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The results of integrated investigations of the Lithuanian coast of the Baltic Sea: geology, geomorphology, dynamics and human impact

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Integrated investigations of the Lithuanian coast of the Baltic Sea were carried out in 1999–2004 in order to satisfy an increased demand for information about the shoreline. The area of investigations included the beach and the protective dune or cliff (i.e. an onshore belt 100–300 m wide) and reached 15–20 m isobaths in the offshore region. This study has resulted in the Geological Atlas of the Lithuanian coast of the Baltic Sea, which consists of digital maps including a geological-geomorphological map, a map of anthropogenic load at a scale of 1:5000 and an explanatory note. Data arrays from shoreline geodynamic monitoring and from field and analytical studies as well as descriptions of borehole sections are provided in graphic and textual annexes. On basis of these investigations 92 morpholithological profiles of the offshore zone and 101 geological cross-sections of the onshore zone were prepared. The basic geological information in the form of maps and special data arrays allows assessment of the current geological condition of the Baltic Sea shores and enables forecasts for their development. It also can be used for environmental protection and land use in the shoreline area: prevention of erosion, designing of protected, recreation and urban areas, as well as substantiation and development of a seashore monitoring system.

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INTRODUCTION

The shoreline area is constantly exposed to increasing human impact. By the end of the 20th century, human impact became an independent geological factor affecting many shore-formation processes. Lately, problems affecting the Lithuanian coast of the Baltic Sea have become particularly acute. On the one hand, this has been caused by natural factors (heavier storms, more intense outwashing of sand from the littoral area, a rise in global sea level and so on) and on the other hand, by man-caused factors such as harbour development and dredging and growth in the recreation "industry".

Though the Lithuanian coastline of the Baltic Sea is only 90.6 km long (Fig. 1), it has not yet been studied sufficiently: neither in fundamental terms as a transit area between surface and marine geosystems nor in applied terms as regards development of marine industry, recreation and marine resources.

An integrated study has been carried out as a response to increased demand for information about the Baltic Sea coast. This study has been possible due to cooperation of experts from the Geological Survey of Lithuania, the Institute of Geology and Geography and the universities of Vilnius and Klaipėda. Digital maps, including a geological-geomorphological map and a map of anthropogenic load at a scale of 1:5000, have been compiled. Graphic and textual information includes a catalogue of repeated grading curves obtained by geodynamic monitoring of shorelines, data arrays from field and analytical studies, and descriptions of borehole sections. The geological-geomorphological map covers the beach and the protective dune or cliff, i.e. an onshore belt 100–300 m wide. The map covers the underwater slope of the offshore zone up to the 15–20 m

