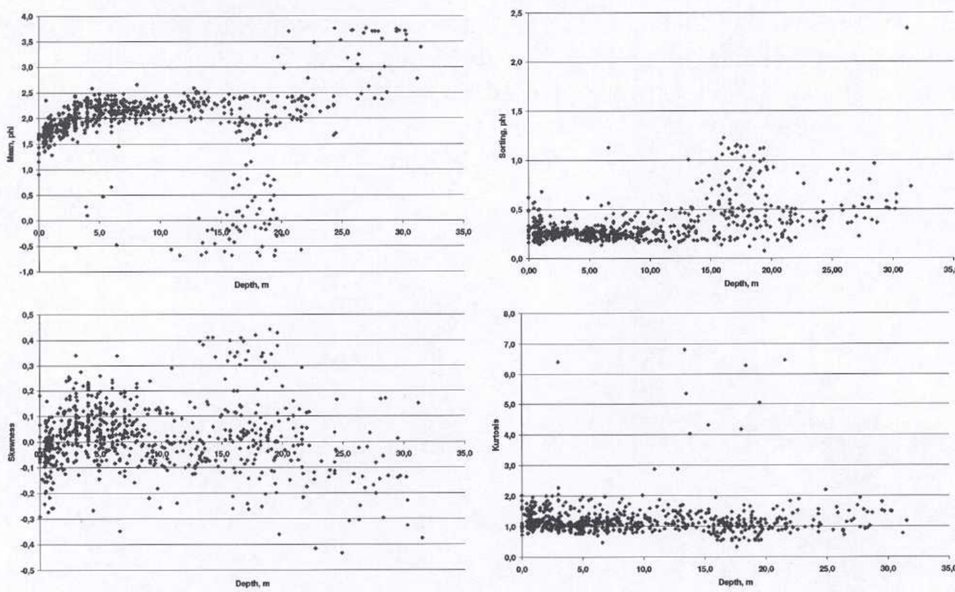

Fig. 6. Grain-size statistical parameters: mean grain size, sorting, skewness and kurtosis versus water depth.

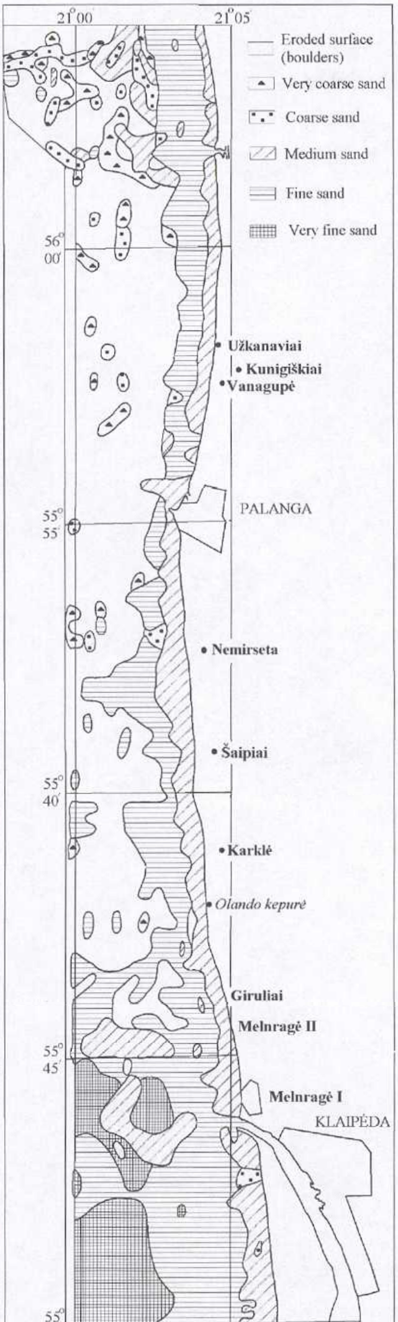

Fig. 7. Sediment textural classes (based upon classification of Wenthworth, 1922).

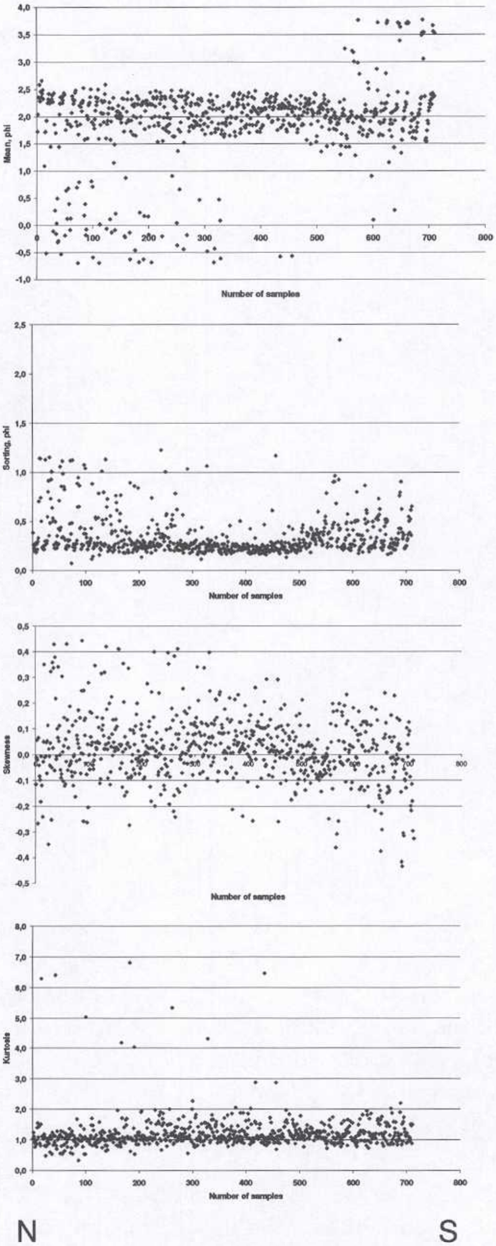

Fig. 8. Grain-size parameters from north (left side of diagrams) to the south (right side of diagrams).

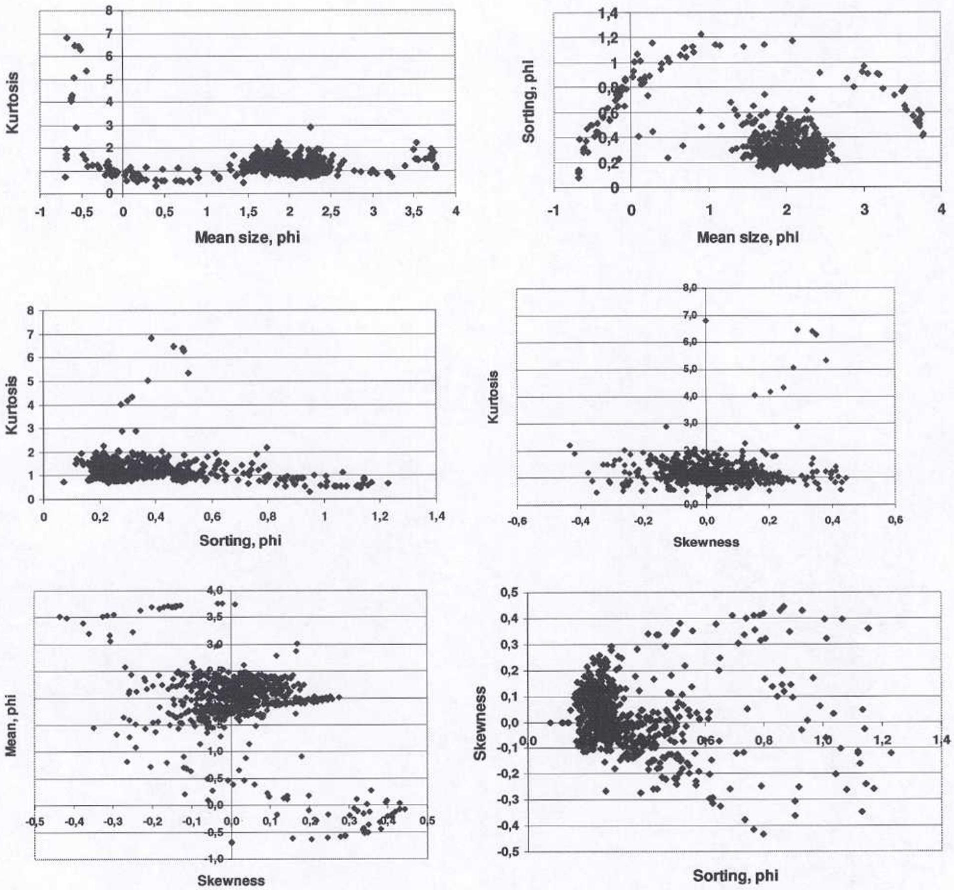

Fig. 9. Bivariate plots of grain-size parameters.

Using bivariate plots the analyzed samples can be grouped into four to five different sub-populations. One subpopulation is predominant and distinct on all graphs and spread along the entire coast (Figs. 8, 9). This majority of samples belong to medium to fine, well to very well sorted sand (M=1.5 - 2.5 φ; σ=0.35 - 0.5 φ) with normal to leptokurtic and coarse to fine skewed distribution curves (K=0.9 – 2.0; Sk=-0.3 - +0.3). The coarse sand fractions have extremely peaked (high kurtosis values) distribution patterns, because prominent modes in the sediment coincide with the best sorting (Folk and Ward, 1957). Therefore, the very coarsest sampled sediments are well to very well sorted with very finely skewed, extremely leptokurtic distribution. Sorting worsens when the fine fractions increases in relation to a predominantly coarse sand subpopulation. The poorest sorting corresponds to mean sizes midway between fine and coarse modes. An addition of the finer sediment also shifts skewness toward the negative side. A predominance of fine sand is reflected by better sorting and a relatively normal distribution curve except in the finest samples, which have a very leptokurtic, coarse-skewed distribution curve.

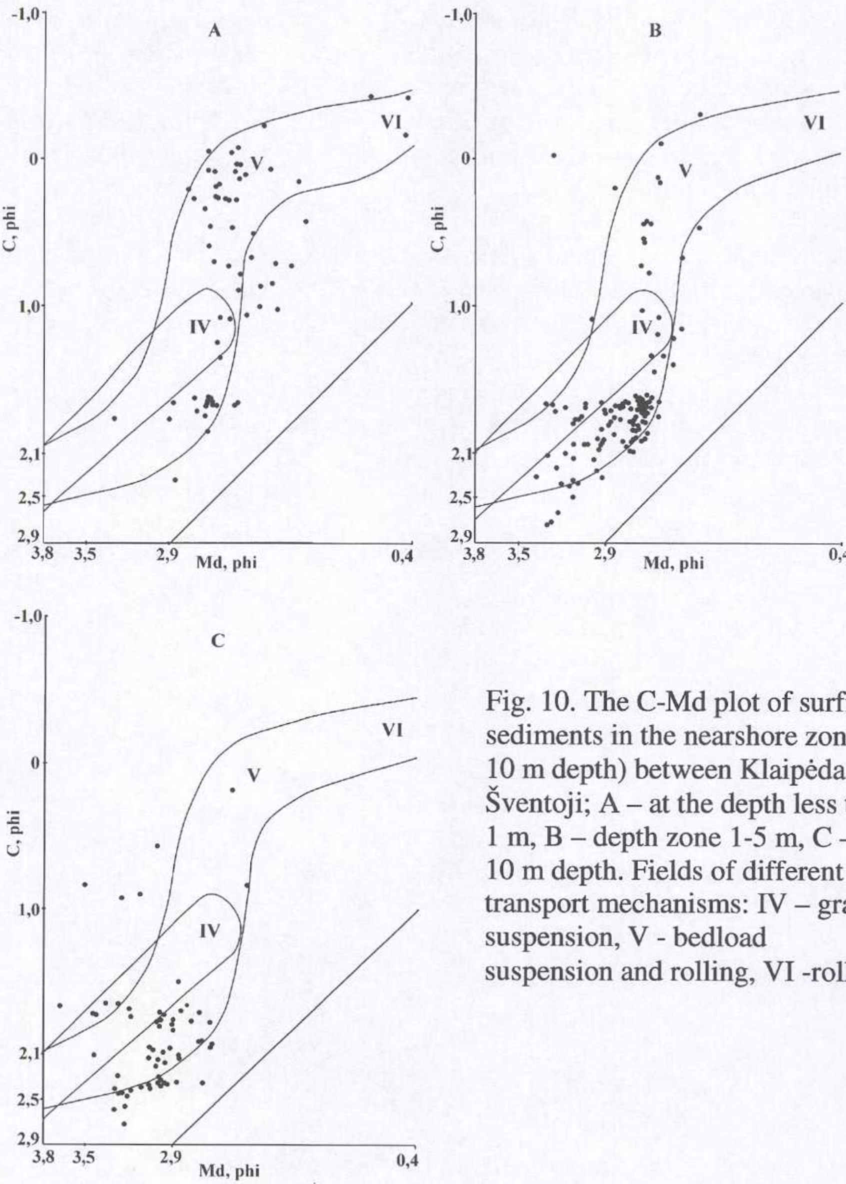

Fig. 10. The C-Md plot of surficial sediments in the nearshore zone (0-10 m depth) between Klaipėda and Šventoji; A – at the depth less than 1 m, B – depth zone 1-5 m, C – 5-10 m depth. Fields of different transport mechanisms: IV – graded suspension, V - bedload suspension and rolling, VI -rolling.

Passega´s diagram C-Md (Fig. 10; Passega, 1964) is based on the assumption that the ratio of the coarsest one percentile, C, to the median diameter, Md, reflects the dynamics of environment, and the strongest currents should define the largest stable particle size. It shows that sediments of the Lithuanian coastal zone in the shallow nearshore (0-10 m depth) have the same grain-size characteristics as sediments transported by: *graded suspension*, where mixed sediment types of sand and silt are transported in suspension together; *bedload suspension and rolling* transport of relatively coarse sediment near the bottom by saltation and bouncing; and *rolling* to transport the coarsest part of sediment (Fig. 10). These three fields of the diagram describe the most dynamic sedimentary environments among the six represented.

The coarsest sediments are found in the shallowest part on nearshore zone and become appreciably finer at depths greater than 5 m. Using features of sediment texture we divided the shallow nearshore into three depth zones: <1 m, 1-5 m, and 5-10 m (Paper I).

A second tool to help interpret the role of sources and processes is the modes of the size distributions, which have been documented in Paper III.

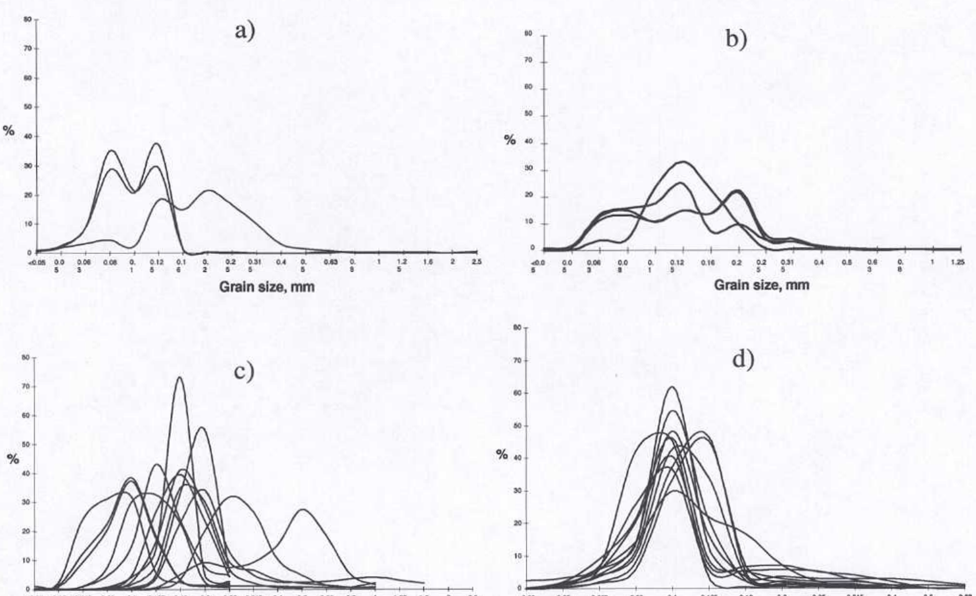

Fig. 11. Representative grain-size distribution curves: a) in the north, b) in the south, c) <10 m water depth and d) >10 m depth.

Unimodal sediments occur predominantly throughout the central part of the study area (Klaipėda – Palanga) and near the coast in the north and south. Gradual improvement of sorting and sediment fining and increasingly Gaussian grain-size distributions towards offshore areas are interpreted to reflect the decreasing influence of wave activity (Fig. 11). Bimodal sediments in the northern area (Šventoji-Būtingė) are believed to result from coastal processes, including local till erosion and alluvial sediment transported from the Šventoji River. The highest modal complexity (two, three or four modes) is present south of Klaipėda and reflects the influence of the Sambian Peninsula source, modified by coastal reworking, supply from the Nemunas River and offshore seafloor erosion products.

Interpretation of transport and deposition

The sediments closest to the shoreline represent the balance between erosion and accumulation processes (Paper I). Some areas of local shore erosion are present, mostly at Klaipėda and to the south, and north of Palanga (Fig. 12, Paper II). Increasing depth and the decreasing strength and variability of wave-induced turbulence allow accumulation within a continuous zones (5 – 13 m) along the entire coastline (Fig. 12), consistent with the interpreted sediment movement into this depth zone (Fig. 13A). Seaward of the accumulation zone there exists a coast-parallel area where sediment transport is predominant, with little erosion or accumulation. Longshore currents and occasional storm-wave turbulence rework these sediments. The deepest areas offshore are characterized by erosion of the sea floor in the north and a deep-water accumulation in the central part of the study area (Figs. 12, 13A). According to the PA method, transitional or dynamic equilibrium predominate offshore in the most southern part, with some sites of local accumulation or erosion (Fig. 12).

TV analysis of grain-size trends (case FB-) indicates that sand is mostly transported into the relatively deep area (> 20 m) south of Klaipėda. CB+ is interpreted as selective deposition indicating weak sediment removal. The inconsistency between FB- and CB+ trends in the south might be related to the dominance of one or two parameter trends when the three parameters are summed in the TV method. The southern deposits have the finest grain size in the entire investigation area. Despite the normalization, the distinct decrease in mean grain size in the southern study area is a dominant trend. On the other hand, the PA evaluation indicates dynamic equilibrium offshore in the most southern part of the investigation area, where the bed is neither accreting nor eroding. This relatively indecisive PA characterization may also be compared with mixed TV trends (FB- and CB+) in this area. It is tentatively concluded that dynamic equilibrium conditions are not consistent with the TV model assumptions, and TV interpretations are less reliable.

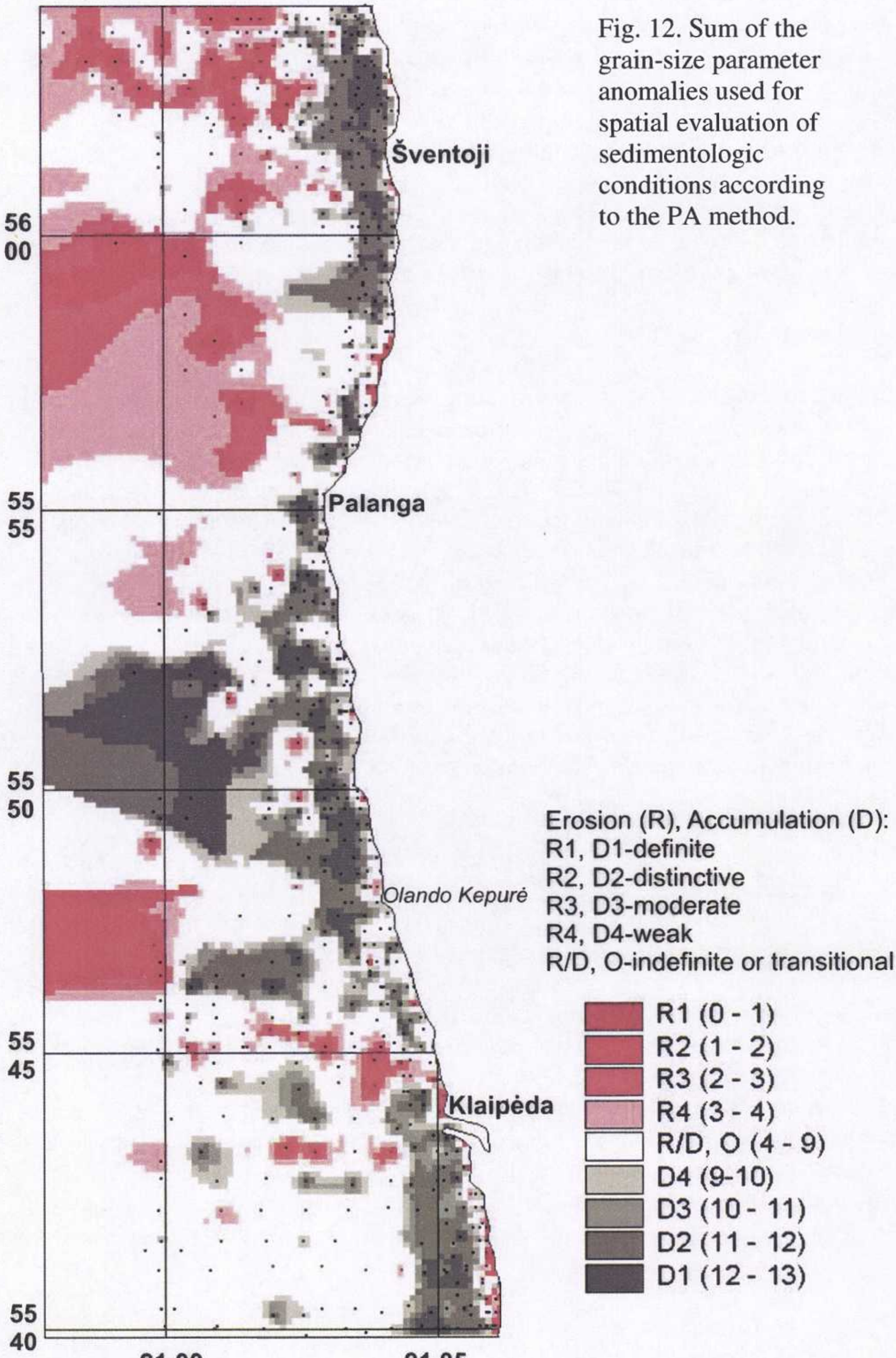

Fig. 12. Sum of the grain-size parameter anomalies used for spatial evaluation of sedimentologic conditions according to the PA method.

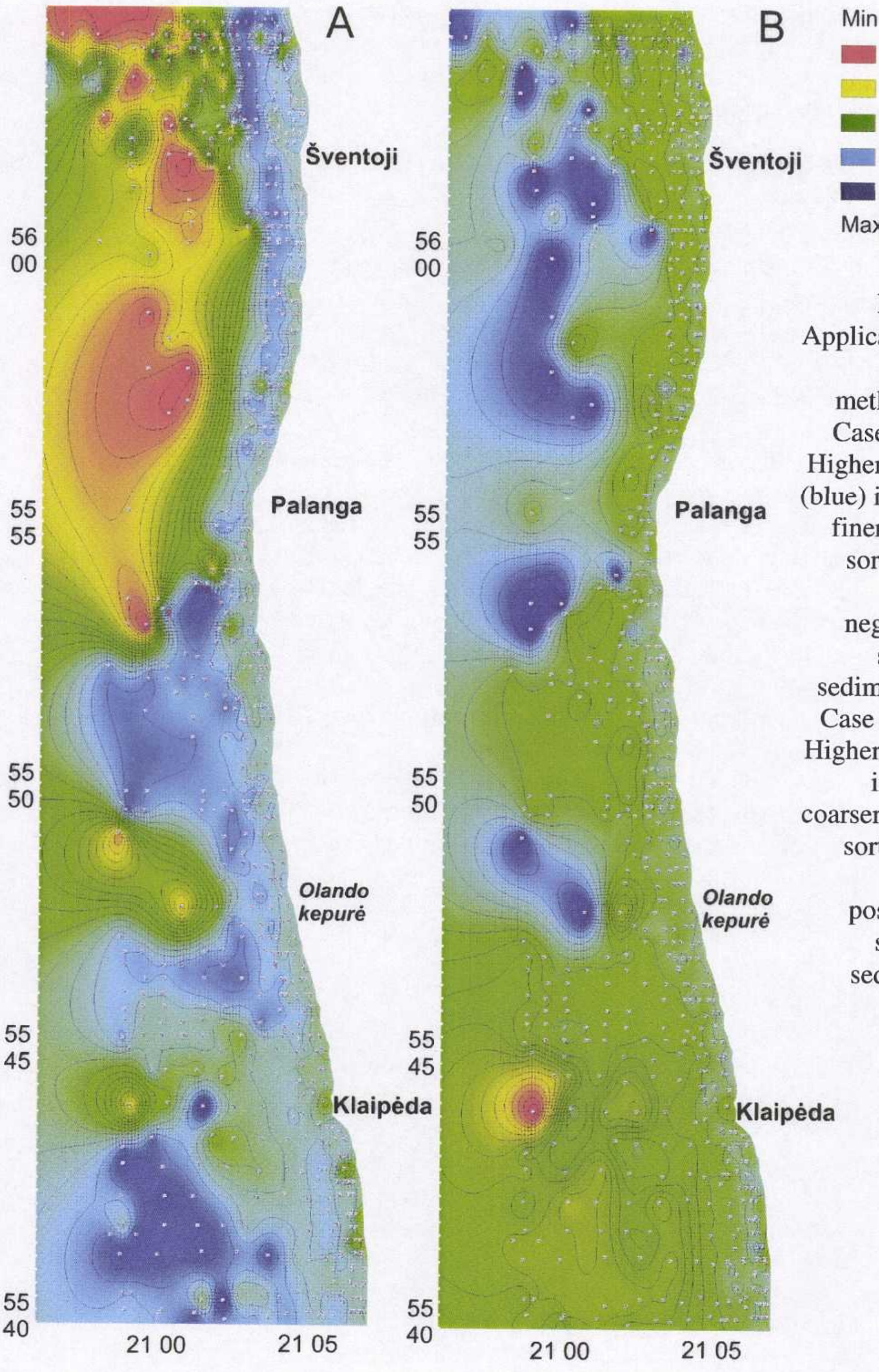

Fig. 13. Application of the TV method: A) Case (FB-). Higher values (blue) indicate finer, better sorted and more negatively skewed sediment; B) Case (CB+). Higher values indicate coarser, better sorted and more positively skewed sediment.

Although case CB+ is commonly interpreted as selective deposition, the CB+ map can contain trends related to both coarsening selective deposition and lag deposit development, since the CB+ characteristics are the same for both (Fig. 6B). But these two alternatives would indicate opposite transport directions. McLaren and Bowles (1985) avoid this problem by assuming that the lag by itself does not provide a transport direction, although it may if compared to adjacent deposits. We do not produce one final TV map by adding both fining and coarsening trends together, which has been done in several studies (McLaren and Little, 1987; Gao and Collins, 1991; Wu and Shen, 1999; Duman et al., 2004; Hughes, 2005), but analyze them separately. Le Roux and Rojas (2007) have also proposed to analyze these two cases separately in order to be able to compare and combine the results with additional information, such as from the PA method, and produce meaningful and valid conclusions about transport directions.

Each of the methods considered is limited by its perspective: the PA focuses largely on general trends, and the TV method assumes consistent changes, which may not always be realistic. To help compensate for the uncertainties over generalization or due to the natural variability apparent with greater resolution, the strengths of one method can be used to compensate for the weaknesses of the other. The alternating but simultaneous application of these two approaches is proposed. The objectives of these successive steps are:

1. PA – to obtain a general characterization (erosion, deposition, reworking)
2. TV – to identify possible pathways
3. PA – to eliminate illogical/contradictory pathway alternatives
4. TV – to interpret probable (rather than possible) pathways
5. PA+TV – to synthesize general conditions and specific pathways into a coherent conceptual model of the sedimentological setting.

A detailed description of methods is presented in Paper II (this volume).

<u>Provenance Interpretations</u>

To characterize sediment sources, we combined known source information with mineral associations related to regional geological provinces and processes. The correlation between minerals and grain-size parameters, as well as geographical distribution of minerals in the area were also used for support.

The greater mineralogical variability in the fine silt and clay allows more sources to be represented than in the coarser fractions or bulk sediment. The finest fraction is transported in suspension and deposited largely as aggregates that prevent extensive hydraulic sorting, and therefore supply a mineralogic suite closely representative of the original sources. The finest part of sediment can be transported in suspension over large distances and can represent even remote sources. The limited grain-size range (<0.01 mm) used for analyses reduces the mineralogical effects of different grain-size distributions among samples.

The main sources supplying sediment to the study area are: the Sambian Peninsula to the south (erosion of Pleistocene till and "Blue Earth" Paleogene sediments), the Nemunas River, whose discharge passes through Curonian Lagoon, and Pleistocene till, eroded on the sea floor in the north and at the Olando Kepurė shore cliff (Table 2):

Table 2. The main sources and their characteristic minerals, which are used for further quantification of source contributions for the <0.01 mm fraction.

Source (<0.01 mm)	Characteristic minerals
The Sambian Peninsula	Orthoclase, glauconite and micas (biotite and muscovite)
Nemunas River	Feldspars (microcline, albite)
Local Pleistocene till erosion	Feldspars (albite, orthoclase) and dolomite

The Sambian Peninsula source. In the area of our investigation sediments brought from the south are from two different origins: eroded till, characterized by abundant quartz, and "Blue Earth" sediment, similar to that documented from the amber mining query at Yantarnyj, containing clay minerals (glauconite), micas (biotite and muscovite) and orthoclase. Based upon our mineralogical modeling, erosion in the Sambian Peninsula supplies approximately 33% of the fine-grained sediment in the area of investigation average. The maximum contribution at a specific site is 41% (Fig. 14A). The minimal contribution of this source is in the most northern part of the investigation area, farthest from the source, where 27% of the fine-grained sediment is transported from the southernmost source. Geographical variation of the calculated supply is very low (the standard deviation 3.8).

The Nemunas River and drainage from the Curonian Lagoon provide sediment with abundant feldspars (especially microcline and albite; Blashchishin and Usonis, 1970). Quartz is present, but less predominant. The average supply of fine-grained sediment from the Nemunas River source to the coastal sediments is estimated to be 17%. The maximum input from Nemunas River is near Klaipėda Strait (41%), where sediment from the Nemunas River first reaches the coastal zone. There is a gradual decrease further northwards, where the belt of high feldspar concentrations narrows and is closer to the shore. The minimum contribution of this source is close to offshore till erosion sites in the north (Fig. 14B). The geographic variation of this source contribution is greater (Std. Dev. 9.3) than for the Sambian source.

Late Pleistocene till erosion on the seafloor and at the Olando Kepurė shore provides relatively fine sediments with poor sorting and large amounts of quartz and feldspars (especially albite and orthoclase, respectively), at the proportional expense of clay minerals. The amount of sediment supplied from these sources and accumulated generally increases seaward in the north and south, and near to the Olando kepurė coastal outcrops. Till erosion is estimated to contribute an average of 50% of the fine-grained sediment. The highest values are in proximity to offshore sites with till erosion in the north (72%, Fig. 14C). Sediments in the southern part of the investigation area are rich in quartz (66%) and dolomite is relatively more abundant (9% in average). This is explained by the proximity of Pleistocene till and clay deposits exposed offshore, which are known to contain a considerable amount of dolomite and other carbonates eroded by glaciers from Paleozoic deposits (sandstones, marls and dolomite rocks; Emelyanov et al., 1995). The standard deviation of this source supply is 11.7, highest relative to the other two sources.

Knowing the site-specific proportions of identified source contributions, it is possible to reconstruct the quantified content of minerals present at the initial source (Table 3; procedures in Paper IV).

Table 3. Calculated End-members.

