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Facies model of the contemporary delta lobe of the Vistula River

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Abstract

This study presents a morphodynamic and facies model of the currently active section of the Vistula River delta lobe, with considerations of the delta front and prodelta that have been active since 1895. The morphodynamic model was created based on bathymetric charts of the contemporary river mouth area from 1890 – 2000. Deposits of the delta front primarily comprise sand facies of up to 13 m thick. Three lithofacies of the Vistula delta lobe have been identified: X – loamy silt, fine-grained sand with an admixture of medium-grained sand, YI – medium-grained sand with an admixture of fine-grained sand, and YII – coarse-grained sand with an admixture of medium-grained sand.

Vertical succession and thicknesses of the identified facies vary considerably depending on the region of the lobe. In 1894, an underwater slope descended to a depth of 15 m over 1500 m, yielding a mean gradient of 1:100. In 1895, a 7 km canal, the Przekop Wisły, was excavated to channel most of the Vistula River's water. In 2000, 105 years after the opening of the Przekop Wisły, the volume of sediment accumulated in the lobe had reached 133.39 million m³.

Over the past 112 years, the shoreline around the Vistula River mouth has moved seaward by 1.5 km on the eastern side and by ca. 2.5 km on the western side. The 5 m isobath has shifted seaward by ca. 3 km, and the 10 m and 15 m isobaths by 2.5 km each.

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INTRODUCTION

The Vistula River delta is an example of a delta of a large river flowing into an epicontinental, semi-enclosed sea, and whose outlet is located in a temperate humid climate zone. The Vistula River flows through marshy areas on which human activities have continuously exerted strong pressure for almost a thousand years (Drwal 2002).

Prior to 1840 the outlet of the Vistula River into Gdańsk Bay was located near Gdańsk (Fig. 1). But on February 1st, 1840 high water levels in the Vistula coincided with a large ice jam at its mouth, and a strong storm in the Baltic Sea, which was accompanied by a high water level in Gdańsk Bay. Levees and dunes separating the Vistula River channel from the sea were breached, and a new river mouth formed ca. 10 km east of Gdańsk. This new short section of the Vistula was named Wisła Śmiała, and the section between the new and old outlets, which was later cut off by locks, was called Martwa Wisła. Shortly afterwards, a delta lobe formed in the Wisła Śmiała river mouth, but its advance was suspended in 1895 after the opening of the new man-made Vistula outlet into Gdańsk Bay, ca. 20 km east of Gdańsk near the town of Świbno. Since then, after the remaining channels of the Vistula delta have been cut off by locks, almost all of the Vistula River water and sediments reach Gdańsk Bay through the Przekop Wisły. Over the last 100 years, a system of accumulation forms of delta and prodelta has developed in the forefield of the mouth of Przekop Wisły.

STUDY AREA

The study area covers ca. 20 km² and is located within the administrative boundaries of Pomeranian voivodeship and the Obwód Ochrony Wybrzeża (Coastal Protection District) in Stegna. The coastline of the investigated area is located between the 45th and 50th km of the sea coast (Fig. 2).

From the south, the Vistula Spit borders the Vistula Delta Plain (Żuławy Wiślane region). Near the villages of Mikoszewo and Świbno the width of the spit has increased to ca. 3000 m since 1895 as a result of the Vistula delta lobe advance. In this area the spit consists of three generations of dunes, with corresponding brown, yellow, and white dune coloration. Yellow dunes are the largest, with crests rising up to ca. 33 m and 23 m above sea level to the east and west of the Vistula River, respectively. Linear dunes with heights not exceeding 5 – 6 m predominate in the shore zone. Between the 45th and 50th km of the coastline the youngest generation of coastal forms, located between the water line and the yellow dunes on both banks of the Vistula River, includes low (up to 1.5 m) berm ridges partially transformed into dunes. These are