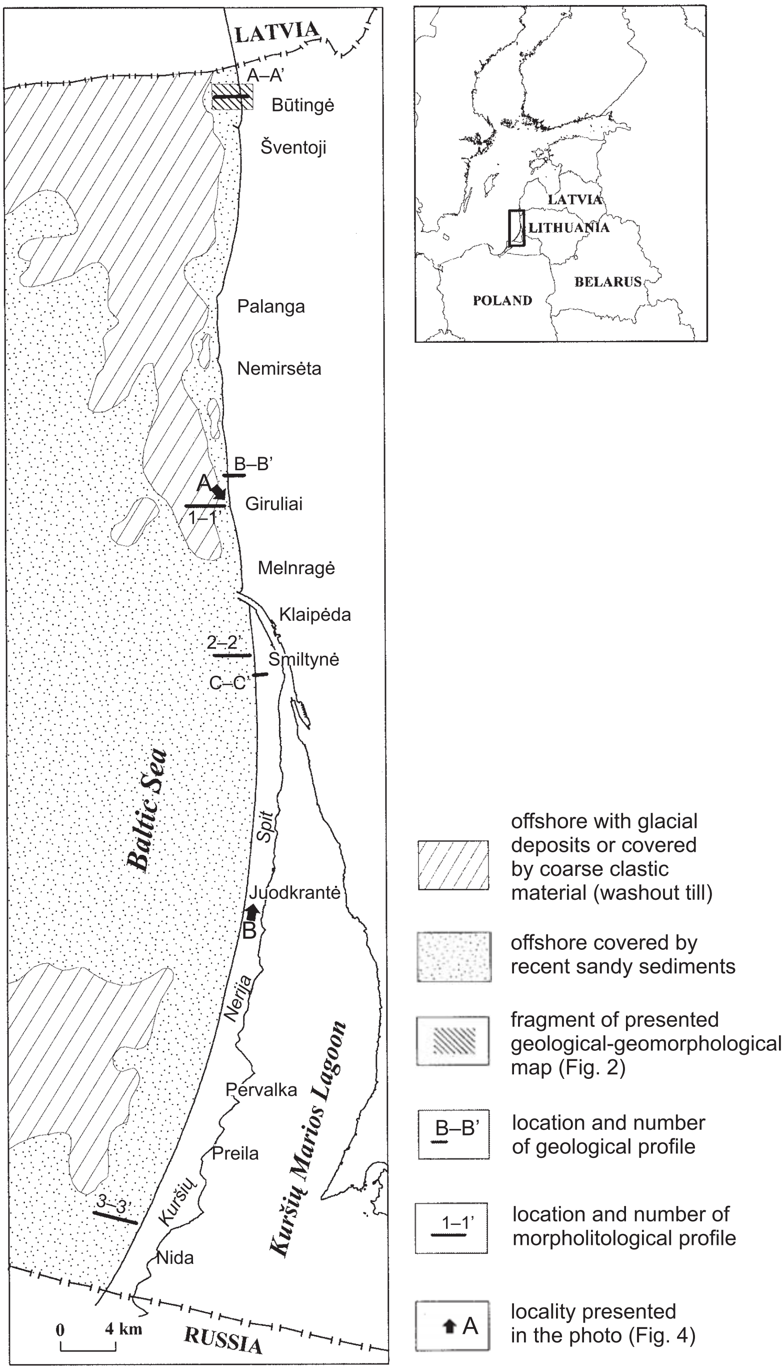

Fig. 1. The Lithuanian coastal area of the Baltic Sea

isobaths. The geological-geomorphological map is illustrated by 92 morpholithological profiles of the offshore zone and 101 geological cross-section of the onshore zone.

OVERVIEW OF COASTAL STUDIES

Studies of the Lithuanian coast of the Baltic Sea can be divided into a number of stages differing in the subject of investigation, level of detail, methods, number of publications and so on. The first studies were geological and palaeogeographical in nature and were begun in the 19th century by Schumann (1861) and Berendt (1869), followed by the works by Tornquist (1910), von Wichdorff (1919), Kraus (1925) and other researchers. These studies revealed the basic features of the geological structure of the Lithuanian seashore as well as the distribution of deposits in the sea and in the Kuršių Marios (Curonian) Lagoon. Later they were supplemented by studies by Gudelis (1979), Kabailienė (1999) and many other Lithuanian specialists in the second half of the 20th century.

Hydrometeorological studies that are closely related to shore formation have revealed the characteristics of the offshore area and the currents and water level fluctuations in the Kuršių Marios Lagoon, as well as the effects of the heaviest storms in the south-east Baltic region (Stellmacher, 1920; Willer, 1933; Schmidt-Ries, 1939). In the second half of the 20th century, many papers on swash flow dynamics and offshore mesoscale circulatory and flow processes were published by Lithuanian scientists.

Litho- and morphodynamic processes play an important role in the shore formation mechanism. On land they are determined mainly by eolian processes and in the sea and on the beach by hydrodynamic ones. The eolian aspects of the shore formation process were considered in the 19th century by Berendt (1869) in Prussia and by Sokolov (1896) in Russia, who formulated the basic statements about the formation and the coastal-protective role of coastal dunes. In Lithuania, studies of coastal dunes effectively started after World War II (e.g. Gudelis and Michaliukaitė, 1976). The current status of these studies is exemplified by the work of Žilinskas *et al.* (2001).

New directions of study developed after World War II; on offshore and beach morpho- and lithodynamics. Results of investigations into the structure and textural features of offshore and beach deposits were published in Dolotov *et al.* (1982).

In the last decade of the 20th century, coastal studies centred on a number of practical problems: the effect of hydrotechnical settings upon the seacoast; the distribution, structure and protection of underwater landscapes; land-management aspects of the littoral area. The intensification of investigations into the coastal zone was one reason for preparing the quadrilingual "A glossary of coastal research terms" (Gudelis, 1993).

Geological studies of the Baltic Sea coast were scarce in the second half of the 20th century. In the 1960s, investigations were conducted into littoral deposits as a potential source of accumulation of heavy minerals. In 1993–2000, studies were carried out as part of the state geological mapping programme, of both the onshore and offshore zone at a scale of 1:50 000. The first detailed stratigraphic investigations of Mid- and Late Pleistocene as well as of Holocene sediments of the Baltic Sea

