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Influence of sea bottom relief on coastal processes of the Southern Baltic

Elżbieta Zawadzka-Kahlau

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Sea bottom forms influence the hydrodynamic processes along the Polish coast and facilitate the generation of semi-stable macro- and meso-circulation systems in the coastal zone. Due to hydrodynamic factors, in conditions of a permanent system of forms in the outer and inner nearshore zone, a specific coastal system of erosion/accretion forms has developed along the coastline. The macroforms of the Southern Baltic seafloor, occurring at the lower boundary of wave influence, help to conserve the trend prevailing along certain stretches, in certain regions, bistructures, groups of bistructures and in the whole coastal system of the Southern Baltic coast. The many-year observations carried out along the Southern Baltic coast suggest that along many parts of the coast, erosion is permanent. One of the reasons for coastal zone changes is the geomorphological predisposition of the closer and further nearshore zone, inherited from the glacial and postglacial age. Investigations confirm that macro- and mesoscale forms on the seafloor play a basic role in the shaping of circulation systems. As a result of their long-, medium- and short-term influence, erosion / accretion bistructures of various scale are generated in the nearshore zone and on the shore. Changes in the thickness of the coastal zone's dynamic layer, determined by means of parameterization of the nearshore zone and based on seismoacoustic profiling, are also indicators of the erosion / accretion system of the coastal zone. Analysis of the obtained field data showed a distinct relationship between the systems of forms, the resources of the dynamic layer and the coastal abrasion / accretion systems in the region of the Southern Baltic coast.

Key words: coastal barriers, sandbars, morpho-dynamic, South Baltic coast

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Elżbieta Zawadzka-Kahlau. Department of Geomorphology and Quaternary Geology, Institute of Geography, University of Gdańsk, Dmowskiego 16A, 80-952 Gdańsk, Poland. E-mail: geoez@univ.gda.pl

INTRODUCTION

Morphological investigations of the Southern Baltic shores and nearshore zone vary with respect to the spatial scale in which morphological forms were studied. The most comprehensive analysis is provided by Rosa (1963) in his discussion of the development of the Polish coastline in the light of old morphological forms, and by the same author in his morphological analysis of the Southern Baltic seafloor (Rosa, 1967). The Holocene coastline, located at the foot of the Southern Baltic slope, determines the boundary of the occurrence of forms and remnants of previous coastlines (Fig. 1). Within the shallow nearshore zone, there are various types of seafloor profiles connected with the geological structure.

The relationship between the forms occurring on land and seafloor of the Southern Baltic is a fact observed also by other authors (Marsz, 1966; Rosa, 1968; Mojski, 1989; Uścinowicz, 2003). The area of northern Poland and the South Baltic region are characterised by a similarity of formations and form systems in the late glacial and at the beginning of the Holocene. Up to the Atlantic transgression, considerable areas of the bottom of the Southern Baltic were land with forms of a young glacial and subaeral relief (Mojski, 2000). The two areas were shaped by different relief-forming factors. The present coastal zone occupies a random place in the geological evolution (Mojski, 2000). However, the impact of relief-forming factors, exerted on lithologically diverse sediments, caused the development of different relief forms on the bottom and shore. The system of correlations of the influence of forms and sediments within units of various orders has been causing certain dynamic reactions on the shore.

The random distribution of abrasion and accretion forms occurring on the seafloor on each stage of the development of the Southern Baltic generated different shore reactions manifested in the development of abrasion / accretion systems. The above correlations established on the basis of the author's research (Zawadzka, 1999; Dubrawski, Zawadzka, 2006) and taking into consideration the results of the coastal zone monitoring (Dubrawski et al., 2008; Dubrawski, 2009), confirm to a large scale the defined thesis and are the subject of the article (Table 1).

RESEARCH TO DATE ON BOTTOM RELIEF OF SOUTH BALTIC COASTAL ZONE

Till and clay, resistant to marine erosion, result in convex surfaces while glacifluvial sand and gravel result in concave shapes (Subotowicz, 1989). The dynamics of bar forms depends on the phases of storm development and decline (Rudowski, 1986). The nearshore zone in regions with prevailing accretion is characterised by a stable dynamics and geometry of the bars (Pruszak, 1998). Analysis of the photo-interpretation map of the coastal zone along the Swinoujscie–Dzwirzyno stretch (Furmańczyk, Musielak, 1986) shows systems of bars, suggesting the presence of circulation cells of various orders. The spatial arrangement of forms of the shallow nearshore zone along the Polish coast shows continuous bars, breaks in the bars, and locally even a complete lack of bars. The characteristics of bars as an element indicating the volume of the dynamic layer and significantly influencing the degree of dissipation of wave energy in the coastal zone (Semrau, 1974; Zawadzka, 1998) allowed to evaluate the erosion / accretion systems in many regions along the Polish coast. Analysis of the transformation of the nearshore forms on profiles and in space allowed to calculate the balance of sediments for some spits sheltering coastal lakes and for near-port stretches (Zawadzka, 1996b). The influence of the development of nearshore forms was analysed for the Lake Jamno and Lake Kopan spits and other stretches of the Polish coast (Zawadzka, 1997). The observed processes of erosion were considered to be strongly related with crosshore transport along the steep, concave nearshore slope. This paper presents a description of forms of the inner and outer nearshore zone and attempts an evaluation of their influence on coastal processes, especially on the abrasion / accretion systems in the coastal zone.

