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Composition and formation of sand massifs in the Curonian–Sambian submarine plateau (Baltic Sea)

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Geological and geophysical investigations were carried out in the Juodkrantė–Preila polygon westwards of the Curonian Spit. Sand massifs on the sea bottom of the Curonian–Sambian plateau appear as hilly elevations of a relative height of up to 4–5 m and extend in the southern–northern and southwestern–northeastern directions. The dominant type of the bottom surface sediments at a depth of 5 to 50 m and deeper is grey and yellowish grey, good-sorted quartzy fine sand. The central parts of the elevations are mainly composed of homogenous light yellow and yellowish grey medium sand and coarse sand lies only in small local areas at a depth of 20–28 m. The applied seismoacoustic methods allowed to affirm the fact that the sand layers of the bottom elevations are not less than 4–5 m thick. The sand massifs in the underwater slope of the Curonian Spit started developing during the Ancylus Lake regression. The intensive sand accumulation coincided with the first phase of the Litorina transgression when the sedimentary material flows from the eroded underwater slope of the Sambian peninsula intensified. At times, fluvial and eolian processes (Ancylus stage) might have added variety to the uneven and discontinuous sand accumulation yet hydrodynamic factors have always played a decisive role. Distribution patterns of the grain-size composition and the types of the surficial sediments in the underwater slope of the Curonian Spit show that there is no circulation of sedimentary material between the shallow nearshore and hilly sand massif. Thus, the present coastal zone of the Curonian Spit is virtually independent of the lithodynamic processes taking place in the plateau surface (deeper than 20 m).

Key words: Baltic Sea, sand massifs, grain-size, surficial sediments, seismoacoustic profiles, accumulation processes, underwater slope evolution

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INTRODUCTION

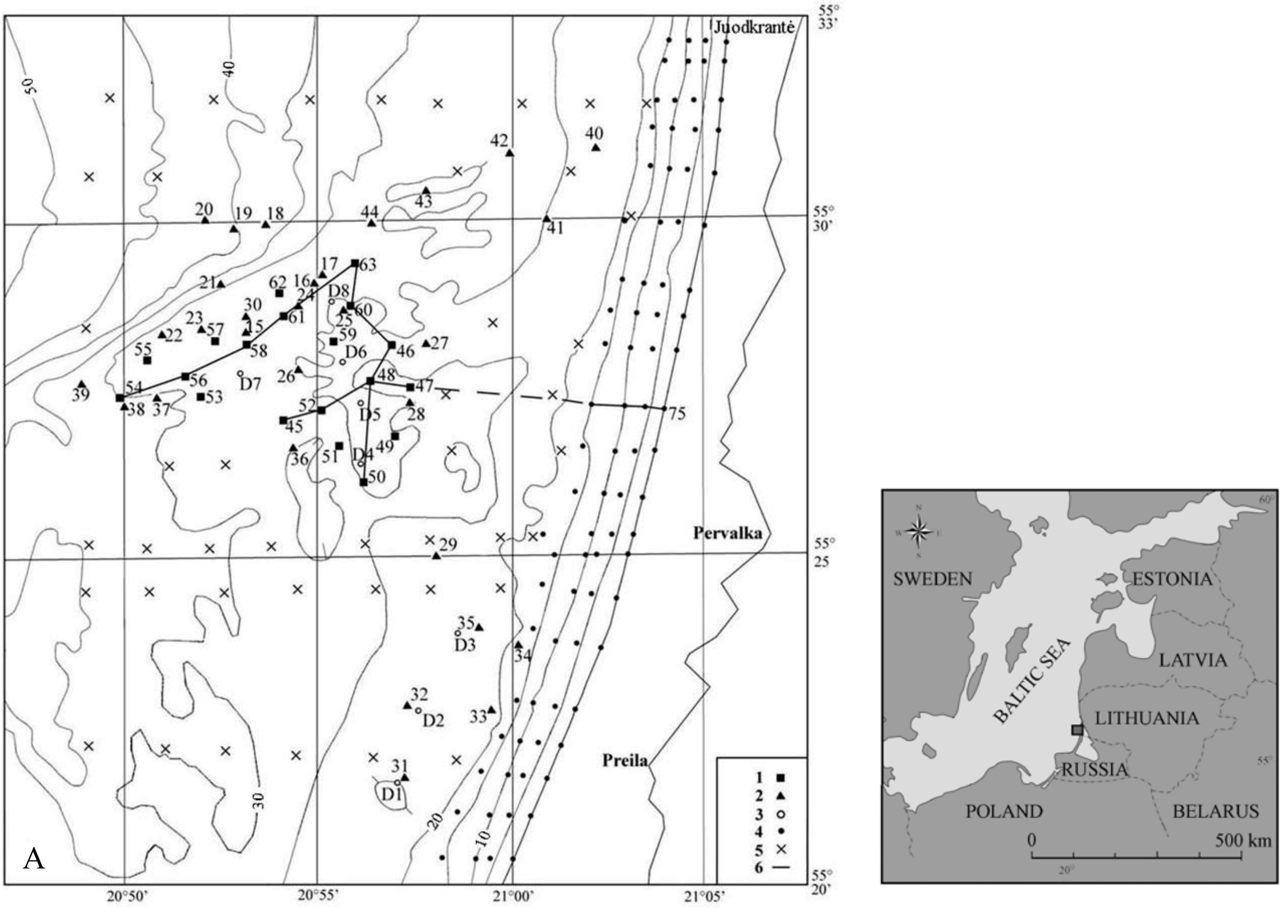
The bottom of the sea in the northern part of the Curonian–Sambian plateau to the west of the Curonian Spit is covered with sand deposits. Their undulate and hilly surface is marked by relative depth differences of a few meters. There is many geological–geophysical, geomorphological and other evidence that in the late post-glacial time and the beginning of the Holocene (Yoldia and Ancylus stages) the altitude of the greater part of the present underwater slope in the southeastern part of the Baltic Sea was above the sea level (Гуделис, 1976; Блажчишин, 1984;1998a; Gelumbauskaitė, Šečkus, 2005; and others). Therefore, the present unevenness of the relief has been inherited from the earlier development stages of the Baltic Sea, when the water level was lower. The present contrasting surface of the sea bottom bears marks of various nearshore formations (cliffs, terraces, bars, etc.) that existed in the past. The diversity of preserved fragments evidences different formation conditions. There are opinions that the hilly bottom surface represents wind-blown dunes or, perhaps, sand accumulations deposited by the glaciofluvial flows which emerged under the water after the Litorina sea transgression or even earlier.

The geological composition and palaeogeographic evolution of the old coastal formations and their fragments in the southeastern part of the Baltic Sea were investigated earlier (Блажчишин et al., 1982). The present work is aimed at finding out the composition and possible formation conditions of the sand massifs in one of the bottom structures of the Curonian–Sambian plateau – the Juodkrantė–Preila polygon based on the new geological–geophysical information.

MATERIALS AND METHODS

Complex investigations of the sand massifs were carried out in 2005–2006 in the Juodkrantė–Preila polygon (between 55°31'–55°23' N and 20°48'–21°03' E), where the sea depth reaches 20–48 m, using Polish research vessels "Nawigator XXI" (Gulbinskas, Trimonis, 2006) and "IMOR" (Gulbinskas et al., 2007). The complex of the geophysical investigations included a detailed bathymetric bottom survey, seismoacoustic sub-bottom profiling and hydroacoustic examination with a sidescan sonar. The depth was measured using a multi-beam echosounder (with the working frequency of 455 kHz) and a single beam echosounder (210 kHz transducer). A profiler Ore Tech 3010S (3.5–14 kHz) was used for the sub-bottom profiling. The bottom survey was performed with a sidescan sonar DF 1000 with the frequency range of 100–500 kHz. Twenty profiles were investigated geophysically. The composition of the bottom structure was examined at a depth of 5–10 m below the surface (Fig. 1).

The geological structure of the bottom and the bottom sediments composition was determined by vibrocoring and sediment sampling. The sediments from the bottom surface (5–10 cm) were taken by a standard grab in twenty nine sites. The sand sediments were vibrocored to the depth of 3.3 m below the bottom surface. The mentioned works were done in nineteen sites to 24.0 m of sea depth (Fig. 1).