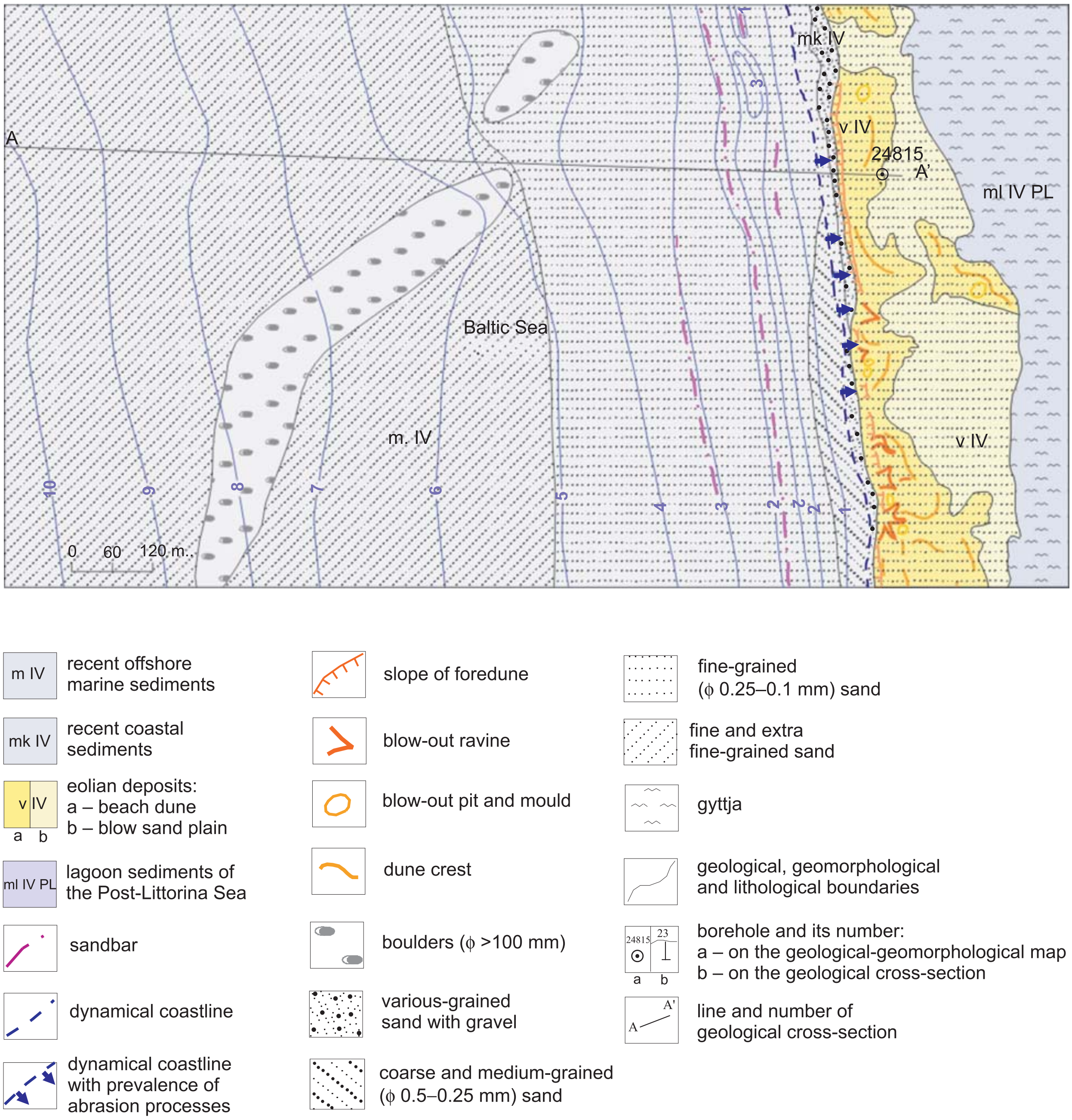

Fig. 2. Fragment of geological-geomorphological map

For location see Figure 1

coast were carried out during these mapping projects (Bitinas *et al.*, 1999; 2001*a*, *b*).

Throughout the second half of the 20th century Soviet censors did not permit Lithuanian researchers to publish their findings on hydrodynamics, lithodynamics, morphometry and so on with references to specific locations. It became clear after the restoration of Lithuania's independence that there were many gaps in the data coverage of the Baltic Sea coast, which would be needed for both research and practical purposes. This was one of the most important motives for conducting large-scale integrated geological studies of the coastal area.

METHODS OF INVESTIGATIONS

The choice of methods of investigation was determined by a number of factors: firstly, the geographic and geological characteristics of the shoreline the available information base (topographic surveys, satellite and aerial photographs), and the availability of various technical means.