	The Sambian Peninsula	Nemunas River	Local till erosion
Maximal calculated contribution, % (C_{max})	41.0	41.0	72.0
Weight % of characterizing source minerals at the site of max contribution	$X_{at\ max} = 34.6$	$Y_{at\ max} = 22.8$	$Z_{at\ max} = 8.9$
Calculated weight % of characteristic minerals at the initial source (End-members)	84.4 = 23.2 orthoclase + 52.9 micas + 8.3 glauconite	55.6 = 38.5 microcline + 17.1 albite	12.4 = 8.6 dolomite + 3.7 orthoclase

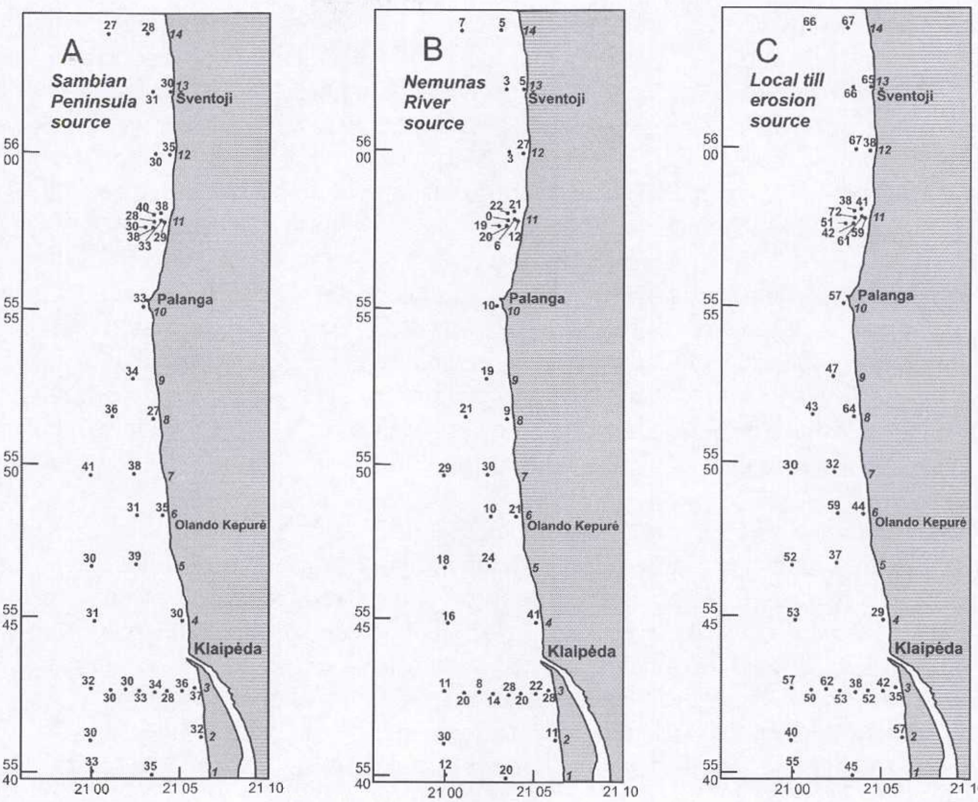

Fig. 14. Calculated contributions of: A) Sambian Peninsula source, B) Nemunas River source, and C) Local till erosion source.

Synthesis of grain size and mineralogy

The ultimate goal of sedimentological studies is to interpret sedimentary processes involved in the sediment formation and to understand their effects. Interpretations of both mineralogy and grain size contribute to this purpose. Grain-size characteristics contain information about the source, transport and depositional environment of sediments. Mineralogy is used for provenance interpretations and site-specific budgeting of source contributions. Together they can quantitatively specify sediment sources, transport pathways and sinks from complementary perspectives.

The supply of the fine-grained sediment from the Sambian Peninsula source is uniform along the entire coast; it delivers approximately 1/3 of the sediment. This sediment has most likely become widely and uniformly dispersed in the coastal zone in connection with longer suspension transport. Supply from the Nemunas

River varies along the way, with the greatest contribution proximal to the Klaipėda Strait and as little as only 5% of sediment in average reaching the most northern part. The minimum (0%) of Nemunas River contribution is at one site in the north (sector 5, Fig. 14, 15). The most northern area is characterized by a relatively greater sediment supply from till erosion (66% average in sector 6, Fig. 15). The fraction 0.01-0.063 mm at two northern sampling sites contains also mica and the heavy minerals ilmenite, magnetite, zircon, rutile and epidote. The relative abundance of heavy minerals is related to the sea floor erosion of till exposures, because Pleistocene till is known to contain abundant heavy minerals, especially in the coarser part of the sediment in the shallow nearshore zone (Blashchishin and Usonis, 1970). Absence of heavy minerals in the fine fractions suggests that medium-to-fine silt and clay sediment does not undergo extensive hydraulic sorting during suspension transport in contrast to coarser sediment where heavy minerals are more easily enriched.

Proximity to the source appears to be the main influence for variations in mineralogical content of fine-grained fraction in many cases. Sedimentological conditions favorable to erode, transport and deposit the sediment are also necessary for sediment availability. Farther from the original source sediment undergoes compositional and textural changes related to mixing of sediments from different origins and changes in hydrodynamic conditions. A combined interpretation of grain size and mineralogy helps answer the main questions regarding the provenance and fate of sediments, such as what, where from, where to, and how much.

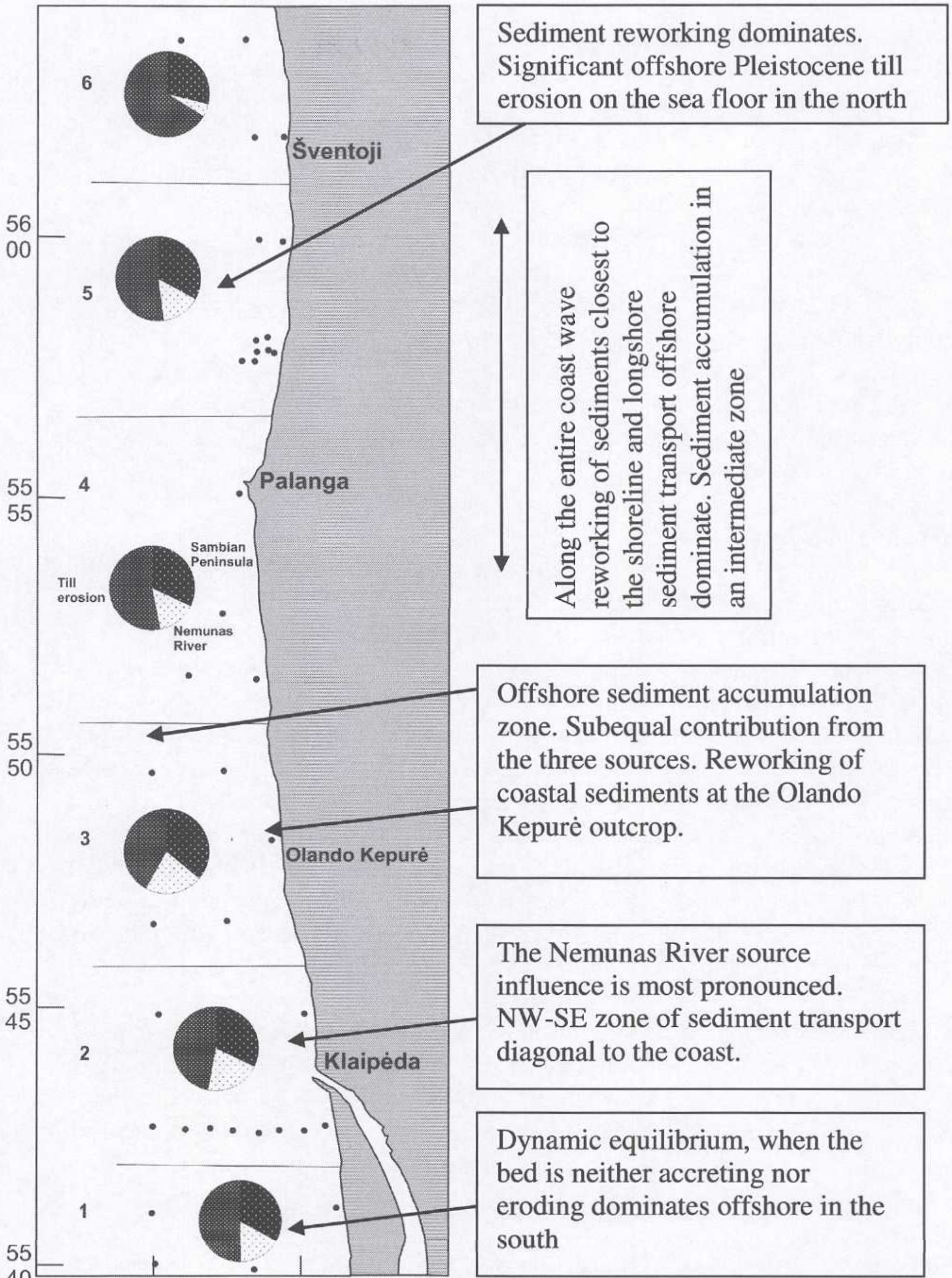

Fig. 15. Circle diagrams for six sectors showing the averaged contributions of three main sources supplying sediment: Sambian Peninsula, Nemunas River and local till erosion.

VI CONCLUSIONS

Identification of sources and transport pathways can be used for establishing the sedimentologic relationships between different sedimentologic environments, such as river, estuary, lagoon and coastal systems in the SE Baltic area. An understanding of the sediment transport relationships is important for predictive and remedial environmental planning as well as sustainable development in the future. Quantification and modeling of source contributions is a major accomplishment for any geological and environmental study. The erosion, transport and deposition of sediments in aquatic environments is of interest regarding contaminant transport and sediment-water interactions, as well as quantitative assessments related to shore erosion, longshore drift, resource extraction and dredging.

The main differences in the interpretations according the TV and PA methods relate to the different goals they have. The TV method aims to interpret monotonic depositional processes along a pathway, whereas the PA approach analyses sedimentary effect in more generalized view. The TV method considers two possible deposition cases. Sediment with energy decreasing in the direction of transport can become finer and be deposited completely in low-energy environments. A coarsening trend can arise due to selective deposition in high-energy environments. Comparison of successive changes in grain-size parameters relative to the source sediment allows interpretation of sediment transport directions. The PA method assumes sediment fining and coarsening as well, and interprets these as low- and high-energy environments, respectively. However, the sediment accumulation is assumed only with sediment fining, whereas in high-energy environments the fine-grained components are eroded and only the coarse part of sediment remains.

The choice of one method for interpretation depends on the aims of the investigation. However, the combined use of both methods in focus can provide complementary and robust information about the balance between erosion and accumulation and sediment transport pathways. Their interpretation together also provides a basis for distinguishing between alternative explanations and strengthens the resultant conclusions.

Quantitative source and transport pathway modelling can answer central questions regarding the origin and fate of the materials within environments impacted by human activities, providing essential knowledge for sustainable management. The suggested "sediment perspective" is opposite to most environmental budgets, where mass-flux budgets are often done by measuring the inputs from known sources. However, because of rate uncertainties and erosional events, the net effects are difficult to model using the "source perspective". Using the time-integrated and net-effect perspective provided by sediment-based budgets avoids most of these problems.

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Kisses to Pukas☺

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PREFACE

This doctoral thesis consists of an introduction and four appended papers.
By now all four papers included in the Thesis are published in scientific journals.

Gaigalas, A., Kairytė, M., Gulbinskas, S., 1999: Lithodynamic interpretation of granulometric composition of the nearshore sediments between Klaipėda and Šventoji in Lithuania, *Quaternary studies in Poland*, ed. K. Rotnicki. 95-103.

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Kairytė, M., Stevens, R.L., 2009: Quantitative provenance of silt and clay within sandy deposits of the Lithuanian coastal zone (Baltic Sea), *Marine Geology* 257, 87-93. ISSN 0025-3227. doi:10.1016/j.margeo.2008.11.001

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I

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QUATERNARY STUDIES IN POLAND, Special issue, 95-102 (1999)

LITHODYNAMIC INTERPRETATION OF GRANULOMETRIC COMPOSITION OF THE NEARSHORE SEDIMENTS BETWEEN KLAIPĖDA AND ŠVENTOJI IN LITHUANIA

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ABSTRACT. The paper present results of granulometric studies of sediments occuring in the Baltic shore zone between Klaipėda-Šventoji in Lithuania (Fig. 1). The mean grain size, median diameter, standard deviation or sorting, skewness coefficient and excess or kurtosis are discussed (Table 1). The situation in the nearshore zone revealed by generalisation of grain-size results of recent sands is depicted (Fig. 2). R. Passega's diagram *C-Md* was chosen as the one best reflecting the relations between the granulometric composition and flux energy (Fig. 3) and all investigated sediments were distributed in three fields: gradational suspensions, bottom suspensions and drifted material. These fields match three zones of different hydrodinamic regime: swash zone, wave deformation in surf zone and wave transformation in the open sea. Statistical granulometrical cofficients are grouped in different depth zones moving from the zone of drift currents. They reveal the weakening of the sedimentation environment dynamics. In the bottom sediments of the nearshore the well and very well sorted fine-grained sand dominates. Moving from the sources of sedimentary matter sediments become finer and their skewness become more negative.

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Introduction

The lithodynamic environment of the nearshore zone is fixed in the granulometric composition of bottom sediments. This circumstance makes it possible to use analysis of statistical coefficients of granulometric composition in interpretations of lithodynamic environments (Larson, Morang Gorman, 1997). Namely for this purpose R. Racinowski (1996, 1997) analysed in detail the granulometric composition of sands in the Polish nearshore of the Baltic Sea. The journal "Coastal Research", edited in 1995 by K. Rotnicki (1995), contained discussions on the recent condition, development and future perspective of the Polish coasts of the Baltic Sea.

The Lithuanian and Polish nearshores have many similarities. They are – a common palaeogeographical development, similar geological – geomorphological structure and lithodynamic processes. The Lithuanian investigations of the nearshore have so far been devoted mainly to morphogenetic zonation of the coasts (Kirlys, Janukonis, 1993, Gudelis, 1998) and distribution of lithological types of bottom sediments (Gulbinskas, Gaigalas, 1997).

The lithodynamic processes taking place in the underwater shore slope have been investigated but little. The present article is an effort to evaluate in the lithodynamic aspect the underwater shore slope from the dynamic shoreline till the depth of 10 m on the basis of statistical coefficients of granulometric data. The investigation area included 46 km of the Lithuanian continental coast stretching between Klaipėda and the Republic of Latvia. The following granulometric coefficients were used for determination and evaluation of the intensity of lithodynamic processes: median diameter (*Md*) of grains, mean size of grains (*x*), coefficient of skewness (S_k), excess or kurtosis of the curve (K_G) and standard deviation or sorting (δ). R. Passega's diagram *C-Md* was made for the purpose of determination of relation between the structure of sediments and sedimentation processes. Samples of bottom sediments were collected within the frame marine work of State Geological Survey on sc. 1:50 000 in the Klaipėda-Šventoji aquatory.

Methods

Bottom sediment samples were taken in the August - September of 1995 under calm weather conditions. Small waves dominated during the whole period of expeditional work. Bottom sediment samples were taken from 92 profiles perpendicular to the shoreline and spaced 500 m. Samples were taken in the area between the dynamic shoreline till the depth of about 10 m. The number of samples taken from one profile ranged from 2 to 8 depending on the bottom relief and peculiarities of geological structure. Samples were taken with the aid of dredge sampler from the surface layer of bottom sediments (0-3 cm). The total number of samples was 392.

The granulometric composition of bottom sediments was determined by a standard sieving method. A set of 22 sieves "Fritsch" and sieving machine "Analysette 3" were used for this purpose. Twenty two fractions from 0.05 to 10.0 mm were distinguished.

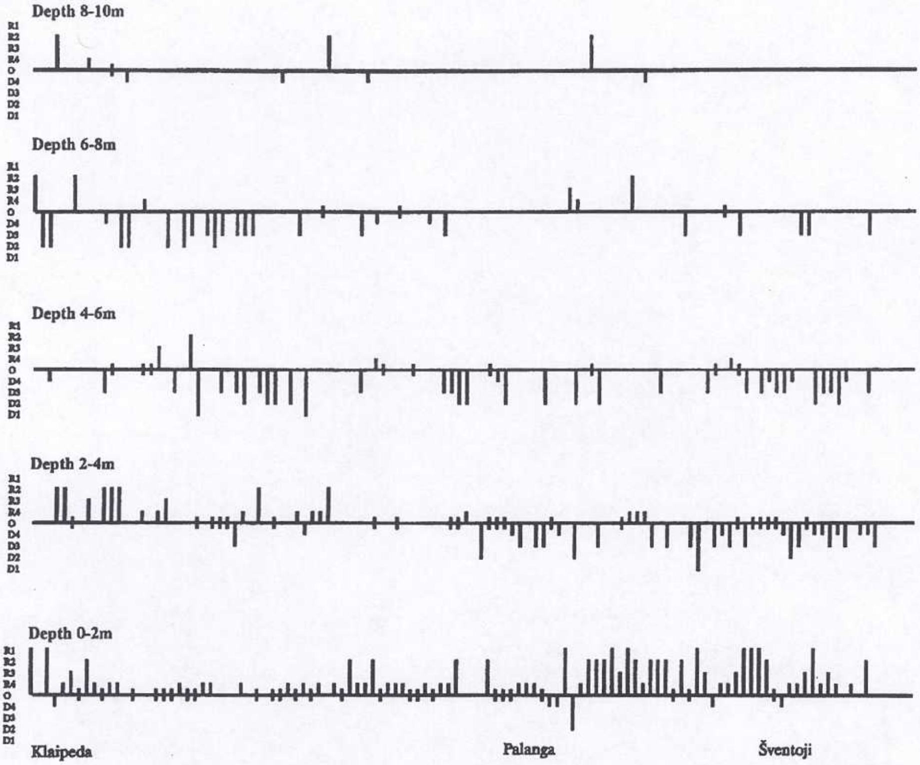


Fig. 1. Lithodynamic interpretation of granulometric data of the different depth zones of nearshore between Klaipėda-Šventoji. Compiled by M. Kairyte, 1998; Lithodynamic situation: 0 – lithodynamic equilibrium, R – abrasion, D – accumulation. Intensity of the process: 1 – definite, 2 – distinctive, 3 – moderate, 4 – weak

Statistical coefficients of granulometric data (mean grain size (x), skewness (S_k), kurtosis (K_G) and standard deviation or sorting (δ) were calculated by momentary method using Folk-Wards's formulae and software "Sietan". Coefficients included in the interval of average values are characteristic of lithodynamic equilibrium, whereas the values outside it, i. e., included in intervals of positive or negative anomalies, reveal the dominance of abrasion (washout) or accumulation (settling down) processes.

The mean grain size (x) is determined by the type of transportation (in suspensions, drift, saltation or rolling over the bottom), its speed and distance. Thus, the coarser the sediment particles the closer to the source they settle down and the higher top speed is necessary to move them and transport. Sediment particles exceeding the mean grain size (negative anomaly) reveal abrasion, i. e., a dynamic sedimentation environment. Positive anomalies indicate a weak hydrodynamics of the environment and a tendency of sediment accumulation.

A negative standard deviation (δ) is characteristic of better sorted sediments, whereas their anomalies reveal lower oscillations of sedimentary environment dynamics and sedimentary matter transportation in the bottom layer or accumulation tendency. Positive anomalies (worse sorting) reflect hydrodynamic changeability of the environment and stronger abrasion.

Skewness coefficient (S_k) deviation towards negative values indicate the washout of fine fractions of sediments and dynamically more active environment. Under the washing out conditions finer sediment grains are the first and more often to be transported. Positive skewness anomalies are determined by domination of finer particles in the sediments. Their presence indicate a weak tendency of washout, sediment movement in the bottom layer and process of settling down.

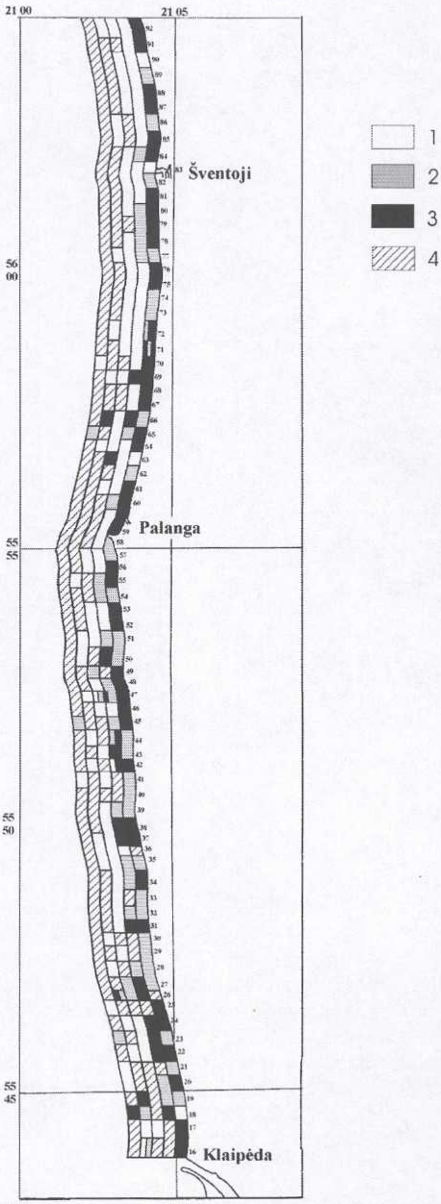


Fig. 2. Lithodynamic situation in the nearshore zone Klaipėda-Šventoji revealed by generalization of granulometric results of recent sands. Compiled by M. Kairyte, 1999; 1 – accumulation, 2 – equilibrium, 3 – abrasion, 4 – eroded surface covered with boulders and coarse-grained deposits (residuum)

A negative deviation of kurtosis (K_G) implies a pulsating sedimentation in the past – sedimentary material would periodically come from the land and be transported in the shallow nearshore. Positive anomalies simply a weaker abrasion and transition of the sedimentary matter.

A genetic R. Passega's diagram *C-Md* (Passega, 1964) was used for evaluation of the processes taking place in a shallow sandy nearshore. The diagram is made on the basis of *Md* (50% quartile) and *C* (1% quartile). The latter shows the maximal size of sediment grain which can be moved and transported by a water flow of a certain force.

Results of granulometric statistical coefficients

There exists in the nearshore zone a relation between the depth and intensity of lithodynamic processes, i. e., concomitantly, the granulometric composition of bottom surface sediments (Racinowski, 1996). For this reason five depth zones were chosen for generalisation and interpretation of the results of statistical coefficients: 0-2, 2-4, 4-6, 6-8, 8-10 m (Table 1).

Mean grain size (x). Sediment particles of the size 2.5-3.0 phi dominate in the nearshore. The content of particles included in the interval > 3.0 phi is somewhat smaller. The prevailing sediments according to Wentwoth's classification belong to the fine-grained type of sands, whereas sediments > 3.0 phi – to the extremely fine-grained type of sands. The tendency of sedimentary matter getting finer in the increasing depth was obvious. The finest grain size of sediments was observed at the depth of 4-6 m. This zone contained 49% of grains 2.5-3.0 phi (fine sands) and 49% of grains > 3.0 phi (extremely fine sands). In deeper places – grain size of sediments at the depth of 6-8 and 8-10 m was similar-particles 2.5-3.0 phi in size prevailed (64% and 67% respectively). The content of sediments sized > 3.0 phi was somewhat smaller – 33% at each depth. The sedimentary matter gets somewhat coarser though does not reach the size of sediment grains at the depth of 0-2 m.

Standard deviation or sorting (δ). The sorting of sediments deposited in the Baltic nearshore ranges from very good to good (0.35-0.5). However, very well sorted sands (< 0.35) prevail. Besides the values δ also depend on the depth of sediment accumulation, i. e., moving from the dynamic shoreline the sorting becomes better until at the depth of 4-6 m it reaches a hundred-per-cent quality. A similar situation exists at the depth of 2-4 and 6-8 m where very well sorted sediments make up 96% and 94% respectively – there occurs a small amount of well sorted sediments. Only in the most shallow part near the dynamic shoreline (0-2 m) there occur 5% of medium well sorted sediments (0.5-0.71). The worst sorted

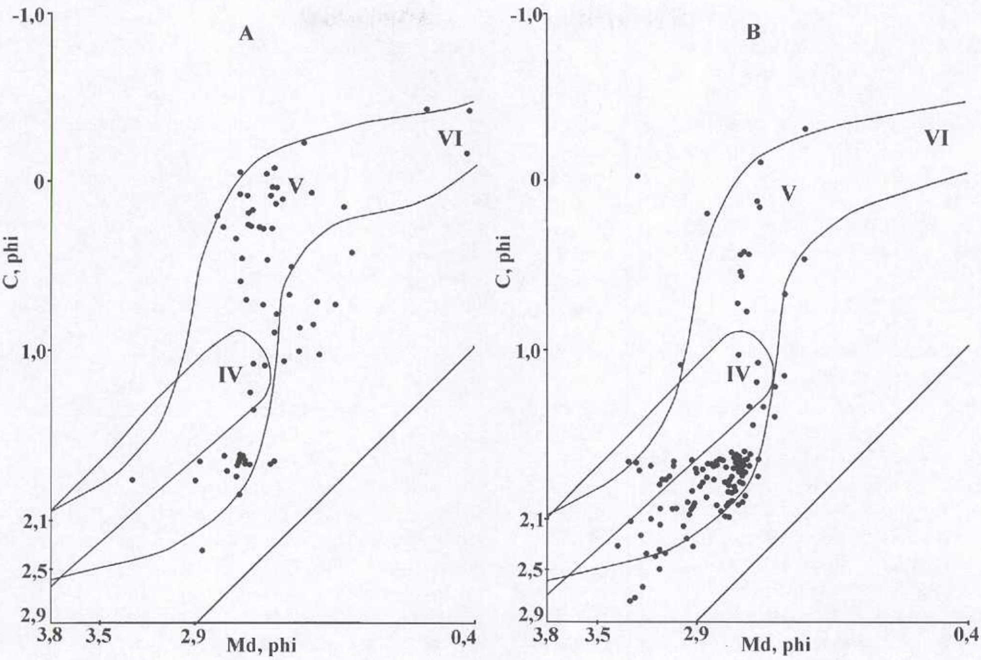
Table 1. Distribution of statistical granulometrical coefficients (x, δ, S_k, K_G) in the nearshore zones of different depth (%)

Depth, m		1.5-2.0 medium sand	2.0-2.5 fine sand	2.5-3.0 very fine sand	3.0-4.0 very fine sand	Number of samples
0-2	x, φ	10.64	67.02	21.28	1.06	94
2-4		–	19.12	61.76	19.12	68
4-6		–	2.04	48.98	48.98	49
6-8		–	3.03	63.64	33.33	33
8-10		–	–	66.67	33.33	9
		< 0.35	0.35-0.5	0.5-0.71		
		very well sorted	well sorted	moderately well sorted		
0-2	δ	81.72	12.9	5.38		
2-4		95.78	4.23	–		
4-6		100	–	–		
6-8		94.12	5.88	–		
8-10		44.44	55.56	–		
		-0.3--0.1	-0.1-0.1	0.1-0.3		
		coarse-skewed	near-symmetrical	fine-skewed		
0-2	S_k	15.62	81.25	3.13		
2-4		1.41	64.79	33.80		
4-6		–	61.22	38.78		
6-8		3.03	69.70	27.27		
8-10		11.11	55.56	33.33		
		0.65-0.9	0.9-1.11	1.11-1.50	1.50-3.0	
		platykurtic	mesokurtic (normal distribution)	leptokurtic	very leptokurtic	
0-2	K_G	4.26	30.85	41.49	23.4	
2-4		5.63	50.70	25.35	18.31	
4-6		12.25	67.35	12.24	8.16	
6-8		17.65	58.82	17.65	5.88	
8-10		11.11	11.11	55.56	22.22	

sediments of the investigated zone are deposited at the depth of 8-10 m. More than a half of the analysed material from the mentioned depth could be included in the interval of 0.35-0.5 which corresponds the level of well sorted sediments. In the direction of transportation sediments gradually become more homogeneous and their sorting improves.

Skewness coefficient (S_k). The values of skewness coefficient of nearshore sediments range from −0.3 to +0.3. However, values from −0.1 to +0.1 prevail. Almost all negative values of skewness coefficient were contracted in the most shallow zone (0-2 m) of sediments, i. e., the zone nearest to the dynamic shoreline. Positive values of skewness coefficient serve as an indicator of bottom sediments abrasion and intensive hydrodynamics, what is characteristic of swash zone. Most distribution curves are almost symmetrical (+0.1-+0.3). Thus, the greater part of bottom sediments in the investigated zone is bedding in a sedimentation environment of weak hydrodynamics ($S_k > 0$). However, it is evident that the skewness of grain distribution curve decreases with an increasing depth, becomes symmetric and more and more positive till the depth of 6-8 m. From this point and deeper the number of negative values increases though over the whole nearshore the values of skewness +0.1-0.1 dominate.

Excess or curve kurtosis (K_G). The values of kurtosis (K_G) range between 0.65 and 3.0, i. e., the distribution curve is flat through to a pointed one. Most values of kurtosis (42%) in the shallow zone (0-2 m) can be included in the interval 1.11-1.50 with a pointed curve. A somewhat smaller number of values (31%) belong to



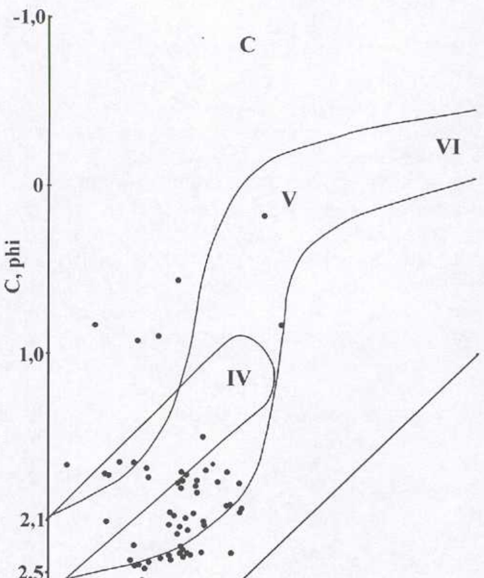


Fig. 3. Genetic diagrams (*C-Md*) of surfacial sediments in nearshore zone (depth 0-10 m) Klaipėda-Šventoji). Compiled by M. Kairyte, 1998; A – wave swash zone (< 1 m), B – wave deformation and surf (shoal and trough) zone (depth 1-5 m), C – wave transformation in open sea (depth > 5 m). Genetic fields: IV – gradational suspension, V – bottom suspension and VI – drifted coarse-grain sediment particles

the interval 0.9-1.11 showing a normal distribution (medium flat curve). Extremely pointed curves (K_G = 1.5-3.0) at the mentioned depth make up 23%. With an increasing depth (2-4, 4-6, 6-8 m) medium flat distribution curves become the dominating ones (0.9-1.11). Sediments with kurtosis values ranging between 1.11 and 1.5 (pointed curve) and 1.5 and 3.0 (extremely pointed curves) decrease. At the depth of 8-10 m 56% of kurtosis values are included in the interval 1.11-1.5, 22% - 1.5-3.0 and 11% in each of the intervals 0.65-0.9 and 0.9-1.11 where the kurtosis curve ranges from a flat to medium flat are (normal distribution).

Lithodynamic interpretation of statistical coefficients of granulometric data

On the ground of statistical granulometric coefficients (x, S_k, K_G, δ) obtained in the Klaipėda-Šventoji nearshore zone an attempt was made to reveal the lithodynamic condition of this zone. Similar reconstructions have been done in some sectors of Polish nearshore (Baraniecki, Racinowski, 1996; Dobrzynski, 1997; Racinowski, Dobrzynski, Seul, 1996, etc.).

For statistica granulometric coefficients of sediments positive and negative anomalies were determined. They reveal the dominating position of washout (abrasion, redeposition) or settling (accumulation, deposition) processes in a concrete spot. Sediment washout processes are reflected by positive anomalies of δ and K_G and negative anomalies of x and S_k. In the opposite case settling down of sedimentary matter takes place. Statistical coefficients included in the interval of average values imply an equilibrium of litho- and morphodynamic processes.

Each sample of bottom sediments was given an index reflecting the lithodynamic situation in the sampling site (Fig. 1). The lithodynamic equilibrium is marked by a symbol O, sedimentary matter accumulation – D and abrasion – R. The intensity of the process is expressed by numbers: 1-definite, 2-distinctive, 3-moderate, 4-weak.

In the most shallow (0-2 m) sector of the nearshore a weak washout of sediments (R4) alternates with a lithodynamic equilibrium of sedimentation environment (O4) (Fig. 1). In some observation sites in the Klaipėda environs a somewhat more intensive bottom abrasion was recorded. In the environs of Palanga a weak lithodynamic (O4) equilibrium with a tendency of sedimentary matter transition (R/D) was determined. Between the Palanga and Šventoji accumulative promontories the number of areas of sedimentary matter washout increases of compared with the Klaipėda-Palanga sector – evidences of weak (R4) and moderate (R3) bottom abrasion were recorded. At the described depth near Šventoji itself a weak lithodynamic equilibrium and sedimentary matter accumulation dominate.

With an increasing depth and quieting hydrodynamics of sedimentation environment – in the most dynamic swash and backwash zone – the abraded sediments pass into the state of unstable lithodynamic equilibrium or transportation. The number of sectors of unstable lithodynamic equilibrium-transition-(R/D) increases though at the depth of 2-4 m between Klaipėda and Palanga a weak lithodynamic equilibrium (O4) and a weak washout of sediments (R4) still prevail. Moving further from the dynamic shoreline, with an increasing depth and weakening effects of the wave action on the bottom, the moderate (D3) accumulation of sedimentary matter becomes the dominating one with rare exceptions. Distinctive (D2) and definite (D1) accumulation are also characteristic.

The situation in the nearshore zone revealed by generalization of results about granulometric composition of recent sands is depicted in Fig. 2.