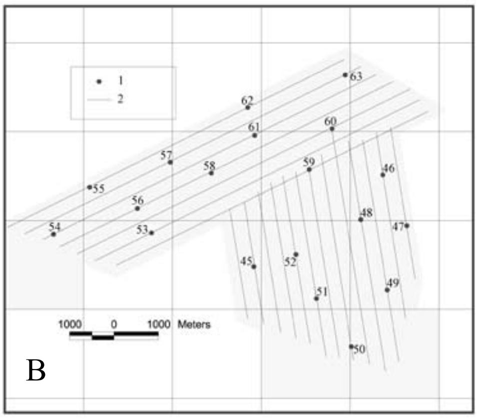


Fig. 1. Situational map of the study area.

A – location of sampling and vibrocoring sites (bottom topography after Gelumbauskaitė (ed.), 1998): *1* – r/v *IMOR*, *2* – r/v *Nawigator XXI*, *3* – r/v *Darius*, *4* – survey for the geological atlas of the Lithuanian coasts, *5* – sea bottom survey in 1 : 200000 scale, *6* – lines of sediment cross-sections;

B – positions of seismic profiling lines and vibrocorings

1 pav. Tyrimų rajono schema.

A – Dugno nuosėdų mėginių ėmimo ir gręžimo vietos (dugno batimetrija pagal Gelumbauskaitė (ed.), 1998): *1* – m/l *IMOR*, *2* – m/l *Nawigator XXI*, *3* – m/l *Darius*, *4* – kartografavimas geonuotrauka Lietuvos krantų geologiniam atlasui, *5* – jūros dugno geologinė nuotrauka masteliu 1 : 200000, *6* – nuosėdų pjūvių padėtis.

B – Seisminio profiliavimo ir vibrogręžimo schema

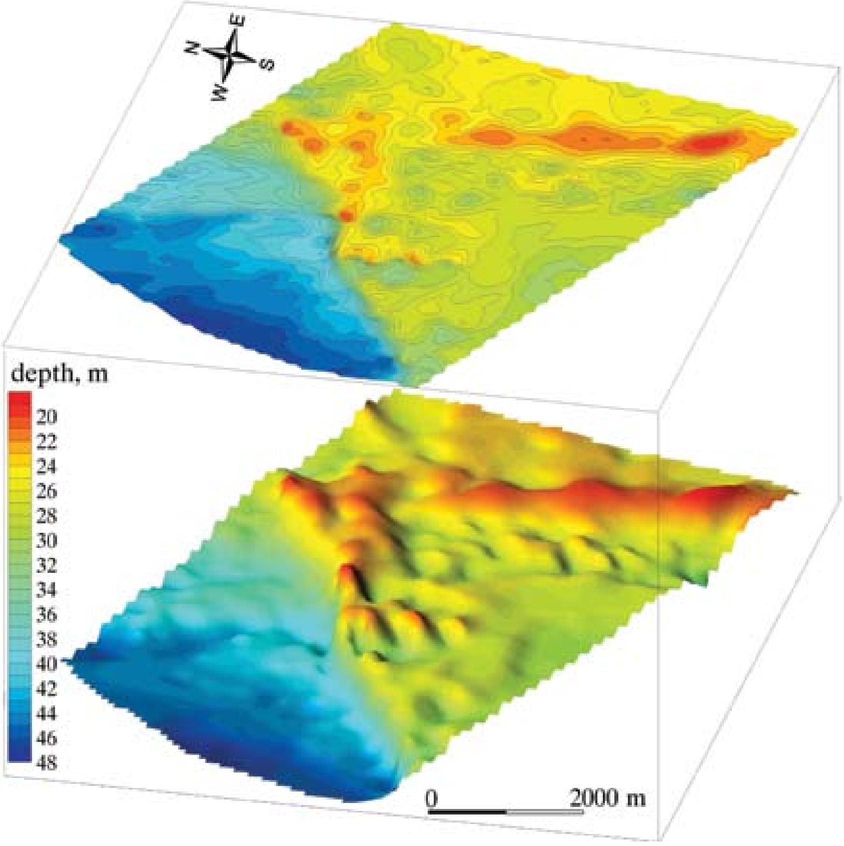


Fig. 2. Bottom relief of the study area
2 pav. Tyrimų rajono dugno reljefas

The grain-size composition of the bottom sediments was determined by laboratory sieving method. Eighteen fractions (from > 2.5 mm to < 0.05 mm) were distinguished. The type of sediments was determined according to the median diameter (Md) and the dominant fraction within the decimal classification system. A few sand samples were examined using other analytical methods (mineralogical, chemical analysis, etc.).

GEOPHYSICAL DATA INTERPRETATION

Bottom surface 3D relief was depicted by a multi-beam echosounder in the investigation polygon (an area of about 55 km^2). Two hilly elevations (up to 4–5 m in height) extending in the southern–northern and southwestern–northeastern directions were distinguished (Fig. 2).

The view of the bottom surface was also analysed according to the readings of the sidescan sonar (Fig. 3). The interpretation of a "shadow mosaic" recorded on a sonarogram allowed distinguishing two belts with pronounced hilly relief forms determined by the echosounder data. The distribution area of the medium sand (the coarsest bottom sediments in this region) coincides with the central part of these relief forms (Fig. 4). The northern–southern belt is surrounded on both sides by a surface of a rather even inclination covered by fine sand sediments. The small areas at a depth of 23–26 m distinguished in the bottom surface sonarograms were identified as mesorelief forms filled with vari-size grained sand.

Seismoacoustic profiling helped to determine the structure of the bottom and deeper sediment layers. Seismic reflection horizons proving a heterogeneous structure of the sediments at a depth of 5–10 m below the bottom surface are visible in the subbottom profiles. The geophysically determined variations of the grain-size composition of the sediments or sediment types were confirmed by vibrocoring.

Such horizons in seismic profile I–I (Fig. 5) reflect sharp and pronounced interfaces in the sand sediments. A layer of dark grey medium sand (22–50 cm) contrasting with the under- and overlying sediments of the same type was distinguished (site 58) during the preliminary visual description. Another visually distinct boundary was determined in site 63 of the same profile, where the surface greyish yellow homogeneous sand had a pronounced interface with underlying slightly finer sand (the median diameter of the sand decreases from 0.37 to 0.32 mm).

Due to insufficient resolution of seismic methods, minor variations of the sediment composition determined by a visual description and then confirmed by analytical results were not reflected in the seismograms. It was in those cases, where the median diameter of the sediments had insignificant changes (site 45, hor. 0–41 cm) or the interlayers were very thin and their identification was not easy (site 52, interval 59–66 cm).

The seismic reflection horizons in profile II–II (Fig. 5) coincide with the sediment type variations. The most distinct interfaces occur between the grey medium sand with a large amount of shells and its detritus layer (155–243 cm) and the underlying and overlying grey fine sand intervals (site 52). This medium sand layer wedges eastwards, and in site 48 it was inaccessible to vibrocoring (the depth of the borehole reached 295 cm). Due to this, the correlation of the seismic boundaries in the eastern part of the profile is complicated. Two distinct reflection horizons are seen in site 46: one of them is 277 cm below the bottom surface and coincides with the pronounced interface between fine sand abounding in shell detritus and almost homogeneous coarse silt, and the other represents and interfaces with a brownish black sapropel layer at the bottom of the core (299–322 cm). This interval contains small inclusions of light brownish wood, and the age of the sediments as determined by ^{14}C is 10400 ± 140 years BP (the dating was performed at the Laboratory of Radioisotope Analysis of the Institute of Geology and Geography). The sapropel layer was recorded in a few seismograms, which allowed determining its territorial distribution eastwards and southwestwards from site 46.