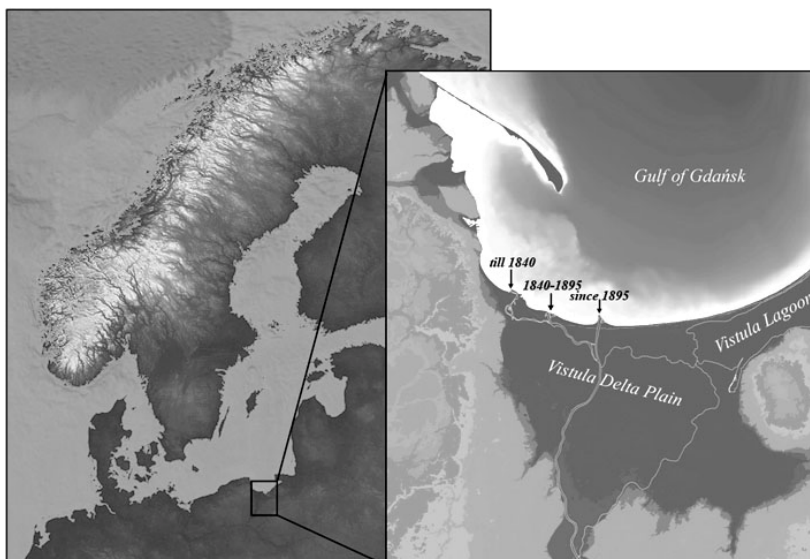


Fig. 1. The study area and varying position of the Vistula River mouth over time.

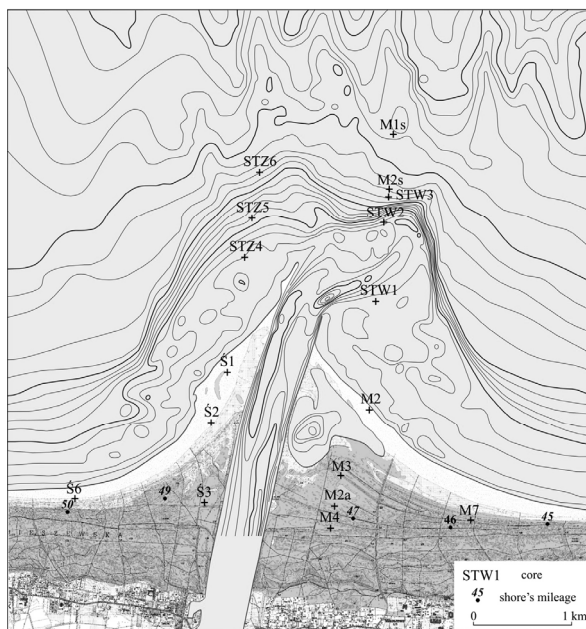


Fig. 2. Location of drilling sites on a bathymetric map from 2000.

arranged in fan shapes and have waterlogged areas located between the ridges, which are less than 0.5 m above sea level.

In the nearshore zone, to the east and west of the Vistula River mouth, isobaths run parallel to the shoreline in an east-west direction. The 5 m isobath is located ca. 400 – 450 m from the shoreline, while the 10 m isobath is ca. 1000 m from it. Isobath contours become more complicated around the Vistula delta lobe, where on the western side of the river mouth the distance between the shoreline and the 5 m isobath increases to ca. 1000 m and on the eastern side to 1400 – 1700 m. On the western side of the river mouth, the 10 m isobath is located 1200 – 1300 m from the shoreline, while on the eastern side this line is very close to the 5 m isobath and runs 1500 – 1800 m from the shoreline. A system of 2 or 3 longshore bars has developed in the nearshore zone (to a depth of 5 m), and locally, near the river mouth in the eastern section this number increases to 4.

In its outlet section the ca. 450 m-wide channel of the Vistula is enclosed by stone guiding embankments. The Przekop Wisły is 2 – 4 m deep; however, between the embankments, its depth exceeds 5 m and locally increases to 8 m. The river depth is variable in time and space. The average flow rate measured during a multi-year study at the river mouth was calculated as ca. $1015 \text{ m}^3 \text{ s}^{-1}$ (Majewski 1995, Jasińska 2002).

Pools or lagoons are common in the terrestrial section of the delta lobe. The largest pool is 1130 m long, 1010 m wide and 4 m deep, and was formed at the end of 1950s on the eastern side of the lobe.

Marly sediments of the Upper Cretaceous sampled in Mikoszewo, at 80 m below sea level, constitute a substratum of Cenozoic sediments. Paleogene and Neogene sediments have been destroyed by the process of abrasion (Mojski 1990). Pleistocene sediments are represented by fluvio-glacial deposits, till and ice-marginal deposits formed during the South-Polish and locally Middle-Polish Glaciations and marine sediments of the Eemian interglacial.