It became clear after the start of work that the diversity of geological objects, geomorphological forms and the anthropogenic objects in a narrow coastal strip 200–300 m wide, which was the subject of investigation, could only be shown on a map scaled not less than 1:5000. However, there is

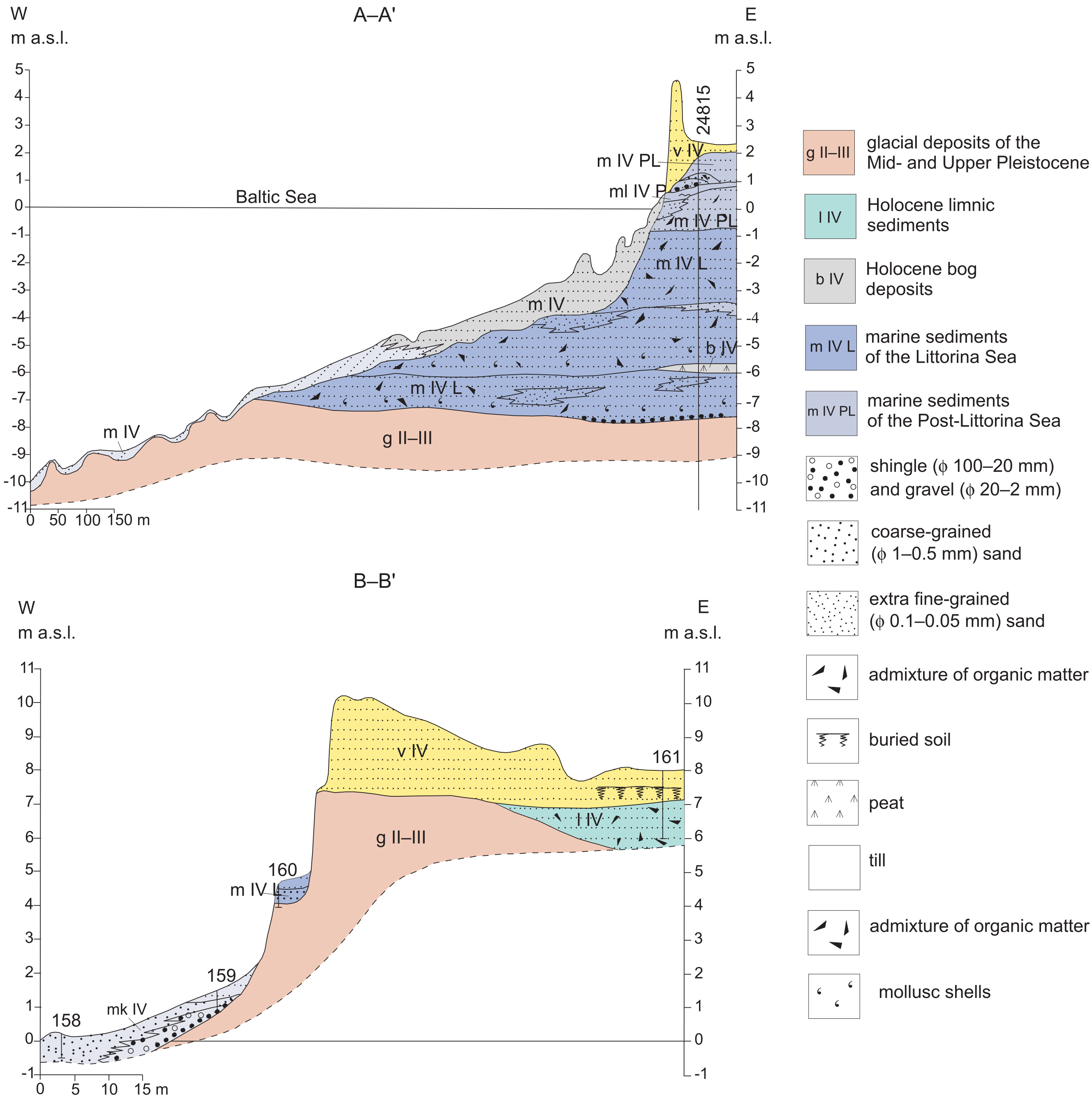

Fig. 3. Geological structure of coastal zone close to Būtingė (profile A–A') and to the north of Giruliai (profile B–B')

For other explanations see Figure 2

still no topographic base map at this scale for the entire Lithuanian coastal area, and so orthophotographs were used as a background for the geological-geomorphological map and the map of anthropogenic load. Many effects of human activity were deciphered using these images. The geological-geomorphological map of the land area was compiled based on interpretation of aerial photographs. Black-and-white aerial photographs were used: from the years 1979 and 1982 (scale 1:25 000), 1990 (scale 1:20 000), 1991 (scale 1:18 000) and 1993 (scale 1:21 400). For the compilation of the geological-geomorphological map of the central and southern part of the coast of the Kuršių Nerija spit, computer-aided interpretation of stereo images was used. For this purpose the aerial photographs from 1991 were processed with the *PhotoShop* program. The results of interpretation for the purposes of both geological-geomorphological and anthropogenic load maps were verified and adjusted during fieldwork.