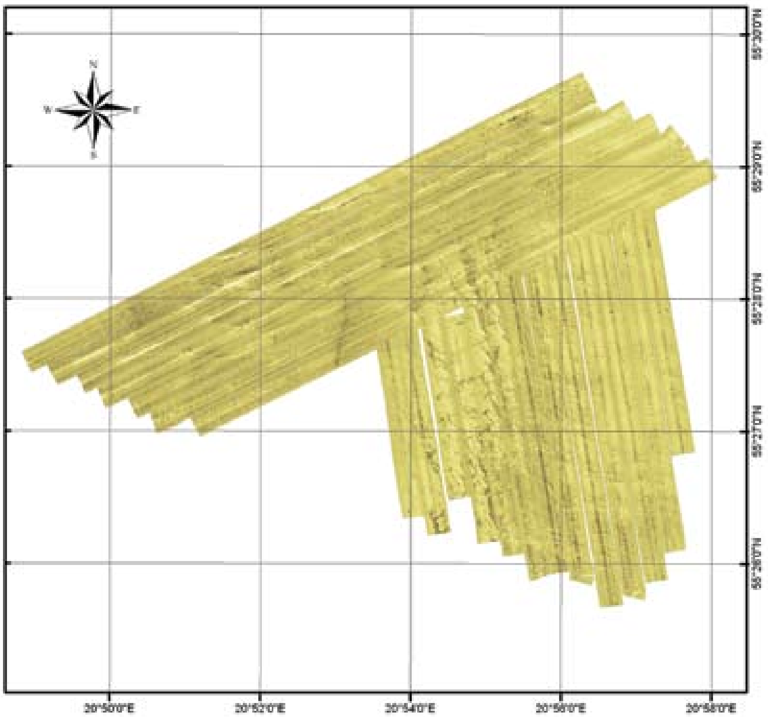


Fig. 3. Sidescan sonar image of the sea bottom
3 pav. Dugno paviršiaus vaizdas pagal sonarogramas

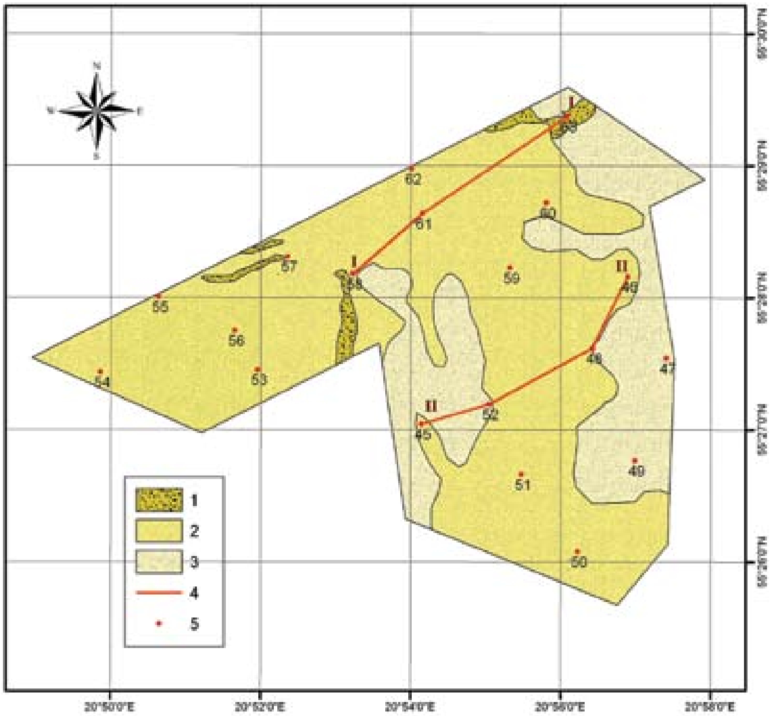


Fig. 4. Types of surficial bottom sediments according to sonarograms: *1* – various sand, *2* – medium sand, *3* – fine sand, *4* – geological cross-section, *5* – vibrocore
4 pav. Dugno paviršiaus nuosėdų tipai pagal sonarogramas: *1* – įvairiagrūdis smėlis, *2* – vidutinis smėlis, *3* – smulkus smėlis, *4* – geologinis pjūvis, *5* – vibrogręžinys

COMPOSITION OF THE BOTTOM SEDIMENTS

The grey and yellowish grey fine sand found at a depth of 5 to 50 m and deeper is the dominant type of the bottom surface sediments in the underwater slope of the Curonian Spit (Fig. 6A). The sorting of the bottom surface sediments is good ($S_o < 1.3$) (Fig. 6B).

The central part of the study area (approximately at a depth of 20–30 m) is covered by light yellowish often greyish yellow medium sand. Its distribution boundaries are close to the outlines of the hilly elevations oriented in southern–northern and southwestern–northeastern directions. The medium sand is mainly homogeneous, somewhere with fine shells (*Macoma baltica*, in rarer cases *Cardium edule, Mya arenaria*). The sorting of the sediments is good (S_o 1.2–1.6).

Coarse sand (Md 0.59–0.67 mm; S_o 1.3–1.7) lies in small bottom areas at a depth of 20–28 m. It is light yellow with brownish tint or grey and contains different portions of shells or shell detritus.

Sand sediments are predominated by fine-grained and medium-grained fractions which alternate at a regular pattern depending on the morphological features of the bottom and the sea depth (Fig. 7). The highest concentrations (> 50%) of the fine-grained fraction (0.1–0.25 mm) occur in the shallow nearshore of the southern part of the region at a depth of 20–25 m and of the northern part at a depth of 35–40 m (Fig. 7A). The highest concentration of the medium-grained fraction (0.25–0.5 mm) occur in the central part of the region (Fig. 7B) and the highest concentration of the coarse-grained fraction (0.5–1.0 mm) – in the local areas of the northern part of the hilly bottom zone (Fig. 7C). The amount of silt material (fraction of 0.1–0.01 mm) in the surface sediments is small (Fig. 7D).