To the north from Klaipėda the Baltic Sea underwater shore slope is divided from remaining sea aquatory by a morainic plateau. The surface of this plateau is eroded and covered with coarse-grained deposits: boulder, shingle, gravel, etc. Relict deposits are exposed even in some areas of the underwater shore slope itself. In the spreading areas of relict deposits the deposition of recent sands does out take place. Therefore, this zone was not lithodynamically evaluated.

Display of sedimentation environments in a genetic diagram *C-Md*

R. Passega's diagram *C-Md* was chosen as the one best reflecting the relations between the granulometric composition and flux energy which are reflected in the type of sedimentary matter transportation. In Passega's diagram six genetic fields are distinguished by a hydrodynamic principle: I – pelagic suspension, i. e., sediments of calm environment; II – mud flows; III – homogenic suspension; IV – gradational suspension, i. e., fluxes of suspended different grain-size material (silt, sand); V – bottom suspension where sediment particles are transported by saltation; VI – drifted coarsest sediment particles.

In our diagrams (Fig. 3) the points were arranged only in three genetic fields (IV, V, and VI) characterized by a highest hydrodynamic activity. In the cross profile of the nearshore three sectors of different water dynamics were distinguished: 1 – from 0 to 1 m; 2 – from 1 to 5 m and 3 – from 5 to 10 m in depth. Sediments were distributed in genetic fields distinguished by a dynamic principle and revealing their accumulation conditions, i.e., character of sedimentation processes.

The most dynamic and changing environment was recorded at the depth < 1 m. Sediments of this zone –

under the conditions of sandy nearshore – are mostly formed by wave swash. Sediments deposited nearest to the dynamic shoreline were distributed within a wide interval of *C* and *Md* values. Most of these coarsest (*Md* = 0.5-2.6 phi) sediments affected by the strongest, in the investigated zone, water flow (*C* = 0.9-1.8 phi) were included into field V (56.92%) where sedimentary matter is transported by drift and saltation. A somewhat smaller number of points at this depth were included into field IV of the diagram (33,85%).

Sediments at the depth of 1-5 m, where the greater part of sediments forms in the zone of wave deformation and surf, concentrated in field IV (87.5%). *Md* of the greater part of sediments ranged between 2.4 and 2.9 phi, whereas *C* – between 1.65-2.05 phi. 11.67% of points were concentrated in field V (Fig. 3B).

At the depth > 5 m sediments become finer and are affected by a law energy water flow. They are deposited in the wave transformation zone where flows of different origin are active but wave action is felt only during strong storms. Almost all sediment points at this depth (90.32%) were arranged in field IV. Not a single point was included in field VI. At the depth of 5-7 m *Md* of sediments ranges between 2.35 and 3.4 phi, whereas *C* – between 0.05 and 2.65 phi. At the depth > 7 m *Md* ranges between 2.65-3.5 phi, *C* – between 0.25-2.4 phi (Fig. 3C).

It must be pointed out that the arrangement of points in the genetic diagrams does not precisely reveal the conditions of sedimentation environment because they depend on many other important factors: geological structure, sources of sedimentary matter, morphological properties of the bottom (an increased speed of water flows between the bars determines the coarsening of sediments).

Conclusions

Generalizing the results of investigations carried out in the Klaipėda-Šventoji nearshore of the Baltic Sea we can make several conclusions.

In the bottom sediments of the nearshore the well and very well sorted fine-grained sand dominates. Moving from the sources of sedimentary matter sediments become finer and their skewness become more negative.

In the cross profiles the granulometric composition of sediments changes with an increasing depth. The coarsest sediments are bedding on and nearest to the dynamic shoreline (0-2 m). With an increasing depth sediments become finer, more homogenic (sorting improves), their coefficient of skewness becomes positive, kurtosis approaches the normal distribution.

Statistical granulometrical coefficients are grouped into different depth zones where they reveal the weakening of the sedimentation environment dynamics in the cross profile moving from the zone of active waves into the zone of drift currents. Moving from the shore towards an increasing depth the lithodynamic activity of sedimentation environment gradually calms down till the state of lithodynamic equilibrium is reached (the grain distribution curve is symmetrical). After this lithodynamic phase the tendency of sediments accumulation gains force until - with rare exceptions conditioned by sources of sedimentary matter, hydrodynamic peculiarities of water thickness and morphological properties of the bottom – definite, distinctive and moderate accumulation becomes the dominating one.

In R. Passega's genetic diagram *C-Md* all investigated sediments were distributed in the three fields: IV (gradational suspensions), V (bottom suspensions) and VI (drifted material). These fields match three zones of different hydrodynamic regime: swash zone (depth < 1 m), wave deformation and surf zone (1-5 m) and wave transformation in the open sea (> 5 m).

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II

Manuscript

Sediment transport pathways interpreted from spatial trends in grain size, the SE Baltic Sea, Lithuanian coast

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Abstract

Grain-size characteristics of 712 surface samples of sandy sediments are used to delineate sediment transport pathways and detect predominant sedimentological conditions in the Lithuanian coastal zone. The study is focused upon two different interpretation techniques: 1) the sediment trends analysis (McLaren model) interprets successive changes along transport pathways assuming that sediment in the direction of transport should become either coarser, better sorted and more positively skewed, or finer, better sorted and more negatively skewed, and 2) the population anomalies method estimates the balance between erosion and accumulation processes at each sampling site based on individual site deviations compared with average values for grain-size parameters in the area of interest. In general, coast parallel sediment transport predominates in the entire investigation area, although wave-induced movement perpendicular to the coastline is interpreted in the shallow nearshore zone. The deepest areas offshore are characterized by sea-floor erosion in the north, whereas an accumulation zone occurs in the relatively deep central part of the study area. The methods are implemented using two-dimensional GIS tools. This also helps to produce comparable results. The simultaneous use of both methods gives a basis for distinguishing between transport alternatives and processes separately suggested by the different approaches. The differences in assumptions between these two methods are related to different goals for the interpretations of grain-size trends. The combined application of site-specific and general trends provides complementary and robust information about sedimentary processes involved in sediment formation.

Keywords: Baltic Sea, Lithuanian coast, sandy deposits, grain size, sediment transport, sediment trend analysis.

Introduction

Sediment sources and transport pathways are commonly inferred from grain-size data. In this paper, the combination of two perspectives offers improvements for relating grain-size trends to these interpretative goals. These two approaches are separately focused upon: 1) the successive changes along possible pathways, and 2) in more general terms, the spatial deviations of sample from local population statistics. A synthesis of site-specific and averaged statistics is favorable in order to utilize the strengths of each approach and to accommodate the inherent or induced variability in textural data.

Emphasizing the process effects of selective erosion and deposition, McLaren (1981) proposed a method for interpretation of sediment transport directions based on specific, successive changes of grain-size parameters (mean, sorting and skewness) along possible paths. In addition to the characteristics of the source sediment, main factors influencing grain size are the energy relationships within the environment, defined in this method by 1) winnowing, 2) selective deposition of a portion of the grain-size distribution in transport and 3) total deposition. McLaren and Bowles (1985) concluded that there are two possible changes in the direction of transport: sediment can sequentially become finer as a consequence of decreasing energy in a low-energy environment or coarser in response to energy decreasing in a high-energy environment. The sediment trend analysis (STA) has been tested in a variety of environments, such as river, shelf, coastal zone, estuary, floodplain, microtidal beach, bay and others (McLaren and Bowles, 1985; McLaren and Little, 1987; Gao and Collins, 1992; Le Roux, 1994; Stevens et al., 1996; Mohd-Lokman et al., 1998; Wu and Shen, 1999; Asselman, 1999; Duman et al., 2004; La Roux and Rojas, 2007). Although, the results have shown that the model describing changes in sediment distributions can be used to indicate the most likely sediment transport direction in many environments, some studies have noted that inconsistencies with trends known to exist in the area may occur (Masselink, 1992; Hughes, 2005). Most of these studies were applied on sandy environments or on the sand fraction only. Similar interpretations of fine-grained deposits can be expected to be less reliable if cohesion influences erosional processes and aggregates limit the effectiveness of sorting during transport and deposition.

Independently of this, but following similar assumptions regarding changes in grain-size statistical parameters relative to environmental energy, Baraniecki and Racinowski (1996) evaluated sedimentological processes based on deviations from the average values of mean, standard deviation, skewness and kurtosis in a particular area. This method aims to characterize the balance between erosion and deposition at each sampling site relative to average characteristics in the investigation area. The population anomalies take into account the entire data set or subsets of grain-size parameters from different coastal-morphological settings and thereby reflect net effects of sedimentation processes in the region with a generalized and relatively long-term reference in comparison to the STA method, above. In this approach, which we refer to as the Population Anomalies method (PA), sediment that is finer, better sorted, more positively skewed and more platykurtic compared to the population average is characteristic of accumulative environment. The opposite textural features (coarser, worse sorted sediment with a more negatively skewed and more leptokurtic distribution curve) describe reworked sediment and a more dynamic sedimentary environment. The PA method has been applied to coastal sediments (Baraniecki and Racinowski, 1996; Racinowski et al., 1996).

The two methods in focus are similar in that, if environmental energy is sufficient to rework the sediment and is not limited by flocculation or shielding by coarse particles, fine grains are more likely to be removed than coarser grains. The different perspectives of the STA and PA methods are largely related to their specific objectives. The STA method assumes monotonic depositional processes along an interpreted pathway, whereas the PA approach analyses sedimentary effects in a more generalized view.

Uncertainties exist interpreting a coarsening trend along a possible pathway using STA method since there are two separate explanations, namely development of a lag deposit or selective deposition of the coarsest portion of the transported material. Both deposits can have similar characteristics, i.e. coarser, better sorted and more positively skewed than the source material (McLaren, 1981; McLaren and Bowles, 1985; McLaren and Little, 1987; Wu and Shen, 1999; Hughes, 2005). The differentiation between lag and selective, coarser deposition depends on the independent interpretation of the environments being sampled (McLaren and Bowles, 1985). In this context, the STA method can be complemented by the more general environmental information utilized in the PA method.

An understanding of sediment transport is important for both predictive environmental planning and for remediation of existing problems, two requirements for sustainable development in the future. A coastal model involving sediment transport pathways is, for instance, of interest for applied studies regarding shoreline erosion, and harbor and fairway management of siltation and pollution. We evaluate if the simultaneous usage of site specific (the STA approach used in our study) and general trends (the PA method) provides sufficient basis for distinguishing between transport alternatives. The study area used here to illustrate grain-size interpretations is the approximately 45 km long, nearshore zone of Lithuania (Fig. 1).

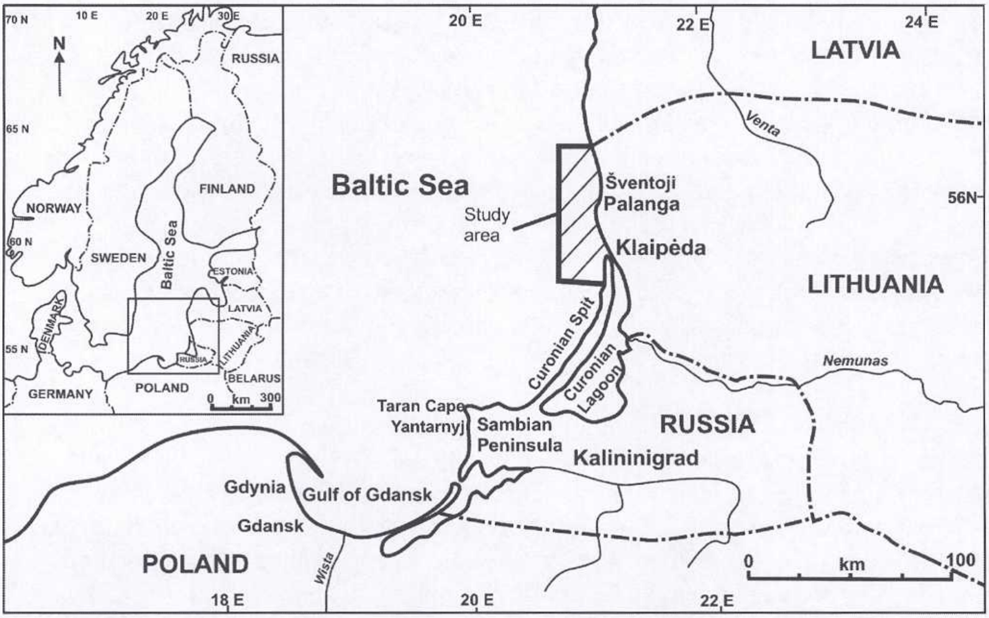

Fig. 1. Situation map of the SE Baltic Sea (modified from Ūsaitytė, 2000) with the study area indicated.

Analytical and Interpretative Methods

Seafloor sediment samples from the coast of Lithuania were taken along 92 transects oriented perpendicular to the shoreline and spaced 500 m apart. Samples were taken from the shoreline to a depth of about 31 m. Surface sediments (0-5 cm) were sampled at 712 stations (Fig. 2) during four years (1993, 1994, 1995, 1997).

Grain-size distribution was determined using standard pipette methodology (0.005 to 0.5 mm) and dry sieving analyses with a set of 22 sieves for the coarse-grained fractions (0.05 to 10.0 mm). Statistical parameters of the grain-size data were calculated according to the graphic method of Folk and Ward (1957).

Sediment Trend Analysis (STA)

The Sediment Trend Analysis using line-by-line site comparisons (STA) proposed by McLaren (1981) is built upon assumption that sedimentary processes produce predictable changes in grain-size parameters (mean, sorting and skewness) in the direction of transport so that the possible transport directions can be delineated by comparing adjacent sites along the pathway. McLaren´s model applies the theoretical arguments that 1) sediment in transport must be finer, better sorted, and more negatively skewed than its source sediment (case: FB-); 2) a lag must become coarser, better sorted, and more positively skewed (case: CB+); and 3) succesive deposits may become finer or coarser, but the sorting must become better and skewness more negative or more positive with finer or coarser deposits, respectively (Mclaren and Bowles, 1985). In the first case (FB-) sediment is selectively eroded, and these textural changes, reflected in the transported material, may be preserved with near-complete deposition. While in the CB+ case sediment in transport undergoes selective deposition due to decreasing energy of the transport process.

In McLaren (1981) STA approach the grain-size parameters were compared along the survey lines, chosen by investigator. To reduce the subjectivity possibly introduced by selection of the sampling lines Gao and Collins (1992) modified the STA line-by-line method originally proposed by McLaren (1981) and McLaren and Bowles (1985) by using two-dimensional site comparisons in all directions. In this vector approach each sample is compared with its neighboring samples (two at a time) and a summarized trend vector is defined at a station whenever a trend is present. Le Roux (1994) suggested equalizing the importance of grain-size parameters and comparison of groups of five samples at a time. Later Asselman (1999) proposed implementing the grain-size data into a gridded, GIS environment. The GIS evaluation is less sensitive to irregularities of the sampling configurations because comparison is not limited to neighboring sampling sites. Each raster cell is compared with its near-by cells within a certain range of association determined by geostatistical analysis of semivariogram plots (Asselman, 1999). The GIS gives smooth map patterns, especially when a filtering operation in the form of moving-average technique is performed to reduce the remaining noise. However, filtering reduces the spatial resolution and can result in loss of valuable information, such as when the applied grid cells are large in comparison with the spatial variability in transport directions (Asselman, 1999).

In our study the three grain-size parameters (mean, sorting and skewness) were recalculated into relative values (interval 0-1) to equalize the weight of importance between them. The normalized variables were then added together for two separate cases: 1) FB- and 2) CB+, and implemented in a GIS. In the first case higher values represent finer, better sorted and more negatively skewed sediment. In the second case higher values indicate a coarser, better sorted and more positively skewed deposit. The sum of these values may allow large changes in one parameter to dominate, masking deviations in the other values. However, this is considered justified and adds robustness when dealing with large areas and significant natural variability, as is discussed later. Two interpolated raster maps using nearest neighbour technique are produced for the entire area of investigation. The smoothing operation is not performed. We refer to this as the Transport Vector (TV) method.

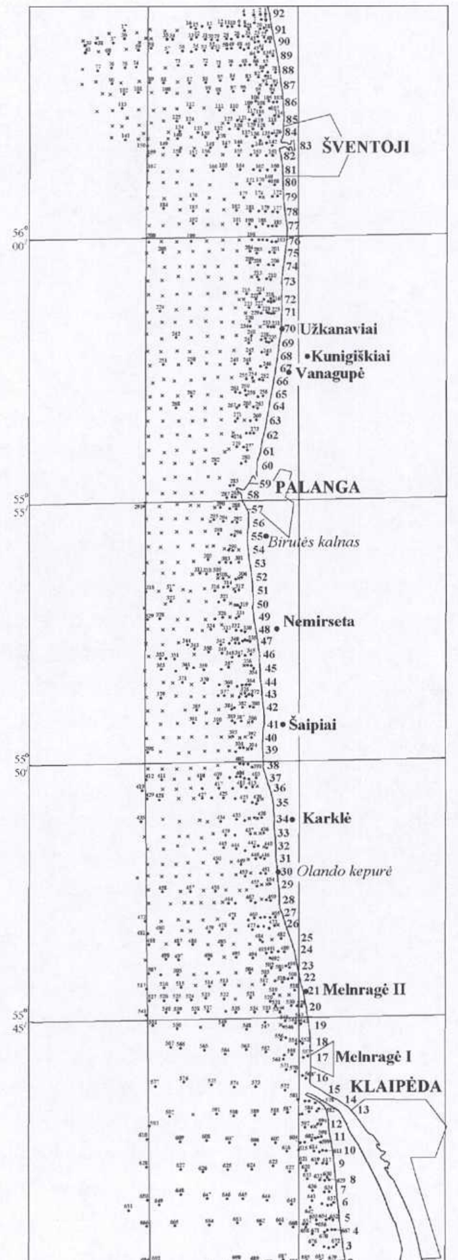

Fig. 2. Sampling sites (1-712) for surficial sediments along the Lithuanian coast (circles). Profiles 1-92 are indicated on the right. Eroded surfaces covered with boulders and coarse-grained deposits (x) were not possible to sample.

Population Anomalies (PA)

The Population Anomalies method (PA) (Baraniecki and Racinowski, 1996) classifies areas of erosion or accumulation based on the deviation of grain-size parameters (mean, sorting, skewness, kurtosis) at a specific sampling site in comparison to the population averages in the surrounding area. Individual sites are not compared with each other. Once the regional distribution pattern is mapped by this method, anomalies at individual sites allow interpretation of sediment reworking, accumulation or an "equilibrium" balance. In addition, the strength of the predominant condition (reworking, deposition or equilibrium) is classified and assigned an intensity class at each station.

The identification of population anomalies is done (Baraniecki and Racinowski, 1996) using 95% confidence intervals calculated for the average values of each of four statistical parameters: mean grain size, sorting, skewness and kurtosis for the entire area. The values within the confidence intervals are considered to reflect dynamic equilibrium (symbol o). Deviations from the confidence interval are considered anomalous and suggest the predominance of erosion or accumulation processes. Anomalies or deviations from confidence intervals of statistical parameters are assigned symbols: r – reworking and d – deposition (Table 1).

Table 1. Anomalies of grain-size parameters.

Grain-size parameter	Negative Anomaly	Within confidence interval	Positive Anomaly
Mean (M_z)	**r**	**o**	**d**
Sorting (δ)	**d**	**o**	**r**
Skewness (S_k)	**r**	**o**	**d**
Kurtosis (K_G)	**d**	**o**	**r**

The interpretation of anomalies suggested by Baraniecki and Racinowski (1996) is summarized here as a background for this methodology. Negative anomalies of mean grain size (coarser sediment in relation to average) suggest *reworking* (r); positive anomalies of this statistical parameter indicate lower environmental energy and a tendency for sediment *deposition* (d; Table 1). Negative anomalies of sorting (better sorting relative to average) reflect more uniform- environmental energy, where a tendency for near-bottom sediment transport and *deposition* exist (d); positive anomalies (relatively worse sorting) suggest variable environment energy, where sediment winnowing occurs (r). Negative skewness anomalies (more negative skewness in relation to average) are related to winnowing of finer grains in relatively high-energy environment (r); positive anomalies (relatively more positive skewness) suggest a weak tendency of *erosion*, near-bottom transport and *deposition* (d). Negative kurtosis anomalies (relatively flatter grain-size frequency curves) indicate limited grain-size differentiation (d); positive anomalies (steeper than average frequency curves) suggest a tendency for *erosion* and *transport* with effective grain-size differentiation (r).

The intensity of the predominant condition is assigned a class (1 – 4) at each station based on an assessment of the four grain-size parameters:
O1 – all four grain-size statistical parameters at a particular station lie within the confidence interval (all have symbol **o**), general balance between erosion and accumulation, defines a dynamic equilibrium.
R1 - all four grain-size statistical parameters at a particular station have symbol **r**, a *strong* trend toward *erosion and reworking* is expected.
D1 - all four grain-size statistical parameters at a particular station have symbol **d**, suggesting *strong accumulation*.
O2, R2, D2 – three grain-size statistical parameters at a site are assigned identical symbols **o**, **r** or **d**, reflecting moderately strong *balance between erosion and deposition* (O2), moderately strong *erosion* (R2) and moderately strong *accumulation* (D2), respectively.
R3, D3 – two grain-size statistical parameters have symbols **o**, other two are either **r** or **d**, corresponding to moderately weak *erosion* (R3) and moderately weak *accumulation* (D3), respectively.
O4, R4, D4 – only two grain-size statistical parameters are given similar class symbols. This characterises a weak *balance between erosion and accumulation* (O4), weak *erosion* (R4) and weak *accumulation* (D4).
R/D – grain-size statistical parameters have two symbols **r** and two **d**, indicating indefinite processes.

Results and Interpretations

Grain-size characteristic of coastal sediments

Sediments in the Lithuanian nearshore zone are predominately very well sorted (σ <0.35 φ), fine to medium sands (1.5 to 2.5 φ) with near-symmetrical, Gaussian grain-size distributions ($S_k = 0.02$, $K_G=0$; Fig. 3). The sediments vary from poorly to very well sorted ($\sigma = 1.23$ to 0.345 φ), very coarse to very fine (-0.69 to 3.76 φ) sand, with coarse to very fine-skewed (-0.43 to +0.44), extremely leptokurtic to very platykurtic (0.33 to 6.82) distribution curves.

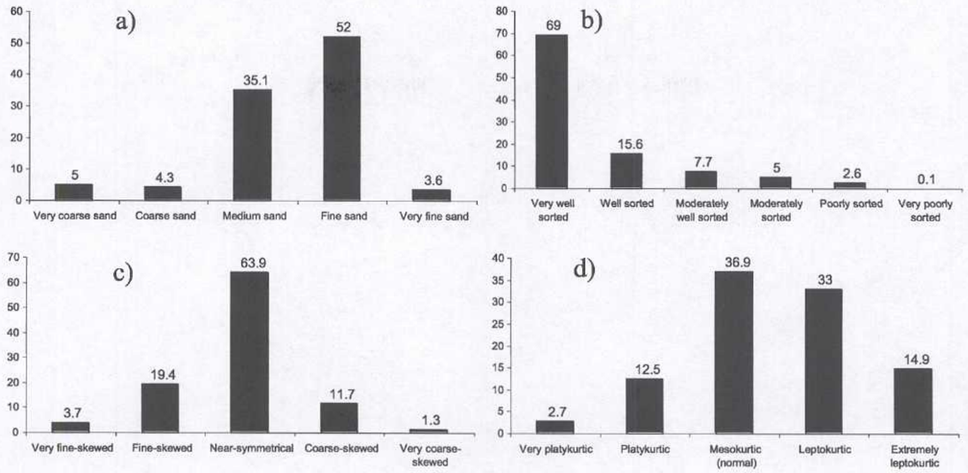

Fig. 3. Distribution of grain-size parameters in the nearshore zone (0-31 m of depth): a) mean grain size, b) standard deviation (sorting), c) skewness, d) kurtosis; (classifications of Wentworth, 1922; Folk and Ward, 1957).

Grain-size parameters along the sampling lines associate largely with five depth zones (Fig. 4). Sediment closest to the shoreline (till ca. 1 m depth), where the wave influence is the most pronounced, is predominantly very well sorted medium sand with coarse-skewed to near-symmetrical grain-size distribution curves and kurtosis ranging from platykurtic till very leptokurtic. Increasing depth (1-5 m) correlates with finer mean grain size, better sorting and more positive skewness of the medium to fine sand deposits. Deeper (5-13 m) areas are dominated by fine sand with greater sorting variability and near-symmetrical skewness. The greatest variability of all parameters, including the coarsest, most positively skewed and worst sorted deposit, is found at 13-20 m depth. These sediments are interpreted to be derived from till erosion in northern offshore areas. Deeper than 20 m, fine to very fine-grained sand with more negative skewness and a wide range of sorting and kurtosis values is present. These southern deposits have the finest grain size and accumulate below normal wave base.

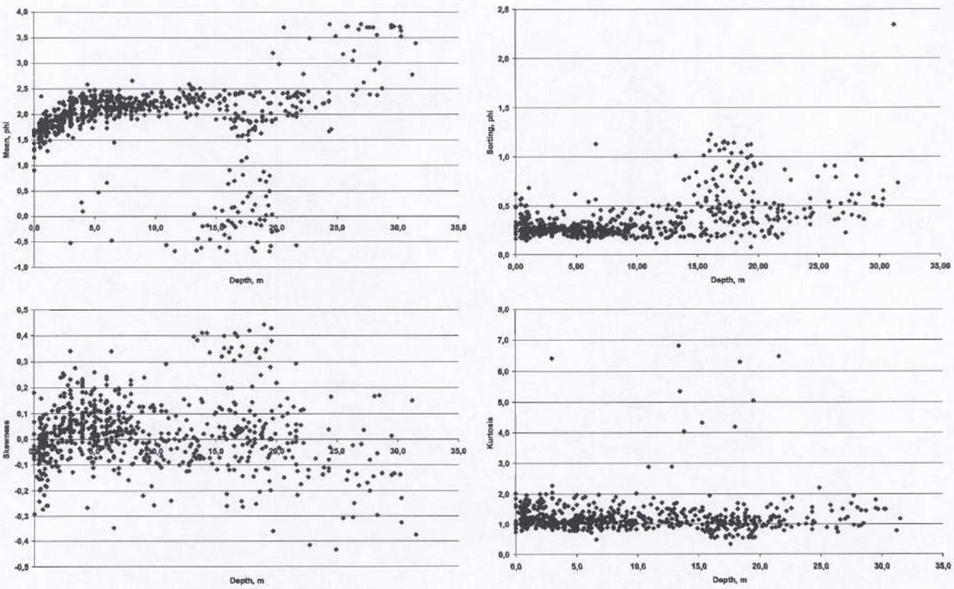

Fig. 4. Grain-size statistical parameters: mean grain size, sorting, skewness and kurtosis versus water depth.

Sedimentological conditions and depositional processes

According the PA method, the sediments closest to the Lithuanian shoreline reflect a balance between erosion and accumulation processes. Some areas of local shore erosion are present at Klaipėda, in the southernmost part of the study area, and north of Palanga (Fig. 5). Increasing depth and decreasing strength and variability of wave-induced turbulence allows accumulation within laterally continuous zones along almost the entire coastline. The interpreted strength of the accumulation character becomes greater offshore. Seaward of the accumulation zone there exists a coast-parallel area where sediment transport is predominant, with little erosion or accumulation. This most probably reveals the zone where wave reworked sediments are mixed with deposition from the longshore current. The deepest areas offshore are characterized by sea-floor erosion in the north and a deep-water accumulation area in the central part of the study area. Near Klaipėda there is northwest - southeast zone of erosion diagonal to the coast. Offshore in the most southern part, transitional or dynamic equilibrium predominates, with some sites of accumulation and erosion.

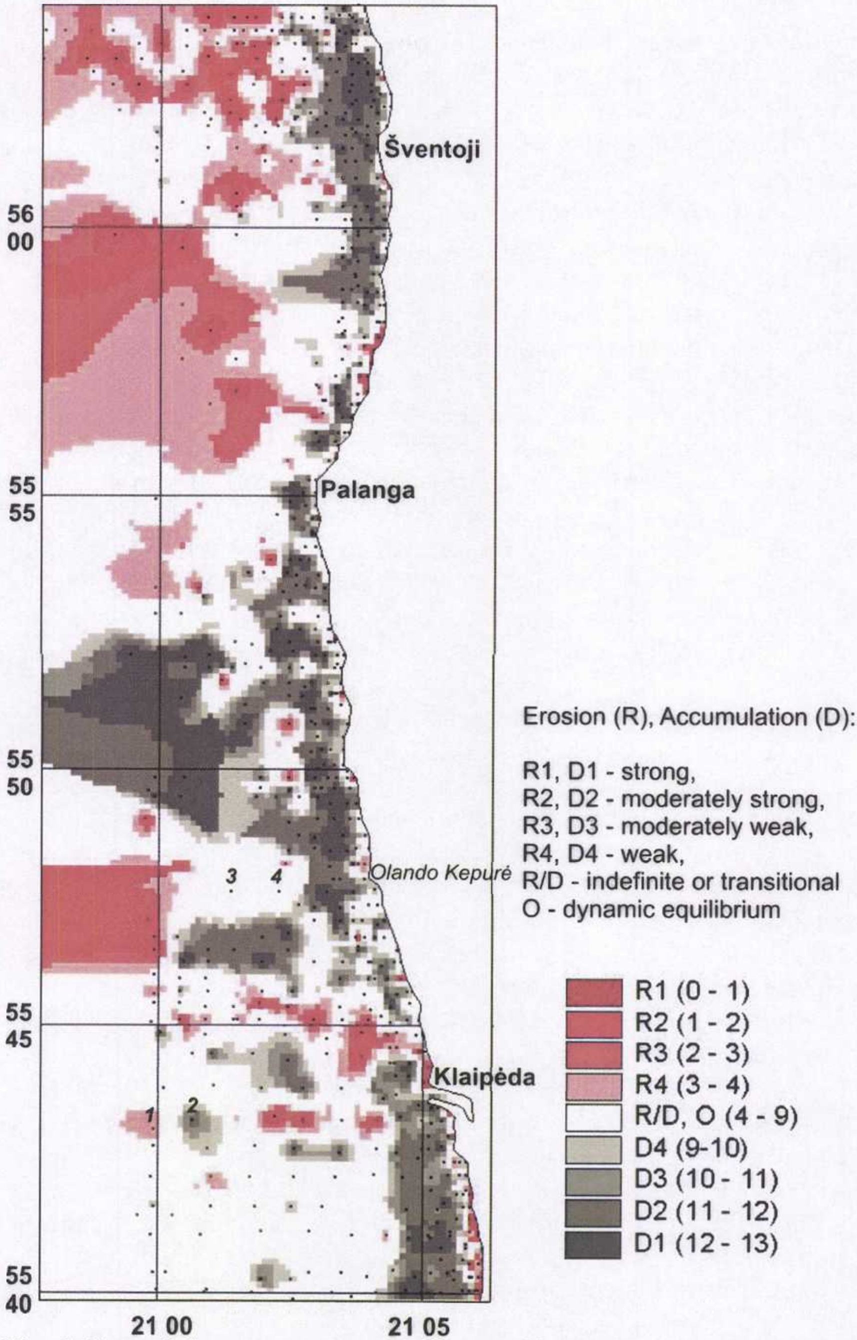

Fig. 5. Sum of the parameter anomalies used for evaluation of sedimentologic conditions based on spatial changes of grain-size parameters, according to the PA method. The numbered sites are taken as examples in the text.

TV interpretations of site-specific changes (Fig. 6) suggest largely similar patterns. Sediment transport from the broad area offshore is present in the north. Central offshore accumulation areas according to the PA method are consistent with the deposition associated with the FB- case on the TV maps (Fig. 6A). Sediment accumulation due to the movement into deeper water is present along the entire coast in the nearshore zone. In the southern part of the investigation area the TV case FB- (blue) indicates that sand is mostly transported into the zone deeper than 20 m south of Klaipėda. CB+ is interpreted as selective deposition with slight fine sediment removal. The inconsistency between FB- and CB+ trends in the south (Fig. 6a, b) might be related to the dominance of one or two parameter trends when the three parameters are summed in the TV method. The southern deposits have the finest grain size in the entire investigation area. Despite normalization, the distinct decrease in mean grain size in the southern study area is a dominant trend. On the other hand, the PA evaluation indicates dynamic equilibrium offshore in the most southern part of the investigation area, where the bed is neither accreting nor eroding. This relatively indecisive PA characterization may also be compared with mixed TV trends (FB- and CB+) in this area. It is tentatively concluded that dynamic equilibrium conditions are not consistent with the TV model assumptions, and TV interpretations are less reliable.

Although case CB+ is commonly interpreted as selective deposition, the CB+ map can contain trends related to both coarsening selective deposition and lag deposit development, since the CB+ characteristics are developed in both cases (Fig. 6B). But these two alternatives would indicate opposite transport directions. McLaren and Bowles (1985) avoid this problem by assuming that the lag by itself does not provide a transport direction, although it may if compared to adjacent deposits. With increasing energy selective deposition with relative sediment coarsening can characterize sedimentation during active transport (McLaren and Bowles, 1985). But increasing energy at a specific site will lead to reworking and erosion. Therefore, the lag deposition case is presumably a more common effect in a high-energy environment.