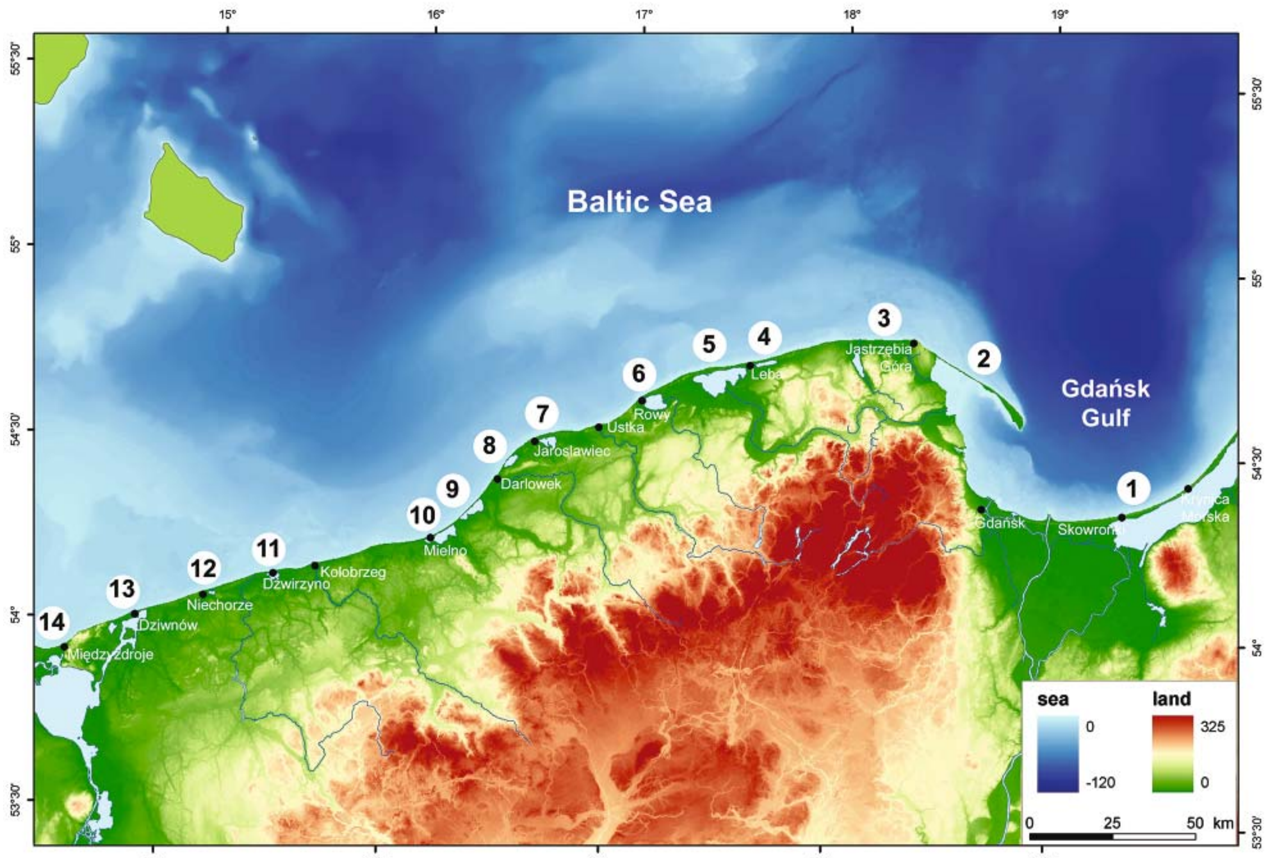

Fig.1. Location of spits and barriers and shoals along the South Baltic coast (Map according to PGI, Dept. in Gdańsk). *1* – Wislana, *2* – Hel, *3* – Karwieńska, *4* – Sarbsko, *5* – Łebsko, *6* – Gardno, *7* – Wicko, *8* – Kopań, *9* – Bukowo, *10* – Jamno, *11* – Resko, *12* – Liwia Łuża, *13* – Dziwnów, *14* – Brama Świny

1 pav. Pagrindinių barjerų išsidėstymas išilgai Pietų Baltijos kranto

Table. **Characteristics of the geomorphological system from the aspect of the development of erosion-accumulation systems of the southern Baltic (Dubrawski, Zawadzka, 2006)**

Lentelė. **Geomorfologinių sistemų charakteristika – pietinės Baltijos jūros akumuliacinės sistemos erozijos vystymosi pavyzdys (Dubrawski, Zawadzka, 2006)**

Area of Southern Baltic	Geomorphological system		Hydrodynamic system	Effects of inter-system relationships	Erosion-accumulation system	
	Basic features	Main forms			Basic features	Impact of sea level rise
Baltic slope (<15 m below sea level)	natural, random distribution of accumulation and erosion forms in the slope area, very slowly changing in time and space	Accumulation: shoals, flatlands, platforms, coastal banks, spits Erosion: ice margin valleys, troughs, flatlands, platforms, abrasion remnants	Waving and deep-water currents	Large-area transport of water masses and sediments, bottom transformation, formation of nearshore and coastal zone structure of marine origin	Large-area, spatial system of natural accumulation and erosion forms of the Baltic slope, stable correlations among forms, very slow exchange of sediments, impact on formation of erosion-accumulation systems of closer nearshore zone and shores	Not subject to changes under impact of sea level rise Possibility of accumulation changes of bottom by shore sediments, increase in hydrodynamic activity
Slope of closer nearshore zone (0–15 m below sea level)	Natural, anthropogenically changed in places, belt-shaped – longshore, fast changing forms, diverse dynamic layer, longshore and cross-shore sediment transport, semi-stable	Slope behind bar zone (deep water) Bar-trough zone Shore slope	Waving and currents of nearshore zone: longshore and landward and seaward Transformation, wave refraction and breaking, heavy dissipation, various circulation cells Wave dissipation, circulation cells Changes of water level	Formation of longshore geomorphological structure of nearshore zone, of sediments transport, large-scale erosion-accumulation system of nearshore zone, weakening and attenuation of impact of hydrodynamic factors on shores	Longshore system of three types of forms of varying cubature, stable spatial morpho- and lithodynamic structure, strong relationships among forms, sediments exchange between forms, direct relationship with shore and nearshore zone, possibility of parameterization of forms and systems of nearshore zone	Further development of erosion of forms system of nearshore zone, increase in sediments deficit and in resistance to effects of hydrodynamic factors, increase in erosion gradient especially on cross-shore, increase in hydrodynamic activity in nearshore zone, stronger inter-system relationships of nearshore zone and shore
Sea shore (≥0 m above sea level)	Natural, partially heavily anthropogenically transformed, belt-shaped – longshore, fast changing forms, landward and seaward transport and eolian transport of sediments	Beach Dune / cliff	Wave run-up Wave energy dissipation; Ultimate loss of wave energy	Formation of longshore geodynamic shore system, sediments transport, large-scale shore system	Longshore and cross-shore system of two forms of varying cubature, varying spatial structure, exchange and transport of sediments to nearshore zone and shift of forms landwards (erosion) or seawards (accumulation), close relationship with nearshore zone, possibility of parameterization of forms and systems of shores	Increase in rate and extent of erosion, rise of loss of shore sediments, bigger structural changes in erosion-accumulation systems, increase in anthropogenic transformation of shores

THE NEARSHORE COASTAL SYSTEM ALONG THE POLISH COAST

The development of coastal forms is connected with the period of the Litorine transgression which started in the Southern Baltic about 8000 BP and ended 5000–4500 BP. Sediment sequences depended on the accessible space in the basin in which accretion was able to occur depending on variable sediment supply (Coe, 2005). The accretion space, in the above understanding, depended also on eustatic and neotectonic changes which influenced relative changes in the sea level. The forming and changing space for sea sediment accretion was partially filled with sediments in areas of the bottom with relief predisposition forming a space for accretion. In case of a lack of appropriate pace, sediments are transported to other areas (Coe, 2005). Lowerings of the Pleistocene surface of the land part were filled with limnic and fluvio-limnic sediments.

The surface of postglacial formations was gradually reshaped in conditions of a rising sea level. Depending on the rate of sea level rise and the type of material, the structure of the outer and inner nearshore zone was differentiated, and this influences the run of coastal processes today (Fig. 2).

One of the indicators of that influence is the continuity of marine erosion which for 150 years has been forcing coastal defence measures along the same stretches of the coastline. Spit parts of the coast, which developed in the Holocene, retreat due to wind action, ‘longshore and crosshore (seaward) transport, and due to the process of deepening of the nearshore seafloor (Bird, 1996; Zawadzka, 1997).

The concave shape of the coastal profile in front of spits causes a cease of progradation, limitation of landward sediment migration, and occurrence of erosion and losses of the coast. As a rule, hydrotechnical coastal defence measures stop the retreat of the eroded coasts, but they also cause the further lowering of the beach (Bird, 1996). Similarly, the defence of cliff coasts results in the lowering of the nearshore seafloor along increasingly long stretches of the Southern Baltic coast, with the effect of decreasing the dissipation of wave energy (Zawadzka, 1996b). This is one of the factors that cause increased coastal erosion.