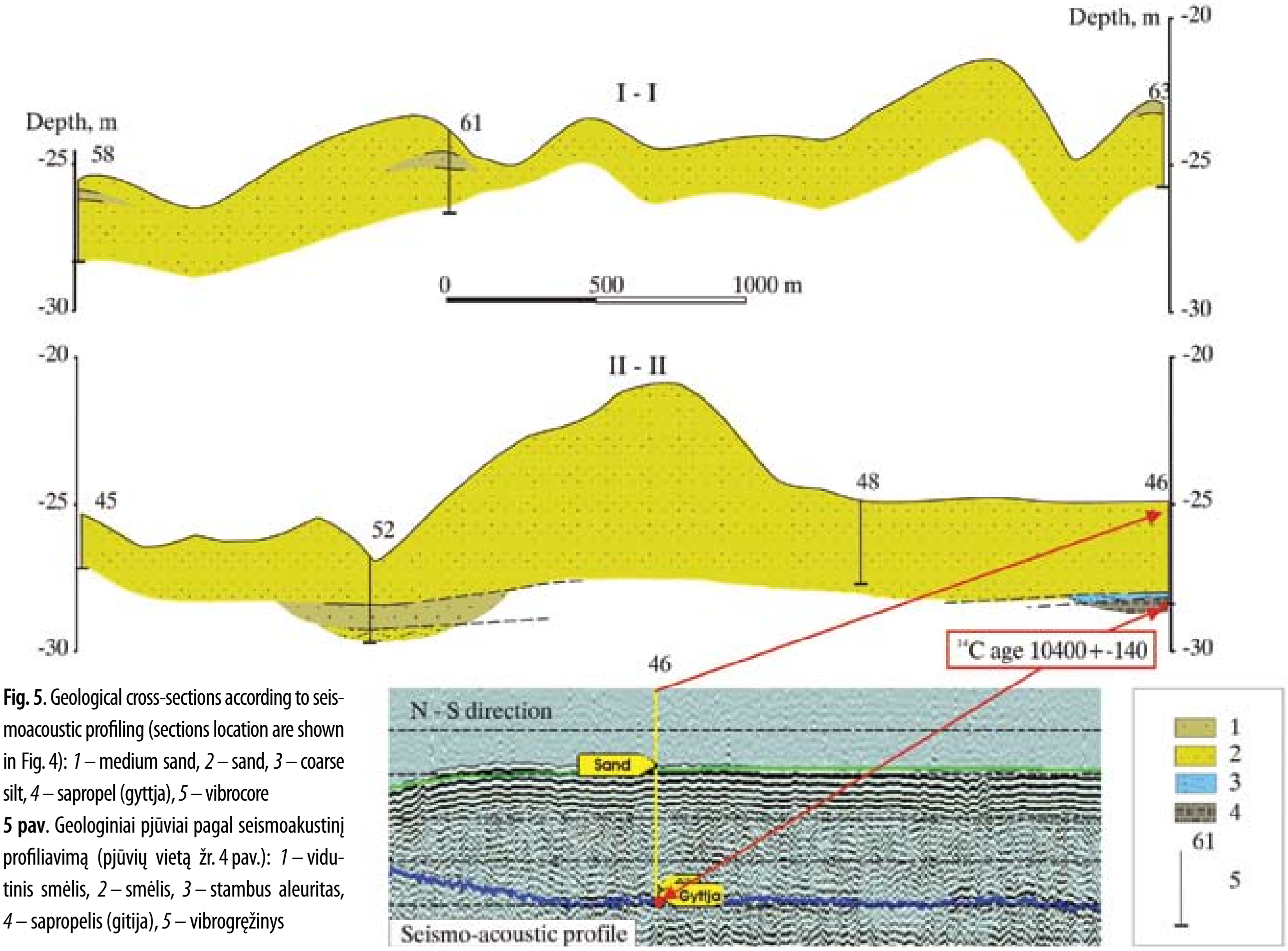


Fig. 5. Geological cross-sections according to seismoacoustic profiling (sections location are shown in Fig. 4): *1* – medium sand, *2* – sand, *3* – coarse silt, *4* – sapropel (gyttja), *5* – vibrocore

5 pav. Geologiniai pjūviai pagal seismoakustinį profiliavimą (pjūvių vietą žr. 4 pav.): *1* – vidutinis smėlis, *2* – smėlis, *3* – stambus aleuritas, *4* – sapropelis (gitija), *5* – vibrogręžinys

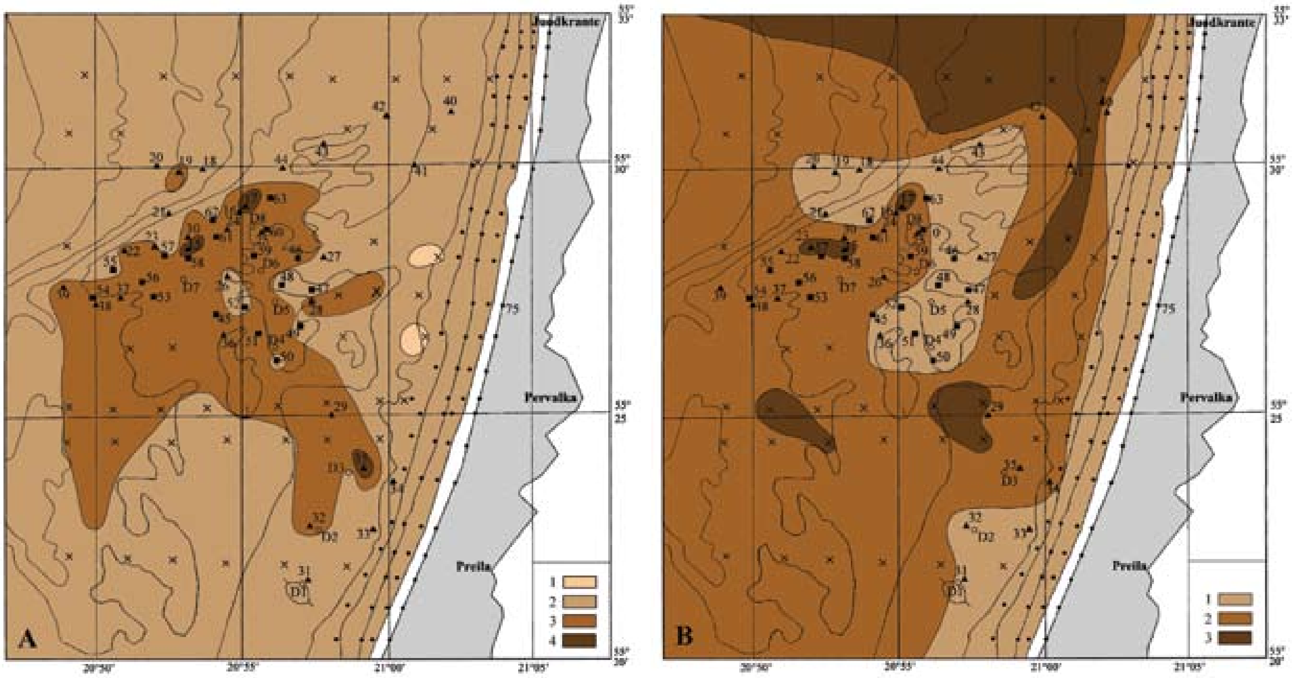


Fig. 6. Granulometric characteristics of surficial bottom sediments:

A – median diameter (Md, mm): *1* – <0.1, *2* – 0.1–0.25, *3* – 0.25–0.5, *4* – 0.5–1.0; *B* – sorting (S_0): *1* – ≤1.3, *2* – 1.3–1.5, *3* – >1.5

6 pav. Dugno paviršiaus nuosėdų granuliometrinė charakteristika:

A – medianinis diametras (Md, mm): *1* – <0,1; *2* – 0,1–0,25; *3* – 0,25–0,5; *4* – 0,5–1,0; *B* – išrūšiuotumas (S_0): *1* – ≤1,3; *2* – 1,3–1,5; *3* – >1,5