Drilling of boreholes was the main method that allowed determination of the characteristics of the geological structure of the coastal area. 320 boreholes up to 5 m deep were drilled using a hand auger. The boreholes were drilled along lines perpendicular to the shoreline, with on average 4 boreholes for each line: usually 3 boreholes on the beach and 1 borehole behind the beach dune. The borehole co-ordinates were established by means of GPS and the borehole mouth height by grading the drilling profiles. In order to determine the possibilities for a more detailed investigation of the geological structure of the coastal area, small-scale geophysical investigations were conducted along several drilling lines by the electro-tomographic method. The results obtained from over 40 boreholes drilled earlier (up to 20–25 metres depth) in the course of state geological mapping at a scale of 1:50 000 were also used.

Determination of the coastal dynamic trends was based on measurements carried out at 98 coastal posts in 1993–1994 and 2002–2003. Changes in the position of coastal elements (the shoreline, the protective dune and the cliff tops and bases) were established by comparing the results of repeated grading from different years. However, the best indicator of multi-year geodynamic trends of the coast is the budget of surface littoral alluvium (m^3/m): the sum of temporal and spatial changes in the coastal material that was washed off or blown out and accumulated, calculated up to the median multi-annual sea level.

Echo sounding and bottom deposit sampling was carried out during the study of the geological and geomorphological structure of the offshore area up to a depth of 15–20 m. The investigations were carried out along 92 lines perpendicular to the shoreline. The distances between lines varied from 500 to 1000 m. In each line, bottom sediment samples at depths of 1, 2, 3, 5, 7, 10 and 15 m were taken. The sampling was carried out taking into account the geomorphological characteristics of the offshore area.

Granulometric analyses of bottom and coastal sediments occupied the major part of the laboratory examinations. Small-scale mineralogical, chemical, pollen, x-ray structural and x-ray spectral analyses were made as well. To determine the age of coastal sediments more exactly, dating of several samples by the method of optically stimulated luminescence (OSL) and by the radiocarbon (^{14}C) method has been done.

RESULTS OF INVESTIGATIONS

GEOLOGICAL STRUCTURE AND GEOMORPHOLOGY

The results of earlier geological investigations and the information obtained in this study show that the deposits that are found on the Lithuanian coast of the Baltic Sea formed during the Quaternary. There are two geologically and geomorphologically different sectors of the Lithuanian coastal area (Fig. 1): the continental sector (to the north from Klaipėda) and the Kuršių Nerija (Curonian) spit.

The continental sector of the Lithuanian coast is geologically diverse. While sandy sediments that had formed mainly in the Littorina and Post-Littorina seas and their lagoons prevail in the northern part (Šventoji, Palanga) (Figs. 1–3, profile A–A'), the southern part of the coastal sector (Nemirseta, Giruliai) is characterized by glacial (moraine) deposits formed during the Late Nemunas (Late Weichselian) and Medininkai (Saalian) glaciations (Bitinas *et al*., 1999), in most cases occurring in the abraded cliffs (Figs. 3, profile B–B' and 4A). A natural eolian beach dune occurs along the entire continental coast. Its parameters vary from a height of 4–6 m and a width of 50–60 m at Būtingė or Melnragė to a height of 9–10 m and a width of 100–130 m to the south of Šventoji. Here and there the beach dune has been fully destroyed by abrasion caused by waves as well as by deflation. Processes of suffosion in the beach dune (developed on the 2–3 metres high cliff composed of moraine) were observed close to Nemirsėta. While in the northern part of the continental coast, a Post-Littorina marine lagoon plain occurs behind a beach dune (Fig. 2), glacial landforms formed during the Late Nemunas (Late Weichselian) glaciation may be traced to the south of Palanga.