INFLUENCE OF FORMS IN THE OUTER NEARSHORE ZONE ON THE COASTAL PROCESSES ALONG THE POLISH COAST

The assessment concerns the influence of the following forms: coastal shoals, oblique and perpendicular troughs, remnants of accumulative coasts, accumulative flatlands, remnants of uplands of the ice margin zone, erosional flatlands and large forms with a “hilly” relief. The influence of the nearshore forms on the directions and intensity of coastal processes results from differences in the alimentation of the coastal zone with sandy sediments. Coastal shoals generate tombolo effects, thereby reducing wave energy (Marsz, 1966). Troughs, oblique or perpendicular to the coastline, strengthen erosion along the same stretches as is the case in the basal part of the Hel Peninsula. Depressions (troughs) in the outer nearshore zone result in a smaller dissipation of wave energy (Zawadzka, 1996a). Measurements of currents in the trough in the basal part of the peninsula showed that longshore transport may be deformed, which facilitates erosion of the shore. Depending on size, the distance from the shoreline, the depth of occurrence and geological structure, forms of land or marine origin exert a range of influences on the transformation of coastal forms. Relics of accumulative coasts and forms of land origin, such as remnants of ice margin uplands, ice margin valleys and river valleys, shape the generation of macro-circulation systems in the coastal zone. Their spatial location on the seafloor increases the predispositions for erosion or accretion of certain stretches of the coast. Relics of the accumulative coast are located in the western part of the Polish coast in the form of an accumulative flatland situated 12–14 m b. m. s. l. The flatland is built of fine sand and is subject to remodelling by wave- and wind-generated currents. An especially strong effect on the processes of accumulation may be exerted by the shallowest parts of the accumulative flatland in the southern part of the Odra Shoal, where the depth is 5–8 m. In the central part of the Koszalin Bay (region of Lake Jamno), at a depth of 15–30 m, there are erosion flats sloping slightly to NW, which may be the source of sediments supplied to spits located to the SE of the flats. Accumulative flats north of Lake Wicko facilitated the development of extensive dune fields to the south-east. Remnants of ice margin uplands, occurring in the Koszalin Bay (Sarbinowo–Dzwirzyno) within the abrasion / accretion flatlands, are large forms with a hilly relief. The hills are built of boulder till covered by sandy and sand / gravel deposits (Uscinowicz, 1989). Their occurrence in the 10–20 m deep zone allows a periodical shearing of their surface. No large accumulative forms are present on coasts neighbouring with the hilly forms on the seafloor, as can be seen along the stretch between Lake Bukowo and Darłówko.

The proximity of large convex forms, such as erosion remnants or dune field flatlands, resulted in the development of dune fields on the shore, such as Wicko, Lędowo, Model, Łebsko Dunes, the Hel Peninsula, the Vistula Spit. In the light of the theory that coastal dunes are supplied by undersea shoals, sea level rise – besides increasing the erosion of the shore – by reducing wave action on the shoals will reduce sediment supply from these sources. In the past, during periods of a stable mean sea level, in regions where land elevation occurs, the seafloor rose above the lower boundary of erosion by waves, resulting in longer periods of scouring of the bottom surface. This was one of the reasons for the development of the large dune fields in the Łeba elevation area (Marsz, 1966). In areas with tendencies of land lowering, the difference between the rising sea level results in a reduction of the area of eroded seafloor. At present, even in rising or stable areas, with the predominant sea level rise, accumulation on the shore becomes smaller and gradually turns into erosion. This is because of the less intensive action of waves on

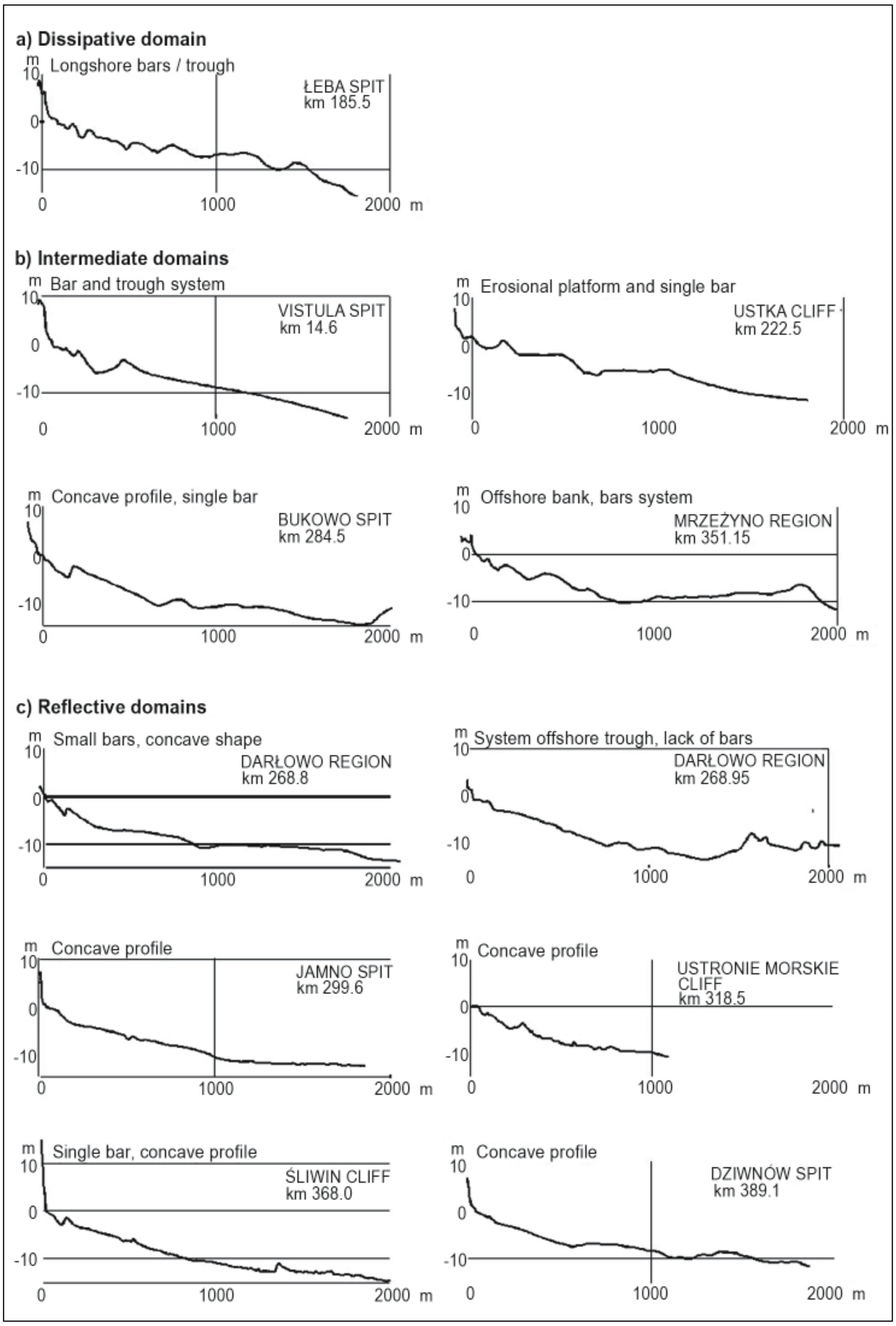

Fig. 2. Nearshore domains: *a* – dissipative, with two or more bars and gentle slope, *b* – intermediate of different type with erosion platform and single bar, offshore bank and single bar or erosion platform and single bar, *c* – reflective, mostly concave with single bars or without bars

2 pav. Priekrantės sritys: *a* – disipacinė (energiją išsklaidanti), *b* – tarpinė, *c* – energiją atspindinti)

the neighbouring seafloor and an increasing influence of the higher level of erosion on the coastal zone. The valley forms contacting the coastal zone cause the occurrence of regions with repeated erosional tendencies on the shore. The axis of the Kuźnica–Łeba ice margin valley ends 2–3 km in front of the coastline and forms a "guide" for wave and current energy during NW winds, facilitating erosion of the Hel Penisula in the Kuźnica area (Fig. 3).