We do not produce one final map by adding both fining and coarsening trends together, which has been done in several studies (McLaren and Little, 1987; Gao and Collins, 1991; Wu and Shen, 1999; Duman et al., 2004; Hughes, 2005), but analyze them separately. Le Roux and Rojas (2007) have also proposed to analyze these two cases separately in order to be able to compare and combine the results with additional information, such as from the PA method, and to produce meaningful and valid conclusions about transport directions.

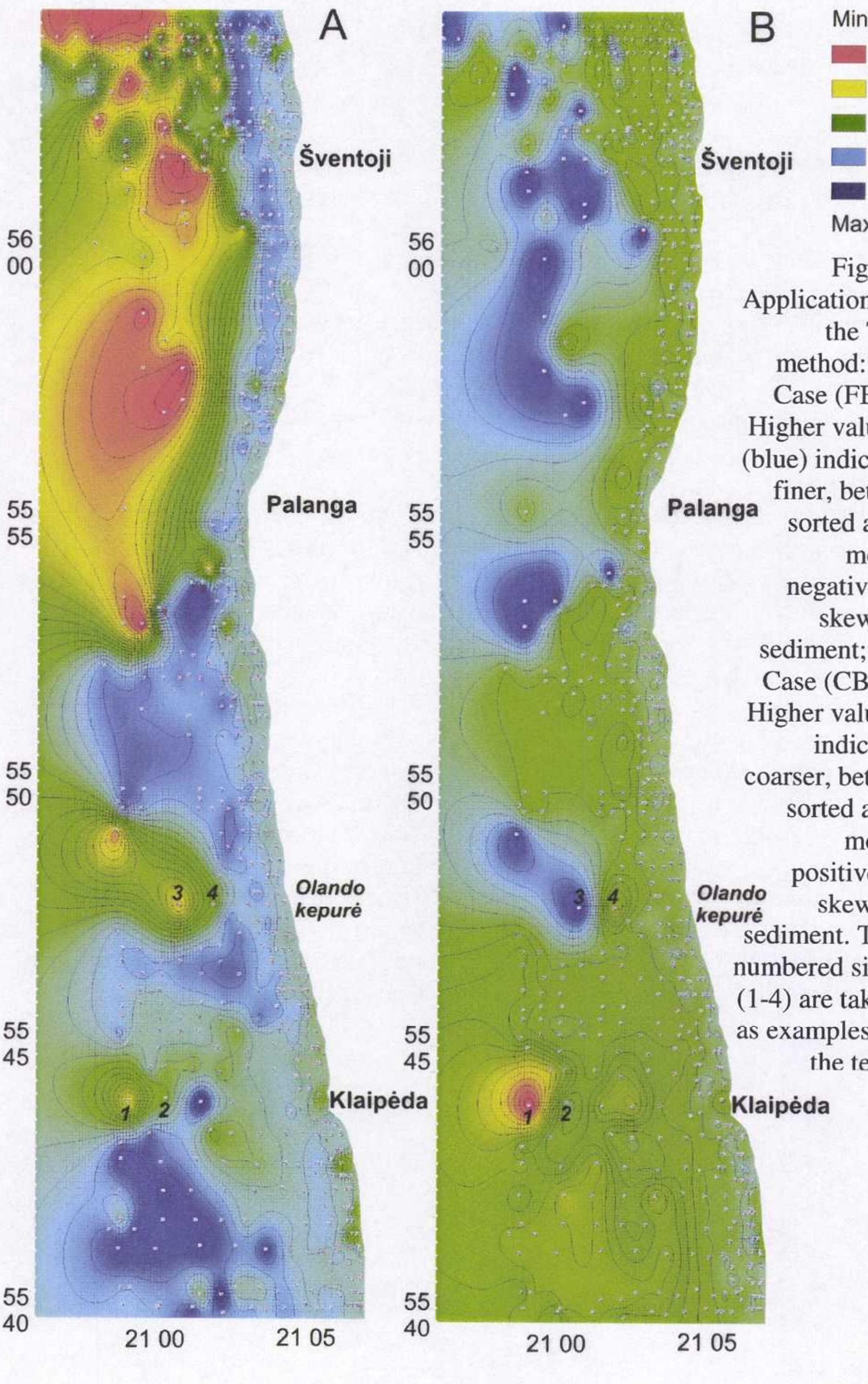

Fig. 6. Application of the TV method: A) Case (FB-). Higher values (blue) indicate finer, better sorted and more negatively skewed sediment; B) Case (CB+). Higher values indicate coarser, better sorted and more positively skewed sediment. The numbered sites (1-4) are taken as examples in the text.

Each of the methods considered is limited by its perspective: the PA focuses largely on general trends, and the TV method assumes consistent changes, which may not always be realistic. To help compensate for the uncertainties over generalization or due to the natural variability apparent with greater resolution, the strengths of one method can be used to compensate for the weaknesses of the other. The alternating but simultaneous application of these two approaches is proposed and illustrated in examples below. The objectives of these successive steps are:

1. PA – to obtain a general characterization (erosion, deposition, reworking)
2. TV – to identify possible pathways
3. PA – to eliminate illogical/contradictory pathway alternatives
4. TV – to interpret probable (rather than possible) pathways
5. PA+TV – to synthesize general conditions and specific pathways into a coherent conceptual model of the sedimentological setting.

Sampling sites 1-2 (Figs. 5, 6). The PA method indicates weak erosion at sampling site 1 and accumulation at site 2. This is in agreement with the TV method case FB-, according to which sediment is transported from site 1 into site 2. TV case CB+ is defined as coarsening, selective deposition, i.e. sediment movement is from site 1 to 2, which is consistent with total deposition along a fining trend (TV case FB-). Both TV and PA methods suggest that sediment is being transported from sampling site 1 and deposited at site 2.

Sampling sites 3-4 (Figs. 5, 6). Dynamic equilibrium or sediment transit, when neither accumulation nor erosion is predominant, is indicated at sampling sites 3 and 4 by the PA method. The TV case FB- supports sediment transport from sampling site 3 toward 4, but case CB+ is defined as coarsening selective deposition with sediment movement from 4 into 3. These opposite directional trends on the two TV maps (according the CB+ and FB- cases) do not allow a simple interpretation of direction. Considering the transient sediment character according to the PA method, the variability between sediment accumulation and erosion might well explain the inconsistent TV trends.

Discussion and Conclusions

The grain-size distribution of the bottom sediments reflects both the energy of the environment of deposition and the sizes available from the source sediment (provenance). Environmental and process orientated grain-size interpretation techniques dealing with complex areas are aggravated with problems, such as multiple sources, different environments and sedimentary events, as well as sampling irregularities.

For instance, nearshore sediment in transport may be combined with new sediments from local river supply, beach or sea-floor erosion (Masselink, 1992). Any addition of fresh sediments disrupts the equilibrium state the sediment had reached and complicates the interpretation of grain-size trends in the area (Baraniecki and Racinowski, 1996; Mohd-Lokman et al., 1997; Wu and Shen, 1999). McLaren et al. (2007) state that a new source of sediment or a change in a dynamic regime would break down the existing transport trend. They therefore advice to analyze transport lines in different transport environments with unique source and/or dynamic behaviour separately. Baraniecki and Racinowski (1996) propose to divide the data set based, for instance, on geomorphological conditions of the area, which would allow deposits accumulated in different environments to be interpreted separately. This also reduces the dataset, which could be advantageous, because although the uncertainty in detection of transport pathways is presumably reduced when many sampling sites are analyzed, the number of possible pathways may be too large to test all possibilities (Hughes, 2005). However, some subjectivity is introduced while subdividing the areas within which grain-size parameters are compared. Also, some information is lost because the region or local patterns can suggest transport alternatives.

Commonly one set of samples is considered to represent a phenomenon or event and related time interval, which can be chosen at different levels of resolution (Hartmann, 2007). In order to represent a deposit from one transporting agent accumulated under one set of conditions, the suite of samples has to be collected immediately after a sedimentary event (Tanner, 1995). This is not easy to achieve in a changeable nature. There are many factors, such as the wave energy level and cross-shore sediment transport processes affecting the nearshore sediment texture (Masselink, 1992). Sediment accumulation character largely depends on the environment of deposition. There is no consensus regarding the sample spacing, and different sedimentary studies use various sampling techniques depending on the specific goals of the investigation. Sediment trend analysis aims to determine if there is a transport relationship between two samples. To have samples related by transport they should be collected as close as possible. Since sediment trend analysis does not aim to represent one transport process nor has any direct time connotation, the depth to which surface sample is taken is not significant (McLaren et al., 2007). The interpreted sediment texture is considered to represent an integration of all processes responsible for transport and deposition at the sampling site (Wu and Shen, 1999; Hughes, 2005).

The interpretation of grain-size trends is closely related to specific goals of each approach (Fig. 7). Site-specific changes along a pathway are used to interpret sediment transport directions (TV, left side of figure), whereas site deviations in comparison with population statistics of the area aim toward understanding of sedimentologic conditions in general (right side). Both perspectives predict sediment accumulation with sediment fining in connection with decreasing energy. Interpretation of sediment coarsening trends is more complex. The PA method assumes that coarser sediment is a result of sediment reworking in a high-energy environment. The TV method suggests two possible explanations: development of a lag or the coarsening at successive deposits along a transport path due to selective deposition. The lag case is presumably a more common effect in a high-energy environment and is most consistent with reworking, as suggested by PA for the general response to high energy. Coarsening in connection with selective deposition is, however, possible if energy increases along a specific transport pathway. Natural variability complicates the assumption of continuous changes along a pathway (TV method). Therefore, the interpretation of sedimentologic conditions within an area of interest by the PA approach can give basis for distinguishing between transport alternatives or for judging their overall reliability.

In sedimentary process studies winnowing is a common explanation of negative skewness (phi-values), whereas an addition of fine particles skews the frequency curve toward more positive values (Duane, 1964; McManus, 1988). However skewness is treated differently when interpreting the direction of sediment movement in the TV method because it is not skewness itself but changes in this parameter value relative to the sediment source that are diagnostically important (McLaren, 1981). In the PA method finer, better sorted sediment with more positive skewness and a flatter distribution curve relative to the average values is characteristic of accumulative environments. However, the fining trend in the FB+ case of the TV method is considered invalid in the transport direction because with sediment fining the skewness must become more negative relative to the sediment source (McLaren and Bowles, 1985). The TV FB- case from total deposition is known in low-energy environments, where there is little chance for selective deposition and the sediment is left behind during a single sedimentary event, for instance, in ocean basin deposits, lake bottom sediments, beach berm and flash flood deposits (McLaren, 1981). This is the only trend (FB-) logical for interpretation of silty and clayey sediments, in which suspension deposition is essentially the only influence upon fine fractions, i.e. where a fining trend is observed toward areas with calm water settlement (Stevens et al., 1996). We consider two cases (FB- and CB+) out of eight possible because one or both of these have been shown to produce statistically significant results in most of the studies in different environments as fluvial deposits, longshore transport, river floodplains (McLaren and Bowles, 1985; Gao and Collins, 1992; Asselman, 1999; Le Roux and Rojas, 2007).

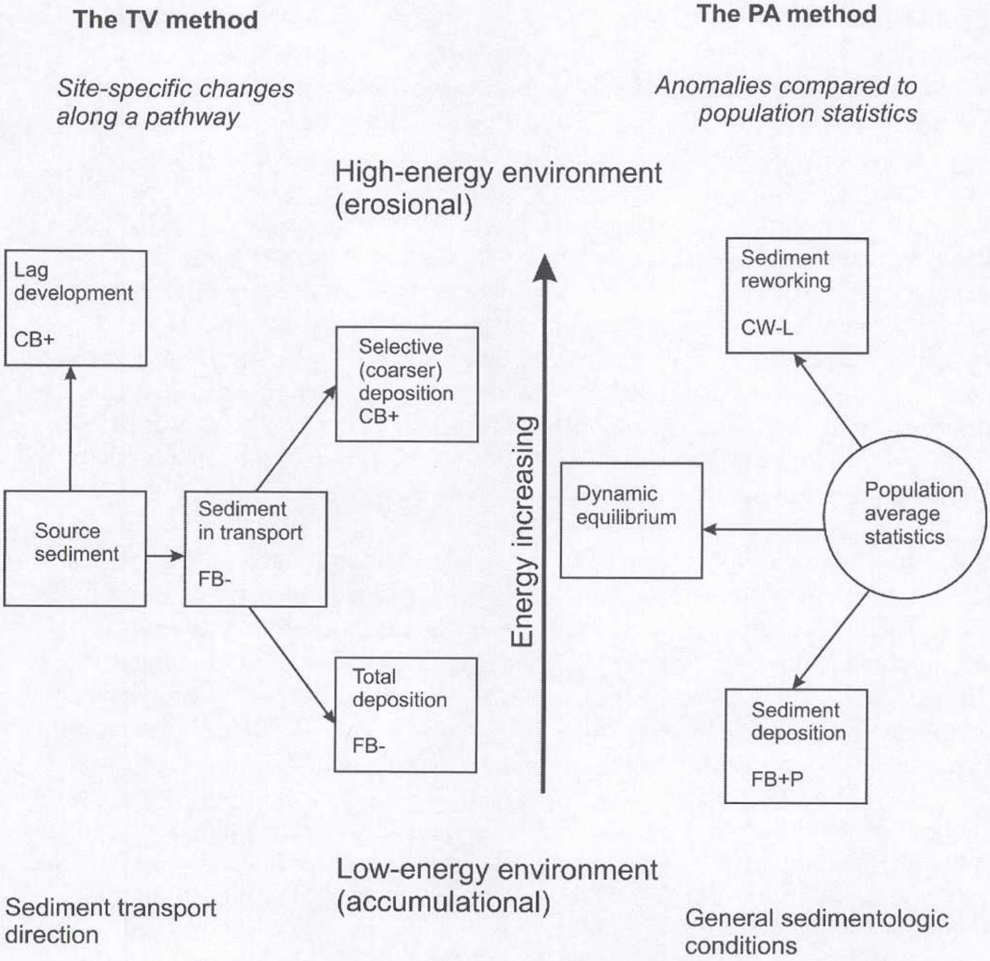

Fig. 7. Summary of the TV and PA approaches. Both methods utilize spatial differences in grain-size parameters: coarser mean (C), finer mean (F), better sorting (B), worse sorting (W), more negative skewness (–), more positive skewness (+), more leptokurtic kurtosis (L), and more platykurtic kurtosis (P).

The improvement of sorting in the direction of transport has been considered to be related largely to sediment fining (Griffiths, 1951; Inman, 1949). However, Baertholomä and Flemming (2007) note that size-sorting does not necessarily result in better sorting with decreasing grain size in the direction of transport.

Inman (1949) states that once sediment attains the best sorting, continued transport and fining will cause the sorting to become worse. Interpreting transport direction sorting is assumed to improve in the direction of transport and in the lag deposit too (McLaren model), when in evaluation of sedimentary environment two possible changes are considered (the PA method).

Both methods, TV and PA, consider all grain-size parameters to be of equal importance, but the PA method also uses kurtosis. Some authors do not consider kurtosis to be environment-sensitive and diagnostic (e.g. Friedman, 1961). Other authors stated that both skewness and kurtosis are valuable in identifying the sedimentary environments because differences between samples are noted mostly in the "tails" (Douglas, 1946; Mason and Folk, 1958 cf. Tanner, 1995). Flatter (more platykurtic) than average frequency curves and better sorting in the PA method is used to characterize weaker energy environment, implying a tendency for sediment accumulation with gentle reworking. Steeper (more leptokurtic) frequency curves and relatively worse sorting suggest variable environmental energy and sediment erosion. In such environments sediment is deposited and buried so rapidly that there is limited sorting (Baraniecki and Racinowski, 1996). Kurtosis helps identify deviations from a normal distribution, information that strengthens environmental interpretations from grain-size trends.

Different cases in the TV method can give contradicting transport directions, in addition to complications related to the CB+ case discussed above. To control the correctness of the resultant interpretation it is necessary to use any additional information available, for instance bathymetric data or coastal morphology (Hughes, 2005; Le Roux and Rojas, 2007; McLaren et al., 2007). We suggest that simultaneous usage of the two methods in focus (PA and TV) gives basis for distinguishing between true and false trends, strengthening the final conclusions.

Methodological modifications of sediment trend analysis have led to development of two main alternatives of STA: line-by-line and two-dimensional vector approaches. McLaren et al. (2007) argue that vectors should only be used in a preliminary stage to discern possible trends then followed by a more rigorous line-by-line approach. Although they agree that 2-D vectors can provide information about possible sources and sinks, they also state that averaging of samples used in vector methods can reduce the information content. Le Roux and Rojas (2007) basing on a few comparative studies of various modified STA methods conclude that a two-dimensional (vector approach) produces more representative trends than a one-dimensional (line-by-line) technique, but if used together they can complement each other.

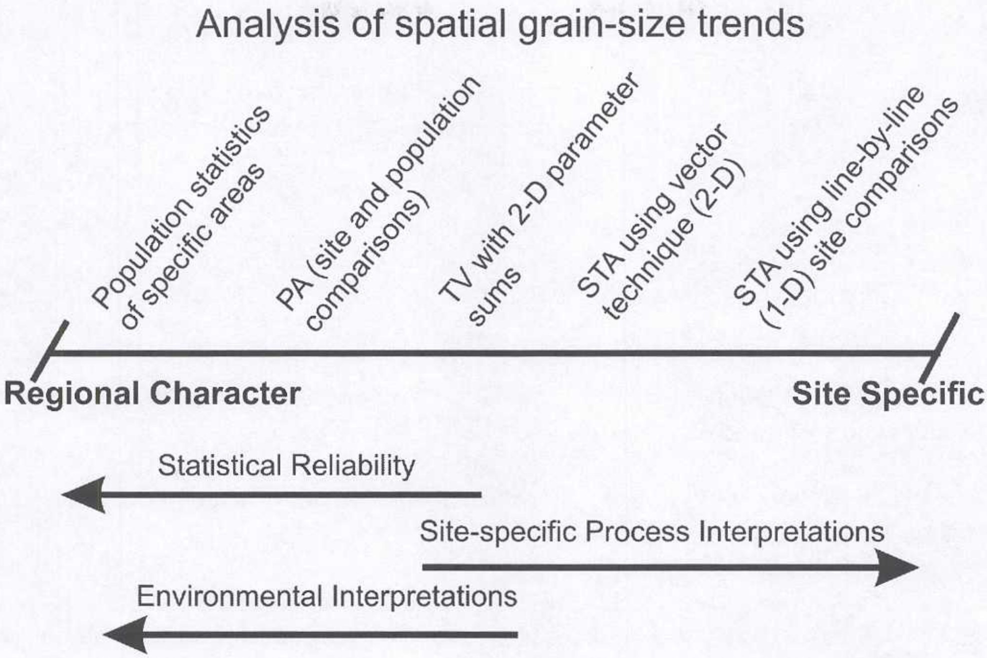

Fig. 8. Methodological alternatives for grain-size trend analysis.

An analysis of grain-size interpretation techniques and their modifications suggests that the combined use of different approaches provides complementary information about the sedimentary environment (Fig. 8). Population statistics give a general understanding about the balance between erosional and depositional processes, whereas site-specific techniques provide interpretations of sediment transport directions. The erosion, transport and deposition of sediments in aquatic environments is of interest regarding contaminant transport and sediment-water interactions, as well as quantitative assessments related to shore erosion, longshore drift, resource extraction and dredging.

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Provenance of silt and clay within sandy deposits of the Lithuanian coastal zone (Baltic Sea)

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Abstract

Mineralogical analysis of the silt and clay fraction of sandy deposits of 37 surface samples and grain-size data are used to interpret sediment sources acting in the SE Baltic Sea along the Lithuanian coast. Mineralogical composition was determined using X-ray diffraction (XRD) methods. Grain-size distribution was obtained by standard dry sieving and pipette techniques. For identification of sources we combined known compositional information of possible sources with logical models for mineral combinations related to regional geological provinces and processes, supported by results of correlation and factor (principal component) analyses between minerals, grain-size parameters and bathymetric features of the area. The main sources supplying sediment into the area are: 1) the Sambian Peninsula to the south, 2) the Nemunas River, whose discharge passes through the Curonian Lagoon, and 3) Late Pleistocene till erosion on the sea floor in the north and at the Olando Kepure shore cliffs. The general pattern of spatial distribution related to the identified sources for the fine-grained sediment fraction is interpreted as a shore-parallel transport of suspended matter, flowing northwards in the southeastern part of the Baltic Sea.

Keywords: Baltic sea; sediment sources; mineralogy; fine-grained sediments; sediment dynamics; grain size

1. Introduction

Sediment source (provenance) identification is a traditional geologic task for basin analysis and a central issue in the field of environmental management. The most common sediment criteria employed to identify sources are: 1) analysis of bulk composition, e.g. total mineralogy of the sample (Pettijohn, 1975), magnetic properties (Oldfield et al., 1985; Lepland and Stevens, 1996), sediment geochemistry (Nagender Nath et al., 2000); 2) the analysis of a specific group of minerals, e.g. the semi-quantitative distribution of clay minerals (Bengtsson and Stevens, 1998; Gingele et al., 2001), the content and trends of heavy minerals in bottom sediments (Rittenhouse, 1943; Briggs, 1965; Pettijohn, 1975; Luepke and

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Clifton, 1983; Morton, 1987; Bengtsson and Stevens, 1996; Lång and Stevens, 1999) and 3) the morphological, chemical and radiometric analysis of single grains from suitable mineral phases (Weltje and Eynatten, 2004), for instance quartz grain-surface features (Moral-Cardona et al., 1996).

The heavy-mineral analyses commonly used for provenance studies have been plagued by the problems of compositional changes due to mineral instability in sedimentary environments and selective hydraulic sorting during transport (Rittenhouse, 1943; Briggs, 1965; Luepke, 1980; Morton, 1984; Blatt, 1985). The strong dependency of both mineralogy and geochemistry upon grain size is usually dealt with by selecting narrow size intervals for analysis, but changes in the overall grain size of the deposit may also shift the frequency modes of individual mineral components differently, changing the composition within the analyzed interval. The disadvantage of single-grain techniques, which focuses on variability within a certain mineral phase (e.g., the chemical composition of detrital tourmaline), is that they can be utilized only if their results can be firmly connected to the bulk mass transfer from source to basin, i.e., the parent-rock mass corresponding to a single grain must be known (Weltje and Eynatten, 2004).

Most of the provenance studies have been focused on the sand fractions or bulk sediment samples. The silt fraction has been avoided in provenance studies despite the fact that sediments from many depositional environments do not contain enough sand to make statistically significant petrographic determinations (Poppe et al., 1991) and despite the possibility that the fine sediments transported in suspension have quite different sources and environmental influences than do the sandy fraction sediments. In addition, many of the sources in areas with contaminated soils or other point sources of pollution supply fine-grained sediments with relatively high metal contents. This is in part due to high specific surface area of the smaller particles, their surface adsorption and ionic attraction (Hochella and White, 1990). The provenance and transport history information contained in mineralogical characteristics of fine-grained sediment or the fine-grained part of coarse sediment can be used, therefore, to evaluate the source and fate of pollution.

Although the medium-to-fine-silt and clay fraction that is primarily used for our evaluation represents only a minor fraction of the total grain-size distribution of the sandy deposits, it was chosen because it contains greater mineralogical variability than coarser fractions or bulk sediments (Stauskaitė, 1962; Blatt et al., 1972; Blashchishin, 1976; Blatt, 1985; Buckley and Cranston, 1991) and thereby providing alternative components to distinguish the anticipated sources. Quantitative mineralogy of fine-grained fractions has only recently become feasible on a more routine basis with the modeling programs for X-ray diffractograms based upon the Rietveld methodology (Ward et al., 1999). Since this finest part of the Lithuanian sandy coastal sediments is present in only small amounts, X-ray diffraction is an appropriate, non-destructive technique. A suspension-transported, fine-grained fraction is efficiently mixed, limiting the risks for modifications during transport due to selective sorting (Komar, 1987) and causes mud-derived provenance signal to be much more representative than sand-based provenance signals (Blatt, 1985). Furthermore, the finest part of sediment can be transported in suspension over large distances and can, therefore, represent even remote sources (Blashchishin, 1976). Limited grain size (<0.01 mm) is used also in order to reduce the effects of different grain-size distributions between samples.

The sandy nearshores of the Lithuanian coast are strongly affected by the East-Baltic nearshore current, which begins near the Sambian Peninsula, annually supplying from 0.1 to 1 million m^3 of fine sand and silt sediment (Knaps, 1966; Blashchishin and Usonis, 1970). The summarized sediment flow direction in the SE Baltic Sea is north-northeast, with an average water flow velocity of 3–4 cm/s (Žaromskis, 1996). Sources and transport pathways for the sediment in the Lithuanian coastal zone of the Baltic Sea have been previously interpreted using the mapped distribution of heavy minerals (Stauskaitė, 1962; Linchius and Uginchius, 1970; Blashchishin, 1976; Apanavičiūtė and Šimkevičius, 2001) and other mineral components within fine-sand and coarse-silt fractions and for bulk samples of bottom sediments (Blashchishin and Usonis, 1970; Blashchishin, 1976; Blashchishin and Lukashev, 1981; Emelyanov and Trimonis, 1981; Trimonis, 1987; Emelyanov, 1995). Grain-size characteristics have also been used for sediment transport interpretations (Janukonis, 1994–1995; Kairytė, 2001). From these previous investigations, a number of coastline settings can be linked along the transport pathways in the SE Baltic Sea, and each area exerts a certain influence on the composition of coastal sediments. The sediment environments of particular importance are: a) Sambian Peninsula coast in the south, including shore erosion, b) Curonian lagoon, including the Nemunas River discharge, c) linear shorelines, characterized by long-shore northward transport and both depositional

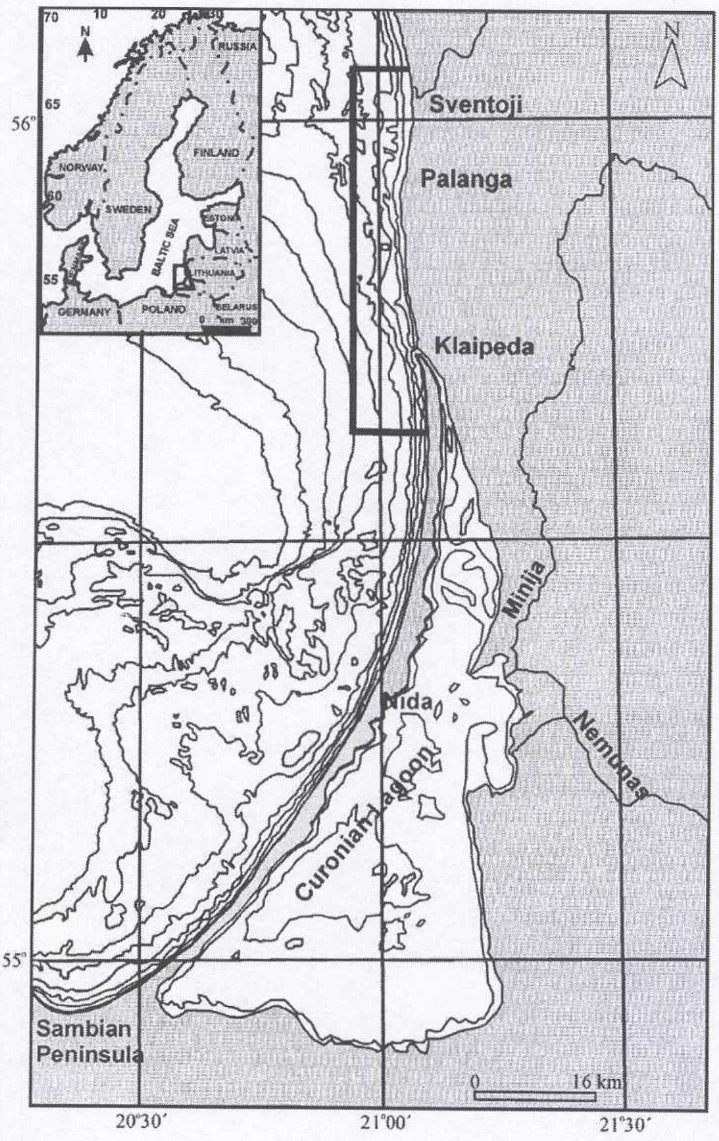

Fig. 1. Situation map of the Lithuanian Baltic Sea nearshore area (from Gelumbauskaitė et al., 1998). Isobaths on the seashore are drawn at every 5 m, and on the Curonian Lagoon at 2 and 5 m. Part of Sambian Peninsula is seen at SW corner of the map. The borders of the study area are marked in black.

and erosional nearshore areas, d) areas of sea-floor erosion of exposed late Pleistocene till deposits and e) accumulation areas, e.g. offshore deeps (Fig. 1).

The earlier studies of the Lithuanian coastal deposits, and in fact nearly all provenance investigations of sandy sediments, do not attempt to evaluate the finest fractions. The known problems with selective hydraulic sorting, well documented by heavy-mineral enrichment in the nearshore zone of the SE Baltic (Blashchishin, 1976) and the size variability of the sediment supplied from different sources interpreted for this region, suggests that the fine-fraction would be suitable as a complement and test for sand-based interpretations. The main objectives of this study are, therefore, to: 1) identify the sources for fine-grained fraction of the sediments in the Lithuanian coastal zone using mineralogy data of the <0.01 mm fraction, and 2) discuss the possibilities and limitations of the fine-grained fractions for provenance analyses of sandy deposits.

2. Methods

2.1. Sampling

Bottom sediment samples from the coast of Lithuania (the Klaipeda–Ventspils marine plateau) were taken along 92 transects oriented perpendicular to the shoreline and spaced at 500 m. Samples were taken from the shoreline to the depth of about 35 m. Surface sediments (0–5 cm) were sampled at 712 stations during 4 yrs.

Thirty-seven samples for mineralogical analyses were selected from the data set. The sites included those situated closest to the shoreline and those farthest offshore along 15 cross-shelf transects, and additional samples to provide good areal coverage and enable statistical procedures, but keeping a manageable number of samples for analysis (Fig. 2).

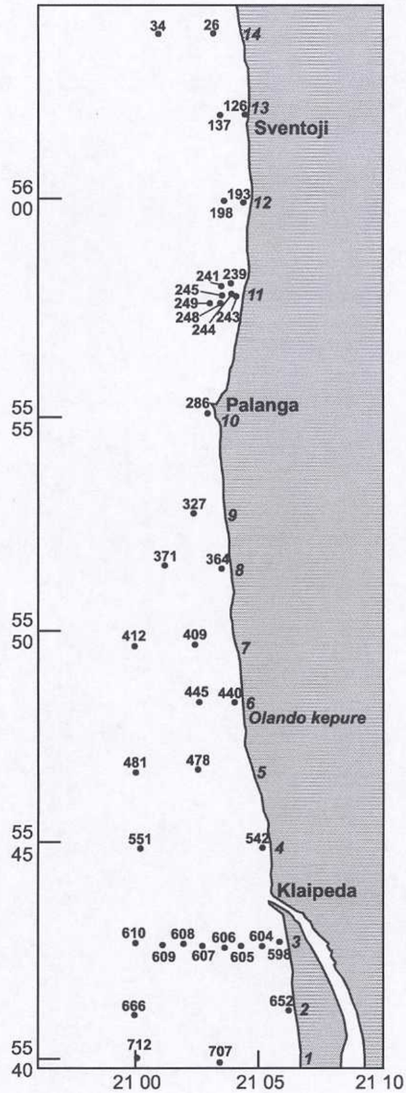

Fig. 2. Location of sediment sampling sites (circles). 26, …, 712—numbers of samples, 1–14—profile numbers.

2.2. Analyses

The samples for mineralogical analyses were dispersed with sodium diphosphate and ultrasound. Fractions less than 0.01 mm and 0.01–0.063 mm were separated from the coarse sediment using wet sieving and suspension settling time. The <0.01 mm size limit is defined as silt and clay size particles according to the classification of Bezrukov and Lisitzin (1960), widely used in Eastern Europe.