The upper part of the Quaternary succession in the shore of the Kuršių Nerija spit is composed of deposits that had formed in the basins of various stages of the Baltic Sea development — starting from the Baltic Ice Lake and ending with recent marine sediments (Bitinas *et al*., 2001*a*, *b*) (Fig. 5). In the spit sector of

Fig. 4. A — active abrasion wall with exposure of glacial deposits in the Olando Kepurė cliff close to Giruliai; B — view of protective beach dune at Juodkrantė

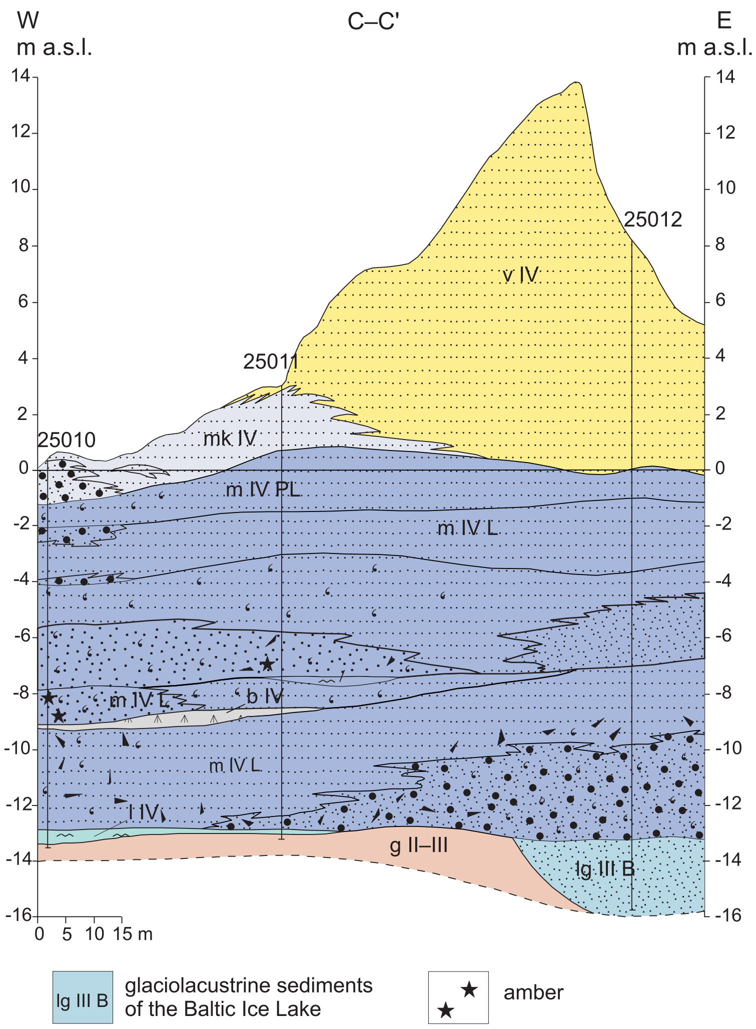

Fig. 5. Geological structure of coastal zone of the Kuršių Nerija spit at Smiltynė (profile C–C')

For other explanations see Figures 2 and 3

the Lithuanian coast, there is a man-made protective beach dune, whose formation started 200 years ago, stretching along the entire length of the spit (Fig. 4B). Its height varies from 7–8 m at Juodkrantė to 15 m at Kopgalis; the width mostly ranges from 50–60 m to 90–100 m. It should be noted that around Pervalka the beach dune widens to 150 m, acquiring a two-humped shape. Throughout the spit coast, a blown sand plain overgrown with plants occurs behind the protective beach dune. Apart from eolian sedimentation, intensive blowout processes as a result of which ravines, pits, moulds and so on have been formed characterize the beach dune.

BOTTOM RELIEF AND SEDIMENTATION

The offshore areas of the continental coast and of the Kuršių Nerija spit differ in their geological and geomorphological structure. Glacial landforms formed of moraine (till) or coarse clastic material (washout till) prevail in the northern sector of the Lithuanian offshore (Figs. 1 and 6, profile 1–1'). The distribution of coarse clastic material (boulders, shingle, gravel) is mosaic in character. Sedimentation of sandy deposits currently takes place at depths ranging from 0 to 20–27 metres. The most intensive accumulation is generally in the nearshore zone, in up to 4–5 metres water depth. Mainly two, locally three sandbars are found there.

Sandy sediments form the nearshore part of the Kuršių Nerija spit: an accumulative relief is characteristic of this sector of Lithuanian coast (Gelumbauskaitė, 2003). The distribution of recent bottom sediments is strongly influenced by the N–S longitudinal offshore sediment drift. Two, or locally three sandbars are characteristic of the underwater slope (up to a depth of 8–9 metres) in the central part of the Kuršių Nerija spit, at Nida; their relative height reaches up to 4–6 metres (Fig. 6, profile 3–3'). In the northern part of the Kuršių Nerija spit the depth of formation of sandbars is reduced to 3–4 m. The sandbars become smaller but their number increases to 4–5 (Fig. 6, profile 2–2').