Lower order forms are also located at the eroded basal part of the peninsula. Permanent abrasion trends in the Hel Peninsula region are caused by trough-like forms running at an angle of 25–27° to the coastline (Zawadzka, 1996a). These troughs are of glacifluvial origin in the eastern part (Tomczak, 1995) and in the western and central part are the remnants of the Yoldia Sea coastline (Musielak, 1989). The presence of trough forms results in a permanent erosion of the shore and sea bottom. The relative stability of the position of the erosion / accretion system is confirmed both by the cartometric analysis of the coastal changes (Zawadzka, 1994, 1996b), the relief of the offshore sea bottom (Gajewski et al., 2004) and by results of hydrodynamic modelling (Skaja, Szmytkiewicz, 1995). A similar role as that of forms along the Hel Peninsula is played by lower order trough forms such as river valleys present on the seafloor of the Western Coast (regions

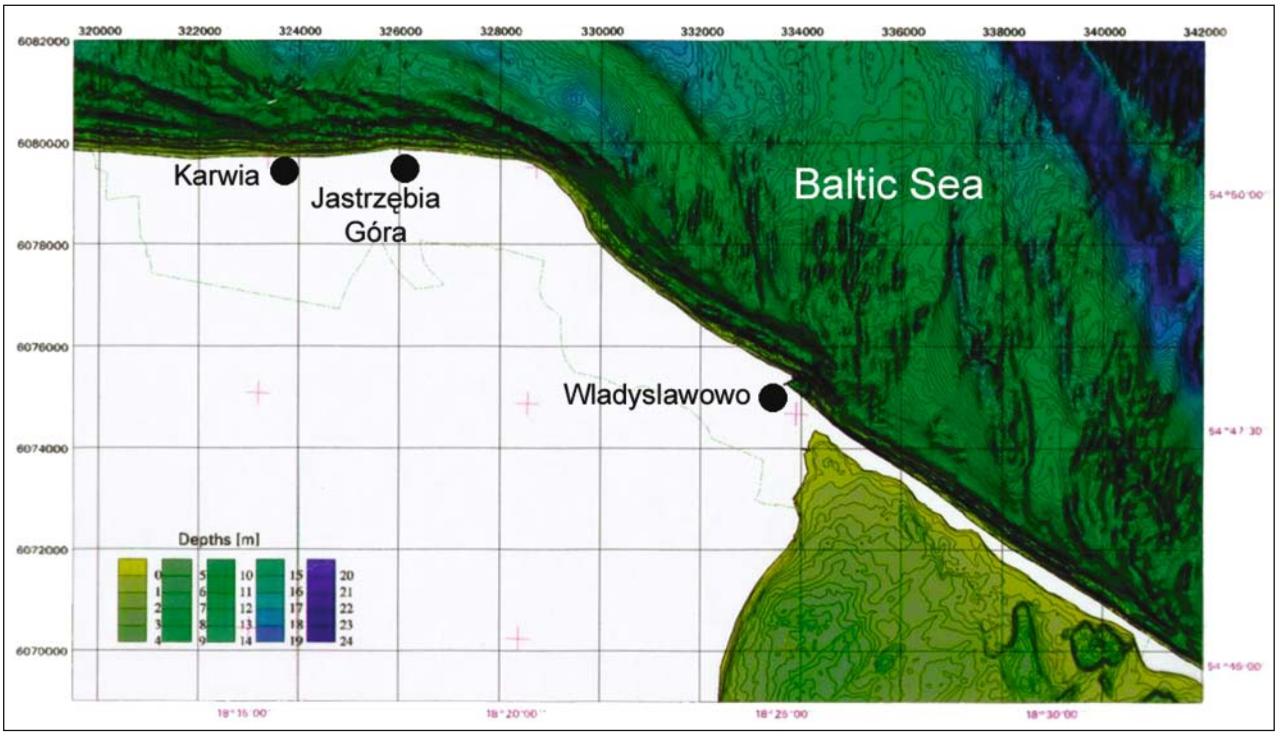

Fig. 3. Relief of sea bottom near Hel Peninsula, cliff Jastrzębia Góra and Karwia Spit-system of valley, ridges, runnels, bars and through different ranges, 2000. WGS 84, UTM 33 (Department of Operational Oceanography, Maritime Institute in Gdańsk, 2000)

3 pav. Jūros dugno reljefas ties Helės pusiasaliu, Jastrzębia Góra klifu ir Karwia slėnių tinklu

of Darlowko, Lake Bukowo, Lake Jamno, Lake Resko). The influence of the forms present in the outer nearshore zone on the progress of erosion / accretion processes is also observed along the Dziwnow Spit.

Morpholithodynamic processes along the Western coast are connected with the geological structure of the land and sea parts of the coastal zone. The convex forms of the Pleistocene seabed and eroded cliffs are sources of the material nourishing accumulative stretches. Abrasion platforms with a diversified surface in the nearest neighbourhood cause stabilisation or accretion of the shore. West of the cliff, at Trzęsacz, at a depth of 10–15 m, there is a 16 km^2 abrasion platform along 4 km of the coastline. Behind that platform, there is a 7.5 km long stretch of the accumulative coast; in its neighbourhood there is a 14 km stretch with medium rates of erosion. The erosional platform of the Lake Kopań and Jarosławiec region influences the development of an erosion / accretion system in its "shade", characterised by an eastward diminishing amplitude of erosion / accretion changes. Abrasion / accretion diminishing eastwards amplitude of erosion / accretion changes. Abrasion / accretion changes along the Łebsko Spit suggest a significant influence of the Czołpino Shoal (built of redeposited glacifluvial and river sands), especially when the wind from the NE and N sectors predominates. The Stilo Shoal causes a division of sediment transport directions to the west in its west part and to the east in the east part, resulting in diversified dynamics of erosion / accretion forms.

In the region of the Gulf of Gdansk, directions of sediment transport change several times as a result of changes in the exposure of the coast, due to the influence of sediments supplied by the Vistula River and of the Pleistocene platforms located in the eastern and western parts of the Gulf. Analysis of coastal changes during the last 100 years in the regions lying east and west of the Teysere–Tornquist line marking the position of the fault in the crystalline substratum shows the prevalence of eroded areas along the neotectonically lowering Western Coast (Zawadzka, 1996c).

CHARACTERISTICS OF THE INFLUENCE OF FORMS IN THE NEARSHORE ZONE ON COASTAL PROCESSES

Seabed structures occurring in the inner part of the nearshore zone may be divided into three basic groups, depending on their reaction to energy supply: dissipative, dissipative / reflecting (intermediate) and reflecting (Halcrow et al., 1991). An important indicator in the classification of crosshore profiles is the general slope of the nearshore bottom and the forms occurring on it.