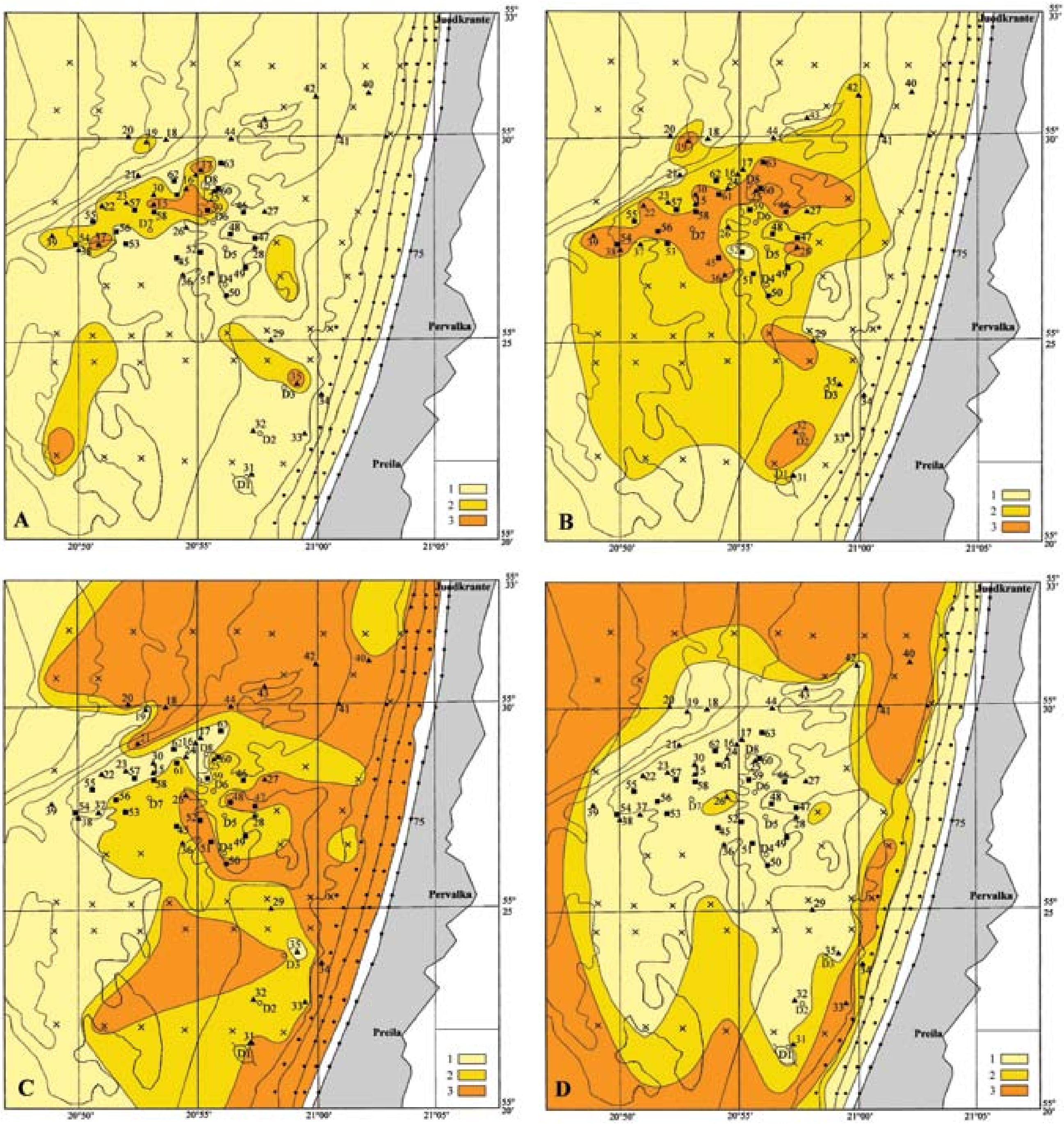


Fig. 7. Distribution of grain-sized fractions in the bottom surface sediments (%):
A – fine-grained sand (0.25–0.1 mm): *1* – <20, *2* – 20–50, *3* – >50; *B* – medium-grained sand (0.5–0.25 mm): *1* – <20, *2* – 20–50, *3* – >50; *C* – coarse-grained sand (1.0–0.5 mm): *1* – <20, *2* – 20–30, *3* – >30; *D* – silt (0.1–0.01 mm): *1* – <10, *2* – 10–20, *3* – >20

7 pav. Granuliometrinių frakcijų pasiskirstymas dugno paviršiaus nuosėdose (%):
A – smulkaus smėlio (0,25–0,1 mm): *1* – <20, *2* – 20–50, *3* – >50; *B* – vidutinio smėlio (0,5–0,25 mm): *1* – <20, *2* – 20–50, *3* – >50; *C* – stambaus smėlio (1,0–0,5 mm): *1* – <20, *2* – 20–30, *3* – >30; *D* – aleurito (0,1–0,01 mm): *1* – <10, *2* – 10–20, *3* – >20

In a shallow part of the nearshore (between the dynamic shoreline and a depth of 5 m), the composition of sediments is rather variable. A zone of bars and erosion troughs extends at a depth of 4–6 m along the Curonian Spit. Sand sediments of varisize grained composition even containing gravel occur on the bottom surface between the bars. Accumulative bars are usually composed of better-sorted fine sand deposited by the wave action (Trimonis et al., 2005).

Variations of sand types in the bottom surface are best reflected by a granulometric profile of the sediments between the shoreline and a depth of 25 m (Fig. 8). A very distinct and relatively deep (almost to 6 m) erosion trough can be distinguished in the shallow nearshore relief between Juodkrantė and Pervalka. It is situated at a distance of about 400 m from the shore (profile 75). Its slope is covered by fine sand with Md from 0.13 mm (at a depth of 15 m) to 0.23 mm (closer to the

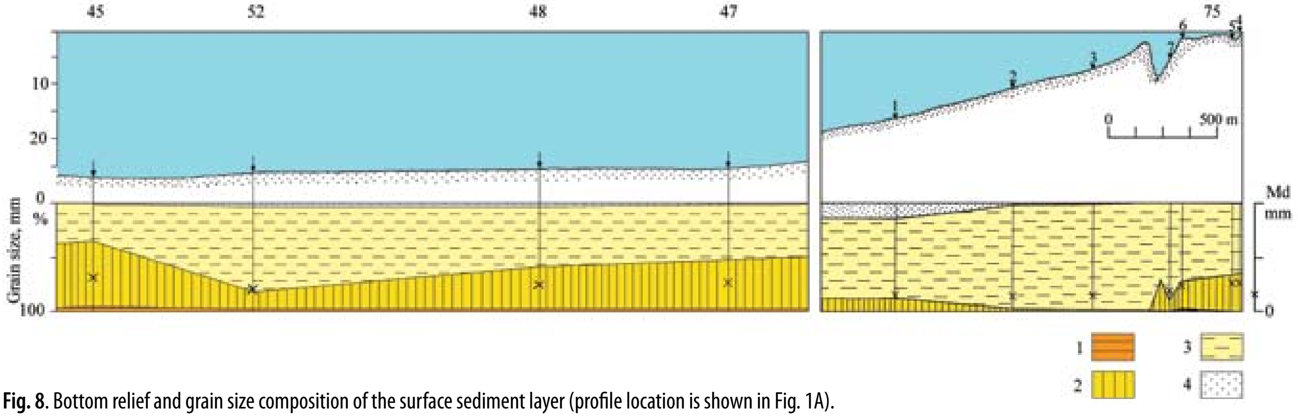


Fig. 8. Bottom relief and grain size composition of the surface sediment layer (profile location is shown in Fig. 1A).
Fractions, mm: *1* – 1–0.5, *2* – 0.5–0.25, *3* – 0.25–0.1, *4* – 0.1–0.05

8 pav. Dugno reljefas ir paviršinio nuosėdų sluoksnio granuliometrinė sudėtis (profilio vietą žr. 1 pav., *A*).
Frakcijos, mm: *1* – 1–0,5; *2* – 0,5–0,25; *3* – 0,25–0,1; *4* – 0,1–0,05