In the land section, the upper plane of the fine- and medium-grained sand layer of the Eemian Sea is located at depths ranging from 20 to 27 m below sea level. The Eemian sands are covered by delta sediments deposited by the Vistula from the Late Glacial to Middle Atlantic periods. These are primarily river-bed sand sediments and silts. In the Mikoszewo and Świbno area the upper bedding plane of these sediments occurs at ca. 5 – 7 m below sea level, and drops down to ca. 20 m below sea level in the terrestrial section of the delta lobe (Mojski 1990). In that area, delta sediments are covered by a layer of lagoon silts dating from the Atlantic period. Above this stratum lies a layer of marine and spit sands up to 5 – 8 m thick in the terrestrial section of the lobe and decreasing rapidly seaward to 1 – 2 m. The marine and spit sediments, consisting of fine- to medium-grained sands, have been deposited in the area

since the Middle Atlantic period. In the terrestrial section of the investigated area (Vistula Spit), which was dry land before 1895, the marine and spit sediments are covered by aeolian sands deposited in dunes. The former underwater downslope of the nearshore is covered by sediments of the Vistula delta lobe deposited since 1895.

MATERIALS AND METHODS

Basic information was obtained from bathymetric maps of the contemporary Vistula River mouth the collections of the Regional Board of Water Management, Naval Hydrographic Office, Marine Office, and Maritime Institute. Selected materials were positioned spatially in the rectangular coordinate system "1992" in ArcGIS software. Isobaths from specific time brackets were digitalized in ArcINFO and encoded. Using the Spatial Analyst extension, spatial models were generated for 1894, 1933, 1970 and 2000, and the increases in volume of material deposited in the Vistula delta lobe calculated. Orthophoto maps of the area were developed based on panchromatic aerial photos from 1947, 1958, 1964, 1976 and 1997 provided by Zarząd Geografii Wojskowej (Military Geography Office). The project was a part of the Polish Geological Institute program „*Geoindykatory strefy brzegowej – rejestracja i analiza zjawisk (Geo-indicators of a shore zone – phenomena recording and analysis)*” and used the Gauss-Kruger projection on a geocentric ellipsoid EGS-84 and the coordinate system 1992. The area covered by a photo from 1997 was used to calculate changes in Vistula lobe surface area between 1947 and 1997.

Core samples of sediments from the Vistula delta lobe were collected during the Polish Geological Institute program "*Geologiczne warunki ochrony i kształtowania południowego brzegu Bałtyku oraz obszarów ujściowych Odry i Wisły – etap 3 (Geological Conditions for the Protection and Development of the Southern Baltic Coast as well as Oder and Vistula River Estuaries – Stage 3)*". During that project, 9 cores were collected with a core drill and 2 with a vibrocorer (Fig. 2). Six additional holes were drilled in the underwater section of the delta lobe and prodelta as part of the KBN (Committee for Scientific Research) project „*Model przestrzenny rozwoju form i osadów współczesnego ujścia Wisły (Spatial Model of Development of the Contemporary Vistula River Mouth Sediments)*” (Fig. 2). The present study was based on the results of a granulometric analysis, which consisted of 290 analyses of sediment grain-size composition. The share of individual sediment fractions was expressed as percent of sample weight. Parameters of grain distribution were calculated using the formulas of R. L. Folk and W. C. Ward (1957).

When characterizing the deposits of the Vistula delta lobe, sediment groups were analyzed by calculating Euclidean distances, which represented the contents of specific granulometric fractions. The following parameters were calculated for the different groups: graphic average diameter (M_z), graphic standard deviation (σ_I), graphic skewness (Sk_I), and graphic kurtosis (K_G). Sorting classes, skewness types, and kurtosis of grain-size distribution curves were adopted according to the division proposed by R. L. Folk and W. C. Ward (1957).

RESULTS

Morphometric analysis

The surface area of the Vistula delta lobe terrestrial section was calculated using aerial photographs. In 1997, the surface area of this section was 3,019,000 m². The lowest annual increase rate, 12,500 m² year⁻¹, occurred between 1947 and 1958, and the highest, 50,200 m² year⁻¹, was seen between 1958 and 1964 (Graniczny et al. 2004).