In the offshore area of the Lithuanian coast the composition of the sediment is quite diverse: from coarse clastic material, to sands of various grade, to silt. There are three main lithological facies: boulders with shingle and gravel, coarse and medium sand, and fine sand. The diameter of boulders is usually limited to 30–40 cm, though sometimes boulders up to 6 m in diameter are found. Their surface is often overgrown with colonies of Mytilus and Balanus. Fine sand prevails among the type of bottom sediments. In the wave set-up area to 4–10 m depth, the prevailing median sand diameter Md is between 0.25 and 0.16 mm. In the slope beyond the sandbar, sands become finer, with the Md decreasing to the 0.16–0.1 mm range or even less.

COASTAL DYNAMICS

Analysis of the field data collected in monitoring the coastal dynamics has revealed (Fig. 7) that in the period 1993–2003 the budget of continental coastal surface sediments was negative: the annual loss of sand was 48 000 m^3 on average (or 1.3 m^3 per linear metre). The balance of the Kuršių Nerija spit coastal surface sediments was positive, with the annual accumulated quantity of sand being around 34 000 or 0.7 m^3 per linear metre. So, the total annual sand balance of the Lithuanian coast was negative — around 13 000 m^3. The length of the accumulating sectors of the Lithuanian coast has decreased by a factor of 3.4 (from 36 to 10.6 km). The length of eroded and stable coastal sectors has increased 1.5 times (from 16 to 24.2 km and from 37.5 to 54.7 km respectively). Unfortunately, the total length of stable coast sectors has increased at the expense of accumulating sectors and not as a result of stabilization (Žilinskas and Jarmalavičius, 2003). The same situation is observed in the beach dune area (in 1994–2002): the positive annual balance in the Kuršių Nerija spit (more than 130 000 m^3) does not compensate for the losses of sediments in the continental beach

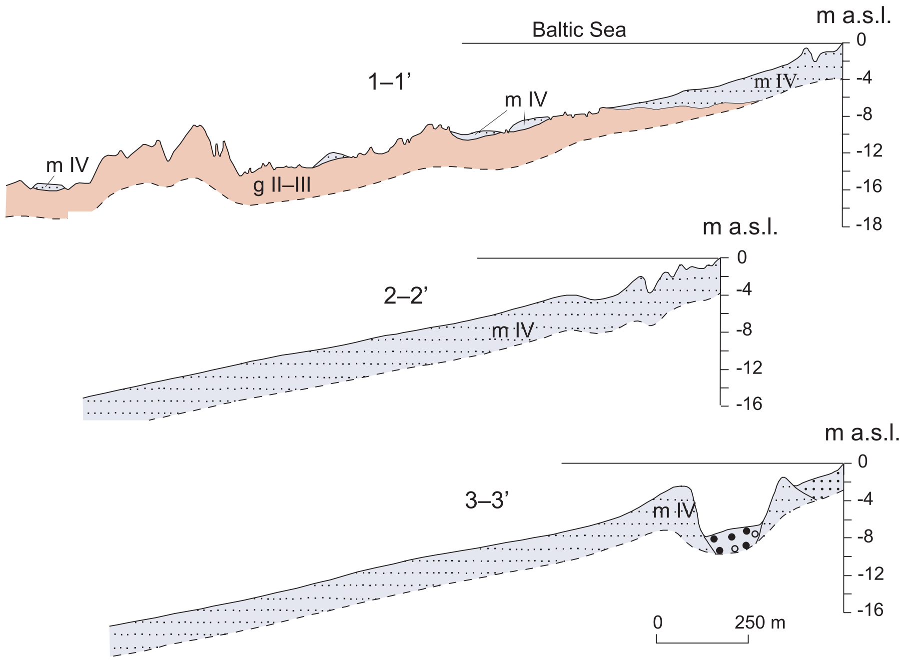

Fig. 6. Bottom sediments on the underwater slope close to Giruliai (morpholithological profile 1–1'), Smiltynė (profile 2–2') and Nida (profile 3–3')

For other explanations see Figures 2 and 3

formed 200 years ago. The map of anthropogenic load of the Lithuanian shore of the Baltic Sea shows the negative side of economic activity including harbour operations and, recreation infrastructure. The distribution of human influence is uneven: it is much lighter on the shore of the Kuršių Nerija spit than on the continental coast. Likewise, human impact is not evenly distributed along the continental coast. It is more intense around cities and large settlements, where it results from resort infrastructure. Furthermore, the human impact is related to major industrial objects (the Klaipėda seaport, pipelines of the Būtingė terminal) or former military sites (around Nemirseta and Giruliai). In the latter case, these are mainly ruins of various buildings and scattered remains of metal or concrete. On the shore of the Kuršių Nerija spit, traces of human impact are concentrated at Smiltynė and the four settlements comprising Neringa (resort infrastructure). The greater part of the shore is little affected by economic activities except for individual buildings or dumps left by the military border-guards of the former Soviet Union and shipwreck remains.

dune area and cliffs (around 415 000 m^3). As a result, every year the Lithuanian coast (the Kuršių Nerija spit and the continental sector) loses 285 000 m^3 of sand from the beach dune area, or 0.4 per linear metre on average (Jarmalavičius and Žilinskas, 2002; Jarmalavičius *et al.*, 2003).