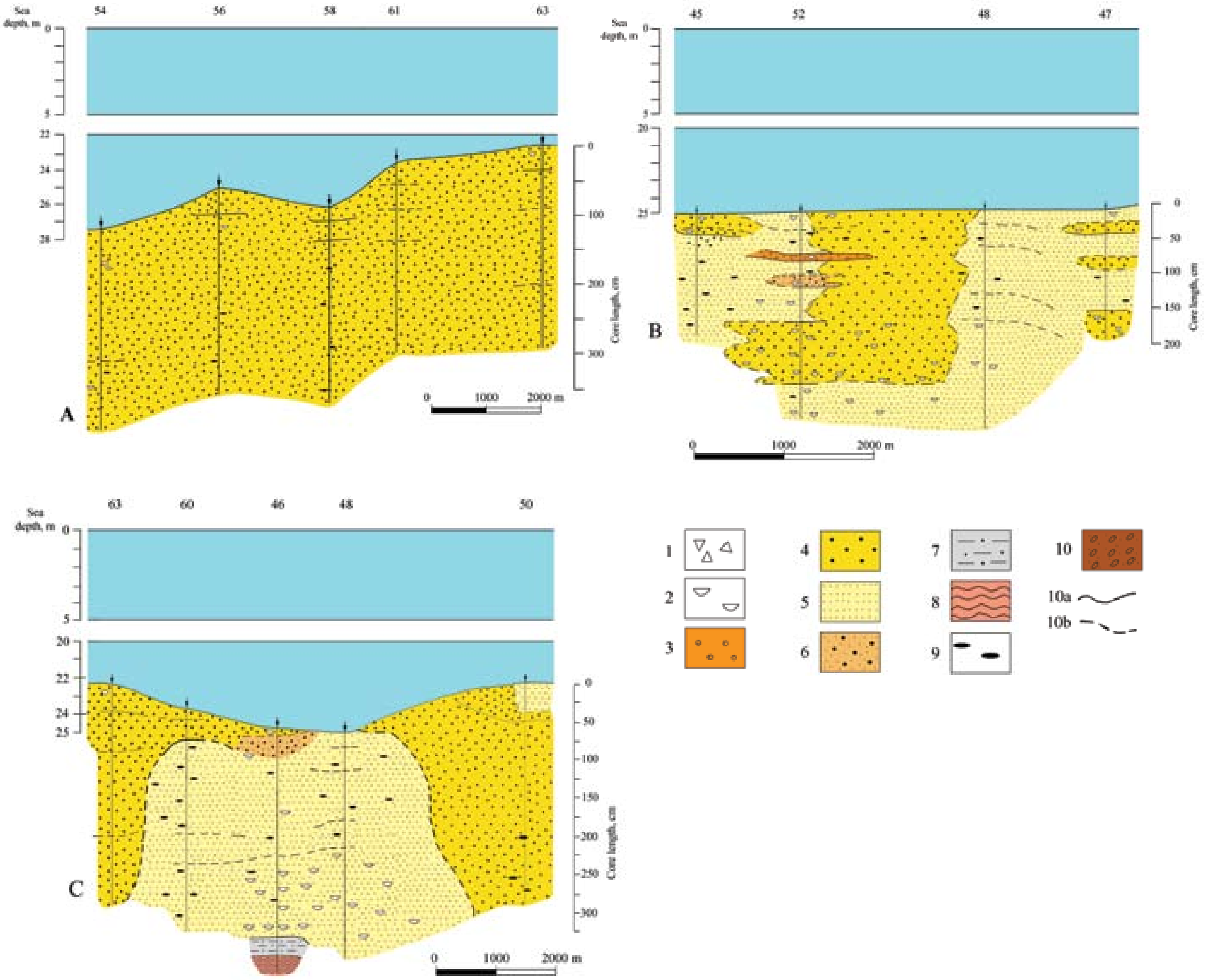


Fig. 9. Sediment cross-sections (*A, B, C*) according to the vibrocoring data (position of cross-sections are shown in Fig. 1A): *1* – gravel, *2* – shell, *3* – coarse sand, *4* – medium sand, *5* – fine sand, *6* – vari-grained sand, *7* – coarse silt, *8* – sapropel (gyttja), *9* – various dark streaks, *10* – boundaries: *a* – sharp, *b* – gradual or indistinct

9 pav. Nuosėdų pjūviai (*A, B, C*) vibrogręžimo duomenimis (pjūvių vietą žr. 1 pav., *A*): *1* – žvirgždas, *2* – kriauklės, *3* – stambus smėlis, *4* – vidutinis smėlis, *5* – smulkus smėlis, *6* – įvairiagrūdis smėlis, *7* – stambus aleuritas, *8* – sapropelis (gitija), *9* – įvairūs tamsūs intarpai, *10* – sluoksnių ribos: *a* – staigios, *b* – laipsniškos arba neryškios shoreline – at a depth of 0.7 m) typical of the whole nearshore. The dominant fine-grained sand fraction accounts for 96%, and its sorting index is 1.16. The portion of silt fractions increases with depth to 15.42% (at a depth of 15 m). At an underwater slope depth of 15–20 m, in places the grain-size spectrum of the sediments includes relatively greater portion of silt fractions (up to 62.4%) and considerably smaller concentration of sand grains.

The grain-size spectrum of the hilly sand elevation (the western part of the profile) is predominated by two sand fractions: medium-grained (17.9–56.57%) and fine-grained (36.72–79.4%). The portion of silt fraction reduces to the minimum (0.3–2.9%). Md of sand is 0.20–0.28 mm and S_o is 1.2–1.3. The grain-size composition of the surface sediments of the elevation differs considerably from the sand composition in the nearshore bar (the eastern part of the profile) (Fig. 8).

According to the data obtained by vibrocoring, the north-eastern hilly elevation (at a depth of 27–22 m) is composed of almost monotonous homogeneous medium sand layer of 3 m thick (Fig. 9A). The medium sand is light yellow and yellowish grey. The colour gradually changes with the depth, though these changes are not marked. The variations of the grain size composition are negligible: in the cross-sections of sites 54 and 56, the sand gradually fines down, while in site 58 the changes are opposite. In other sites the variation trends are uncertain. There occur small dark grey interlayers, streaks (site 58) or rare shells *Macoma baltica* in the sand. The Md of the sand is from 0.23 to 0.46 mm, yet sand grains of a diameter smaller than 0.25 mm are very rare and occur only in small intervals. The sorting index is good – S_o 1.2–1.6. Due to this sand composition, the visually observed boundaries between layers are obscure (except a few cases) and the changes are gradual.

The southern most sublatitudinal profile 45–47 crosses the sand massif at a depth of 25 m (Fig. 9B). On both sides it is composed of fine sand (Md 0.18–0.25), yet layers of medium and even coarse sand (site 52, interval 59–66 cm) can be observed below the bottom surface. According to the seismoacoustic data, the central part of the sand massif is mainly composed of medium sand. The boundaries between the layers are mostly well-expressed, yet there are also blends of colour and slight changes of the grain size composition. The heterogeneous character of the sands is predetermined by a varying content of the shells (*Macoma baltica*). They also have numerous dark grey silt patches. The greatest variations of sand Md are characteristic of site 52: from 0.2 to 0.65 mm. S_o varies from 1.2 to 2.0. The fine sand is sorted the best and the coarse sand – the worst. Well-rounded fine pebbles occur in the lower part (140–180 cm) of the sediment core in site 47.

Table. **Mineral composition of sand fraction 0.25–0.1 mm in the Juodkrantė–Preila polygon (%)**
Lentelė. **Juodkrantės–Preilos poligono 0,25–0,1 mm smėlio frakcijos mineralinė sudėtis (%)**

Minerals	Sites and horizons (cm)											
	17	28	30			38	43	D–1	D–3	D–6	D–7	D–8
	0–5	0–5	10–20	40–45	75–80	0–5	0–5	0–5	0–5	0–5	0–5	0–5
	Light subfraction											
Quartz	93.6	94.0	94.8	95.6	94.2	94.8	93.8	94.8	94.6	94.8	93.6	94.4
K-feldspars	5.2	5.2	4.4	3.6	4.8	4.2	5.2	4.6	4.6	4.8	5.8	5.2
Mica colorless	0.6	0.4	0.6	0.8	0.8	0.6	0.6	0.6	0.6	0.4	0.6	0.4
Glauconite	0.6	–	–	–	–	0.4	0.4	–	0.2	–	–	–
Agregates	–	0.4	0.2	–	0.2	–	–	–	–	–	–	–
	Heavy subfraction											
Rutile	0.8	0.8	1.2	0.8	0.4	1.2	0.4	0.6	0.4	0.8	1.2	0.8
Zircon	2.8	2.0	2.6	2.6	2.2	1.8	2.6	3.2	2.4	2.6	3.4	2.8
Tourmaline	3.2	2.2	3.2	3.4	2.4	3.6	3.2	3.4	3.6	3.2	2.8	3.6
Garnet	15.8	26.8	24.0	24.2	22.2	24.6	26.2	20.2	19.6	19.4	24.6	26.0
Hornblende	17.2	18.8	20.4	19.6	20.2	18.8	19.8	19.2	16.8	17.2	18.8	22.2
Pyroxenes	8.4	4.6	5.4	6.6	6.2	6.2	5.8	6.8	8.4	8.4	5.8	5.2
Epidote group	6.6	5.2	4.8	6.2	5.6	4.8	5.6	5.6	6.6	6.2	4.8	4.4
Disthene	2.8	2.0	2.0	1.4	1.4	1.2	1.4	2.6	2.2	1.4	1.6	1.2
Staurolite	5.2	4.4	3.2	3.6	3.8	3.6	3.8	3.0	3.6	3.4	3.6	3.8
Glauconite	0.2	–	1.2	0.6	0.6	0.8	–	–	–	1.2	0.4	0.6
Sphene	–	0.8	0.6	–	–	0.2	0.2	1.2	0.4	–	0.2	0.2
Biotite	1.6	1.2	2.2	1.8	1.8	1.8	1.0	0.8	1.6	2.2	1.6	1.8
Phosphates	0.4	–	–	–	–	–	–	–	–	0.6	0.6	0.4
Fe hydroxydes	7.4	6.8	6.2	7.2	6.8	5.6	4.8	7.6	8.2	7.8	6.4	4.8
Magnetite–ilmenite	21.2	19.4	16.8	17.4	19.6	18.8	18.4	19.6	18.8	19.2	18.2	16.4
Leucoxene	6.4	4.6	6.2	4.6	6.8	7.0	6.8	6.2	7.4	6.4	6.0	5.8
Dolomite	–	0.4	–	–	–	–	–	–	–	–	–	–

The central and the deepest (25 m) parts of the northern–southern sediment profile (Fig. 9C) are composed of fine sand, whereas the peripheral ones – of medium sand, which is light yellowish or light grey almost homogeneous with rare *Macoma baltica* shells. Its Md is 0.30–0.40 mm. The fine sand is light yellowish, grey and dark grey, heterogenous with silty interbeds and streaks that often are small black molluscous shells. Its Md is 0.18–0.25 mm. In places the Md increases and the sand gradually changes to medium-grained one. The S_o varies within 1.2 and 1.5. The interfaces between the layers often are indistinct, yet very well expressed between the layers of a conspicuously different composition. In the lower part of core 46, the fine sand is interfaced with grey sapropel-bearing coarse silt (277–299 cm) overlying the sapropel layer. These boundaries were identified in the seismic profiles.