2.2.1. Mineralogical composition

Mineralogical composition of the samples was obtained by X-ray diffraction (XRD). Analyses were

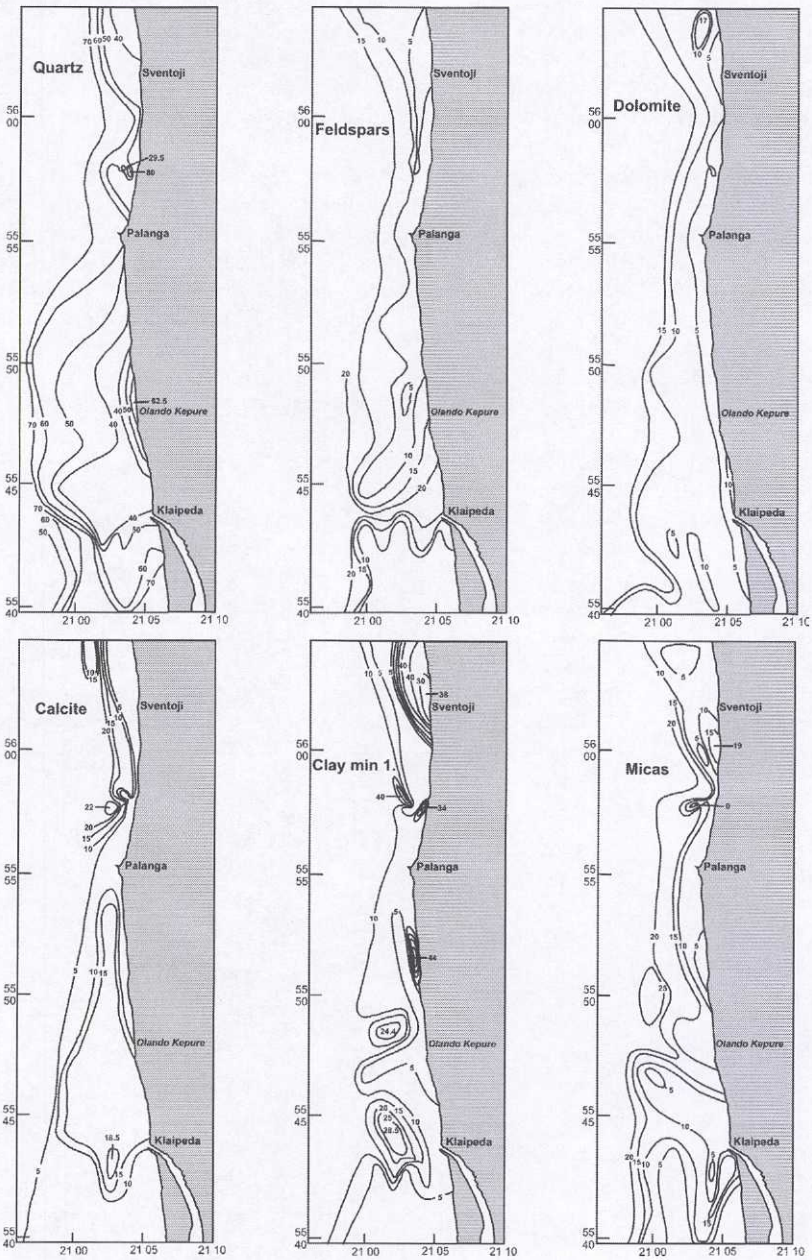

Fig. 3. Distribution maps of the <0.01 mm fraction of quartz, feldspars, dolomite, calcite, clay min. and micas. Mineral groups: Feldspars = orthoclase + microcline + albite + anorthite; Clay min. 1 = montmorillonite + illite + kaolinite + chlorite; Micas = muscovite + biotite.

performed using a Siemens D5005 diffractometer with Ni-filtered, Cu-Kα radiation tube. Samples were scanned between 2–65° 2Θ at 40 kV and 40 mA effect and with a scanned speed of 1° 2Θ per min. The *Siroquant* program (Ward et al., 1999), based upon the Rietveld methodology for diffractogram simulation, was used for quantification of the identified minerals. The mineral composition was determined for powdered, non-oriented samples within specific grain-size intervals: 37 analyses of the <0.01 mm fraction and 17 analyses of the 0.01–0.063 mm fraction. Bulk-sample mineralogy was documented for 7 sites.

2.2.2. Grain-size composition

Grain-size composition was determined using standard pipette methodology (0.005–0.5 mm) and dry sieving with a set of 22 sieves for the coarse-grained fractions (0.05–10.0 mm). Statistical parameters of the grain-size data were calculated according to the graphic method of Folk and Ward (1957).

2.2.3. Statistical procedures

Statistical correlation analysis (Pearson correlation) was applied to establish the possible mineral associations and relationships between the mineralogy, grain size and water depth. The weight percentage of minerals identified in the <0.01 mm fraction, statistical parameters of the grain-size data (mean, sorting and skewness), and the water depth were used to build the correlation matrix. Statistical significance of the obtained values of Pearson correlation coefficients (r) was assessed by t-test. Since the correlation coefficients presented below are generally relatively weak, factor analysis, by means of principal component extraction and Varimax rotation, was performed on the same set of variables to support interpretation of parameter relationships and simplify the complex data by identifying a relatively small number of controlling factors that represent relationships among sets of interrelated variables. Factor analysis was performed on the set of 17 variables and 37 samples.

3. Results

3.1. Mineral distribution trends

The Lithuanian coastal sediments are composed of quartz, K-feldspar (orthoclase, microcline), plagioclase (albite, anorthite), carbonates (dolomite, calcite), micas (biotite, muscovite) and clay minerals (illite, chlorite, kaolinite, montmorillonite, glauconite, vermiculite). Other minerals found in trace amounts include actinolite, magnetite, ilmenite and zircon. Bulk samples and fractions 0.01–0.063 mm show that the coarser part of sediment is consistently

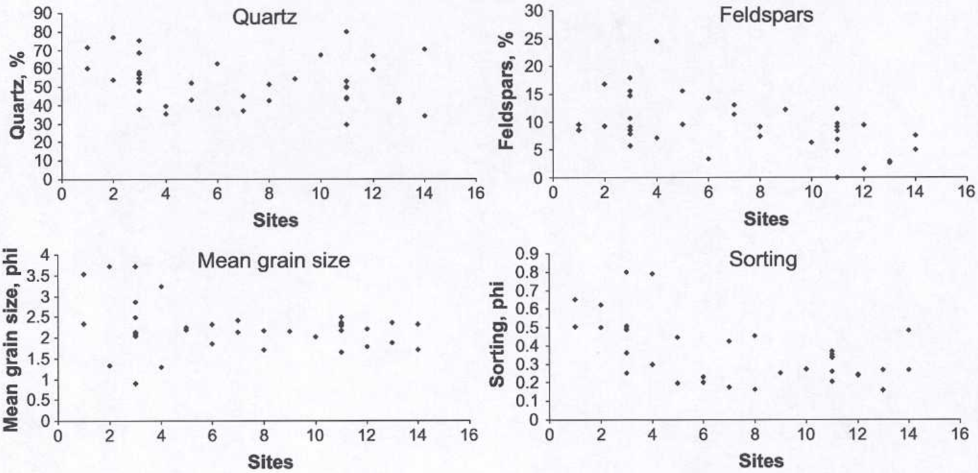

Fig. 4. Mineral content of the <0.01 mm fraction and changes in grain-size parameters from south to north. Sites correspond to profile numbers on the location map (Fig. 2).

predominated by quartz, and includes only a few percent feldspars (Appendix A). Considering this limited mineralogic variability, the following descriptions are focused on the considerably greater mineralogical variation in the finest of analyzed fractions (less than 0.01 mm).

Quartz is also predominant in the fine fraction, with an average of 52.6%. In rare cases, quartz is less than 40%. The maximum quartz concentrations are observed in the southern part of the investigation area. Quartz concentration decreases considerably at Klaipeda strait (Fig. 3). Locally high concentrations of this mineral are documented at Olando Kepure (62.5%). The content of quartz is higher offshore in the north and a slight increase occurs with water depth (Figs. 4 and 5).

For most samples the second most abundant mineral group is the feldspars. In the <0.01 mm fraction K-feldspar, especially microcline and orthoclase, and plagioclase, generally albite, are common. The total feldspar content ranges from 1.5% to more than 24% with an average of 9.7% (Appendix A). The main feature of the feldspars is their maximum concentration at Klaipeda, resulting in smaller quartz concentrations. The sediments to the north and south of this area are not as rich in feldspars (Fig. 3). The concentration of feldspars gradually decreases northwards, where the belt of high feldspar concentrations (>10%) narrows and moves toward coastline (Fig. 4). However, considering all samples the concentration of total feldspars also increases slightly with water depth (Fig. 5).

The third largest group of minerals found in the study area is carbonates, including dolomite and calcite. Dolomite occurs at all sites, the average content being 7.5% (Appendix A). Although this mineral reaches its maximum in the north (17.1%), the main trend is a distinct increase with water depth and the occurrence of a field of higher values in the south, near Klaipeda (Fig. 3). Calcite is found in 25 samples, with an average content of 9.4% (0.5–22.4%; Appendix A). The field of greatest calcite content begins at Klaipeda, where it is the widest, and gradually narrows northward, ending south of Palanga (Fig. 3). Calcite concentration increases again north of Palanga, whereas south of Klaipeda it is relatively low. Because calcite often reflects biogenic production, it is therefore not further considered in our later discussion of provenance.

The content of clay minerals is generally less than 10%, but in some places 20–50%, with maximum values present in the north (Fig. 3). Usually illite is the main component. Glauconite ranges from 0.7% to 4.7% and is identified mainly in the <0.01 mm

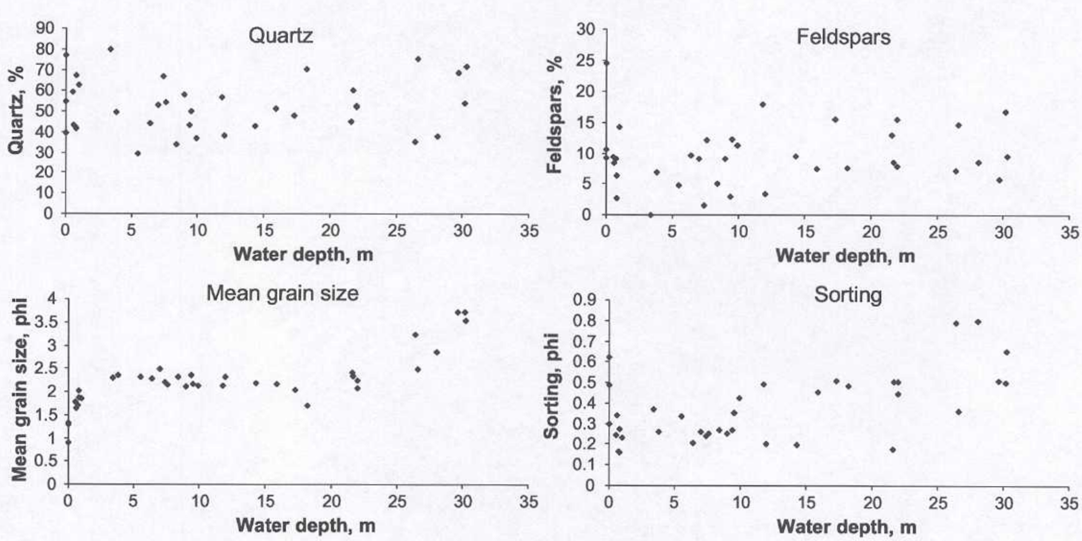

Fig. 5. Mineral content of the <0.01 mm fraction and changes in grain-size parameters versus water depth.

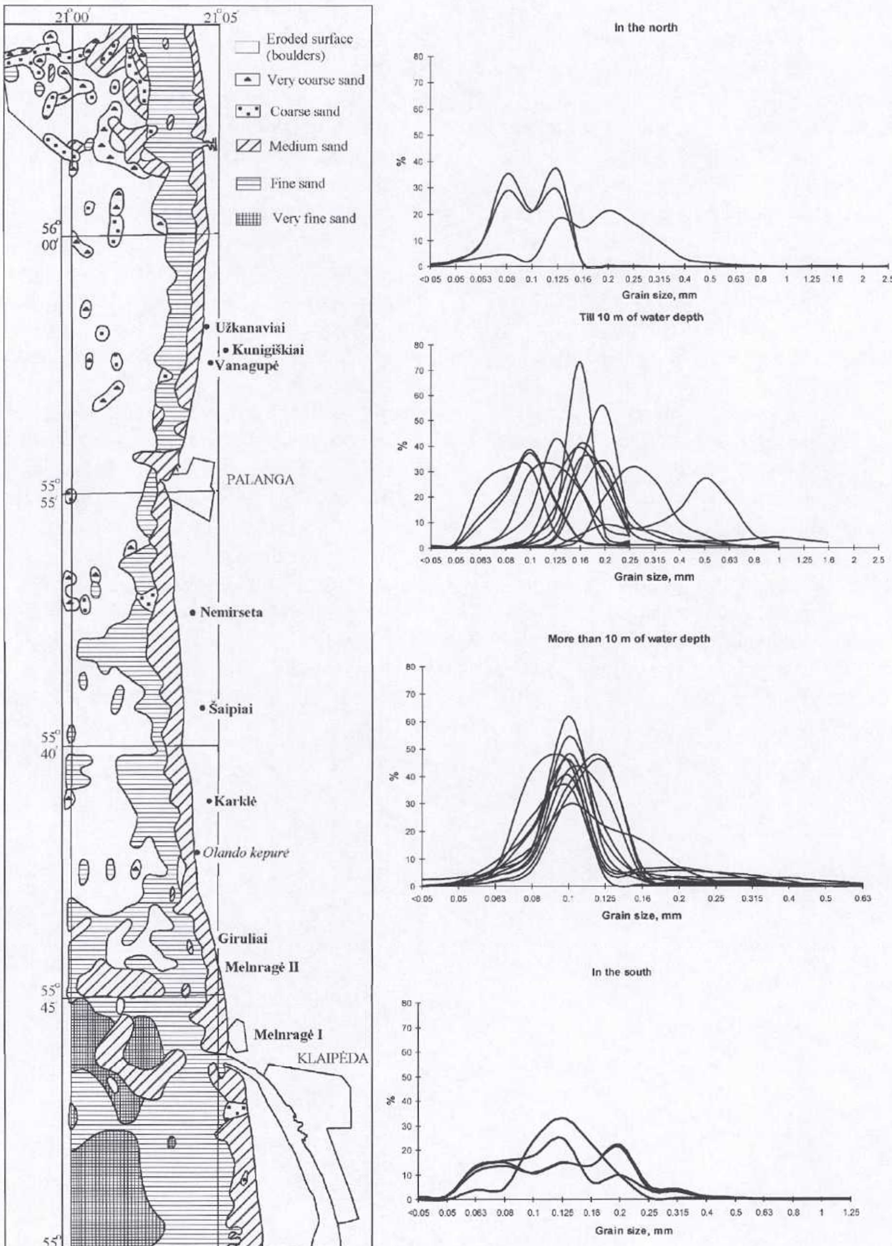

Fig. 6. Sediment composition (based upon classification of Wentworth (1922 (from Larson et al., 1997))) and grain-size distribution curves.

fraction (average 2.8%; Appendix A). Chlorite varies from 2% to 8% (average 4.4%; Appendix A). This mineral is best represented between Palanga and Klaipeda. Vermiculite and kaolinite are found in very few samples and only in the north.

The concentration of micas (muscovite and biotite) in the silt fraction is predominated by muscovite, representing up to 21.7% of the total mineral content. The average mica concentration is 11% (Appendix A). The variation of these minerals shows lower amounts in greater than 25 m of water depth. The locally high concentrations of micas reach ca. 20%, such as near the Klaipeda strait and along the seaward shore of the Curonian Spit, while the background concentration in the area south from Klaipeda varies from 0% to 10% (Fig. 3).

3.2. Grain-size distribution

Generally, sediments are very well to moderately sorted (σ=0.16–0.8φ), medium to very fine sands (1.3–3.7φ) with a variable skewness (coarse to fine) (S_k=−0.3 to +0.3). The coarsest sediments are found in the shallowest part, the nearshore zone, and become appreciably finer at depths greater than 5 m (Fig. 6). The finest material is found at greater than 25 m water depth south Klaipeda (Figs. 4 and 5). These two areas, with the coarsest and finest sediments, also show the worst sorting (Figs. 4 and 5).

The samples analyzed for mineralogy are mostly fine and very fine sand. As a complement to grain-size statistical parameters, the modes of the distribution have been documented. Unimodal sediments are most common near the coast (Fig. 6) and in the entire central part of investigation zone (Klaipeda–Palanga). The sorting of unimodal sediments increases with depth. Polymodal sediments are present in deeper parts. The highest modal complexity (two, three or four modes) is present south of Klaipeda. Several bimodal sediments are also found in the northern area (Sventoji–Butinge).

4. Provenance interpretations

Mineral trends in the investigation area are characterized by gradual changes in concentration away from the coastline, while continuous zones of composition exist parallel to the coast. This mineralogical pattern is apparently controlled by the East-Baltic near-shore current, which has been acting for ca. 5000 yrs (Linčius, 1991). However, deviations of these general trends are probably due to sediment supply from sources along the coastal pathway, as discussed below. The northward sediment flow is strongest along the coasts of the Sambian Peninsula, but decreases considerably when reaching the distal end of the Curonian spit (Blashchishin and Usonis, 1970). This decrease also allows other, more local sources to become significant.

According to earlier investigations the southeastern part of the Baltic Sea is part of Paleozoic petrographical province, which during glacial periods was fed by products of mechanical abrasion of Precambrian granites and gneisses from Scandinavia and Ordovician, Silurian and Devonian carbonates exposed in the central and northern Baltic Sea (Blashchishin, 1976; Blashchishin and Lukashev, 1981). Sediments in the eastern Baltic Sea therefore consist mainly of quartz, feldspars, micas and carbonates. Fine-grained fractions of the deposits also contain glauconite and other clay minerals (Blashchishin, 1976; Blashchishin and Lukashev, 1981). Our results are in agreement with these general compositional expectations, although more specific geographic trends are discussed bellow.

4.1. Southern sources

In our results, the highest concentration of quartz observed in the south is consistent with sediment derived from the mineralogically mature till of the Sambian Peninsula, where quartz reportedly accounts for 84% and 87% of the fine-sand and coarse-silt fractions, respectively (Blashchishin and Usonis, 1970).

Although glauconite occurs in only 20 of our samples and only in the fraction <0.01 mm, its presence is important because it is interpreted as a characteristic detrital mineral derived from the Sambian Peninsula, Paleogene age, sediments (Blashchishin, 1976). The “Blue Earth” of amber mining quarry at Jantarnyj on the Sambian Peninsula has glauconite concentrations reaching 48% and 42% of the fine-sand and coarse-silt fractions, respectively (Blashchishin and Usonis, 1970; Blashchishin, 1976). A detrital origin of glauconite is consistent with suggestions that authigenic marine glauconite requires slow sediment accumulation rates (Pettijohn, 1975), usually in deeper marine settings (e.g. >30 m). Earlier studies in the southeastern Baltic Sea (Stauskaitė, 1962) show that this mineral continues to increase to the south, beyond the area of our investigation, reaching its maximum at the Sambian Peninsula. The direction of glauconite transport is similar to the longshore sediment flow (Trimonis and Stryuk, 2002) and glauconite has been observed up to 200 km north of Sambian Peninsula, indicating sediment flow along the coasts of the southeastern Baltic Sea (Blashchishin, 1976). In the Nemunas River alluvium glauconite occurs only in trace amounts (Blashchishin and Usonis, 1970). This leads us to the conclusion that glauconite accumulates in the bottom sediment almost exclusively from the northward sediment supply from the abraded shores of Sambian Peninsula to the south.

Glauconite has a positive correlation with micas, particularly biotite and orthoclase (Appendix B). Although relatively weak, this association is consistent with the higher concentrations of micas documented by Blashchishin and Usonis (1970) in the sediments of Jantarnyj (Sambian Peninsula), which increased in the fine-grained fractions. Orthoclase bears a positive relationship with micas (biotite and muscovite) and all these minerals including glauconite, correlate positively between themselves, but negatively with the sum of clay minerals. The first factor from the factor analysis, explaining more than 20% of the total variance (Appendix C), is characterized by orthoclase, muscovite, biotite and glauconite (Appendix D). This factor corresponds, we conclude, to the Sambian Peninsula source outside of the area of investigation (Table 1).

The maximum concentration of dolomite occurs in the north, but there is an overall increase of this mineral offshore and in the south, the deepest part of the study area, where the finest and the worst sorted sediments are documented. The third principal component of our factor analysis includes dolomite's positive correlation with water depth, its increase together with the fine fraction, and association with the most poorly sorted sediments, in relative terms. Pleistocene till and clay deposits are known to contain a considerable amount of dolomite, as well as other carbonates eroded by glaciers from Paleozoic deposits (sandstones, limestones and dolomite rocks) exposed in the northern and central part of the Baltic Sea (Blashchishin, 1976; Emelyanov and Trimonis, 1981; Emelyanov, 1995; Emelyanov et al., 1995). Therefore, dolomite in the Baltic Sea is interpreted to be detrital, which is also suggested by grain-morphology (Blashchishin, 1976) and the fact that deep waters of the Baltic Sea are undersaturated with respect to carbonates (Blashchishin, 1976; Emelyanov and Trimonis, 1981; Emelyanov, 1995).

Table 1
The main sources and their characteristic minerals in the <0.01 mm fraction

Source (<0.01 mm)	Characteristic minerals
Till of the Sambian Peninsula	Quartz Dolomite
"Blue Earth" from amber mining quarry at Jantarnyj (Sambian Peninsula)	Clay minerals (glauconite) Micas (biotite, muscovite) Feldspars (orthoclase)
Nemunas River	Feldspars (microcline, albite) Quartz (most abundant, but less predominant)
Sea floor erosion of Pleistocene till	Quartz Feldspars Dolomite
Coastal till erosion (Olando Kepure outcrop)	Quartz Feldspars

The Sambian Peninsula and the Nemunas River are much larger sediment sources than are the others.

4.2. Nemunas River source

The concentration of quartz is considerably less and feldspars are more abundant at Klaipeda strait and immediately to the north. The Klaipeda strait connects the coastal environments and the Curonian Lagoon, where the Nemunas River provides the main sediment input. The feldspar concentrations in the silt and sand fractions of Nemunas alluvium are 1.5–2 times higher than in the sediment supplied from tills of Sambian Peninsula (Blashchishin and Usonis, 1970). Our mineralogical data from the <0.01 mm fractions supports this difference between these two principal sources, which is most distinct in the finest fractions where feldspars and micas tend to be better represented relative to quartz. Even though a considerable part of the sediment brought by Nemunas River accumulates in the Curonian Lagoon, deposition of silt outside the Klaipeda strait has been related to the discharge of the Nemunas River (Blashchishin and Usonis, 1970; Blashchishin, 1976). The Nemunas River annually supplies 647,000 tons of fine material in suspension (Pustelnikovas, 1998). Although the Nemunas alluvium is rich in sand-sized quartz (up to 86%), the concentration of quartz becomes lower away from the river mouth in the Curonian lagoon. The coarse-silt and sand components are probably affected by selective sorting, however, we believe that fine-silt and clay fractions are considerably less susceptible due to their low thresholds for suspension transport and their likelihood of the inclusion within aggregate particles. In the bottom sediments at Melnrage microcline constitutes 15.8% and the albite content is 7.0%. Microcline has a negative (weak) correlation with orthoclase. The concentration of orthoclase at Melnrage is only 1.7%. The sediment input from the Curonian Lagoon (Nemunas drift) is apparently the main source of microcline and albite, but not orthoclase. The distribution pattern of feldspars and maximum at Klaipeda strait supports the interpreted supply by suspension, transported from the Nemunas River (Table 1).

4.3. Local erosion of late Pleistocene till

Off the central Lithuanian coast relatively large contents of quartz imply that the feldspar-rich sediments of the Nemunas River are less represented than closer to the Curonian strait to the south (Fig. 3). In addition to the northward coastal transport of quartz-rich sediments from the Sambian Peninsula, a local influence on sediment composition is the erosion of Pleistocene till deposits in some shore cliffs and on the sea floor. Locally higher concentrations of quartz, such as near the Olando Kepure cliff (62.5%) are most likely related to the erosion of these local till exposures. The areas with relatively high quartz content offshore in the north are also coincident with widespread till exposure on the sea floor where on-going erosion is interpreted (Blashchishin, 1998; Kairytė, 2004). We do not believe that selective mineralogical sorting has been extensive in the <0.01 mm fraction and quartz does not correlate with water depth, therefore a strong negative correlation between quartz and the total content of clay minerals is consistent with quartz supply from till-derived sediment, rich in primary minerals at the expense of clay minerals. Since local till composition is similar to till in the Sambian Peninsula, the geographic distributions are used here to suggest the significant influence of these local sources.

From factor analysis, factor 2 exhibits high positive loadings for actinolite, vermiculite and kaolinite, which are only observed at a few northern sites and are also correlated (Appendix B). Geographically, this is consistent with earlier results by Stauskaitė (1962), where it was noted that concentration of amphiboles increases northwards. The other factors are too weak to justify further interpretation.

4.4. Grain-size interpretations

Unimodal grain-size distributions of sediments in the entire central part of the study area (Klaipeda–Palanga) and near the coast in the north and south are interpreted to reflect the dominant influence of wave activity and the increasingly homogenized character of the sediments in transit from the south. Sediments present closest to the shoreline (0–2 m) are predominately well sorted, medium sand with coarse to nearly symmetrical skewness (Fig. 6). Increasing depth (2–4 m) correlates with finer mean grain size, better sorting and more positive skewness of the medium to fine sand deposits, which reflects the decreasing strength and variability of wave-induced turbulence. Fine sand with worse sorting and more negative skewness present in deeper water (4–13 m) is most probably longshore current deposits mixed with some wave reworked sediments.

Polymodal sediments show the areas of sediment supply from more than one source or where different processes are acting simultaneously (Dias and Neal, 1990). Bimodal sediments found in the northern area (Sventoji–Butinge) may be explained by coastal reworking, combining sediment from local till erosion and alluvial sediment transported from the Sventoji River. However, greater variability of grain-size parameters, including the coarsest, most positively skewed and worst sorted deposits found at 13–20 m of water depth, suggest that these sediments are mainly derived from till erosion in northern nearshore areas.

The highest modal complexity (two, three and four modes) is present just south of Klaipeda (Fig. 6), where the influence of Sambian Peninsula source is the highest, but increasingly modified by Nemunas River sediment supply and coastal reworking. Also to the south, deposits with the finest grain size are accumulating in the deepest zone of the area of investigation (20–35 m), below normal wave base.

5. Conclusions

The mineralogical variability in the fine silt and clay changes more significantly than in the coarser fractions or bulk sediment. Based on the lack of correlation between minerals in the fine fraction and grain-size parameters, grain-size sorting is interpreted to be limited. Although hydraulic sorting may affect the silt fraction as a whole, we do not believe that mineral trends have been significantly influenced in the suspension transported, fine-silt and clay fraction of the eastern Baltic Sea sediments. We conclude that the mineralogical composition of fine fraction does provide provenance information for suspension transported sediments, complementing traditional provenance studies with coarser, traction-dominated fractions.

Two principal sediment sources acting in the area are identified:

1. The Sambian Peninsula source supplies sediments from till deposits, with abundant quartz, and from the "Blue Earth" in the amber mining quarry at Jantarnyj, characterized by glauconite, micas and orthoclase.
2. The Nemunas River and drainage from the Curonian Lagoon provides sediment with relatively abundant feldspars (especially microcline and albite). The contribution of fine-grained sediments from Nemunas River diminishes northward from Klaipeda Strait, where the near-shore reworking of coastal sediments increases and coarser sediments accumulate in response to wave activity.

In addition to the two principal sources, above, Late Pleistocene till erosion on the sea floor and at the Olando Kepure shore provides sediments with relatively worse sorting and high contents of quartz, feldspars and dolomite. The sources for the fine-grained fractions are the same as has been identified by other authors for the sand and coarse-silt fractions. We conclude, therefore, that previous interpretations are correct even for the bulk sediments. These fractions are transported differently and cannot be assumed to necessarily accumulate together. The fact that this occurs along the Lithuanian coast seems suggest that there are only a few main sources involved. Also, the variability in the turbulent energy that is described for this coastal setting allows both suspension and traction deposits to be represented.

Unimodal sediments in the central part of the study area (Klaipeda–Palanga) and near the coast in the north and south are interpreted to reflect the dominant influence of wave activity, which is also reflected by improved sorting offshore. Bimodal sediments in the northern area (Sventoji–Butinge) are believed to result from the combination of coastal processes, including the erosion of local till deposits and the sediment supply from the Sventoji River. The complex polymodal character of sediments in the south is explained by the supply of sediments from Sambian Peninsula, further strengthened by the addition of Nemunas River sediments near Klaipeda and products of coastal reworking.

Identification of sources and transport pathways can be used for establishing the sedimentologic relationships between different environments, such as the river, estuary, lagoon and coastal systems in the SE Baltic area. An understanding of these relationships is important for predictive and remedial environmental planning as well as for remediation of existing problems and sustainable development in the future. For instance, coastal models are important for applied studies regarding shoreline erosion and harbor and fairway management of siltation and pollution, problems that are closely related.

Our main conclusion is that the finest part of the sandy deposits (<0.01 mm) provides a favorable variability in mineral composition and makes the observations more source-sensitive and sorting-insensitive. Since there is considerable documentation of sand-based provenance in the southeastern Baltic and elsewhere, comparisons with the fine-fraction provenance are valuable to combine interpretations regarding the material transported from potentially different sources.

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Appendix A. Mineralogical composition of the <0.01 mm, 0.01–0.063 mm fractions and bulk sample, grain-size parameters, and water depth

Variable	Number of samples in which variable is determined	Min	Max	Average	SD
Mineralogical composition of the fraction <0.01 mm for 37 samples					
Quartz	37	29.60	79.80	52.62	13.02
Albite	27	1.20	11.60	3.77	2.37
Orthoclase	24	1.50	9.50	4.19	2.27
Sanidine	10	1.80	5.40	2.75	1.08
Microcline	21	1.60	15.80	5.55	3.57
Actinolite	7	0.10	5.30	2.14	1.67
Calcite	25	0.40	22.40	8.67	6.48
Dolomite	37	2.60	17.10	7.55	3.46
Muscovite	32	1.80	16.80	4.57	9.47
Biotite	18	1.10	5.90	3.29	1.65
Vermiculite	5	0.40	2.90	1.32	0.97
Montmorillonite	3	0.70	3.80	2.00	1.61
Illite	10	14.20	37.20	27.68	9.10
Kaolinite	4	1.00	4.50	2.40	1.51
Chlorite	33	2.10	8.10	4.44	1.44
Glauconite	20	0.70	4.70	2.85	1.05
Phyllosilicates[a]	37	4.80	48.50	23.69	12.26
Clay min. 1[b]	35	0.70	44.00	12.55	13.95
Micas[c]	33	2.70	21.70	10.98	5.98
Carbonates[d]	37	2.60	28.60	13.87	8.00
K-feldspars[e]	34	1.60	17.50	7.20	3.57
Plagioclase[f]	27	1.20	11.60	3.83	2.33
Feldspars[g]	37	1.50	24.50	9.67	4.74

Appendix A (*continued*)

Variable	Number of samples in which variable is determined	Min	Max	Average	SD
Mineralogical composition of the fraction 0.01–0.063 mm for 17 samples					
Quartz	17	43.80	95.00	68.28	14.71
Albite	14	3.50	11.30	5.96	2.25
Anorthite	3	1.50	3.60	2.63	1.06
Orthoclase	5	1.00	8.10	5.52	3.06
Microcline	12	1.90	24.20	9.06	6.12
Actinolite	3	1.40	3.80	2.33	1.29
Calcite	13	0.70	11.40	4.15	2.94
Dolomite	16	2.40	28.10	10.18	8.00
Muscovite	1	3.10	3.10	3.10	
Biotite	1	1.60	1.60	1.60	
Chlorite	9	1.50	4.80	3.17	1.04
Glauconite	1	1.20	1.20	1.20	
Ilmenite	2	2.50	10.10	6.30	5.37
Magnetite	1	11.60	11.60	11.60	
Zircon	1	17.30	17.30	17.30	
Rutile	2	4.30	5.60	4.95	0.92
Epidote	1	2.10	2.10	2.10	
Phyllosilicates	10	2.70	4.80	3.44	0.73
Micas	2	1.60	3.10	2.35	1.06
Micas	2	1.60	3.10	2.35	1.06
Carbonates	17	2.60	28.80	12.75	8.62
K-feldspars	15	1.90	24.20	9.09	5.29
Plagioclase	15	2.80	11.30	6.09	2.45
Feldspars	17	3.70	24.20	13.39	5.92
Mineralogical composition of the bulk sample for 6 samples					
Quartz	6	81.20	89.30	84.00	3.29
Albite	6	5.30	14.30	9.87	3.99
Anorthite	2	2.10	2.30	2.20	0.14
Microcline	5	3.30	8.50	5.90	1.89
Dolomite	1	2.90	2.90	2.90	
Plagioclase	6	5.80	14.30	10.60	3.42
Feldspars	6	10.70	18.80	15.52	3.67
Grain-size parameters of samples analyzed for mineralogy					
Mean grain-size	37	0.91	3.72	2.23	0.60
Sorting	37	0.16	0.80	0.38	0.17
Skewness	37	−0.26	0.33	0.00	0.13
Water depth, m	37	0.00	30.30	11.89	0.00

SD=standard deviation.

[a] Muscovite + biotite + vermiculite + montmorillonite + illite + kaolinite + chlorite + glauconite.

[b] Montmorillonite + illite + kaolinite + chlorite.