The most typical system along the Polish coast is a gently sloping bottom with two bars (Lake Łebsko Spit). The dissipation of wave energy can be facilitated by an outer shoal located at the lower boundary of wave influence on the seafloor (region of Mrzeżyno). Even now, when coastal erosion is generally strengthening, coastal shoals periodically facilitate alimentation of beaches and dunes.

Reflecting structures are connected with large slopes of the nearshore bottom, no bars, and the presence of perpendicular or oblique outer troughs (regions of Darłowo, Lake Jamno, Ustronie, Śliwin) (Fig. 2). The largest differentiation of forms is connected with the intermediate structures. These structures include crosshore bars and interbar trough systems, rhythmical bars and sand bank complexes. Depending on the direction of predominant waves, their influence on the shore is of a very diverse character. In the case of wave direction perpendicular to the shore, bars running obliquely to the coast cause a greater energy dissipation in the case of oblique wave propagation.

On the basis of morphometric measurements of the 1990s of cross-shore profiles performed every 100 m, along 106 km of the coastline, the average width and depth of the occurrence of the shore slope, bar zone, active zone of seafloor and the distance of the 10 m isobath from the waterline were calculated (Fig. 4).

These parameters allow to determine the regional differentiation of the selected elements of nearshore morphology. The average width of the shore slope varies from 68 m at the Ustronie Morskie Cliff to 148 m west of the port at Wladysławowo. The regional variability of this parameter is to a large extent connected with the type of coast, the amount of littoral sediments in the nearshore zone and with the general influence of forms of the outer part of the nearshore zone. Regions with the narrowest coastal slope occur along cliff coasts, at Jastrzębia Góra and Ustronie Morskie, and along intensely eroded spits in the regions of Lake Jamno, Dziwnów and Mrzeżyno. In most cases, these regions have reflecting nearshore profiles. The widest bar zone on the Polish coast lies in front of the west part of the Vistula Spit and of the Lake Łebsko Spit (660 m) (Fig. 5a).

These two regions are characterised by the largest thickness of littoral deposits along the Polish coast. The smallest width of the bar zone occurs in the central part of the Koszalin Bay, in the Ustronie Morskie (Fig. 5e), Kołobrzeg (Fig. 5d) and Dźwirzyno (Fig. 5h) areas; they are characterised by a very thin cover of littoral sediments. Along these stretches, the foredune is underdeveloped and shows trends of abrasion. This confirms a relationship between the thickness of the bars and the stability of the coast. The volume of sand in the bars, which are an intermediate strip of the nearshore zone lying between the seaward boundary of the active part of the seafloor (which in Southern Baltic conditions lies at a depth of about 10 m) and the shore, depends on the grade of the coastal slope and on the geological structure of the outer part of the nearshore zone, including the presence of such forms as underwater accumulative slopes, remnants, ice margin moraine uplands.

On the west coast, which is subjected to a slow lowering motion, the littoral cover is much thinner than along the central and eastern parts which are under the influence of a slight rising motion. For this reason, among others, the thickness of sediments accumulated in the bars along the western part is much smaller. An additional factor is that the Holocene deposits lie quite close to the seafloor along many stretches where depressions of the Pleistocene surface occur. An example is the relationship between the continuity and sand resources of the bar forms and the general pattern of

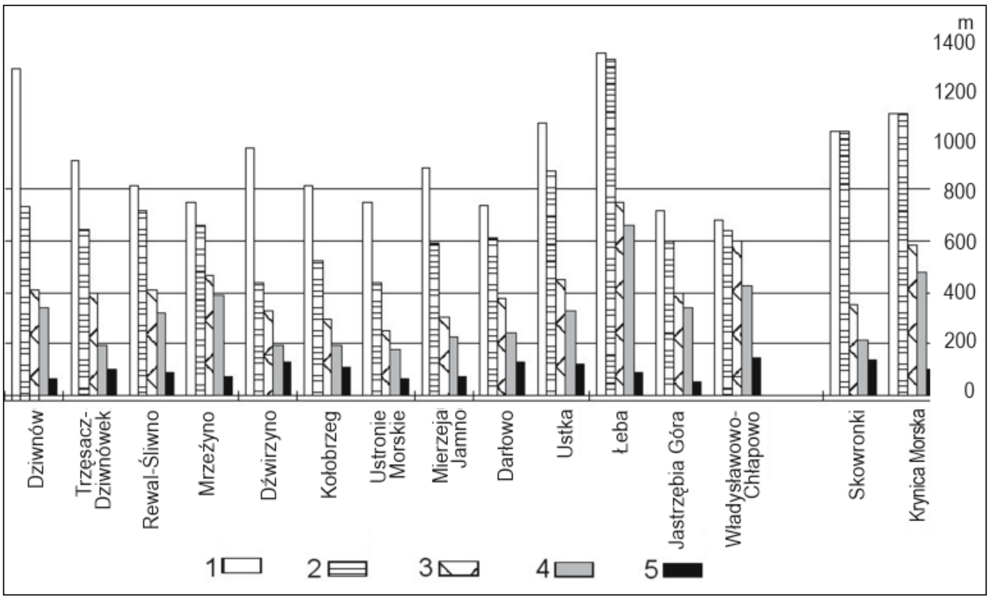

Fig. 4. Average parameters of inner and outer forms along dunes and cliffs of Southern Baltic coastal zone, measured in 1993. Location of settlements as in Fig. 1: *1* – distance of 10 m depth contour from waterline, *2* – active zone below the bar zone, *3* – seaward reach of bar zone, *4* – bar zone width, *5* – shore slope

4 pav. Pasirinktų elementų iš Pietų Baltijos kranto zonos vidutiniai parametrai (1993): *1* – atstumas nuo kranto linijos iki 10 m izobatos, *2* – aktyvi zona (sritis) už sėklių zonos, *3* – sėklių zonos išplitimas į jūrą, *4* – sėklių zonos plotis, *5* – povandeninis šlaitas