The mineral composition of the sand in the studied area differs but little. Its main constituent is quartz (94–96%). Feldspar account for a few percent. Garnets, hornblende and magnetite–ilmenite are dominant among the heavy minerals (Table).

DISCUSSION

A comparison of seismoacoustic and vibrocoring results revealed their good mutual correlation. The boundaries of the sediment types of different compositions determined by the preliminary visual description are easily detectable in the seismic profiles of the bottom (sites 46, 47, 52, 58, 61 and 63). The sediment cores (their maximal length being 3.3 m) are composed of fine and medium sand layers. Though their lower parts were not reached in the most of the seismic profiles, we may assume that the sand layer in the area under study is not less than 4–5 m thick based on the depth of acoustic examination which, depending on the type of the bottom sediments, reached 5–10 m below the bottom surface.

In site 46 (sea depth 24.8 m), a clear interface of sand with the underlying coarse silt layer and one more interface with brownish black sapropel (gyttja) below were identified. The ^{14}C age of the coarse silt layer containing sapropel (277–322 cm) is 10400 ± 140 years BP. As evidenced by a few seismic profiles, this layer extends in southwestern–northeastern direction. Yet it was not reached by vibrocoring in other sites because it was bedded at a depth of over 3 m. These are the oldest sediments, whose age and spatial distribution pattern in the central part of the area under study allow assuming that the overlying sand layers could be accumulated only after the end of the Baltic Ice Lake stage. Therefore, in order to reconstruct the evolution of the sand massif, it is expedient to get acquainted with the palaeogeographic history of the sea during the mentioned period.

The most reliable facts about the events during the Baltic Ice Lake and at the end of the glaciation have been collected in the Central Sweden (Björck, 1995). It was established that after the retreat of the glacier periphery to the north of the Billingen Mountain, there appeared a water link with the Northern Sea (ocean). The water level in the Baltic Ice Lake then dramatically fell down by about 25 m. This was the beginning of the Yoldia Sea stage (10.3–9.5 ka BP) which almost synchronized with the Holocene warming. The major later events in the Baltic basin were predetermined by isostatic Fennoscandian uplifts (Mörner, 1979; Eronen, 1988). The link with the ocean was interrupted by the uplifts of the earth surface what predetermined the isolation of the Yoldia Sea. This was the beginning of the new Ancylus stage (9.5–8.0 ka BP), during which the water level of the lake rose above the sea level again. Yet lake regression set in with the reduction of the retreating glacier melt water. The most intensive water drainage took place through the Danish straits, where a new link with the Northern Sea developed. Soon after that, the salty waters of the Northern Sea surged into the Baltic Sea (Björck, 1995). This was the first Litorina Sea transgression followed by a few other transgression–regression cycles.

On the background of these events, great changes took place in the southeastern part of the Baltic Sea, whose evolution, though studied in many works (Гуделис, 1976; Gudelis, 1997; Блажчишин, 1984; 1998a; Блажчишин et al., 1982; Лукошявичюс, Гуделис, 1974; 1975; Гялумбаускайте, 1982; Gelumbauskaitė, 2000; Kabailienė, 1999 and other), still has many uncertainties related to the local development of the bottom. Substantial water level fluctuations have affected all the processes that took place under the new conditions and left their marks on the bottom sediment composition, their bedding depth, morphology of the coastal zone and changes of the shoreline.

According to the geological–geophysical (including lithological and biostratigraphical) data, the following levels of the old shorelines were distinguished in the southeastern part of the sea: 60–62, 40–46, 30–36, 18–27, 14–16, 8–12 and 0–2 m (Блажчишин et al., 1982). The peaks of the transgressions and regressions were determined based on the seismic and age data (Gelumbauskaitė, Šečkus, 2005): Baltic Ice Lake maximal transgression refers to +6 m NN, Yoldia maximal transgression – to −55.5 m, Ancylus maximal transgression – to −5.5 m, Ancylus regression – to −46.5 m, Litorina L_1 transgression – to 26.5 m, L_2 maximal to +5.0 m, L_3 and PostLitorina to +2.0 m. These levels are reflected in the bottom as abrasion or abrasion–accumulation terraces bounded by cliffs and troughs of the underwater slope. Though the different altitudes of these coastal formations were mainly predetermined by the water level fluctuations, a local influence also may have been produced by differentiated isostatic bottom changes in the Holocene (Гялумбаускайте, 1982). Due to this, the composition of the Late Glacial and Holocene bottom sediments is rather variable as is their thickness. It is natural that under these circumstances, palaeogeographic reconstructions sometimes differ considerably. Straightforward interpretations of the collected material also are impossible due to different points of departure (Bitinas, Damušytė, 2004).

Turning back to the issue of the sand massif formation in the area under study, it should be noted that two old-established large sand massifs in the surface of the Curonian–Sambian plateau to the west of the central and southern parts of the Curonian Spit are related with transgression–regression cycles. It is assumed that they are submerged beach dunes developed in the times of the Ancylus regression and the first phase of the Litorina transgression 8–7 thousand years ago (Блажчишин et al., 1982).

One of the dune massifs now being at a depth of 25–32 m formed as a spit extending (as the present Curonian Spit) in the northeastern direction of the Sambian peninsula. The other dune massif being at a depth of 20–25 m to the west of the central part of the Curonian Spit developed as an accumulative spit-type form at the bottom of the northern slope of the Curonian–Sambian plateau. The mentioned plateau then was a large peninsula projecting far into the sea. The massifs are composed of fine-grained well-sorted sand (average Md is 0.20 mm; S_o is 1.2–1.5) containing up to 25% of coarse silt fraction. The sand is mainly composed of quartz (up to 90%). It also contains feldspars (up to 21%), glauconite, shell detritus and organogenic admixtures. The bottom of the sand layers contains coarse clastic material, till and peat-bearing sediments (Блажчишин, 1998b).

The sand sediments of the study area sculpture hilly relief forms of two directions. The northern ridge of the sand dunes extending to the southwest and gradually dipping from the sea depth of 22 m (site 63) to 32 m (site 39) is composed of medium-grained well-sorted sand with very rare small shells. The hilly uplift extending to the north–south is shallower (sea depth about 22–25 m). It is composed of various sand. The surface layer (up to three meters below the bottom surface) is mainly composed of fine and medium sand with mollusca and black silty organogenic streaks. These differences of the granular composition evidence varying sand accumulation conditions with dominant different factors.

The formation of the sediment cover of the medium sand might have taken place under similar conditions as the formation of the mentioned dune massifs. Yet its orientation and sand composition imply the impact of fluvial flows. As it is known, the bottom relief, the sediment composition and other evidence show the existence of a delta near the Curonian–Sambian plateau (Лукошявичюс, Гуделис, 1975; Гуделис, Литвин, 1976; Блажчишин, 1998b and others). Thus, the formation of sub-latitudinal sand deposits (Fig. 9A) might have started even in the Ancylus stage.

The accumulation of sands composing the hills extending in the north–south direction followed a different pattern. From the age of the sapropelic coarse silt layer (site 46) we may judge that at the beginning of the Yoldia Sea stage (its shoreline was 55–62 m below the present sea level), for some time there existed a lagoon accumulating organogenic sediments at the bottom of the northern slope of the Curonian–Sambian plateau. The sapropelic coarse silt and the overlying fine sand (site 46) are divided by a pronounced boundary marking the hiatus time (Yoldia–Ancylus), which is not reflected in the section sediments. Besides, the fine sand abounds in mollusca, which reached the Baltic Sea from the Atlantic Ocean already in the Litorina stage (Gudelis, 1998). As was mentioned, most fine sand sections are characterized by great amounts of mollusca, whereas shell detritus in the medium sand layers occur in very small amounts. This implies that the sand accumulation started not earlier than in the first phase of the Litorina transgression.