[c] Muscovite + biotite.

[d] Dolomite + calcite.

[e] Orthoclase + microcline.

[f] Albite + anorthite.

[g] Orthoclase + microcline + albite + anorthite.

Appendix B. Correlation half matrix, Pearson coefficients for mineralogical data of the <0.01 mm fraction, grain-size parameters and water depth

	Quartz	Albite	Orthoclase	Microcline	Actinolite	Calcite	Dolomite	Muscovite	Biotite	Chlorite
Quartz	1.00									
Albite	0.05	1.00								
Orthoclase	0.05	−0.05	1.00							
Microcline	0.05	0.09	−0.36*	1.00						
Actinolite	−0.05	−0.30	−0.05	−0.03	1.00					
Calcite	−0.44***	0.14	0.06	−0.08	−0.31	1.00				
Dolomite	−0.30	0.50***	−0.09	−0.02	−0.34*	0.14	1.00			
Muscovite	−0.01	−0.24	0.36*	−0.24	0.17	−0.12	−0.06	1.00		
Biotite	−0.32	−0.14	0.49***	0.05	0.11	0.05	−0.07	0.50***	1.00	
Chlorite	−0.17	0.02	0.24	−0.16	−0.19	0.09	0.05	0.23	0.10	1.00
Glauconite	0.16	−0.08	0.50***	−0.07	0.01	0.14	−0.12	0.31	0.74****	0.25
Illite	−0.38*	−0.28	−0.46***	0.06	0.13	−0.08	−0.01	−0.37*	0.46***	−0.10
Vermiculite	0.17	−0.25	−0.25	0.06	0.71***	−0.20	−0.18	0.10	0.06	−0.53****
Phyllosilicates[a]	−0.72****	−0.47***	−0.19	−0.05	0.27	−0.12	−0.09	0.17	−0.02	0.16
Clay min. 1[b]	−0.61****	−0.28	−0.43***	0.05	0.13	−0.07	−0.02	−0.35	−0.45	0.03
Micas[c]	−0.15	−0.23	0.45***	−0.18	0.17	−0.09	−0.07	0.96	0.71	0.22
Depth, m	0.09	0.39*	0.06	−0.14	−0.35*	0.08	0.46***	0.02	−0.27	0.01
Mean gr. sz.	0.03	0.18	0.02	−0.30	−0.26	0.00	0.40**	0.12	−0.33*	−0.05
Sorting	0.16	0.36*	−0.10	−0.03	−0.24	0.06	0.18	−0.16	−0.23	0.06
Skewness	0.20	0.11	0.03	−0.15	0.17	−0.24	−0.25	−0.04	−0.02	−0.03

	Glauconite	Illite	Vermiculite	Phyllosilicates	Clay min. 1	Micas	Depth, m	Mean gr. sz.	Sorting	Skewness
Glauconite	1.00									
Illite	−0.63****	1.00								
Vermiculite	−0.20	0.32	1.00							
Phyllosilicates	−0.29	0.81	0.38	1.00						
Clay min.1	−0.60****	0.99	0.27	0.84	1.00					
Micas	0.48***	−0.44***	0.10	0.13	−0.42**	1.00				
Depth, m	−0.12	−0.19	−0.21	−0.29	−0.20	−0.06	1.00			
Mean gr. sz.	−0.20	−0.01	−0.05	−0.07	−0.04	0.00	0.77****	1.00		
Sorting	−0.13	−0.12	−0.18	−0.28	−0.13	−0.20	0.59****	0.36*	1.00	
Skewness	−0.04	0.02	0.18	0.00	0.01	−0.04	0.05	0.16	0.20	1.00

[a] Muscovite + biotite + vermiculite + montmorillonite + illite + kaolinite + chlorite + glauconite.

[b] Montmorillonite + illite + kaolinite + chlorite.

[c] Muscovite + biotite.

* $p<0.05$.

** $p<0.02$.

*** $p<0.01$.

**** $p<0.001$.

Appendix C. Eigenvalues and variance explained for the main factors in principal component analysis

Component	Initial Eigen values			Rotation sums of squared loadings		
	Total	Percentage of variance	Cumulative %	Total	Percentage of variance	Cumulative %
1	3.820	21.224	21.224	3.111	17.286	17.286
2	3.402	18.902	40.126	2.680	14.887	32.173
3	1.984	11.023	51.148	2.483	13.797	45.970
4	1.777	9.871	61.019	1.821	10.116	56.086
5	1.342	7.454	68.473	1.707	9.482	65.569
6	1.071	5.948	74.421	1.593	8.852	74.421

Appendix D. Varimax rotated factor loadings on the first six factors from a PCA analysis of mineralogical data of the <0.01 mm fraction, grain-size parameters and water depth (loadings below 0.4 omitted)

Component						
Variable	1	2	3	4	5	6
Quartz				−0.934		
Albite					0.708	
Orthoclase	0.631					0.417
Microcline						−0.793
Actinolite		0.802				
Calcite				0.639		
Dolomite			0.617	0.418		
Muscovite	0.665					
Biotite	0.892					
Vermiculite		0.924				
Montmorillonite					−0.521	−0.505
Illite	−0.720				−0.421	
Kaolinite		0.744				
Chlorite		−0.512				0.466
Glauconite	0.808					
Mean gr. sz.			0.881			
Sorting			0.417		0.494	
Depth, m			0.843			

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IV

Manuscript

Quantitative provenance of silt and clay within sandy deposits of the Lithuanian coastal zone (Baltic Sea)

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Abstract

A quantitative provenance approach is developed and applied for the silt and clay fractions of sandy deposits in the SE Baltic Sea along the Lithuanian coast. Mineralogical composition of 37 surface samples was determined by X-ray diffraction (XRD). Grain-size distributions were obtained by standard dry sieving and pipette techniques. The characterization of mineralogical provenance is based upon known compositional information of possible sources, logical models for mineral combinations related to regional geological provinces and processes, and geographical features of the documented mineral distribution in the area of investigation. These interpretations are further supported by results of correlation and principal component analyses of mineral varieties, grain-size parameters and bathymetric features of the area. Partitioning of source contributions specific for each site of deposition is derived by solving simultaneous equations. Then, the quantified mineral composition at the initial source is reconstructed. The main sources supplying sediment to the area are: 1) Sambian Peninsula to the south (erosion of Pleistocene till and "Blue Earth" Paleogene sediments), supplying 33% of fine-grained sediment on average, 2) Nemunas River, the discharge of which passes through Curonian Lagoon and supplies an average 17% of the coastal fine sediments, and 3) Pleistocene till, eroded on the sea floor in the north and at the Olando Kepurė shore cliff and contributing an average of 50% of the sediment.

Keywords: quantitative provenance, Baltic Sea, sandy sediments, fine-grained fraction, mineralogy, X-ray diffraction, coastal transport

Introduction

The strong trend toward quantitative modeling throughout the Earth sciences (e.g. Griffen, 1999; Parks et al., 2000; Willis and White, 2000; Weltje and von Eynatten, 2004) and recent advances in analytical and interpretative techniques have considerably increased the interest for quantitative provenance. Although relatively few, attempts to partition sediment source contributions and budget the total fluxes have been done using composition information from deposits within either modern or ancient environments (Di Giulio, 1999; Bengtsson, 2000; Brack et al., 2001; Eittreim et al., 2002; Su and Huh, 2002; Audry et al., 2004; von Eynatten, 2004; Vezzoli et al., 2004; Zack et al., 2004). Despite that quantification and modelling of source contributions is a major accomplishment for any geological or environmental studies, it is seldom achieved.

Quantitative basin models, such as mass-flux budgets, are often made for modern settings by measuring the inputs from known sources. However, direct sampling of source areas is not always possible. Furthermore, the complex variability of multiple sources, transport processes, selective sorting, erosion and deposition within most natural environments is difficult to measure and nearly impossible to reliably integrate over time. Therefore, quantitative source partitioning for individual sites of accumulation is seldom feasible to achieve. The "sediment-archive perspective" applied here is opposite to the approach used for most budgets of environmental fluxes and avoids several of these common problems. Our study is focused upon the stable, mineralogical components of the "sediment archive", which offer a time-integrated, net-effect reflection of the combined processes of an entire environmental system, and recorded for each individual site of accumulation.

A principal limitation of methods using sediment composition is the strong dependency of both mineralogy and geochemistry upon grain size, which is usually dealt with by selecting narrow size intervals for analysis. The fine-silt and clay fractions used in our study are largely transported in suspension together, presumably in aggregate form, and are believed to not be extensively effected by hydraulic sorting, which might result in size-dependent mineral segregation and enrichment (Blatt, 1985; Kairytė et al., 2005). Quantitative provenance modeling of fine-grained sediments has become feasible due to the increased resolution of modern instruments and advancements in interpretative theory for XRD quantification based upon Rietveld methodology (Ward et al., 1999).

In addition, fine-grained sediments tend to have relatively high metal contents, due in part to the high specific surface area of the smaller particles and ionic attraction (Hochella and White, 1990). The provenance and transport history, reflected in the mineralogical characteristics of fine-grained sediment or the fine-grained part of coarse sediment, can be used, therefore, to evaluate the source and fate of pollution.

Previous studies have distinguished several sources of particular importance for the sediment in the Lithuanian coastal zone: a) the Sambian Peninsula coast in the south, where shore erosion has been described in the past as the major contributor of sediment (Knaps, 1966; Blashchichin and Usonis, 1970; Trimonis, 1987), but more recently said to be decreasing in significance due to protective measures (Žaromskis, 2007), b) Curonian lagoon, dominated by the Nemunas River discharge of fine-grained sediments (Galkus and Jokšas, 1997), c) linear shorelines, characterized by the prevailing northeast to north, long-shore transport, including both depositional and erosional nearshore areas, and d) areas of sea-floor erosion of exposed late Pleistocene till deposits (Stauskaitė, 1962; Linchius and Uginchius, 1970; Blashchichin and Usonis, 1970; Blashchishin, 1976; Blashchishin and Lukashev, 1981; Emelyanov and Trimonis, 1981; Trimonis, 1987; Emelyanov, 1995; Apanavičiūtė and Šimkevičius, 2001). Areas of predominant accumulation are mainly found in the offshore deeps. These previous interpretations of sources and transport pathways in the SE Baltic Sea have been done using mapped distributions of heavy minerals and other mineral components within fine-sand and coarse-silt fractions and bulk samples of bottom sediments. The medium-to-fine-silt and clay fractions used in our study complement traditional provenance work with coarser, traction-dominated fractions, providing provenance information for suspension transported sediments (Kairytė et al., 2005).

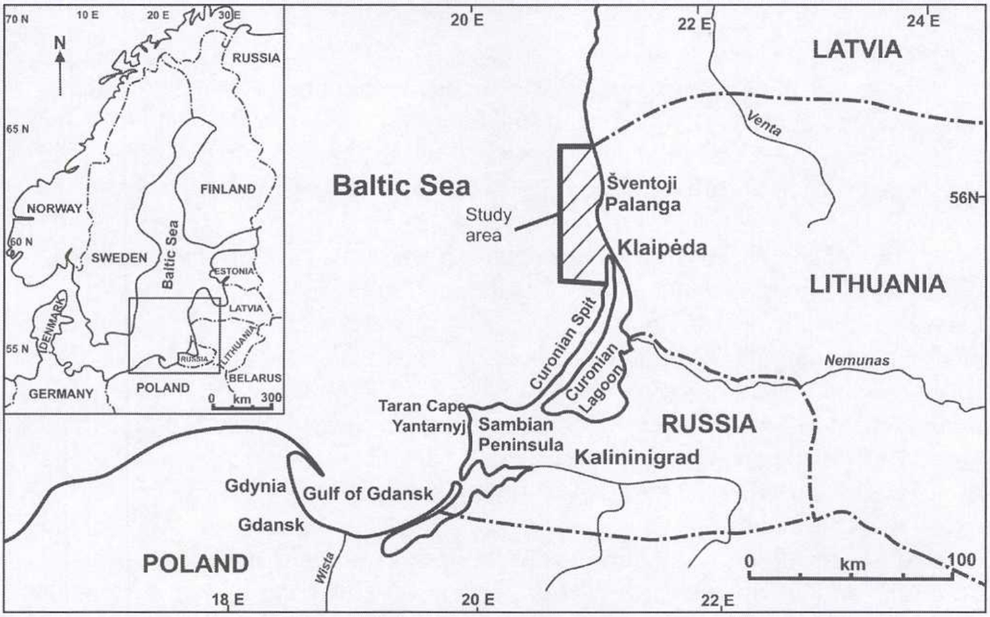

Fig. 1. Situation map of the SE Baltic Sea (modified from Ūsaitytė, 2000) with the study area indicated.

We demonstrate an approach that allows both the identification and partitioning of source contributions in a way that is specific for each site of deposition. In this quantitative approach the mineralogical characterization of the identified sources is in part resolved from the composition of the sediment deposits. The objective of the study is to discuss advantages and shortcomings of the quantitative provenance approach and to exemplify this methodology for interpretation of the specific compositional character of sources and the changing balance of their contributions to the sediments within the Lithuanian coastal zone (Fig. 1), approximately 45x6 km.

Methods

Sampling

Bottom sediment samples from the coast of Lithuania (the Klaipėda – Ventspils marine plateau) were taken during a period of four years (1993 – 1995, 1997) along 92 transects oriented perpendicular to the shoreline and spaced at 500 m. Surface sediments (0-5cm) were taken from the shoreline to a depth of about 31 m. Thirty-seven samples for mineralogical analyses were selected from the total sample set of 712 stations. The sites included those situated closest to the shoreline and those farthest offshore along 15 cross-shelf transects, and additional samples to provide good areal coverage and enable statistical evaluation (Fig. 2).

Analyses

The samples for mineralogical analyses were dispersed with sodium diphosphate and ultrasound treatment. The fractions 0.01 – 0.063 mm and < 0.01 mm were separated from the coarser sediment using wet sieving and decantation after suspension settling of different size intervals.

Mineralogical composition was determined for powdered, non-oriented samples within specific grain-size intervals: 37 analyses of the <0.01 mm fraction and 17 analyses of the 0.01 – 0.063 mm fraction using a Siemens D5005 diffractometer. Bulk-sample mineralogy was documented for 7 sites. Samples were scanned with Ni-filtered and Cu-Kα radiation between 2 – 65° 2Θ at 40 kV and 40 mA effect and with a scanning speed of one degree 2Θ per minute. The *Siroquant* program (Ward et al., 1999), based upon the Rietveld methodology for diffractogram simulation, was used for quantification of the identified minerals.

Grain-size distribution was determined using standard pipette methodology (0.005 to 0.5 mm) and dry sieving with a set of 22 sieves for the coarse-grained sediments (0.05 to 10.0 mm). Statistical parameters of the grain-size data were calculated according to the graphic method of Folk and Ward (1957).

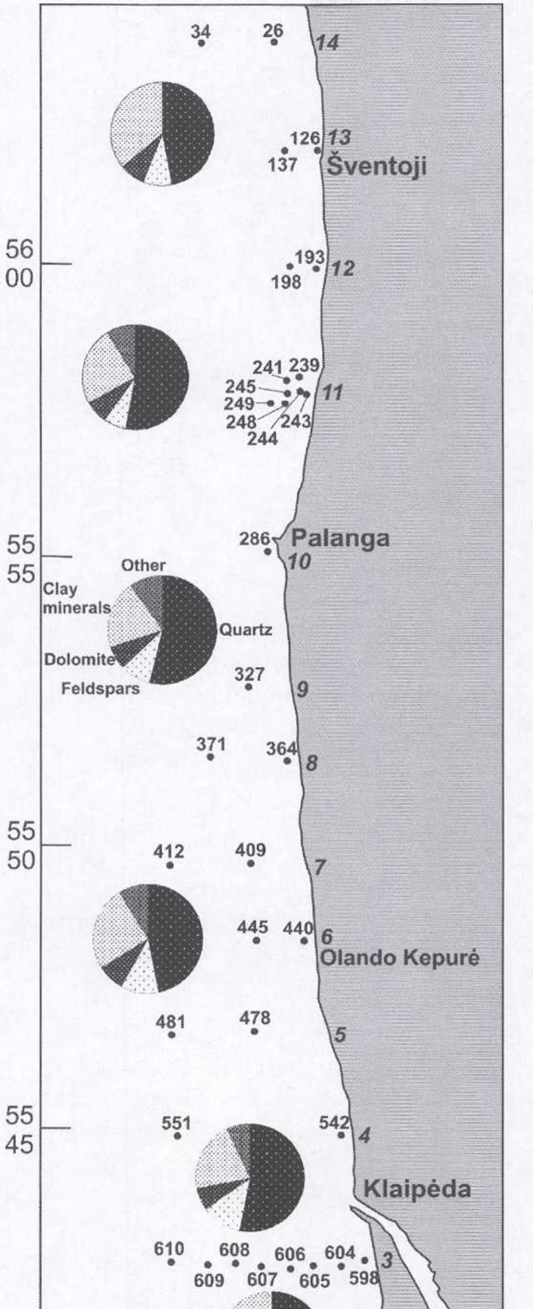

Fig. 2 Sampling sites for mineralogy. The circle diagrams show average mineral compositions in six different sectors of the study area.

Statistical procedures

The weight percentage of minerals identified in the <0.01 mm fraction, statistical parameters of the grain-size data (mean, sorting and skewness), and water depth were used to build the correlation matrix. Factor analysis, by means of principal component extraction and Varimax rotation, was performed on the same set of variables to support interpretation of parameter relationships and simplify the complex data by identifying a relatively small number of controlling factors that represent relationships among sets of interrelated variables. Factor analysis was performed on the set of 17 variables and 37 samples.

Procedures for quantification of source contributions

After the main sources supplying sediment to the area are characterized, their contributions are derived by solving simultaneous equations, with the form:

$$Min_{deposit} = C_1 Min_{source1} + C_2 Min_{source2} + C_3 Min_{source3} + \ldots,$$

where $Min_{deposit}$ = % of a specific mineral, group of minerals or mineral ratios, documented within a specific size fraction; $Min_{source(i)}$ = mineral % available from each source; and C_i = % contribution of each source to the sampled deposit. The number of sources that can be resolved is one greater than the number of simultaneous equations written. For instance, the partitioning of three sources is obtained by solving the equations below:

$$\begin{aligned} C_1x_1 + C_2x_2 + C_3x_3 &= x_4; \\ C_1y_1 + C_2y_2 + C_3y_3 &= y_4; \\ C_1 + C_2 + C_3 &= 1. \end{aligned} \tag{1}$$

where $x_{1,2,3}$; $y_{1,2,3}$ = two different parameters (e.g. content of specific minerals) which are believed to vary between different sources, x_4, y_4 = the corresponding parameters documented at each sampling site. If direct sampling of the sediment sources and deposits is done, then all x_i and y_i values would be known and the solution of these equations would be straightforward. However, even without direct sampling and *quantitative* analyses of the sources, the following approach allows resolution if *qualitative* mineralogy of the source areas is known or can be interpreted. The maximum value of the mineral parameter characterizing an identified sediment source is considered as the initial, quantified expression describing mineral content at that source. In the case of three sources, x_1 is the maximum value of all sites for the mineral parameter characterizing the first source (e.g. the greatest observed % of hornblende), y_1 is the value of the second parameter at the same sampling site where the maximum of the first parameter was identified; y_2 is the maximum value of mineral parameter representing the second source, whereas x_2 is the value of the first parameter taken at the same site as the y_2 – maximum value. The values x_3 and y_3 are taken from the sampling site where the highest value of the parameter representing the third source in the data set is present.

The matrix determinant for C_1 is expressed as:

$$C_1 = [(x_4 - y_2)(y_3 - y_2) + (x_2 - x_3)(y_4 - y_2)] / [(x_1 - x_2)(y_3 - y_2) + (x_2 - x_3)(y_1 - y_2)] \quad (2)$$

Then C_3 may be expressed through C_1:

$$C_3 = [(y_4 - y_2) - C_1 (y_1 - y_2)] / (y_3 - y_2); \quad (3)$$

$$\text{And } C_2 = 1 - C_1 - C_3. \quad (4)$$

When dealing with multiple sources, the maximum values (parameters x, y, z) selected from the investigated deposit sites would only be expected to equal the actual source mineralogy if one specified source supplied 100% of contribution. Detrital sediments in natural environments commonly are supplied from several different sources. Because of this, negative values of calculated contributions may arise. This is resolved by shifting the scale, i.e. adding the absolute value of most negative calculated contribution to the contributions of each source and rescaling to unity. Then the most negative value becomes zero and the final contribution equals the corrected source contribution (C_i + ABS (most negative)) divided by the sum of corrected contributions of all three sources at each sampling site.

Reconstructing the original mineral composition of the sources

When the source composition is identified and its contribution calculated, it is further possible to estimate the theoretical mineral composition of the source. To do this, the maximum contribution (C_{max}) of each source type needs to be identified in the sample set. For this sample the individual mineral parameters of the specified source are then proportionally increased by dividing by the source contribution (as calculated above). The theoretical composition of the source in terms of these parameters may be found as follow:

$$X_{EM} = X_{at\ max} / C_{Xmax}$$

where X_{EM} = theoretical end-member mineral composition of source X; $X_{at\ max}$ = weight % of the characteristic source mineral at the site of max contribution; C_{Xmax} = maximal observed contribution of specified source. Y_{EM} and Z_{EM} are calculated in an analogous way.

Results and Interpretations

Identification of sediment sources

The sediments analyzed for mineralogy are mostly fine and very fine sand. Using the entire data set (712 sites), a detailed presentation of grain-size data and interpretations of the sedimentary processes and transport pathways is given in Gaigalas et al. (1999) and Kairytė and Stevens (Paper II, this volume). The main minerals found in bulk samples are quartz, feldspars and carbonates. The fraction 0.01-0.063 mm in some cases contains also mica and the heavy minerals ilmenite, magnetite, zircon, rutile and epidote. The relative abundance of heavy minerals in several samples in the northern part of the investigation area is most likely related to erosion of shoreline and sea floor exposures of till. Pleistocene till contains abundant heavy minerals, and proximity to till sources is a main influence, especially in the coarser part of the sediment in the shallow nearshore zone (Blashchishin and Usonis, 1970). Absence of heavy minerals in the fine fractions suggests that medium-to-fine silt and clay sediment does not undergo extensive hydraulic sorting during suspension transport in contrast to coarser sediment where heavy minerals are more easily enriched. Bulk samples and coarser fractions are strongly dominated by quartz, and only a few percent of other minerals are observed. The fine-fraction (<0.01 mm) contains a greater variety of minerals, allowing better source specification in areas with low mineralogical variability in the coarse fractions (Kairytė et al., 2005). The following descriptions are focused on the fine fractions.

In rare cases quartz is less than 40%, although with an average of 52.6% it is the most abundant mineral in the <0.01 mm fraction. The overall highest concentration of quartz observed in the south is consistent with sediment derived from the mineralogically mature till of the Sambian Peninsula, where quartz reportedly accounts for 84 and 87% of the fine-sand and coarse-silt fractions, respectively (Blashchishin and Usonis, 1970). Locally high concentrations of quartz documented near the Olando Kepurė cliff are explained by the erosion of exposed till along the shoreline. The higher content of quartz offshore in the north is related to sea floor erosion of Pleistocene till present in the northern part of the investigation area.

Other major minerals include the feldspars. The most common are K-feldspar, microcline and orthoclase. Of the plagioclase feldspars, generally albite is present. The average total feldspar concentration is 9.4%, notably greater near the Klaipėda Strait (24.5%), which is attributed to the Nemunas River supply of feldspar-rich, fine-grained fractions to the area. Much of the Nemunas River sediments accumulate in the Curonian Lagoon, but the finest sediment is transported in suspension over long distances (Galkus and Jokšas, 1997), and the area of fine-grained sediments in proximity to Klaipėda Strait is most likely the result of this sediment supply (Blashchishin and Usonis, 1970). Although a high content of feldspars in fine-grained fractions is also documented in Sambian Peninsula till, feldspar concentrations in the silt and sand fractions of Nemunas alluvium are 1.5-2 times higher (Blashchishin and Usonis, 1970). Microcline, which has its maximum concentration near the Klaipėda Strait, is attributed mainly to Nemunas River sediments. The distribution pattern of albite is consistent with a Nemunas River supply, but it also appears to originate from till at Sambian Peninsula and till exposed offshore in the northern part of our investigation area. Locally higher concentrations of orthoclase, the most abundant among feldspars, are explained by offshore till erosion in the north and along the coast at Olando Kepurė.

The third largest group of minerals found in the study area is carbonates, including dolomite and calcite. Dolomite occurs at all sites, with an average of 7.5%. This mineral is most common in the north (maximum 17.1%), but there is an overall increase of dolomite offshore and in the deepest part of the study area, in the south near Klaipėda. Pleistocene till and clay deposits contain a considerable amount of dolomite, as well as other carbonates eroded by glaciers from Paleozoic deposits (sandstones, limestones and dolomite rocks) exposed in the northern and central part of the Baltic Sea area (Blashchishin, 1976; Emelyanov and Trimonis, 1981; Emelyanov, 1995). The dolomite concentrations in the south and its maximum in proximity to erosional areas with till in the north are interpreted to result from till erosion.

Muscovite predominates among micas, representing up to 21.7% of the total mineral content. The average mica (muscovite and biotite) concentration is 11%, diminishing with water depths greater than 25 m. Locally high concentrations of micas reach ca. 20%, such as near the Klaipėda strait and along the seaward shore of the Curonian Spit. Micas are favored with long distance transportation. Their relative increase in fine-grained fractions compared to the coarser part of sediment at the Sambian Peninsula (Blashchishin and Usonis, 1970) relates them to this southern source.

Glauconite ranges between 0.7 and 4.7%, and is present from 0 until 30 m water depth. It increases to the south (Stauskaitė, 1962). Beyond the study area in this direction the "Blue Earth" sediments of the amber mining query at Yantarnyj on the Sambian Peninsula have glauconite concentrations reaching 48% and 40% in the fine-sand and course-silt fractions, respectively (Blashchishin and Usonis, 1970). In Nemunas alluvium glauconite appears only as solitary grains (Blashchishin and Usonis, 1970). Therefore, the glauconite detected in 24 of our samples is interpreted to originate from Tertiary sediments on the Sambian Peninsula.

Because the observed mineralogical variability of the possible sources is mainly through different proportions of same main minerals and because of extensive mixing of material in a high-energy, nearshore environment, the provenance interpretations are not simple. Only weak correlations exist between most of the sediment components (Kairytė et al., 2005). Nevertheless, the combined use of statistical and geographical information has allowed reasonable source identification. A positive correlation between orthoclase and micas, and their mutual occurrence with glauconite, explains 21% of the total variance in the first component of factor analysis. Micas and glauconite are characteristic minerals of the Sambian Peninsula "Blue Earth" sediments, whereas the orthoclase association with this group is explained by its presence in till deposits of Sambian Peninsula. This is consistent with longshore transport from the Sambian Peninsula.

Dolomite is interpreted to originate from Pleistocene till. The negative relation between quartz and carbonates (4^{th} principal component; Kairytė et al., 2005), despite their mutual occurrence in the till sources, may be related to differences in mineral stability. A grain-size dependency is also likely considering that dolomite increases in the fine, relatively poorly sorted sediments (3^{rd} principal component). The geographical distribution suggests that these two minerals (quartz and dolomite) together with feldspars orthoclase and albite, are mainly related to local erosion. However, quartz, because of its ubiquity, is not used in further calculations.

The Nemunas River supply is characterized by feldspars, especially microcline. Since microcline correlates negatively with orthoclase, the latter is excluded from quantification of the Nemunas River supply.

Quantified source contributions

The main sources supplying sediment to the area are: the Sambian Peninsula to the south (erosion of Pleistocene till and "Blue Earth" Paleogene sediments), the Nemunas River, whose discharge passes through the Curonian Lagoon, and Pleistocene till, eroded on the sea floor in the north and at the Olando Kepurė shore cliff (Table 1):

Table 1. The main sources and their characteristic minerals used for quantification of source contributions for the <0.01 mm fraction.

Source (<0.01 mm)	Characteristic minerals
The Sambian Peninsula	Orthoclase, glauconite and micas (biotite and muscovite)
Nemunas River	Feldspars (microcline, albite)
Local Pleistocene till erosion	Feldspars (albite, orthoclase) and dolomite

Based upon our mineralogical modeling, erosion in the Sambian Peninsula supplies approximately 33% of the fine-grained sediment in the area of investigation in average. The maximum contribution at a specific site is calculated to be 41% (Fig. 3). The minimal contribution of this source is in the most northern part of the investigation area, farthest from the principal source, representing 27% of the sediment. The geographical variation of this supply is very low, standard deviation 3.8, consistent with the general longshore transport pattern northward along the SE Baltic coast, which would allow extensive mixing of in transit materials.

The average supply of the Nemunas River source is estimated to be 17%. The geographic variation of this source contribution is greater (std. dev. 9.3) than for the Sambian source. This is explained by greater variability of hydrodynamic processes, such as wave activity and suspension plume dispersal close to the shoreline, where the influence of the Nemunas River supply is most pronounced. Periodic outflow also changes mixing patterns at the entrance of the Curonian Lagoon. The maximal input from the Nemunas River is near Klaipėda Strait (41%), where sediment from the Nemunas River first reaches the coastal zone. The minimum contribution is close to offshore sites with till erosion in the north (Fig. 3). The contribution pattern is defined by a significant decrease of feldspars, the main representatives of the Nemunas River source, to the north and south of Klaipėda. The northward decrease is also reflected by the belt of high feldspar concentrations which narrows and is closer to the shore.

Local till erosion is estimated to contribute an average of 50% of the sediment. The highest values are in proximity to offshore sites with till erosion in the north (72%, Fig. 3). The standard deviation of this source supply is 11.7, highest relative to the other two sources. High contribution rates can be explained by the proximity to the local source areas.

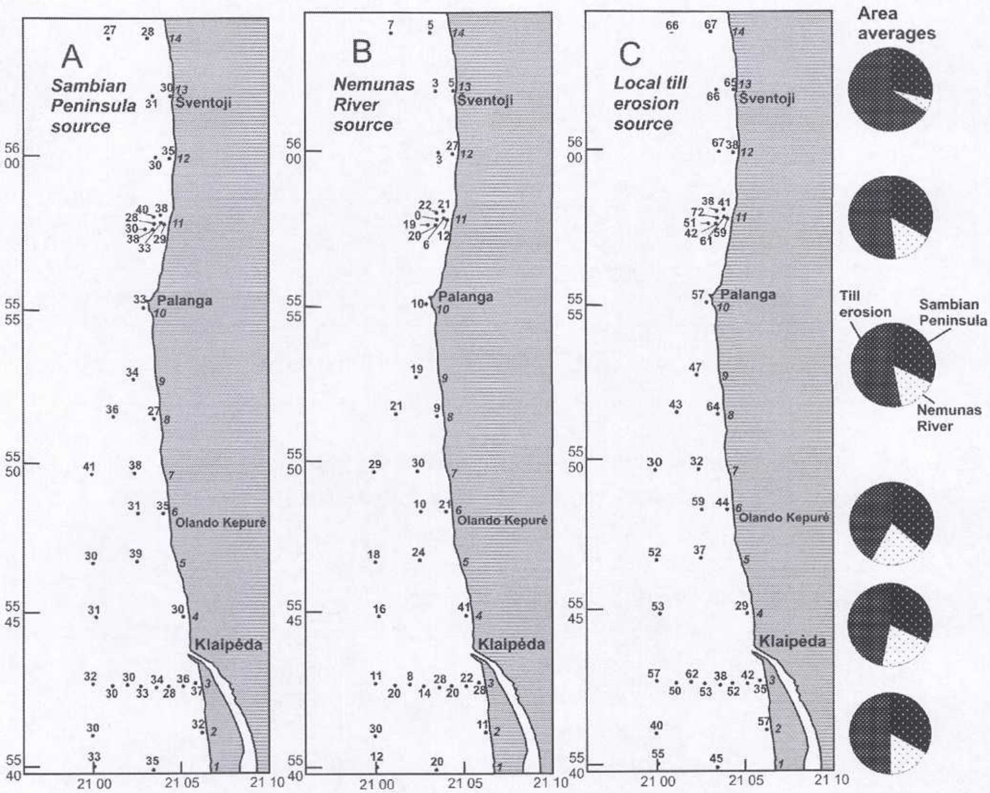

Fig. 3. Calculated contributions of: A) Sambian Peninsula source, B) Nemunas River source, and C) Local till erosion sources. Circle diagrams for six sectors showing the averaged contributions of three main sources supplying sediment.

Table 2 presents the source end-members (EM), calculated according procedures described in the methods section above, and the parameters used for estimation of quantified mineralogical content of the identified sources. EM value is the calculated percentage of characteristic minerals theoretically present at the original source. According to the calculation, for instance, the representative minerals in the fine-grained fraction at the Sambian Peninsula sum to 84.4% of the total composition. More specifically, this source contains 23.2% is orthoclase, 52.9% micas and 8.3% glauconite. The remaining 15.6% are unknown. A complete (100%) characterization of the source would require that all the minerals supplied be first identified or deduced and then documented in the study area. This is generally unrealistic, and the unspecified proportion of the original source is a good measure of how representative the modelled composition is.