The evolution of the delta lobe was analyzed based on selected digital bathymetric maps, which were then used to construct 3-D models of the Vistula delta lobe area for the years 1894, 1933, 1970 and 2000 (Fig. 3). The first model (of 1894) presents the conditions that existed a year before the construction of the Przekop Wisły. Following the opening of the canal, water washed out 2 million m³ of sedimentary material in 16 hours, widening the canal from 50 to 300 m. In the following six months, this amount increased to 9 million m³, and by the end of 1895 was 17 million m³ (Makowski 1995). In 1980, 85 years after the opening of the Przekop Wisły, the shoreline had shifted by ca. 2400 m, and the base of the delta lobe was ca. 4000 m away from the shoreline position in 1894. In 1933, the deltaic lobe contained 71.17 million m³ of material, and the mean accretion rate for those 38 years was 1.89 million m³ year⁻¹. Between 1933 and 1970, the amount of material in the delta lobe increased to 112.18 million m³. The mean accretion rate for that period decreased to 1.11 million m³ year⁻¹, and between 1970 and 2000, to 0.7 million m³ year⁻¹. In 2000, 105 years after the canal opening, the amount of sediment accumulated in the lobe had reached 133.39 million m³ with the mean accretion rate for the entire 105-year period equaling ca. 1.27 million m³ per year.

The growth rate of the terrestrial section of the lobe was largely affected by the construction of the river mouth embankments, which were completed in stages. They were extended when sediments were deposited directly in the river outlet, impeding water outflow and posing a flood hazard.

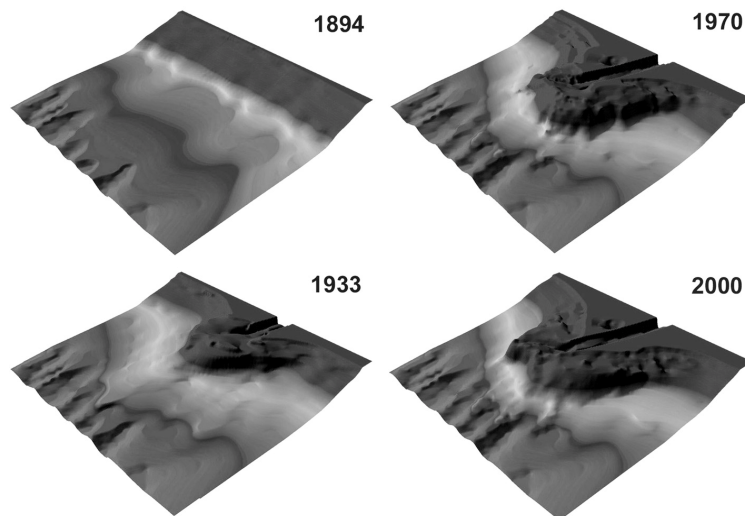


Fig. 3. 3D model of evolution of the Vistula delta lobe over time.

Facies analysis

The purpose of facies classification was to construct a model that would identify different depositional environments, as well as the conditions and processes occurring in them. The delta lobe consists of facies of various sediments. Not all facies that co-occur laterally appear in every vertical profile, and continuity of sedimentation can be discerned only where gradational passages exist between successive facies. The substratum of the lobe was determined based on a bathymetric map of the seafloor made in 1894, a year before the Przekop Wisły canal was opened. The Vistula delta lobe is an area with an intense accumulation of clastic material; as the river enters the sea, it expands and decreases in velocity resulting in a large proportion of the sediment being deposited there.

The sediment groups were classified into several basic categories in order to constrain the collected information. Three distinct groups of samples, sediment lithofacies X, YI and YII, were isolated based on the cluster analyses (Fig. 4).

Lithofacies X was represented by fine-grained sands with an admixture of medium-grain sands and clayey silts, and contained 98% of the <0.25 mm fraction. The bulk of grains belonged to the 0.1 - 0.25 mm fraction. In this lithofacies, the mean grain diameter (M_z) was 2.34ϕ . These were moderately-sorted sediments (mean $\sigma_f=0.74$) with symmetrical grain size distributions (mean $Sk_f=0.01$). Relatively high mean kurtosis of a leptokurtic character (mean