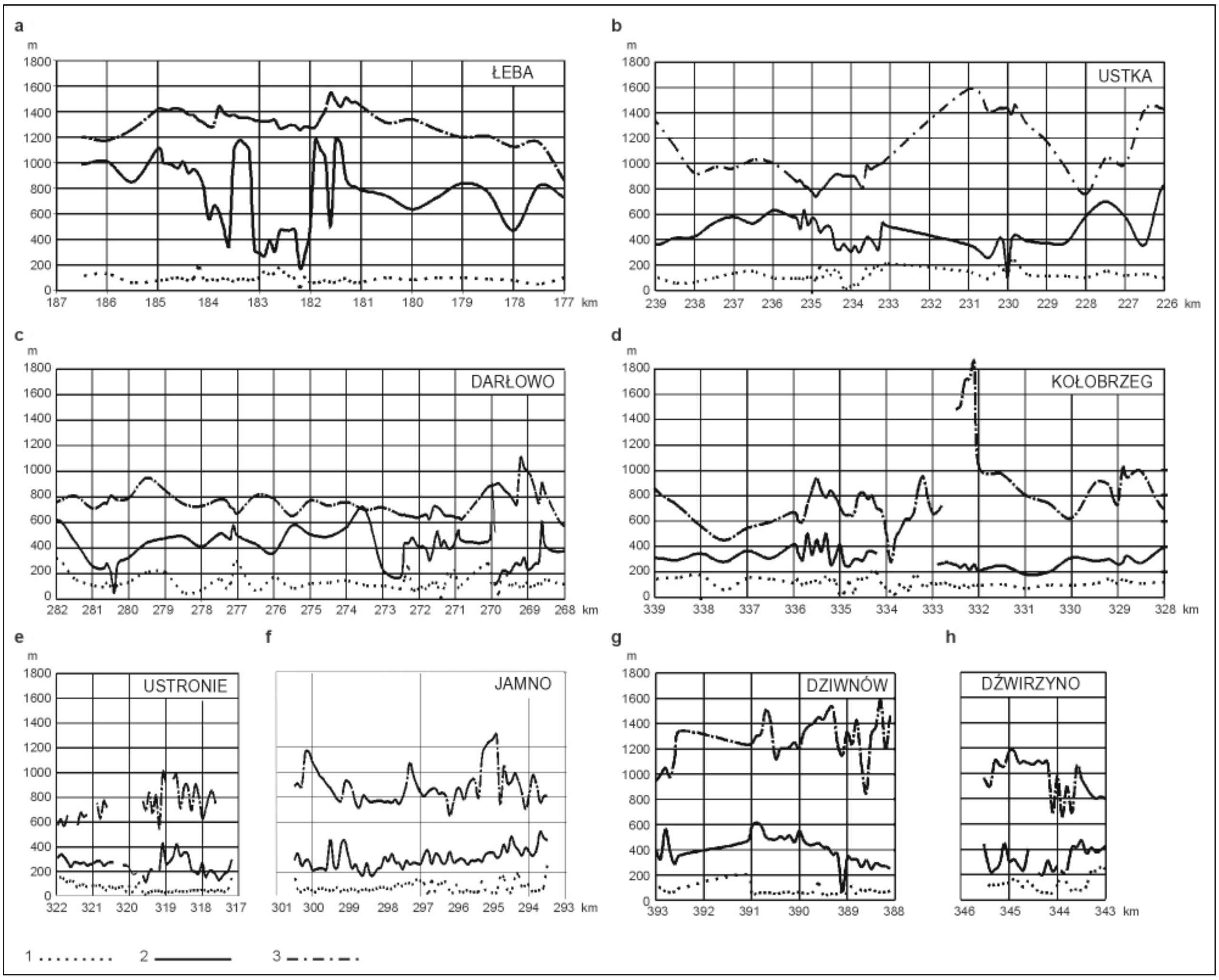

Fig. 5. Pattern of main morphological forms in different regions, 1993: *a* – Łeba, *b* – Ustka, *c* – Darłowo, *d* – Kołobrzeg, *e* – Ustronie Morskie, *f* – Jamno, *g* – Dziwnów, *h* – Dźwirzyno. *1* – shore slope, *2* – seaward reach of bar zone, *3* – distance of 10 m deep contour from waterline

5 pav. Pagrindinių morfologinių formų struktūra skirtinguose regionuose (1993): *a* – Łeba, *b* – Ustka, *c* – Darłowo, *d* – Kołobrzeg, *e* – Ustronie Morskie, *f* – Jamno, *g* – Dziwnów, *h* – Dźwirzyno. *1* – povandeninis šlaitas, *2* – sėklių zonos išplitimas į jūrą, *3* – atstumas nuo kranto linijos iki 10 m izobatos

the pre-Jamno Lake depression which slopes to the NW. This is a disadvantageous condition with respect to the stability of bars since the prevailing winds blow from the NW. At the same time, the dissipative potential of the inner near shore zone is significantly dependent on the influence of forms of the outer near shore, which shape the hydrodynamic system and the multi-directional sediment transport.

CHARACTERISTICS OF THE SYSTEMS OF FORMS OF THE NEARSHORE ZONE OF OPEN SEA IN 2004–2006

Another series of measurements performed in the system of coastal zone monitoring gave a basis for an evaluation of the system of morphological forms of the whole South Baltic shore (Dubrawski et al., 2008; Dubrawski, 2009), (Fig. 6 a–d). Analogously to the course of the pseudo-sinusoidal variability of the shoreline and foredune location (Zawadzka, 1999b), a system of basic morphological lines of the nearshore zone (shore slope, bar zone, active zone and 10 m isobath) were distinguished. The sections of various classes are delimited by the maximum distance of the location of this isobath and other morphological units from the shoreline.

Large-radius oscillations of the 10 m isobath are mainly conditioned by the location of remnants of the Pleistocene formations and mouth fans of coastal rivers. The location of these forms is random, yet their impact on the course of hydrodynamic processes is significant and influences shore processes by developing circulation cells of a higher order, within which cells and forms of lower orders are created. This hierarchical system of bottom forms, by their impact on the bar zone, shore slope and shore, enables forecasting shore changes in conditions of a definite hydrodynamic climate. In the shore stretches in whose nearshore zone vast indentations of the 10 m isobaths are developed, southwards abrasion tendencies prevail. Minimum widths of morphological