Table 2. Calculated source end-members (EM).

	Sambian Peninsula	Nemunas River	Local till erosion
Maximal calculated contribution, % (C_{max})	41.0	41.0	72.0
Weight % of characterizing source minerals at the site of max contribution	$X_{at\ max} = 34.6$	$Y_{at\ max} = 22.8$	$Z_{at\ max} = 8.9$
Calculated weight % of characteristic minerals at the original source	84.4 = 23.2 orthoclase + 52.9 micas + 8.3 glauconite	55.6 = 38.5 microcline + 17.1 albite	12.4 = 8.6 dolomite + 3.8 orthoclase

Discussion

Calculation of the specific mineralogical content of original sources based on the composition of sediment deposits, as in this study, is a new development in provenance interpretation, which is most often limited to qualitative identifications. It is an advantage for the mass-flux modelling, since the more traditional approach of direct sampling of the source material in modern environments is not possible in many provenance studies, especially in geology. One of the main difficulties in provenance investigations is that sediment composition is influenced by factors other than parent lithology, for instance weathering, selective erosion, hydrodynamic sorting, and textural dependencies (Weltje and von Eynatten, 2004). In our approach the identification of the original source content is improved by a combination of statistical associations, geographical distribution and mineral combinations related to regional geologic provinces and processes. However, the proposed method is based on two assumptions: that the study area contains representative minerals of each particular source and that maximum value of these minerals is a valid quantified expression of the supply from these original sediment sources. The calculation of the end-members using the composition of the deposits presents a separate control to mass-flux modeling compared with measurements or estimates of fluxes at the supply source in modern environments.

Minerals with similar transport characteristics and chemical stability are preferable for source budgeting. In an ideal situation each of the sediment sources would be characterized by one specific and diagnostic mineral or association of minerals. However, in natural environments commonly quite similar mineral suites are supplied by more than one source (Pettijohn et al., 1987). The end-member calculation is less reliable if there are not significant differences in the proportions of the minerals supplied by alternative sources. The presence of source characteristic minerals at all sites of investigation is preferable, but not always found. This limits the choice of minerals to be assigned to specific sources; therefore not all minerals detected in the study area were used for calculations. In addition to having multiple sources, sediment composition is influenced by sedimentary processes present in various environments.

Utilizing the fine-grained fraction avoids recognized provenance problems, such as size limitations of the source materials, hydraulic sorting and insufficient number of mineral species for recognition of all anticipated sources (Kairytė et al., 2005). Despite the quite similar mineral character of the coastal deposits, it was possible to use them for the quantification of mineralogical composition of the logically and empirically identified different sources. The limited mineralogic separation of the original sources is a concern that would be even more substantial in a study focused on the quartz-dominated sand fractions. The distribution pattern of the calculated source contributions for the fine fractions suggest that erosion of local till contributes most (ca. 50%) of the fine-grained sediment. The maximum contribution from till erosion is in the north, close to offshore till erosion sites. Supply from the Nemunas River varies along the coast. The greatest contribution of this source is calculated in the area proximal to the Klaipėda Strait, where the fine-grained sediment from the Curonian Lagoon first reaches the coastal zone, and generally decreases away from the Klaipėda Strait. The supply patterns of these two major contributors show moderately well defined spatial trends related to the proximity to their source areas. In contrast, the Sambian Peninsula source is very uniform throughout the investigation area. This source contributes an average 1/3 of the fine sediment in the entire area. The fine-grained sediment from the more remote Sambian Peninsula source has most likely become generally dispersed throughout the coastal zone in connection with longer suspension transport. Also, this relatively low contribution may reflect a tendency for fine fractions to be gradually removed from the coastal zone and transported offshore into deeper Baltic basins.

The geological importance of quantitative sedimentology is related to the understanding of stratigraphic and geographic trends. These trends are the net result of complex processes; and they provide the ultimate test of process models that have necessarily simplified the natural complexity. Understanding and quantifying provenance can add back valuable detail to these models. The applications dealing with human interaction with the environment and controlling the negative impacts motivate a holistic evaluation of pollution dynamics, consistent with the basic objectives in provenance studies.

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Appendices

Appendix 1. Sediment sampling stations with coordinates, grain-size statistical parameters (mean, sorting, skewness and kurtosis) and water depth (m) for 712 samples of bottom surface sediments from the SE Baltic Sea

Nr.	Latitude	Longitude	Mean, φ	Soting, φ	Skewness	Kurtosis	Water depth,m
1	56,070	21,065	1,725	0,383	-0,115	1,035	-0,9
2	56,071	21,063	2,047	0,260	-0,011	1,236	-2,7
3	56,070	21,058	2,356	0,227	0,056	1,098	-4
4	56,070	21,053	2,353	0,195	-0,020	0,918	-6
5	56,068	21,060	2,584	0,262	-0,267	0,765	-4,4
6	56,067	21,061	2,289	0,278	0,065	0,869	-3,5
7	56,068	21,057	2,461	0,184	-0,041	0,984	-4,6
8	56,067	21,053	2,360	0,269	-0,084	0,862	-6,2
9	56,067	21,049	2,656	0,214	-0,098	1,399	-8,1
10	56,067	21,045	2,425	0,292	-0,182	1,545	-9,7
11	56,067	21,042	2,492	0,330	-0,006	1,080	-12
12	56,067	21,039	2,327	0,705	-0,119	1,430	-15,1
14	56,067	21,031	1,093	1,144	-0,241	0,889	-17,1
15	56,067	21,028	1,713	1,141	-0,027	0,810	-18
16	56,067	21,024	1,724	0,743	0,050	1,505	-18,2
17	56,067	21,016	-0,512	0,502	0,350	6,296	-18,4
18	56,066	21,066	1,929	0,236	-0,010	1,117	-1
20	56,066	21,062	2,255	0,219	-0,005	1,038	-3
21	56,066	21,055	2,323	0,249	0,047	1,030	-3
22	56,063	21,063	2,422	0,214	-0,073	1,182	-3
23	56,063	21,061	2,280	0,254	0,053	0,806	-4
24	56,063	21,057	2,252	0,298	0,113	1,071	-5,3
25	56,063	21,053	1,450	1,130	-0,348	0,474	-6,6
26	56,063	21,050	2,314	0,268	0,022	0,782	-8,4
27	56,063	21,045	2,328	0,275	-0,006	0,826	-10,7
28	56,063	21,042	2,396	0,303	-0,042	0,935	-13,4
29	56,063	21,039	2,274	0,547	0,045	1,038	-15,7
30	56,063	21,036	-0,110	0,804	0,323	1,012	-17
31	56,063	21,031	2,433	0,917	-0,252	0,880	-18,3
32	56,063	21,027	1,862	0,355	-0,050	1,070	-17,8
33	56,063	21,024	0,274	1,155	0,358	0,591	-17,2
34	56,063	21,015	1,699	0,484	0,026	1,132	-18,2
35	56,063	21,009	-0,155	0,734	0,337	1,016	-18,3
36	56,063	20,986	0,037	0,930	0,429	0,556	-19,6
37	56,063	20,979	0,495	1,008	-0,061	0,534	-19,4
38	56,063	20,971	-0,308	0,638	0,379	1,237	-19,6
39	56,063	20,965	-0,284	0,534	0,218	1,108	-20
40	56,062	21,067	1,445	0,504	-0,017	0,833	-0,9
41	56,062	21,065	2,045	0,263	-0,005	1,147	-3,1
42	56,062	21,061	2,242	0,228	0,100	0,924	-4

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
43	56,062	21,059	2,359	0,225	0,066	1,128	-5
44	56,059	21,062	-0,526	0,497	0,341	6,415	-3
45	56,059	21,061	2,348	0,287	0,052	0,811	-4,8
46	56,059	21,056	2,256	0,230	0,112	0,705	-6,2
47	56,059	21,053	2,302	0,353	-0,001	1,280	-7,9
48	56,059	21,050	2,389	0,260	-0,059	0,999	-9,3
49	56,059	21,046	2,434	0,272	-0,090	1,063	-12,3
50	56,059	21,043	2,406	0,427	-0,075	1,091	-14
51	56,059	21,038	-0,186	0,713	0,304	1,087	-16,5
52	56,059	21,035	1,754	0,411	0,011	1,159	-16,5
53	56,058	21,030	0,639	1,059	-0,102	0,556	-16
54	56,059	21,027	1,932	0,439	0,034	1,287	-16,8
55	56,059	21,019	0,119	0,860	0,144	0,800	-18
56	56,058	21,009	1,868	0,337	-0,121	1,082	-18,3
57	56,059	21,001	0,683	1,116	-0,113	0,542	-19,1
58	56,059	20,994	0,393	0,988	0,060	0,582	-19,1
59	56,059	21,025	1,860	0,338	-0,026	1,249	-16,5
62	56,058	21,070	1,821	0,313	-0,060	1,045	-1,1
63	56,057	21,066	2,076	0,227	0,026	1,201	-3
64	56,058	21,059	2,382	0,219	0,089	1,092	-5
65	56,054	21,065	2,330	0,251	-0,043	0,921	-3
66	56,054	21,061	2,243	0,253	0,187	0,766	-4,8
67	56,054	21,057	2,295	0,312	-0,035	1,143	-6,2
68	56,054	21,054	2,306	0,302	-0,025	1,028	-7,5
69	56,054	21,050	2,443	0,249	-0,066	1,156	-10,5
70	56,054	21,046	2,485	0,309	-0,084	1,362	-13
71	56,054	21,039	1,907	0,477	0,113	1,111	-16,2
72	56,054	21,031	0,696	1,119	-0,120	0,573	-16,5
73	56,055	21,016	1,835	0,373	-0,007	1,201	-17,8
74	56,054	20,995	-0,690	0,074	0,000	0,738	-19,4
75	56,054	20,987	1,673	0,484	-0,070	1,283	-17,7
76	56,054	20,978	0,800	1,125	-0,163	0,540	-19,4
77	56,054	20,964	2,205	0,241	0,130	0,986	-20,3
78	56,053	21,070	1,860	0,270	-0,025	1,132	-1,1
79	56,053	21,066	2,183	0,205	0,074	0,996	-3
80	56,053	21,063	2,260	0,231	0,059	0,941	-4
81	56,050	21,066	2,104	0,270	0,043	1,039	-3
82	56,049	21,061	2,259	0,271	0,172	0,801	-5,5
83	56,050	21,056	2,298	0,275	0,026	0,877	-6,8
84	56,050	21,047	2,529	0,306	-0,019	1,674	-13
85	56,050	21,039	0,181	0,889	0,143	0,854	-16,5
86	56,049	21,031	1,577	0,648	-0,073	1,028	-17,1
87	56,049	21,023	0,389	0,948	0,006	0,327	-17,6
88	56,050	21,008	-0,178	0,651	0,248	0,990	-18,7
89	56,050	21,001	-0,074	0,868	0,443	0,967	-19
90	56,050	20,980	2,022	0,431	0,003	1,141	-19,5
91	56,048	21,071	1,602	0,438	-0,258	1,463	-1

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
92	56,049	21,069	1,959	0,220	0,249	0,963	-2,5
93	56,049	21,066	2,214	0,268	0,133	1,090	-5
94	56,046	21,067	2,245	0,258	0,074	0,979	-3,3
95	56,046	21,061	2,262	0,252	0,141	0,777	-5,9
96	56,046	21,053	2,360	0,260	-0,034	1,012	-9,3
97	56,046	21,046	2,505	0,374	-0,077	1,350	-13,7
98	56,046	21,039	0,814	1,079	-0,263	0,531	-17,2
99	56,046	21,030	1,902	0,424	0,040	1,097	-17,1
100	56,046	21,009	0,717	1,042	-0,204	0,531	-18,6
101	56,046	20,994	-0,588	0,373	0,279	5,044	-19,5
102	56,046	20,986	1,854	0,337	0,000	1,028	-19,6
103	56,043	21,073	1,784	0,285	-0,057	0,960	-1
104	56,043	21,070	1,957	0,215	0,166	1,008	-2,5
105	56,044	21,067	2,117	0,273	0,069	0,992	-3
106	56,044	21,060	2,357	0,252	0,037	1,012	-7
107	56,041	21,068	2,217	0,286	0,161	0,937	-3,1
108	56,041	21,062	2,281	0,276	0,048	0,866	-5,6
109	56,041	21,054	2,342	0,302	-0,040	1,051	-9,3
110	56,041	21,046	2,499	0,327	-0,056	1,132	-13,2
111	56,041	21,039	1,593	0,430	-0,022	1,480	-17,2
112	56,041	21,023	-0,689	0,118	0,000	1,698	-18,2
113	56,038	20,988	0,019	0,886	0,346	0,816	-19,1
114	56,039	21,073	1,850	0,143	0,047	1,468	-0,9
115	56,039	21,071	2,075	0,225	0,027	1,312	-2,5
116	56,039	21,067	2,299	0,240	0,021	1,059	-4
117	56,040	21,061	2,062	0,281	0,145	0,823	-6
118	56,037	21,069	2,270	0,263	0,050	0,900	-2,9
119	56,037	21,059	2,062	0,542	0,046	0,860	-6
120	56,036	21,044	1,901	0,524	0,105	1,150	-15
121	56,036	21,043	2,289	0,256	0,044	0,770	-15,7
122	56,037	21,053	2,420	0,278	-0,111	0,942	-10,5
123	56,037	21,048	2,589	0,334	-0,094	1,010	-12,8
124	56,037	21,023	1,601	0,537	-0,017	0,996	-17,6
125	56,037	21,015	-0,062	0,788	0,315	0,932	-18,6
126	56,033	21,072	1,866	0,158	0,096	1,579	-0,8
127	56,034	21,069	1,929	0,226	0,141	1,233	-2,9
128	56,035	21,063	2,062	0,283	0,114	0,985	-5
129	56,035	21,058	2,164	0,208	0,073	1,059	-5,5
130	56,035	21,050	2,265	0,264	0,022	1,148	-11,1
131	56,035	21,043	0,112	1,012	0,320	0,741	-15,5
132	56,035	21,037	1,576	0,514	0,022	1,303	-16,8
133	56,035	21,026	1,915	0,474	0,039		-16,6
134	56,035	21,017	-0,128	0,799	0,420	1,030	-17,8
135	56,033	21,066	2,157	0,251	0,176	1,242	-3
136	56,032	21,061	2,156	0,274	0,021	0,974	-4,8
137	56,033	21,053	2,352	0,268	-0,091	0,821	-9,4
138	56,033	21,038	1,151	1,135	0,046	0,636	-17,5

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
139	56,033	21,031	1,489	0,525	0,065	0,985	-17,7
140	56,033	21,016	-0,086	0,648	0,199	0,806	-16
141	55,999	20,987	0,217	0,731	-0,116	0,665	-19,3
142	56,030	21,069	2,021	0,195	-0,067	1,123	-0,8
143	56,030	21,066	2,103	0,234	0,031	1,099	-3,3
144	56,031	21,062	1,985	0,250	0,225	1,006	-4
145	56,030	21,059	2,105	0,209	0,079	1,276	-5,3
146	56,031	21,050	2,206	0,234	-0,003	1,145	-11,1
147	56,031	21,042	2,018	0,556	0,135	1,008	-16,6
148	56,031	21,034	1,965	0,469	0,048	1,014	-16,8
149	56,031	21,000	2,065	0,376	0,026	1,128	-18,8
150	56,031	21,000	1,965	0,400	0,013	1,179	-18,8
151	56,026	21,069	1,893	0,191	0,098	1,081	-1
152	56,027	21,066	2,009	0,238	0,137	0,918	-2,8
153	56,026	21,061	2,336	0,247	0,028	1,064	-5
154	56,026	21,058	2,165	0,210	0,109	1,073	-5,5
155	56,026	21,050	2,330	0,268	0,022	1,333	-11,8
156	56,026	21,033	1,727	0,402	0,020	1,201	-16,3
157	56,026	21,025	-0,197	0,766	0,411	1,254	-13,9
158	56,026	21,016	-0,215	0,694	0,410	0,822	-16,6
159	56,026	21,000	0,875	0,614	0,039	1,009	-18,9
160	56,022	21,070	1,887	0,352	-0,054	1,962	-0,9
161	56,022	21,067	2,100	0,281	0,034	0,800	-3
162	56,022	21,062	2,321	0,236	0,039	1,206	-5
163	56,022	21,059	2,445	0,192	-0,032	1,031	-5,7
164	56,022	21,050	1,944	0,507	-0,126	0,918	-12,6
165	56,022	21,042	1,926	0,581	0,011	0,857	-15,7
166	56,022	21,034	-0,130	0,770	0,354	0,773	-16,3
167	56,022	21,000	-0,626	0,299	0,204	4,178	-18
168	56,017	21,071	1,729	0,406	-0,159	1,705	-1,1
169	56,017	21,069	1,932	0,239	0,069	1,087	-2,4
170	56,017	21,062	2,321	0,241	0,022	0,954	-5
171	56,017	21,058	2,219	0,181	-0,072	0,962	-6,6
172	56,014	21,073	1,668	0,312	-0,145	1,404	-0,2
173	56,013	21,070	2,015	0,270	0,040	1,064	-2,7
174	56,013	21,063	2,189	0,179	0,046	0,900	-4,7
175	56,013	21,054	2,239	0,392	-0,090	1,653	-11,1
176	56,012	21,025	-0,455	0,444	0,335	1,487	-14,5
177	56,008	21,073	1,648	0,380	-0,273	1,693	-0,7
178	56,008	21,071	1,983	0,261	0,029	1,106	-2,2
179	56,008	21,066	2,382	0,209	0,096	1,104	-4
180	56,008	21,062	2,233	0,184	-0,090	1,041	-4,9
181	56,008	21,058	2,231	0,184	-0,083	1,054	-7,2
182	56,008	21,050	2,328	0,321	-0,026	1,045	-13,6
183	56,008	21,025	-0,676	0,386	0,000	6,816	-13,4
184	56,009	21,008	0,233	0,896	0,094	0,626	-18,2
185	56,004	21,072	1,885	0,300	-0,057	1,074	-0,9

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
186	56,004	21,071	2,004	0,263	0,083	1,052	-2,4
187	56,004	21,067	2,213	0,281	0,039	0,991	-4
188	56,004	21,064	2,229	0,185	-0,074	1,010	-4,5
189	56,004	21,061	2,258	0,277	0,110	0,989	-6
190	56,004	21,059	2,280	0,214	-0,017	1,380	-8,4
191	56,004	21,050	-0,624	0,277	0,156	4,031	-13,8
192	56,005	21,026	0,171	0,862	0,199	0,530	-16,3
193	55,999	21,073	1,773	0,245	-0,015	1,126	-0,5
194	55,999	21,071	2,107	0,274	0,014	0,962	-2
195	56,000	21,067	2,293	0,211	-0,027	0,860	-5,1
196	55,999	21,063	2,233	0,198	-0,074	1,034	-5
197	56,000	21,063	2,296	0,303	-0,005	1,155	-7,4
198	56,000	21,059	2,212	0,240	-0,053	1,235	-14,9
199	55,999	21,025	0,163	0,843	0,098	0,850	-15,5
200	56,016	21,001	-0,167	0,230	0,117	1,245	-0,9
201	55,995	21,072	1,815	0,236	-0,021	1,138	-3,5
202	55,995	21,068	2,246	0,283	0,073	1,013	-6
203	55,995	21,061	2,446	0,245	0,052	1,002	-8,2
204	55,995	21,058	2,227	0,353	-0,095	1,902	-15,9
205	55,995	21,008	-0,681	0,137	0,000	1,948	-1,3
206	55,992	21,072	1,980	0,225	-0,087	1,143	-3,1
207	55,992	21,069	2,226	0,262	0,073	1,087	-5
208	55,991	21,063	2,362	0,307	0,010	0,975	-7,2
209	55,992	21,058	2,336	0,241	0,034	1,136	-0,9
210	55,987	21,070	1,830	0,290	-0,023	1,014	-3,4
211	55,987	21,068	2,008	0,283	0,276	0,868	-4,7
212	55,986	21,062	2,193	0,214	0,004	1,059	-5
213	55,987	21,062	2,473	0,246	0,025	1,004	-4,3
214	55,983	21,063	2,340	0,191	0,108	1,607	-6,4
215	55,982	21,058	2,366	0,190	0,129	1,388	-0,45
216	55,981	21,071	1,536	0,376	-0,124	0,991	-1,4
217	55,980	21,071	1,886	0,235	0,025	1,059	-0,9
218	55,980	21,071	1,836	0,436	-0,181	1,655	-2,4
219	55,981	21,069	2,005	0,264	0,243	0,871	-3,5
220	55,981	21,066	2,243	0,278	0,057	1,048	-6,3
221	55,982	21,061	2,444	0,289	0,028	1,084	-7,8
222	55,978	21,063	2,319	0,238	0,025	1,554	-13,9
223	55,978	21,058	2,375	0,180	0,145	1,243	-15,7
224	55,977	21,008	-0,201	0,741	0,399	1,235	-0,45
225	55,977	21,071	1,552	0,514	-0,199	0,986	-1,5
226	55,977	21,071	1,786	0,285	-0,005	1,204	-1
227	55,977	21,070	1,984	0,255	0,015	1,056	-2,5
228	55,977	21,070	2,181	0,250	0,085	1,024	-4
229	55,977	21,065	2,373	0,247	0,046	1,052	-6,8
230	55,973	21,058	2,334	0,318	-0,009	1,976	-0,65
231	55,972	21,071	1,744	0,207	-0,079	1,168	-0,75
232	55,972	21,070	1,819	0,375	-0,067	1,513	-2,2

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
233	55,972	21,069	1,989	0,258	0,239	0,907	-8
234	55,972	21,057	2,063	0,469	0,004	0,863	-0,9
235	55,967	21,070	1,850	0,277	0,002	1,185	-0,4
236	55,967	21,069	1,710	0,417	-0,155	1,598	-2,3
237	55,967	21,069	1,863	0,242	0,058	1,537	-1,1
238	55,967	21,069	1,967	0,380	-0,055	1,798	-3,8
239	55,967	21,065	2,351	0,262	0,027	1,034	-5,7
240	55,969	21,059	2,378	0,337	0,024	1,908	-7
241	55,968	21,058	2,481	0,259	0,033	0,973	-16,1
242	55,969	21,017	0,909	1,228	-0,120	0,665	-0,6
243	55,963	21,068	1,637	0,340	-0,136	1,468	-3,4
244	55,964	21,065	2,303	0,370	-0,017	1,688	-5,5
245	55,964	21,059	2,312	0,336	-0,038	1,862	-0,4
246	55,959	21,067	1,636	0,330	-0,079	1,553	-3,2
247	55,959	21,064	2,186	0,297	0,096	1,159	-6,4
248	55,960	21,058	2,275	0,208	-0,046	1,313	-9,5
249	55,959	21,050	2,162	0,352	-0,071	1,017	-13,2
250	55,960	21,025	0,043	1,006	0,396	0,980	-15,7
251	55,960	21,008	-0,366	0,560	0,352	1,223	-0,5
252	55,955	21,066	1,367	0,577	-0,192	0,792	-1,8
253	55,955	21,064	1,767	0,434	-0,086	1,487	-4
254	55,955	21,060	2,379	0,250	0,102	1,105	-6
255	55,955	21,056	0,662	0,334	0,021	1,117	-0,6
256	55,950	21,066	1,722	0,251	-0,024	1,505	-2,5
257	55,949	21,063	1,897	0,215	0,179	2,000	-5
258	55,951	21,056	2,480	0,291	0,038	0,962	-4,7
259	55,951	21,056	2,366	0,210	0,133	1,514	-9
260	55,951	21,051	2,378	0,468	-0,220	1,212	-7,8
261	55,952	21,050	2,173	0,447	-0,159	1,150	-13,5
262	55,950	21,025	-0,438	0,517	0,382	5,347	-0,4
263	55,946	21,063	1,521	0,567	-0,242	1,173	-1,65
264	55,946	21,061	2,098	0,274	0,026	0,853	-4
265	55,946	21,057	2,298	0,273	0,079	0,890	-5,5
266	55,947	21,053	2,383	0,200	0,152	1,275	-7
267	55,947	21,052	2,240	0,457	-0,134	1,093	-14,3
268	55,946	21,017	-0,178	0,786	0,411	1,414	-0,6
269	55,942	21,061	2,352	0,232	0,060	1,136	-3
270	55,942	21,058	2,439	0,241	0,079	0,973	-4,9
271	55,943	21,052	1,974	0,620	-0,145	0,964	-6
272	55,942	21,050	1,731	0,278	-0,017	1,420	-0,5
273	55,937	21,060	1,813	0,207	-0,003	1,080	-1
274	55,937	21,059	2,064	0,261	-0,018	1,675	-2,4
275	55,937	21,057	2,204	0,270	0,125	1,061	-4,7
276	55,937	21,050	2,255	0,205	-0,071	1,160	-0,8
277	55,933	21,057	1,836	0,274	0,008	1,196	-2,4
278	55,934	21,056	2,026	0,305	0,256	0,977	-4
279	55,934	21,051	2,411	0,250	0,105	1,088	-0,5

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
280	55,929	21,056	1,791	0,246	-0,032	1,373	-2,2
281	55,928	21,054	1,922	0,205	0,168	1,182	-6,6
282	55,928	21,041	1,912	0,565	-0,120	0,967	-0,4
283	55,922	21,050	1,829	0,179	0,003	1,760	-2,1
284	55,922	21,048	2,232	0,266	0,050	1,082	-0,6
285	55,918	21,050	1,901	0,227	0,159	1,347	-0,8
286	55,918	21,050	2,010	0,272	-0,035	1,224	-2,4
287	55,918	21,046	2,244	0,274	0,081	1,051	-0,5
288	55,914	21,050	1,850	0,231	0,016	1,091	-3,2
289	55,914	21,047	2,324	0,244	0,027	1,086	-4,3
290	55,915	21,042	2,215	0,258	0,181	1,070	-17,8
291	55,916	21,000	0,465	1,036	0,033	0,557	-0,6
292	55,910	21,051	1,834	0,380	-0,005	1,365	-2,1
293	55,910	21,049	1,935	0,222	0,119	1,080	-4
294	55,910	21,043	2,336	0,246	0,041	1,148	-5,5
295	55,911	21,038	2,292	0,175	-0,031	1,423	-0,5
296	55,905	21,050	1,755	0,412	-0,079	1,575	-2,4
297	55,906	21,049	2,020	0,278	0,077	1,001	-1,7
298	55,905	21,049	2,064	0,264	0,050	0,936	-2
299	55,901	21,050	1,865	0,189	0,114	1,998	-3
300	55,901	21,047	1,866	0,213	0,124	2,269	-0,6
301	55,898	21,052	1,676	0,218	0,080	1,272	-3
302	55,897	21,048	2,091	0,273	0,038	0,851	-4,6
303	55,897	21,045	2,072	0,290	0,143	0,777	-5
304	55,897	21,042	2,079	0,285	0,107	0,768	-6,4
305	55,897	21,036	-0,479	0,406	0,340	1,718	-0,8
306	55,893	21,054	1,815	0,226	-0,027	1,816	-2,8
307	55,892	21,051	1,971	0,310	0,210	1,025	-5
308	55,892	21,044	2,294	0,244	0,031	0,988	-5,1
309	55,893	21,041	2,163	0,166	0,086	0,818	-9,1
310	55,893	21,034	2,276	0,164	-0,074	1,429	-10,5
311	55,893	21,029	2,411	0,185	0,023	0,989	-0,5
312	55,888	21,053	1,689	0,194	0,073	1,110	-2,5
313	55,888	21,050	1,895	0,230	0,125	1,247	-4,3
314	55,889	21,047	2,291	0,260	0,120	1,048	-6
315	55,889	21,044	2,137	0,270	-0,008	0,942	-6,6
316	55,887	21,040	2,222	0,187	-0,066	0,982	-11,6
317	55,888	21,013	-0,684	0,115	0,000	1,521	-16,1
318	55,888	21,000	-0,426	0,438	0,337	1,186	-0,5
319	55,884	21,053	1,714	0,180	0,076	0,949	-1,7
320	55,884	21,053	1,773	0,274	0,039	1,241	-7
321	55,884	21,042	2,136	0,290	0,017	0,823	-6,1
322	55,884	21,042	2,147	0,173	0,119	0,967	-15,3
323	55,885	21,015	2,375	0,277	0,047	1,559	-0,45
324	55,879	21,051	1,771	0,178	-0,092	1,137	-1,5
325	55,879	21,051	1,868	0,197	0,112	1,553	-5,3
326	55,880	21,043	0,472	0,231	-0,007	1,067	-7,6

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
327	55,879	21,039	2,152	0,251	0,066	1,407	-16,8
328	55,880	21,008	0,085	1,065	0,397	1,132	-15,3
329	55,880	21,000	-0,609	0,318	0,247	4,316	-0,5
330	55,875	21,055	1,677	0,264	0,044	1,511	-1,9
331	55,875	21,054	1,748	0,204	-0,043	1,121	-3,6
332	55,875	21,050	1,880	0,247	0,120	1,457	-6
333	55,875	21,045	2,095	0,290	0,070	0,909	-8,6
334	55,875	21,038	2,195	0,208	0,065	0,974	-0,4
335	55,872	21,057	1,628	0,257	-0,029	1,365	-0,8
336	55,872	21,056	1,678	0,306	-0,011	1,654	-2
337	55,871	21,056	1,862	0,195	0,116	1,811	-1,7
338	55,871	21,055	1,902	0,237	0,133	1,251	-4
339	55,871	21,054	1,834	0,207	0,037	1,660	-4
340	55,871	21,051	1,967	0,265	0,215	1,130	-6
341	55,875	21,045	1,977	0,265	0,211	1,070	-8
342	55,871	21,042	2,207	0,280	0,144	1,068	-12,8
343	55,870	21,030	2,223	0,247	-0,102	1,434	-13,8
344	55,871	21,025	2,254	0,256	-0,067	1,498	-0,5
345	55,867	21,059	1,651	0,335	-0,067	1,595	-1,8
346	55,867	21,057	1,878	0,251	0,084	1,275	-4
347	55,867	21,053	2,001	0,270	0,233	0,904	-6
348	55,867	21,050	1,985	0,262	0,243	1,018	-8,6
349	55,868	21,043	2,144	0,244	0,043	1,082	-11,1
350	55,868	21,036	2,173	0,209	0,082	1,057	-16,1
351	55,867	21,017	2,395	0,190	0,115	1,059	-16,6
352	55,866	21,009	2,382	0,179	0,103	1,072	-19,7
353	55,867	20,992	2,429	0,187	0,080	0,933	-0,7
354	55,863	21,058	1,719	0,218	0,007	1,139	-0,48
355	55,864	21,057	1,639	0,166	0,083	1,501	-1,8
356	55,863	21,056	1,967	0,268	0,015	1,032	-8
357	55,863	21,046	1,987	0,365	0,176	1,450	-9,3
358	55,863	21,042	2,190	0,226	-0,017	1,117	-13,2
359	55,863	21,033	2,252	0,229	-0,067	1,288	-13,2
360	55,864	21,028	2,316	0,269	0,006	1,711	-15,3
361	55,863	21,024	2,223	0,189	-0,072	0,986	-16,6
362	55,863	21,017	2,413	0,213	0,138	1,042	-17
363	55,863	21,009	2,431	0,188	0,027	0,957	-0,7
364	55,858	21,058	1,694	0,166	0,084	0,908	-2,2
365	55,858	21,058	1,769	0,341	0,025	1,346	-3,6
366	55,858	21,054	1,924	0,247	0,220	1,805	-7
367	55,858	21,049	2,076	0,292	0,126	0,783	-6,4
368	55,857	21,047	2,322	0,209	0,006	1,114	-9,7
369	55,858	21,042	2,216	0,195	-0,050	0,988	-12,8
370	55,858	21,034	2,385	0,190	0,134	1,181	-15,9
371	55,859	21,021	2,164	0,455	-0,213	1,324	-0,7
372	55,855	21,059	1,817	0,216	0,007	1,045	-1,1
373	55,855	21,058	1,789	0,172	-0,091	1,439	-2,1