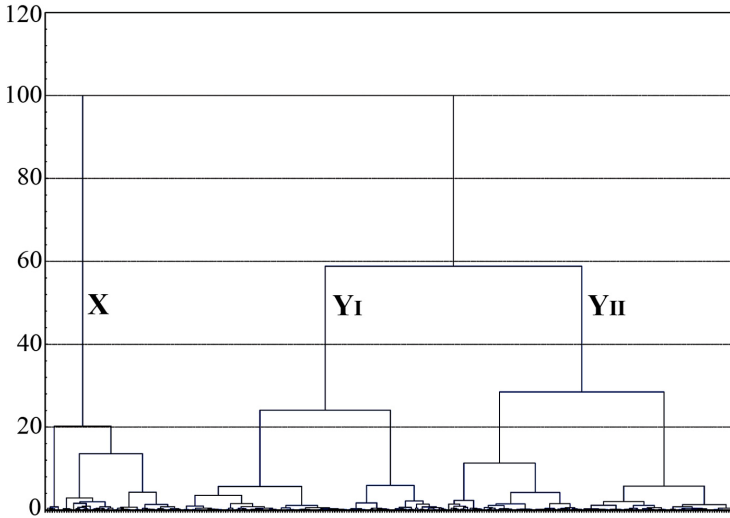


Fig. 4. Dendrogram of the Vistula delta lobe sediments and characterized facies.

$K_G=1.32$) suggested fairly homogeneous conditions in the sedimentation environment.

Lithofacies YI was represented by medium-grained sands with an admixture of fine-grained sands. The former primary belonged to the 0.25 – 0.5 mm fraction, whose share in the sample was an average of 72% of the total weight. The mean grain diameter was 1.66ϕ . These were moderately sorted sediments with a mean graphic standard deviation of 0.67ϕ and a slight dispersion, which is an indication of a lower dynamic variability of the environment. The grain-size distributions are symmetrical ($Sk_f=0.06$). The values of graphic kurtosis (mean $K_G=1.25$) indicate a leptokurtic character.

Lithofacies YII was represented by coarse-grained sands with an admixture of medium-grained sands. A negative value of graphic skewness was a distinct feature of this lithofacies. This might be an indication of the predominance of currents with higher than average velocities and shows that periods of this predominance have been more frequent and lasted longer than periods of lower hydrodynamic activity. A slightly lower mean kurtosis (mean $K_G=1.17$) than lithofacies YI is an indication of less homogeneous conditions of the sedimentation environment. The graphic mean grain diameter (M_z) was 0.95ϕ and was characterized by medium dispersion, reflected in the degree of sediment sorting. Moderately sorted sediments are the most common (mean

$\sigma_f=0.79\phi$). The skewness of grain-size distribution was -0.12 on average. Approximately 50% of sediment samples of this facies had symmetrical and negatively skewed distributions. The graphic kurtosis equaled $K_G=1.17$, and the sediment granulation had a leptokurtic distribution.

The thickness of the lithofacies X was highly variable, ranging from 0.35 m to over 9 m. It reached the highest value at M2, a hole on the eastern side of the Przekop Wisły in the current terrestrial section of the lobe, and decreased seaward for 800 – 900 m (Fig. 2). Sediments of this facies were common in lower sections of profiles in both terrestrial and marine sections of the Vistula delta lobe.

Sediments of the lithofacies YI were observed in the central section of the Vistula delta lobe. Their thickness in the profile STW1 reached 13.0 m, but in the profile STW2 decreased to ca. 1.0 m (Fig. 2). Sediments of the lithofacies YII were thickest in the seaward section of the lobe, in profiles STW2, STZ4, and STZ5 with thicknesses reaching 8.0 m, 9.0, and ca. 6.5 m, respectively (Fig. 2). Their lowest thickness, of 1.0 m, was recorded in profile STZ6.

DISCUSSION

When analyzing the rate of increase of the Vistula delta lobe volume, it should be borne in mind that since the completion of the Przekop Wisły in 1895 the profile of the river outlet section has been relatively stable. Many authors have attempted to estimate the increase in the delta lobe volume using a range of techniques and approximation methods. According to the calculations of Rożankowski (1929), Winkiel (1939), Czernik (1954, 1955), and Słomianka (1958), before the Nogat was cut off in 1915 the river deposited ca. 20 million m^3 of alluvium into the sea. Between 1915 and 1929 the Vistula River deposited ca. 70.1 million m^3 of material into the sea, including 17.424 million m^3 deposited during the 1924 flood (Łomniewski 1960). However, according to Słomianko (1958) the latter quantity was rather lower, at around 5.6 million m^3 . During the next three years (after 1929), sea currents and waves washed away ca. 33.5 million m^3 of deposit from the lobe, and thus, between 1895 and 1929, the volume of material accumulated in the delta was 56.6 million m^3 (Łomniewski 1960).