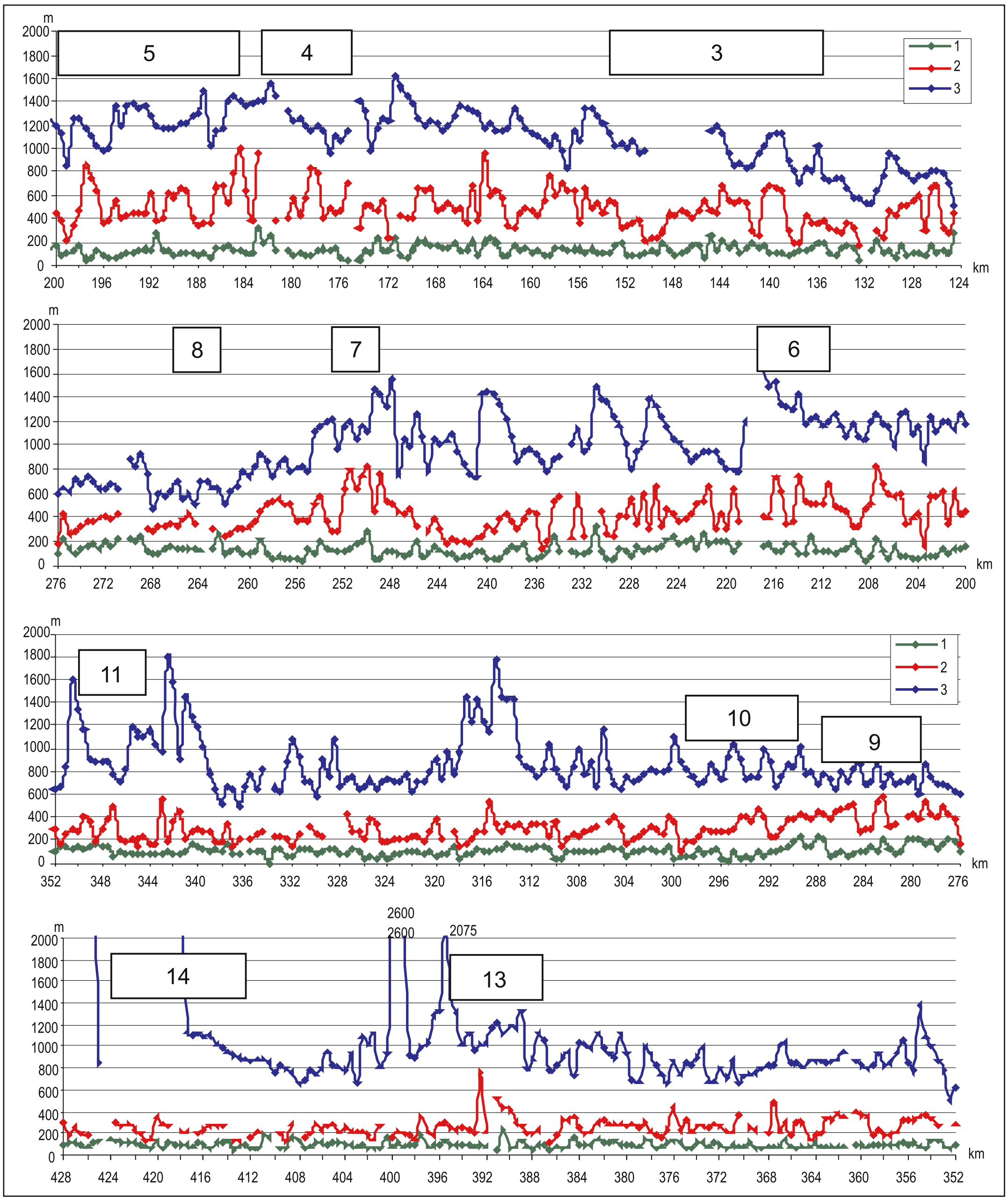

Fig. 6. Pattern of main morphological forms in open sea region from Władysławowo, 125 km to Świnoujście 428 km, in 2004–2006 (Dubrawski, 2009), with location of barriers. Location of barriers and settlements according to Fig.1: *1* – shore slope, *2* – seaward reach of bar zone, *3* – distance of 10 m deep contour from waterline

6 pav. Pagrindinių morfologinių formų struktūra atviros jūros regionuose 2004–2006 m. (Dubrawski, 2009): *1* – povandeninis šlaitas, *2* – sėklių zonos išplitimas į jūrą, *3* – atstumas nuo kranto linijos iki 10 m izobatos

zones within the 10 m isobath, including bar zones, also determine the abrasion predisposition of the shore.

On the Karwia Spit, there is a domination of concordance between the position of the 10 m isobath and the characteristics of the bar zone. In the areas of the closest location of the 10 m isobath, which occur on 138, 142, 148 km, there is also the narrowest bar system, locally discontinuous. The layout of the main forms of the nearshore zone indicates the possibility of an intensive impact of winds and waving from N and NW. West of the Karwia Spit, in the stretch from Białogóra to the spit of Lake Sarbsko, characterised by large resources of sandy sediments on the shore and nearshore zone, there is an angular shift of a narrowing in the course of the 10 m isobath with respect to the bar zone. In the cross-shore layout to the shoreline, at the less developed bar system, the widening of the bottom zone to the 10 m isobath dominates. This contributes to a relative litho-dynamic stability of this shore section and an exchange possibility of sediments within particular dynamic zones of the nearshore zone, depending on the hydrodynamic conditions. During waving perpendicular to the shoreline, waving energy dissipation occurs in deeper parts of the bottom, without causing major changes in the bar zone and shore. On the other hand, when the directions are oblique to the shore, energy which is not lost in bays in the course of the 10 m isobath is partially dissipated in the bar zone, with a weaker impact on the shore. In such a complex system of forms, there is a possibility of sediment transport within dynamic zones of the bottom, the migration of which determines the possibilities of the reconstruction of the shore and bottom zones of this morpho-dynamic unit.

The spit of Lake Sarbsko is exposed to a very strong impact of deep-water waving as a result of the abrasion of the bottom to a depth of 10 m, which caused disturbances in the development of the bar system. Shore abrasion occurs during waving from all directions. Longshore supply can occur mainly during winds from the eastern sector.

In the nearshore zone of the Łeba Spit, the rhythm of the course of the 10 m isobath and the bar zone does not coincide in a layout perpendicular to the shore. Areas of a narrowing bottom zone to the 10 m isobath are larger than narrowings of the bar zone adjacent to them. This causes a big supply of energy from directions oblique to the shoreline and considerable dynamic changes in the morphological zones of lower order. In sections of a smaller slope of the bottom to the depth of 10 m, similarly to the Białogóra lithodynamic unit, there is a stabilisation of the bar zone during waving from the N sector and its protection when the directions are oblique to the shore to the E or W of them. The western part of the Łeba Spit has a less favourable shore exposure with respect to winds from the NW sector, which is related to the formation of a large-radius, bay layout of the 10 m isobath, whose axis is 204 km from the shoreline. The abrasion tendencies of the shore reveal a simple correlation with the bottom relief in this area.

The nearshore zone west of the mouth of the Łupawa is characterised by a wavy shape of the course of the 10 m isobath, of a big amplitude from 600 to 800 m and a considerable extent of undersea "bays" (2.5–5 km). In many sections of the shore, the 10 m isobath occurs at a small distance (700–800 m) from the shoreline. This is a distance by about 200 m smaller than the mean distance for open sea shores and by about 400 m below the average for the Łeba Spit. In these areas, processes of shore abrasion in all the analysed periods repeatedly occur.

West of the cliff in Jarosławiec up to the cliff in Sarbinowo, there is an over 60 km long section of nearshore zone within which the 10 m isobath is situated 200–400 m closer to the shoreline with regard to the mean determined for the open sea. Another large-radius wave in the course of the 10 m isobath occurs between the abrasion platforms Sarbinowo, Dźwirzyno, Mrzeżyno, Dziwnów and Wolin. The length of these undersea bays is 10–35 km (Fig. 6). In each of the estimated areas, in the last century abrasion processes prevailed, and their rate has been growing in the last decades.

CHARACTERISTICS OF NEARSHORE ZONE WITHIN CHOSEN ABRADED AND ACCRETIVE SECTIONS

The division of the shore into abrasion and accretion sections of 1st and 2nd class was determined on the basis of abrasion bays and accretion protrusions during the period 1875–1978 (Zawadzka, 1999b). The set of bathymetric profiles from a long period of observation was assigned to an abrasion / accretion system on the shore, in order to show the influence of the shape of profiles of the closer and further nearshore zone on changes on the shore. The abrasion and accretion sections on the shore, distinguished on a 100-year scale, were referred to nearshore zone profiles within these areas. The described method reveals the basic, generalized features of the nearshore relief, conditioning a certain course of changes on the shore in varying hydrometeorological conditions.