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
374	55,855	21,057	1,836	0,207	0,039	1,854	-3
375	55,855	21,056	1,853	0,246	0,056	1,291	-4
376	55,855	21,055	2,023	0,271	0,214	0,832	-7
377	55,854	21,046	2,363	0,191	0,091	1,160	-9,1
378	55,854	21,042	2,227	0,187	-0,073	1,028	-18,6
379	55,853	21,008	2,435	0,192	0,072	0,926	-0,8
380	55,851	21,061	1,705	0,242	0,036	1,263	-3
381	55,851	21,058	1,851	0,267	0,047	2,050	-3
382	55,850	21,054	1,966	0,246	0,232	1,073	-7
383	55,850	21,049	2,106	0,265	0,046	0,917	-5,3
384	55,850	21,050	2,089	0,249	0,010	1,109	-15,3
385	55,851	21,028	2,365	0,202	0,125	1,455	-0,7
386	55,845	21,060	1,841	0,249	0,019	0,970	-5
387	55,845	21,054	2,178	0,240	0,124	1,068	-6,3
388	55,845	21,050	2,150	0,236	0,083	1,262	-8
389	55,846	21,049	2,334	0,240	0,030	1,116	-11,3
390	55,845	21,042	2,128	0,503	-0,239	1,875	-15,7
391	55,845	21,028	2,472	0,205	0,042	0,935	-0,7
392	55,841	21,059	1,842	0,233	0,021	0,982	-5,3
393	55,841	21,051	2,090	0,234	0,019	1,327	-0,8
394	55,837	21,059	1,723	0,210	0,020	1,072	-3
395	55,837	21,055	1,901	0,208	0,190	1,877	-5
396	55,837	21,052	2,048	0,268	0,089	0,886	-6,1
397	55,836	21,049	2,158	0,244	0,071	1,265	-20,3
399	55,830	21,060	1,714	0,233	0,002	1,162	-2
400	55,832	21,059	1,776	0,221	-0,106	1,619	-4
401	55,832	21,056	2,095	0,228	0,032	1,087	-5
402	55,832	21,053	2,144	0,233	0,130	1,167	-0,8
403	55,828	21,062	1,820	0,270	-0,009	1,391	-3
404	55,828	21,060	1,843	0,256	0,062	1,851	-5
405	55,828	21,057	2,124	0,181	0,152	1,649	-6
406	55,828	21,054	2,272	0,207	-0,021	1,044	-7
407	55,831	21,051	2,147	0,243	0,092	1,046	-7
408	55,828	21,050	2,165	0,171	0,076	0,853	-9,9
409	55,828	21,042	2,140	0,423	-0,257	2,018	-12,6
410	55,828	21,033	2,323	0,174	0,074	1,508	-20,5
411	55,828	21,009	2,409	0,181	0,088	0,946	-21,6
412	55,828	21,000	2,413	0,176	0,009	0,929	-3
413	55,825	21,061	2,021	0,255	0,009	1,065	-5
414	55,825	21,056	1,981	0,243	0,260	0,929	-7
415	55,825	21,052	2,271	0,212	-0,018	1,017	-7,6
416	55,824	21,042	2,180	0,206	0,039	1,050	-10,5
417	55,825	21,050	2,342	0,180	0,111	1,596	-12,8
418	55,825	21,033	2,259	0,329	-0,125	2,882	-21,4
419	55,824	20,998	2,369	0,200	0,127	1,532	-3
420	55,820	21,063	1,895	0,244	0,056	1,091	-2
421	55,820	21,063	1,920	0,225	0,109	1,131	-4

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
422	55,820	21,060	2,130	0,238	0,057	1,056	-6
423	55,820	21,055	2,182	0,231	0,048	1,026	-7,4
424	55,822	21,051	2,170	0,204	0,104	1,057	-10,1
425	55,822	21,045	2,266	0,176	-0,092	1,374	-12,4
426	55,822	21,038	2,368	0,168	0,155	1,515	-13
427	55,822	21,032	2,320	0,220	0,037	1,517	-20,9
428	55,822	21,008	2,412	0,212	0,101	1,131	-21,6
429	55,822	21,000	2,408	0,172	0,057	0,910	-0,7
430	55,815	21,064	1,749	0,244	-0,020	1,122	-4
431	55,815	21,061	1,949	0,262	0,205	1,141	-6
432	55,815	21,056	2,147	0,203	0,102	1,072	-8,9
433	55,815	21,051	2,210	0,182	-0,045	0,931	-11,3
434	55,814	21,042	2,195	0,174	-0,039	0,854	-21,6
435	55,815	20,997	-0,573	0,466	0,293	6,475	-1,1
436	55,810	21,066	1,792	0,241	0,025	1,010	-6
437	55,810	21,059	2,147	0,222	0,076	1,058	-9,9
438	55,809	21,050	2,159	0,160	0,111	0,821	-10,7
439	55,810	21,045	2,240	0,192	-0,080	1,051	-1
440	55,806	21,067	1,845	0,231	0,010	0,924	-3
441	55,806	21,063	1,931	0,252	0,011	1,081	-5
442	55,805	21,060	2,198	0,210	0,135	0,895	-7,2
443	55,805	21,055	2,161	0,205	0,064	1,069	-9,5
444	55,806	21,050	2,193	0,187	0,018	0,915	-12
445	55,805	21,042	2,314	0,202	0,037	1,717	-0,9
446	55,801	21,066	1,764	0,193	-0,086	1,180	-2
447	55,801	21,064	1,720	0,290	-0,051	1,562	-4
448	55,801	21,062	2,031	0,251	0,011	1,039	-6,6
449	55,800	21,055	2,159	0,217	0,030	1,087	-14,7
450	55,801	21,041	2,259	0,610	0,013	1,291	-1,3
451	55,796	21,066	1,869	0,272	-0,026	1,000	-6
452	55,796	21,058	2,213	0,200	-0,001	0,898	-7
453	55,796	21,056	2,376	0,199	0,100	1,220	-1
454	55,793	21,069	1,826	0,244	0,015	0,914	-5
455	55,792	21,062	2,136	0,237	0,069	1,057	-10,9
456	55,792	21,024	-0,567	0,281	0,291	2,877	-15,9
457	55,792	21,039	2,084	1,170	-0,260	0,684	-8,9
458	55,792	21,054	2,180	0,212	0,108	1,118	-1
459	55,788	21,070	1,825	0,218	0,008	0,913	-2
460	55,788	21,067	1,850	0,291	-0,012	0,995	-4,9
461	55,787	21,062	2,013	0,196	-0,112	1,292	-7
462	55,787	21,058	2,158	0,191	0,177	1,124	-10,9
463	55,787	21,050	2,169	0,172	0,110	0,887	-12,6
464	55,788	21,045	2,308	0,172	0,014	1,316	-1
465	55,783	21,072	1,706	0,220	0,053	1,073	-3
466	55,782	21,070	1,767	0,273	0,094	1,126	-4
467	55,783	21,065	1,959	0,293	-0,011	1,032	-5,5
468	55,783	21,062	2,009	0,222	-0,071	1,193	-7

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
469	55,783	21,062	1,955	0,250	0,193	1,075	-7,4
470	55,783	21,058	2,146	0,214	0,083	1,085	-12
471	55,783	21,050	2,240	0,214	-0,101	1,417	-22,2
472	55,783	20,998	2,381	0,375	-0,015	1,434	-2,45
473	55,778	21,072	1,838	0,240	0,038	1,588	-4
474	55,778	21,069	2,021	0,283	0,003	0,970	-5
475	55,778	21,066	1,865	0,184	0,114	1,967	-6
476	55,778	21,063	1,847	0,134	0,000	1,648	-6,6
477	55,779	21,060	2,090	0,201	0,070	1,551	-14,3
478	55,779	21,042	2,181	0,197	0,059	0,969	-16,6
479	55,778	21,034	2,191	0,179	0,010	0,897	-21,1
480	55,778	21,007	2,334	0,279	0,022	1,290	-22
481	55,778	21,000	2,245	0,447	-0,175	1,834	-0,6
482	55,774	21,076	1,571	0,268	-0,059	1,230	-6,4
483	55,775	21,064	2,066	0,239	-0,010	1,149	-8
484	55,774	21,064	2,139	0,246	0,087	1,182	-14,5
485	55,774	21,042	2,288	0,196	-0,073	1,113	-19,3
486	55,774	21,025	2,220	0,216	-0,072	1,120	-20,9
487	55,774	21,017	2,324	0,234	0,053	1,659	-22,6
488	55,774	21,000	2,237	0,421	-0,147	1,528	-0,6
489	55,770	21,077	1,494	0,261	-0,155	1,023	-3
490	55,770	21,075	1,856	0,313	0,068	1,133	-6
491	55,769	21,071	2,129	0,213	0,150	1,431	-6,8
492	55,770	21,068	2,102	0,264	0,012	0,877	-7
493	55,770	21,067	2,012	0,188	-0,113	1,307	-10,3
494	55,770	21,059	2,064	0,267	-0,024	1,232	-14,7
495	55,770	21,050	2,261	0,181	-0,096	1,513	-17,2
496	55,770	21,034	2,422	0,204	0,036	1,025	-20,9
497	55,770	21,017	2,426	0,249	0,159	1,200	-22
498	55,770	21,009	2,401	0,208	0,113	1,134	-0,6
499	55,765	21,079	1,532	0,243	-0,062	1,083	-2
500	55,765	21,077	1,637	0,315	-0,014	1,350	-5
501	55,765	21,073	2,063	0,279	0,035	1,027	-8
502	55,765	21,069	1,913	0,202	0,212	1,784	-7,6
503	55,765	21,067	2,092	0,235	0,030	1,257	-12,4
504	55,765	21,058	2,173	0,236	0,001	1,159	-20,7
505	55,765	21,016	2,067	0,389	-0,073	1,080	-21,6
506	55,765	21,008	2,139	0,430	-0,099	1,081	-23,8
507	55,766	21,000	2,212	0,463	-0,138	1,006	-0,5
508	55,761	21,081	1,353	0,313	-0,061	0,772	-3
509	55,761	21,079	1,809	0,283	0,033	1,133	-5
510	55,760	21,076	2,158	0,255	-0,021	1,004	-7
511	55,727	21,072	2,133	0,272	0,037	1,267	-9,1
512	55,760	21,066	2,252	0,275	-0,082	1,314	-17,8
513	55,761	21,043	2,394	0,224	0,112	1,343	-18,9
514	55,761	21,034	2,323	0,384	0,047	1,480	-20,9
515	55,761	21,017	1,977	0,356	-0,016	1,241	-21,6

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
516	55,761	21,008	2,023	0,350	0,032	1,061	-23,9
517	55,760	21,000	2,218	0,373	-0,111	1,205	-0,4
518	55,757	21,080	1,448	0,242	-0,048	1,034	-7
519	55,756	21,074	2,127	0,263	0,035	1,129	-9,5
520	55,755	21,068	2,088	0,275	-0,011	1,379	-13,6
521	55,756	21,058	2,277	0,182	-0,064	1,403	-18,2
522	55,756	21,042	1,761	0,432	-0,014	1,228	-18,8
523	55,757	21,033	1,942	0,413	0,004	1,371	-19,1
524	55,756	21,025	1,887	0,324	-0,029	1,246	-19,9
525	55,756	21,016	1,907	0,318	0,021	1,228	-21,3
526	55,757	21,008	1,980	0,356	-0,013	1,229	-23,2
527	55,757	21,000	2,136	0,376	-0,076	0,979	0
529	55,752	21,083	1,491	0,323	-0,091	1,228	-3,8
530	55,752	21,079	1,774	0,296	0,058	1,093	-4,9
531	55,751	21,074	2,026	0,265	-0,026	1,226	-9,5
532	55,753	21,071	2,080	0,367	-0,084	1,126	-10,3
533	55,752	21,067	1,960	0,417	-0,099	1,290	-13,4
534	55,752	21,059	2,001	0,383	-0,076	1,056	-16,6
535	55,752	21,050	1,748	0,597	-0,069	1,100	-17,2
536	55,752	21,026	1,851	0,366	-0,076	1,276	-18
537	55,752	21,033	1,890	0,337	-0,143	1,234	-17,6
538	55,752	21,025	1,882	0,329	-0,086	1,097	-18,8
539	55,752	21,016	1,869	0,307	-0,037	1,275	-21,6
540	55,752	21,008	1,958	0,387	-0,010	1,246	-24,3
541	55,751	20,999	2,265	0,306	-0,080	1,565	0
542	55,747	21,084	1,298	0,298	-0,026	1,041	-0,9
543	55,748	21,084	1,464	0,255	-0,059	1,033	-2,35
544	55,747	21,082	1,679	0,265	-0,009	1,074	-7
545	55,748	21,076	2,014	0,362	-0,016	1,285	-8,4
546	55,747	21,073	2,063	0,394	-0,072	1,498	-10,5
547	55,748	21,065	2,144	0,434	0,003	1,265	-13,5
548	55,746	21,054	2,129	0,504	-0,007	0,957	-15,7
549	55,747	21,041	2,314	0,548	0,024	1,062	-21
550	55,747	21,016	2,019	0,476	-0,044	0,867	-26,4
551	55,748	21,002	3,242	0,789	-0,249	0,725	0
552	55,742	21,085	1,436	0,237	-0,058	0,950	-1,7
553	55,742	21,084	1,649	0,275	-0,029	1,169	-2,8
554	55,742	21,083	1,594	0,373	-0,079	1,178	-7
555	55,743	21,076	1,952	0,378	0,119	1,471	-8,5
556	55,743	21,074	1,906	0,389	0,048	1,650	0
558	55,737	21,086	1,442	0,323	-0,133	1,407	-5
559	55,738	21,080	1,978	0,247	0,197	0,927	-7,5
560	55,738	21,075	2,003	0,248	0,166	0,887	-6,2
561	55,738	21,074	2,093	0,326	-0,025	1,246	-8,8
562	55,740	21,065	2,097	0,429	-0,055	1,741	-12,5
563	55,741	21,054	2,032	0,464	-0,050	1,076	-19,7
564	55,739	21,042	3,201	0,903	-0,361	0,886	-19,6

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
565	55,741	21,031	1,883	0,487	0,111	0,821	-25,5
566	55,741	21,018	3,178	0,905	-0,308	0,882	-28,5
567	55,741	21,012	3,007	0,965	0,170	1,025	0
569	55,732	21,085	1,284	0,683	-0,258	1,214	-6,3
570	55,734	21,080	1,990	0,292	0,053	1,099	-7
571	55,734	21,076	1,975	0,240	0,197	0,888	-10,9
572	55,728	21,076	2,005	0,321	-0,009	1,196	-12,9
573	55,730	21,059	1,993	0,463	-0,028	0,877	-20,2
574	55,730	21,047	2,983	0,926	-0,033	0,911	-24,4
575	55,730	21,034	3,761	0,410	-0,032	1,101	-24,5
576	55,731	21,019	1,710	0,426	0,165	1,051	-31,2
577	55,730	21,003	2,777	2,343	0,151	0,774	-1,5
578	55,723	21,092	1,801	0,238	-0,040	1,535	-4,8
579	55,724	21,089	1,974	0,228	0,049	0,990	-5
580	55,724	21,087	2,008	0,217	0,047	0,872	-6,7
581	55,725	21,083	1,939	0,248	0,190	1,173	0
582	55,721	21,094	1,659	0,209	0,021	1,109	-1,5
583	55,720	21,094	1,752	0,265	-0,106	1,622	-2
584	55,720	21,090	1,920	0,245	0,118	1,122	-6
585	55,719	21,087	1,943	0,227	0,233	1,192	-5,2
586	55,720	21,084	2,084	0,309	-0,024	1,184	-7,8
587	55,721	21,077	2,220	0,331	0,130	1,327	-10,1
588	55,720	21,070	2,136	0,477	-0,020	1,285	-15,3
589	55,720	21,059	2,101	0,492	0,008	0,812	-18,7
590	55,720	21,047	1,630	0,414	0,017	1,655	-24,3
591	55,721	21,038	1,668	0,573	0,037	1,408	-27,2
592	55,720	21,012	2,621	0,223	0,035	1,238	-28,7
593	55,717	21,000	2,506	0,360	-0,133	1,451	-1,1
595	55,715	21,094	1,752	0,265	-0,108	1,602	-3
596	55,715	21,092	1,917	0,204	0,105	1,080	-6
597	55,715	21,086	2,094	0,232	0,028	1,060	0
598	55,711	21,094	0,905	0,486	0,181	0,986	-2,2
599	55,711	21,094	1,707	0,268	-0,044	1,553	-2,1
601	55,711	21,094	0,098	0,410	-0,059	0,975	-4,5
602	55,712	21,090	1,994	0,258	0,093	0,958	-5,1
603	55,711	21,086	2,051	0,304	-0,011	1,040	-9
604	55,711	21,084	2,106	0,252	-0,014	0,895	-11,8
605	55,711	21,070	2,140	0,494	-0,035	1,101	-17,3
606	55,710	21,058	2,037	0,508	0,076	0,816	-22
607	55,711	21,044	2,077	0,503	0,054	0,778	-28,1
608	55,712	21,032	2,868	0,801	0,167	0,924	-26,6
609	55,711	21,017	2,479	0,363	-0,136	1,148	-29,7
610	55,712	21,000	3,720	0,507	-0,134	1,496	-1,2
611	55,707	21,098	1,646	0,173	0,078	1,224	-2
612	55,707	21,096	1,899	0,207	0,114	1,163	-2,1
613	55,707	21,094	1,674	0,359	-0,125	1,679	-5
614	55,707	21,091	1,870	0,231	0,035	1,300	-9

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
615	55,708	21,083	2,100	0,242	0,030	0,977	-8,7
616	55,710	21,076	2,242	0,315	0,127	1,275	0
618	55,703	21,098	1,648	0,355	-0,139	1,817	-3
619	55,703	21,096	1,890	0,186	0,127	1,305	-5,2
620	55,702	21,087	2,122	0,267	0,013	1,205	-4
621	55,703	21,092	1,936	0,274	0,087	0,963	-9
622	55,702	21,078	2,236	0,311	0,127	1,267	-13,4
623	55,703	21,069	2,147	0,522	-0,045	0,974	-22,2
624	55,702	21,057	2,788	0,867	0,116	0,963	-24,3
625	55,702	21,044	2,251	0,476	-0,125	0,815	-27,7
626	55,702	21,030	3,703	0,613	-0,201	1,945	-29,5
627	55,702	21,018	3,747	0,583	0,013	1,808	-27,7
628	55,702	20,999	2,387	0,404	-0,081	0,969	0
629	55,697	21,099	1,156	0,495	-0,078	0,733	-1,4
630	55,698	21,098	1,742	0,223	-0,075	1,240	-2
631	55,697	21,097	1,865	0,190	0,113	1,691	-4
632	55,697	21,095	1,941	0,240	0,183	1,126	-8
633	55,698	21,087	2,071	0,232	0,024	0,907	0
634	55,693	21,099	1,633	0,333	-0,057	1,856	-3
635	55,693	21,097	1,868	0,224	0,057	1,164	-6
636	55,694	21,091	2,085	0,248	0,043	1,029	0
638	55,689	21,101	1,429	0,497	-0,217	1,187	-3,9
639	55,689	21,099	0,275	0,443	-0,047	1,137	-4,7
640	55,689	21,095	1,927	0,254	0,175	1,108	-5,8
641	55,692	21,089	2,127	0,270	0,018	1,183	-8,2
642	55,688	21,089	2,131	0,231	0,035	1,051	-10,5
643	55,692	21,079	2,224	0,292	0,133	1,204	-18,5
645	55,693	21,053	2,166	0,525	-0,071	0,884	-21,3
646	55,693	21,043	2,453	0,333	-0,120	0,894	-22,6
647	55,693	21,032	3,717	0,539	-0,158	1,631	-25,8
648	55,693	21,018	3,705	0,546	-0,169	1,689	-27,5
649	55,690	21,006	3,700	0,515	-0,140	1,526	-29,5
650	55,693	21,000	3,390	0,732	-0,376	1,183	-31,5
651	55,690	20,995	3,637	0,568	-0,229	1,499	-30,3
652	55,685	21,102	1,327	0,624	-0,291	1,647	0
653	55,685	21,102	1,567	0,408	-0,184	1,655	-1
654	55,685	21,099	1,765	0,229	-0,048	1,206	-3
655	55,685	21,099	1,730	0,299	-0,066	1,758	-2,3
656	55,685	21,093	1,948	0,277	0,063	0,882	-3,9
657	55,684	21,093	2,105	0,205	0,064	1,115	-6,5
658	55,683	21,087	1,988	0,236	0,239	0,795	-9,1
659	55,684	21,086	2,170	0,256	0,078	1,211	-7,8
660	55,683	21,080	2,266	0,300	0,122	1,033	-9,9
661	55,684	21,073	2,226	0,448	0,008	1,243	-13,2
662	55,684	21,062	3,703	0,517	-0,149	1,566	-20,6
663	55,685	21,049	2,432	0,365	-0,125	0,954	-21,7
664	55,685	21,034	3,724	0,485	-0,126	1,442	-25,9

Nr.	Latitude	Longitude	Mean, φ	Sorting, φ	Skewness	Kurtosis	Water depth,m
665	55,684	21,015	3,702	0,520	-0,145	1,554	-28
666	55,684	20,999	3,714	0,502	-0,138	1,506	-30,2
667	55,680	21,103	1,699	0,162	0,067	0,853	0
669	55,681	21,098	1,809	0,239	-0,013	1,443	-3,1
670	55,680	21,098	1,918	0,232	0,152	1,146	-4
671	55,680	21,090	2,053	0,238	0,050	0,849	-8
672	55,676	21,103	1,608	0,272	-0,038	2,021	0
673	55,675	21,102	1,721	0,175	-0,010	0,912	-1
674	55,675	21,099	1,735	0,320	-0,089	1,872	-4,8
675	55,676	21,097	1,953	0,235	0,068	1,015	-4,3
676	55,676	21,090	1,974	0,223	0,229	0,861	-8
677	55,671	21,103	1,589	0,284	-0,067	1,589	0
678	55,671	21,102	1,726	0,208	-0,021	1,118	-1,5
679	55,671	21,102	1,717	0,265	-0,036	1,375	-3,8
680	55,671	21,100	1,798	0,278	0,000	1,226	-2,3
681	55,671	21,099	1,882	0,210	0,141	1,572	-4
682	55,673	21,094	2,013	0,321	0,028	0,976	-3,2
683	55,670	21,094	2,060	0,259	-0,015	0,934	-4,6
684	55,672	21,092	2,042	0,255	0,040	0,839	-7,1
685	55,672	21,087	2,129	0,277	0,018	1,219	-7,3
686	55,671	21,082	2,226	0,313	0,133	1,127	-9,8
687	55,673	21,075	2,335	0,379	0,021	1,036	-14
688	55,671	21,067	2,357	0,426	-0,145	0,988	-18,1
689	55,672	21,059	3,491	0,761	-0,416	1,895	-22,7
690	55,672	21,049	3,530	0,796	-0,434	2,199	-24,9
691	55,670	21,043	3,765	0,425	-0,020	1,176	-27
692	55,670	21,034	3,054	0,905	-0,305	0,841	-26,3
693	55,672	21,004	3,544	0,624	-0,315	1,510	-27
694	55,672	21,000	2,373	0,387	-0,056	0,951	-28,3
695	55,667	21,103	1,552	0,321	-0,096	1,580	-0,4
696	55,667	21,102	1,596	0,353	-0,101	1,733	-1,8
697	55,684	21,102	1,541	0,363	-0,129	1,355	-3,2
698	55,667	21,101	1,739	0,224	-0,074	1,253	-2,3
699	55,667	21,099	1,919	0,223	0,103	1,133	-4,7
700	55,667	21,097	1,868	0,245	0,041	1,122	-4,5
701	55,666	21,090	2,104	0,244	-0,009	0,894	-8,5
702	55,666	21,086	2,166	0,251	0,076	1,220	-7,7
703	55,666	21,084	2,241	0,303	0,125	1,123	-9,6
704	55,667	21,079	2,296	0,324	0,091	0,929	-11,7
705	55,666	21,070	2,407	0,364	-0,086	0,963	-16,9
706	55,665	21,062	2,226	0,547	-0,199	0,997	-19,5
707	55,666	21,056	2,335	0,503	-0,217	1,077	-21,7
708	55,664	21,044	2,424	0,384	-0,114	0,995	-24,3
709	55,666	21,031	3,667	0,522	-0,180	1,514	-26,8
710	55,667	21,017	3,554	0,614	-0,296	1,461	-28,3
711	55,666	21,016	2,376	0,356	-0,024	0,882	-26,3
712	55,667	21,001	3,525	0,652	-0,326	1,504	-30,3

Appendix 2. Mineralogical composition of 6 bulk samples. SD standard deviation.

Nr.	Quartz	Anorthite	Albite	Microcline	Dolomite
245	89.3	2.1	5.3	3.3	-
327	81.2	2.3	8	8.5	-
409	81.4	-	12.3	6.3	-
478	85.7	-	14.3	-	-
607	81.3	-	13.5	5.2	-
712	85.1	-	5.8	6.2	2.9
Average	84	2.2	9.87	5.9	2.9
SD	3.29	0.14	3.99	1.89	
Min	81.2	2.1	5.3	3.3	
Max	89.3	2.3	14.3	8.5	

Appendix 3. Mineralogical composition of the <0.01 mm fraction for 37 samples. SD standard deviation; tr. traces.

Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
26	34	-	5.1	tr.	-	-	0.4	17.1	2.7	-	3.1	0.4	-	37.2	-	tr.
34	70.3	-	6	-	1.6	-	8.8	8.5	-	-	4.1	-	-	-	-	0.7
126	41.5	-	tr.	-	2.6	5.3	-	2.6	7.5	-	tr.	2.9	-	33.1	4.5	tr.
137	43.5	-	tr.	2.9	tr.	-	-	5.1	7.2	-	4.3	-	-	37	-	-
193	59.5	-	tr.	-	9.4	0.8	1.6	5.8	13.5	5.4	-	1.5	0.7	-	-	1.8
198	66.7	-	1.5	-	tr.	-	11.4	10.7	4	tr.	2.1	-	-	-	-	3.6
239	49.5	-	1.2	5,7	tr.	-	12.6	3.8	14	4.3	4.6	-	-	-	-	4.3
241	52.8	-	-	9,1	-	1.8	4.3	8.3	13.3	5.9	-	0.9	-	-	-	3.6
243	43.2	-	2.5	-	5.9	-	2.4	6.7	5.5	-	4.2	-	-	27.2	2.4	-
244	79.8	-	-	-	-	tr.	1	3.2	13.4	tr.	2.6	-	-	-	-	-
245	29.6	-	-	2.7	2	-	19.6	6.2	-	-	4.9	-	-	33.3	1.7	-
248	44.2	-	1.2	8,5	-	-	12.7	9.7	12.4	3.7	4.3	-	-	-	-	3.3
249	50.1	-	7.1	1,8	3.5	-	22.4	5.6	5.4	-	2.2	tr.	-	-	-	1.9
286	67.3	-	2.2	4.1	-	2.6	1.3	4.2	5.3	1.1	8.1	-	-	-	-	3.8
327	54.2	-	2.4	6,1	3.7	-	11.2	7	6.8	1.9	4	-	-	-	-	2.7
364	42.3	-	-	-	9.1	-	tr.	4.6	-	-	3.5	-	3.8	36.7	-	-
371	51.3	-	-	3.2	4.2	-	4.2	10.1	15.1	1.7	6.9	-	-	-	-	3.3
409	37	-	2.1	4.6	4.6	-	13.3	8.2	15.2	4.6	5.8	-	-	-	-	4.6
412	45.2	-	3.5	9.5	-	-	2.4	7.7	16.8	4.9	6.6	-	-	-	-	3.4
440	62.6	-	4.8	9.5	-	-	1.9	4.6	12.1	-	4.5	-	-	-	-	-
445	38.4	-	-	-	3.4	-	14	8.6	11.2	-	6.2	tr.	-	18.2	-	-
478	43	-	1.9	7.7	-	-	10.1	8.4	12.9	5.2	6.1	-	-	-	-	4.7
481	52	-	4.7	5,6	5.2	tr.	14.6	11.9	2.1	1.2	2.7	-	-	-	-	tr.
542	39.7	-	7	1.7	15.8	-	10.4	10.3	1.8	4.4	5.3	tr.	-	-	-	3.6
551	35.2	-	2.6	-	4.6	0.1	10.2	6.3	11.6	-	4.4	0.9	-	24.1	-	tr.
598	54.6	-	1.4	4,3	4.9	2.7	tr.	3.9	15.3	4.5	5.4	-	-	-	-	3
604	58	-	tr.	4.8	4.3	1.7	tr.	6.6	15.9	1.7	5.3	-	-	-	-	1.7
605	56.9	1.8	1.5	2.9	11.7	tr.	0.9	5.2	-	-	3	-	-	14.2	-	1.9
606	48	-	6.5	5	4	tr.	8.4	8.2	11.1	1.4	5.6	-	-	-	-	1.8
607	52.5	-	4.3	3,6	tr.	-	18.5	5.3	6.6	1.7	2.7	-	1.5	-	-	3.3
608	37.9	-	4.3	4.2	-	-	14.5	14.1	4	-	4.2	-	-	15.8	1	-
609	75.2	tr.	2.3	3.3	9.1	-	-	5	3.2	-	tr.	-	-	-	-	1.9
610	68.6	-	3.1	2.6	tr.	-	0.9	8.6	9	tr.	5.7	-	-	-	-	1.5
652	76.9	-	4.3	5	-	-	-	3	-	3.4	4.1	-	-	-	-	3.3
666	54	-	11.6	-	5.2	-	-	16.5	10	-	2.7	-	-	-	-	-
707	60.2	-	4	2.8	1.8	tr.	-	10.6	11.9	2.3	4	-	-	-	-	2.4
712	71.4	-	2.6	6,9	-	-	-	7	6.3	-	3.5	-	-	-	-	2.3

Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Average	52.62	1.8	3.77	4.72	5.55	2.14	8.67	7.55	9.47	3.29	4.45	1.32	2	27.68	2.4	2.85
SD	13.02		2.37	2.41	3.57	1.67	6.48	3.46	4.57	1.65	1.44	0.97	1.61	9.1	1.51	1.05
Min	29.6	1.8	1.2	1,5	1.6	0.1	0.4	2.6	1.8	1.1	2.1	0.4	0.7	14.2	1	0.7
Max	79.8	1.8	11.6	9,5	15.8	5.3	22.4	17.1	16.8	5.9	8.1	2.9	3.8	37.2	4.5	4.7

Minerals: 1-quartz, 2-anorthite, 3-albite, 4-orthoclase, 5-microcline, 6-actinolite, 7-calcite, 8-dolomite, 9-muscovite, 10-biotite, 11-chlorite, 12-vermicullite,13-montmorillonite, 14-illite, 15-kaolinite, 16-glauconite

Appendix 4. Mineralogical composition of the 0.01-0.063 mm fraction for 17 samples. SD standard deviation; tr. traces.

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
34	79.6	2.8	-	-	3.9	-	2.5	6.4	-	-	4.8	-	-	-	-	-	-
126	51.5	-	4.2	-	14.1	1.4	0.7	28.1	-	-	-	-	-	-	-	-	-
137	49.6	-	4.7	-	14.4	-	0.9	26.9	-	-	3.5	-	-	-	-	-	-
239	61.4	3.6	6	1	9.1	1.8	6	8	3.1	-	-	-	-	-	-	-	-
241	77.8	-	7.2	7.2	-	-	2.9	4.9	-	-	-	-	-	-	-	-	-
243	72	-	3.7	8.1	-	-	5.8	6.8	-	-	3.6	-	-	-	-	-	-
244	79.8	-	11.3	-	6.3	tr.	-	2.6	-	-	tr.	-	-	-	-	-	-
245	43.8	-	3.7	-	-	3.8	6.4	15.4	-	-	2.8	-	2.5	-	17.3	4.3	-
248	51.1	-	5.1	tr.	7.8	-	1.3	5.3	-	-	-	-	10.1	11.6	-	5.6	2.1
249	80.5	-	7.7	-	6.9	-	2.5	2.4	-	-	-	-	-	-	-	-	-
364	82.7	-	6.6	7.6	-	-	tr.	3.1	-	-	tr.	-	-	-	-	-	-
371	67.9	-	5.1	3.7	3.6	-	3.6	13.4	-	-	1.5	1.2	-	-	-	-	-
440	81.9	-	5.5	tr.	1.9	-	4.2	3.8	-	-	2.7	tr.	-	-	-	-	-
445	53.5	-	-	-	24.2	-	5.7	12.8	-	1.6	2.2	-	-	-	-	-	-
551	70.8	-	-	-	6.6	-	11.4	8.2	-	-	3	-	-	-	-	-	-
652	95	1.5	3.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
666	61.9	-	9.1	-	9.9	-	-	14.7	-	-	4.4	-	-	-	-	-	-
Average	68.28	2.63	5.96	5.52	9.06	2.33	4.15	10.18	3.1	1.6	3.17	1.2	6.3	11.6	17.3	4.95	2.1
SD	14.71	1.06	2.25	3.06	6.12	1.29	2.94	8			1.04		5.37			0.92	
Min	43.8	1.5	3.5	1	1.9	1.4	0.7	2.4	3.1	1.6	1.5	1.2	2.5	11.6	17.3	4.3	2.1
Max	95	3.6	11.3	8.1	24.2	3.8	11.4	28.1	3.1	1.6	4.8	1.2	10.1	11.6	17.3	5.6	2.1

Minerals: 1-quartz, 2-anorthite, 3-albite, 4-orthoclase, 5-microcline, 6-actinolite, 7-calcite, 8-dolomite, 9-biotite, 10-muscovite, 11-chlorite, 12-glauconite, 13-ilmenite, 14-magnetite, 15-zircon, 16-rutile, 17-epidote

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