According to data collected during the Hydroprojekt Wisła project, between 1929 and 1953 the Vistula transported ca. 56.4 million m^3 of sediment out to sea. This means that from 1895 to 1953 the Vistula accumulated on average ca. 1.9 million m^3 year⁻¹; therefore, it can be estimated that in 1958 the delta lobe volume was ca. 122.5 m^3 (Czernik 1954, 1955). The difference between the amount of material deposited by the Vistula River and the volume of the delta lobe varies between reports, from 22 to 50 million m^3 . Subsequent reports

(Słomianko 1958) of the Instytut Morski (Marine Institute) indicate that until 1953, the Vistula deposited 113 million m³ of sediment in to the sea, and estimated the volume of the delta lobe at 135 million m³. According to these data, 22 million m³ of material must have been transported by sea currents from other sections of the bay. The difference between the estimated amount of material deposited by the Vistula River and the estimated volume of the delta lobe varies between reports and ranges between 22 and 50 million m³. Kowalski (1976) estimated that in 1958 the volume of the lobe enclosed by the 15 m isobath was ca. 100 million m³. According to his study, increases in volume decreased exponentially, and that between 1960 and 1995 the lobe grew at 0.45 million m³ year⁻¹. Based on these findings, Mielczarski (1976) estimated that the increases in the lobe volume between 1970 and 1995 would reach 0.3 million m³ year⁻¹.

The values reported by these various authors should be treated with a certain measure of caution due to unavoidable errors associated with determination of the lobe volume based on successive sounding projects.

For over 35 years the base of the lobe enclosed by the 15 m isobath has not shifted significantly. But other basic elements of the lobe have been evolving, such as the lobe platform enclosed by the 2 m isobath, which includes shallows and islets, and the outflow troughs on the eastern and western sides enclosed by the 3 m isobath. The shoreline has shifted by ca. 1300 – 1500 m in relation to its original position in 1895. The eastern and western embankments are 2490 and 2070 m long, respectively. The 15 m isobath, which encloses the lobe base, has moved seaward by ca. 2500 m since that time. The configuration of the lobe platform to a depth of 5 m has been also subject to significant changes, which were clearly affected by flow rate and wave action characteristics.

On analyzing changes in the configuration of the Vistula delta lobe it is concluded that most of the significant changes in the seafloor terrain occurred in the direct proximity of the river mouth. Various types of shoals and deeper sections have formed in that area. These forms develop as a result of the strong impact of the sea, which fades out rather quickly upstream. The rate of increase in the lobe volume has been irregular and affected to a greater degree by the construction and extension of the embankments than by natural factors, such as changes in the amount of material transported by the Vistula or coastal erosion.

Considering the current state of knowledge, the results of the sediment analyses unquestionably provide information on the origin of alluvium, and conditions of its transport and deposition. The geological structure of the Vistula delta lobe has certain characteristics that may hinder or even prevent a full interpretation of results. One such feature is multiple re-depositions of sediments, meaning that the same material can be successively deposited in different environments.

CONCLUSIONS

The contemporary Vistula River mouth is a unique area, whose evolution can be investigated from the moment of formation to the present.

Analysis of morphometric models enables estimation of the sediment volume accumulated in the delta lobe, which in the 105 years since the Przekop Wisły was opened is 133.39 million m³.

The Vistula delta lobe comprises sediments of the delta front, represented primarily by sand facies, and only locally by silt facies. Sand sediments of the delta lobe are 11-15 m thick. The prodelta sediments occur in the forefront of the delta lobe, at a depth of 12-16 m, and also underlie the lobe sediments, with their thickness ranging from 0 to ca. 10 m. Cluster analysis and analysis of correlations between granulometric fractions provided the following classification of delta lobe lithofacies:

- lithofacies X (loamy silt, fine-grained sand with an admixture of medium-grained sand),
- lithofacies YI (medium-grained sands with an admixture of fine-grained sands),
- lithofacies YII (coarse-grained sands with an admixture of medium-grained sands).

The Vistula delta lobe has been prograding seaward over time. The sediments of the lithofacies X are deposited in environments characterized by high variability of hydrodynamic conditions. These deposits are then covered by the sediments of the lithofacies YI, deposited from fractional suspension. Subsequently, the latter are covered by sediments of the lithofacies YII, which are transported to the more distant sections of the lobe.

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