Due to sea level fluctuations and shoreline migration, the sand accumulation was uneven and the periods of deposition were often replaced by sediment erosion, which is evidenced by the boundaries between the layers in the vertical sections (Fig. 9). Presumably these processes lasted throughout the whole Litorina stage.

At present the sand massifs in the study area are separated from the recent nearshore sands (up to 20 m in depth) by a sand belt with a larger amount of silt (Emelyanov et al., 2002). The appearance of this belt was predetermined by the regional hydrodynamic field and suspended sedimentary matter flow. The fact that the recent coarse silts surround the hilly sand massif excluding its southern edge can be explained by active hydrodynamic environment in the nearbottom layer. This is also proved by a consistent reduction of sand fractions and increasing concentrations of silt (0.1–0.01 mm) moving from the nearshore to the studied sand massif (Fig. 8). A visual bottom assessment showed that the surface of the sand massif has wide ripple marks. The sand composition and the bottom surface microrelief show that the Juodkrantė–Preila polygon is a transitional zone of sand transport, i. e. it is possible that no accumulation of the recent sedimentary material takes place in it.

CONCLUSIONS

The hilly elevations in the area of study are composed of medium and fine well-sorted quartz sand layers. According to the available information, though the exact thickness of the sediments was not measured, the sand deposits are not less than 4–5 m thick. The applied seismoacoustic methods (able to penetrate to the depth of 5–10 m depending on the sediment type) did not detect any reflections of other layers, excepted that of sapropelic coarse silt.

Based on the new geological–geophysical information, the sand massifs in the underwater slope of the Curonian Spit to the west of the Juodkrantė–Preila nearshore started developing during the Ancylus Lake regression. The intensive sand accumulation coincided with the first phase of the Litorina transgression when sedimentary material flows from the intensively eroded underwater slope of the Sambian peninsula intensified.

The differences of the sand composition in the geological profiles and bedding patterns of the layers were related with variations of sedimentation conditions and with the time of their formation. At times, fluvial and eolian processes (Ancylus stage) might have added variety to the uneven and discontinuous sand accumulation, yet hydrodynamic factors have always played a decisive role.

Distribution patterns of the grain size composition and the types of the surficial sediments in the underwater slope of the Curonian Spit (including the sands of the study area) show that there is no circulation of the sedimentary material between the shallow nearshore and hilly sand massifs. Thus, the present coastal zone of the Curonian Spit is virtually independent of the lithodynamic processes taking place in the plateau surface (deeper than 20 m).

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SMĖLIO SANKAUPŲ SUDĖTIS IR FORMAVIMASIS KURŠIŲ–SAMBIJOS POVANDENINĖJE PLYNAUKŠTĖJE (BALTIJOS JŪRA)

Santrauka

Kompleksiniai geologiniai ir geofiziniai metodai buvo panaudoti vykdant tyrimus Juodkrantės–Preilos poligone, į vakarus nuo Kuršių nerijos. Čia jūros dugno paviršiuje yra iškilusios smėlio pakilumos, kurios tęsiasi pietų–šiaurės ir pietvakarių–šiaurės rytų kryptimis. Tai banguotas ir kalvotas reljefas su santykiniais 4–5 metrų gylio skirtumais. Dugno paviršių 5–50 m gylyje dengia pilkas ir gelsvai pilkas smulkus smėlis, pakilumose vyrauja šviesiai gelsvas ir gelsvai pilkas vidutinis gero rūšiuotumo kvarcinis smėlis ir tik nedideliuose dugno plotuose (20–28 m gylyje) slūgso stambus smėlis. Smėlio sluoksnių apatinė riba daugelyje seisminių profilių nebuvo pasiekta, tačiau, galima teigti, kad čia yra ne mažesnė kaip 4–5 m storio smėlio storymė. Seismoakustiniais metodais (tyrimo gylis priklausomai nuo dugno nuosėdų tipo siekė iki 5–10 m nuo dugno paviršiaus) kitų atspindžių, išskyrus sapropelingo stambaus aleurito sluoksnį, neaptikta.

Pagal naujai surinktą geologinę-geofizinę informaciją, smėlio sankaupos povandeniniame Kuršių nerijos šlaite, į vakarus nuo Juodkrantės–Preilos pakrantės, pradėjo formuotis Ancyliaus ežero regresijos metu. Intensyvi smėlio akumuliacija sutapo su Litorinos transgresijos pirmąja faze, kai sustiprėjo nešmenų srautai nuo Sambijos pusiasalio, kur vyko aktyvi jo povandeninio šlaito erozija.

Smėlio sudėties skirtumai geologiniuose pjūviuose ir sluoksnių slūgsojimo ypatumai yra susiję su sedimentacijos sąlygų kaita ir jų susidarymo laiku. Skirtingais laiko tarpsniais netolygią ir su pertrūkiais smėlio akumuliaciją galėjo paįvairinti fliuviniai ir eoliniai procesai (Ancyliaus stadija), tačiau svarbiausi visada buvo hidrodinaminiai veiksniai.

Paviršinių nuosėdų granuliometrinės sudėties ir jų tipų pasiskirstymo dėsningumai Kuršių nerijos povandeniniame šlaite rodo, kad tarp sekliausios priekrantės dalies ir kalvotų smėlio masyvų nėra intensyvios nuosėdinės medžiagos apykaitos. Taigi dabartinė Kuršių nerijos kranto zona iš esmės yra nepriklausoma nuo plynaukštės paviršiuje (giliau kaip 20 m) vykstančių litodinaminių procesų.

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СОСТАВ И ФОРМИРОВАНИЕ ПЕСЧАНЫХ МАССИВОВ НА КУРШСКО-САМБИЙСКОМ ПОДВОДНОМ ПЛАТО (БАЛТИЙСКОЕ МОРЕ)

Резюме

Для исследований на полигоне Юодкранте–Прейла, расположенном на западе от Куршской косы, были применены комплексные геологические и геофизические методы. Здесь на дне моря возвышаются песчаные поднятия, простирающиеся в направлении север–юг и юго-запад – северо-восток. Волнистый и холмистый рельеф дна характеризуется изменчивостью относительной глубины в 4–5 метров. Поверхность дна на глубине 5–50 м покрыта серым и желтовато-серым мелким песком, на поднятиях доминирует светло-желтый и желтовато-серый хорошо отсортированный кварцевый средний песок и только на небольших участках на глубине 20–28 м залегает крупный песок. Нижняя граница песков на большинстве сейсмических профилей не выявлена, однако можно утверждать, что толща песчаных слоев не менее 4–5 метров. Примененными сейсмоакустическими методами, глубина зондирования которых в зависимости от типов донных отложений была 5–10 м ниже поверхности дна, других отражающих границ, за исключением слоя сапропелевого крупного алеврита, не обнаружено.

На основе новых геолого-геофизических данных предполагается, что песчаный массив на подводном склоне Куршской косы западнее Юодкранте–Прейла начал формироваться во время регрессии Анцилового озера. Интенсивная аккумуляция песчаных отложений была в первую фазу Литориновой трансгрессии, когда усилились потоки осадочного материала от Самбийского полуострова из-за активной эрозии его подводного склона.

Различия состава песчаных отложений и особенности залегания слоев являются результатом менявшихся условий седиментации, а также времени их формирования. Аккумуляция песков по времени была неравномерной и прерывистой. Ее различия также были следствием действия флювиальных и эоловых процессов (стадия Анцилюс), однако решающая роль всегда принадлежала гидродинамическим факторам.

Закономерности распределения типов осадков и гранулометрического состава отложений на подводном склоне Куршской косы свидетельствуют, что интенсивный обмен осадочным материалом между мелководной прибрежной частью моря и холмистыми песчаными поднятиями в настоящее время не происходит. Современная береговая зона Куршской косы по существу не зависит от литодинамических процессов на поверхности плато (глубже 20 м).