HUMAN IMPACT

Today, the Lithuanian shore of the Baltic Sea cannot be called entirely natural. Human activities have been affecting it for around 300 years. As a result of anthropogenic activity a continuous protective beach dune along the Kuršių Nerija spit was

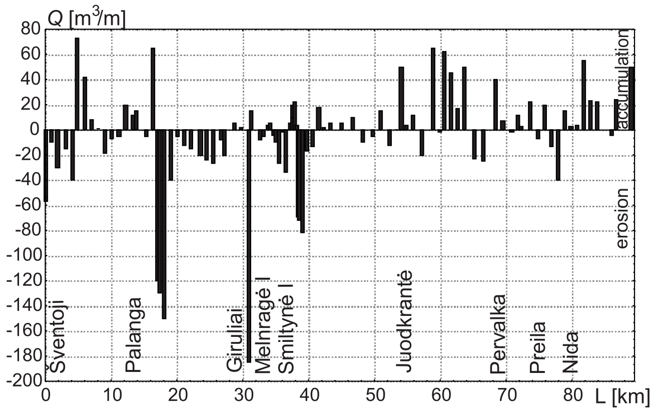

Fig. 7. Changes in coastal sediments (*Q*) in the period 1993–2003

The distance from the state border with Latvia is indicated on the x-axis; see the text for further explanations

Dredging of the Klaipėda harbour and its entrance channel up to 14 m depth has been a significant human impact affecting the system of natural lithodynamical processes of Lithuanian offshore zone. For a long time, all excavated deposits were dumped into the sea at a depth of approximately 45 metres, i.e. they cannot come back to the nearshore zone. Thus, the natural N–S longitudinal offshore sediment drift has been interrupted; this has been one of the most significant reasons for the deficit of sediments and increase in erosion along the northern, continental part of Lithuanian coast.

SIGNIFICANCE OF THE INVESTIGATIONS

The results of integrated investigations of the Lithuanian coast of the Baltic Sea enables answer to certain questions related to its geological structure and palaeogeography. Previously, there has been a lack of relevant data, e.g. concerning the geochronology of onshore and offshore deposits, age of marine terraces, mineralogical and geochemical compositions of the deposits and so on. These questions concern the formation of the shores of the Kuršių Nerija spit, the Klaipėda Strait, the area around the health resorts of Palanga and Šventoji. The data obtained in the course of these integrated investigations enables better definition of the coastal area and of its environmental status.

All the objects located in the atlas by means of GPS, ortophotographs and *GIS* software are related to the co-ordinate system, which increases the value of the investigations: there is a possibility for future repetition of these studies in order to determine coastal development trends. A dense network of morpholithological profiles and geological cross-sections forms a practically complete picture of the lithological composition of the upper part of the sedimentary succession. The morpholithological profile network has been made denser near harbours and other hydrotechnical settings. This allows assessment both of the anthropogenic effects upon the coast area and of the functionality of the installations.

Recently the Lithuanian shores are experiencing an acute deficit of sediment. This contributes to the destruction of shorelines and degradation of beaches. A comparison of repeated coastal profiles enables conclusions about the extent of coastal abrasion or accumulation processes. The results of our investigations contain information about the sand drift reserves both onshore and on the underwater slope, and also enables analysis of trends in the spatial distribution of sediments, thus facilitating the location of sand for artificial feeding of beaches. The data collected on bottom relief, sedimentological processes and coastal dynamics will be used for substantiation and development of the seashore monitoring system. The issue is becoming increasing important in the context of global warming and the associated rise in the sea level.

A detailed analysis of the human impact will be of use for the solution of coastal protection and coastal management problems. Information concerning the width and height of beaches and the form, condition and structure of the dune ridge or cliff enable revision of the morphodynamic and lithodynamic zonation of the coast, identifying coastal sections that are important to the marine and recreation industries and those that need to be protected. Eventually, the results of these integrated investigations of Lithuanian coast of the Baltic Sea, given in the Geological Atlas, is indispensable as regards the adoption of decisions taken at various administrative levels.

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