Lake Łebsko Spit. The mean grade of the bottom of nearshore profiles in areas of abrasion on the shore to the depth of 10 m was 1 : 100. Below the bar zone, there is a gently sloping area of an abrasion platform formed in organogenic sediments of the pre-Łebsko (Zawadzka et al., 2008). The group of the three abrasion bays is characterized by clear differences in the shaping of the bar system below which there is an

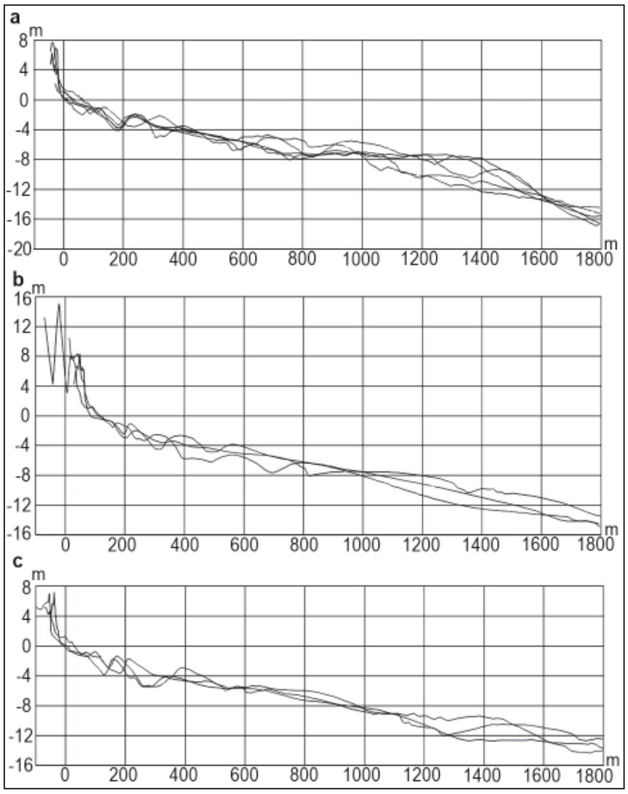

Fig. 7. Different types of nearshore profiles at the Łebsko Barrier: series of bathymetric profiles of 2003, performed every 500 m along the shoreline, situated within abrasion bays or accretion protrusions, shaped in the last century: *a* – accretion tendency on the coast, *b, c* – abrasion tendency on the coast

7 pav. Skirtingi priekrantės profilių tipai Lebsko nerijoje: *a* – kranto akumuliacijos tendencijos, *b, c* – kranto abrazijos tendencijos area of a relatively even bottom at a distance of about 1000–1100 m from the shoreline (Fig. 7 a–c). Accretion sections of the shore are related to a more gentle, on the average, slope of the bottom to a depth of 16 m. The longest stretches of even bottom below the bar zone, with preserved sediments of the former extent of Lake Łebsko, occur in the eastern part of the barrier. In the central part on the bottom, there are abrasion remnants, indicating an advancing abrasion of the bottom, contributing to the lowering of its altitude. The increase in the depth of the nearshore zone as a result of reduction of sediments related to the phase of lake reservoirs and sea sediments causes the occurrence of processes of shore abrasion in sections which were formerly accumulative. The course of the advancing process of bottom abrasion is documented by seismoacoustic research, sonar and underwater camera photography (Figs. 8–10). A comparison of forms of the nearshore zone of the eastern and western parts of the Łebsko barrier reveals on the average larger depths of the bottom of the group of profiles of the western part, indicating that the process of bottom abrasion advances westwards.

Lake Wicko Spit. The forms of the nearshore zone of the Lake Wicko spit in the section of 246.5–253.5 km show a great diversity. At similar distances from the shoreline, bottom depths show differences of 2–4 m. The bottom zone below the bars has locally the character of abrasion surface or a shape of vast underwater banks, indicating the impact of relief-forming processes depending on sediment resistance. Below the depth of 10 m, there are moraine hummocks of an uneven surface. In the eastern part of the spit, the bottom has a considerable grade, 1 : 70, within the shore slope carved in tills. In these sections of the shore, there is a high supply of waving energy without a possibility of its

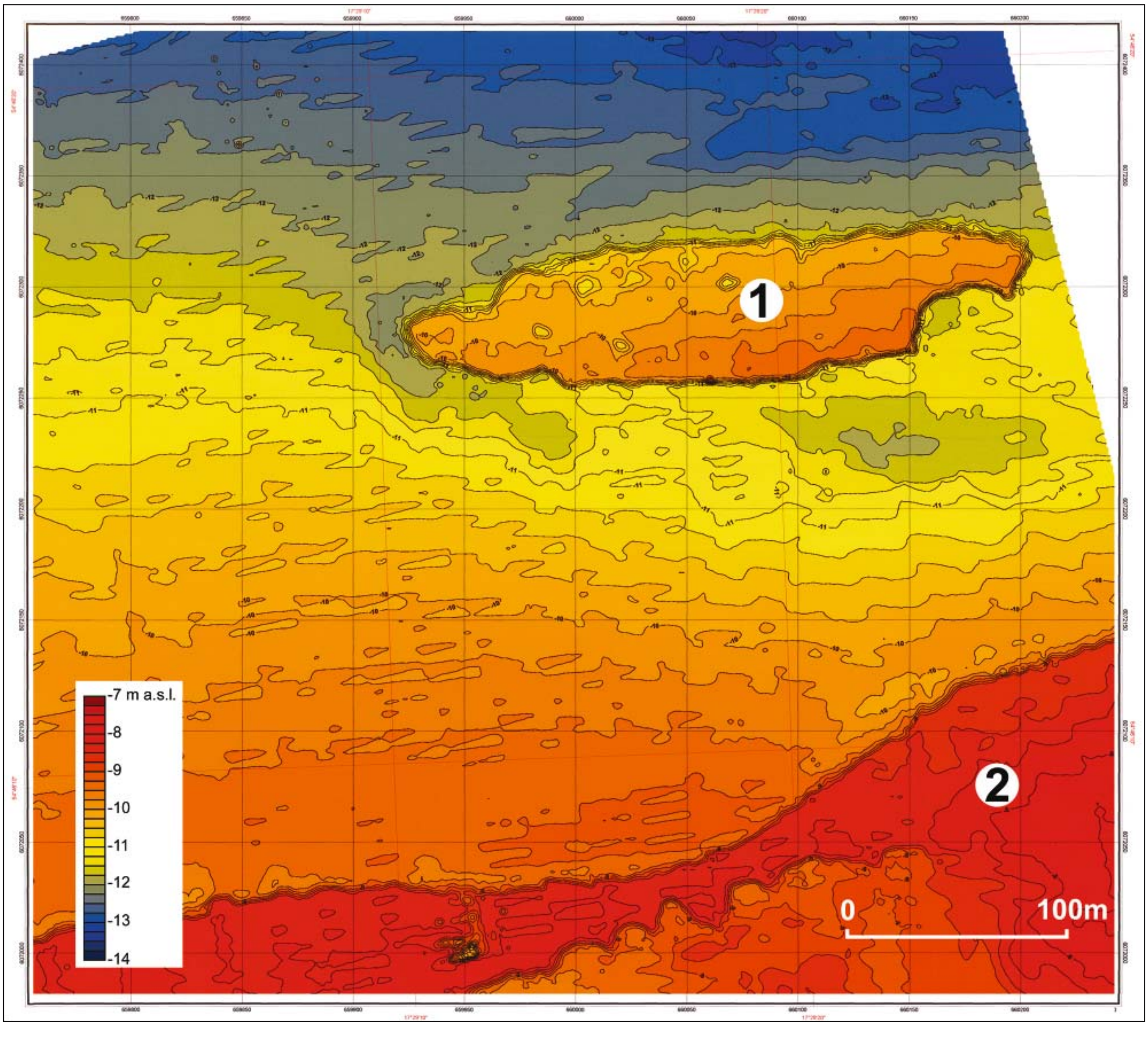

Fig. 8. Map of abraded sea bottom on the Łebsko Barrier. WGS 84, UTM 33 (Operational Oceanography Department, Maritime Institute in Gdańsk, 2003): *1* – abrasion remnant at a depth of 10–12 m, *2* – outer sand bar at a depth of 8–9 m
8 pav. Lebsko nerijos eroduoto jūros dugno žemėlapis: *1* – abrazinė forma, *2* – smėlio sekluma

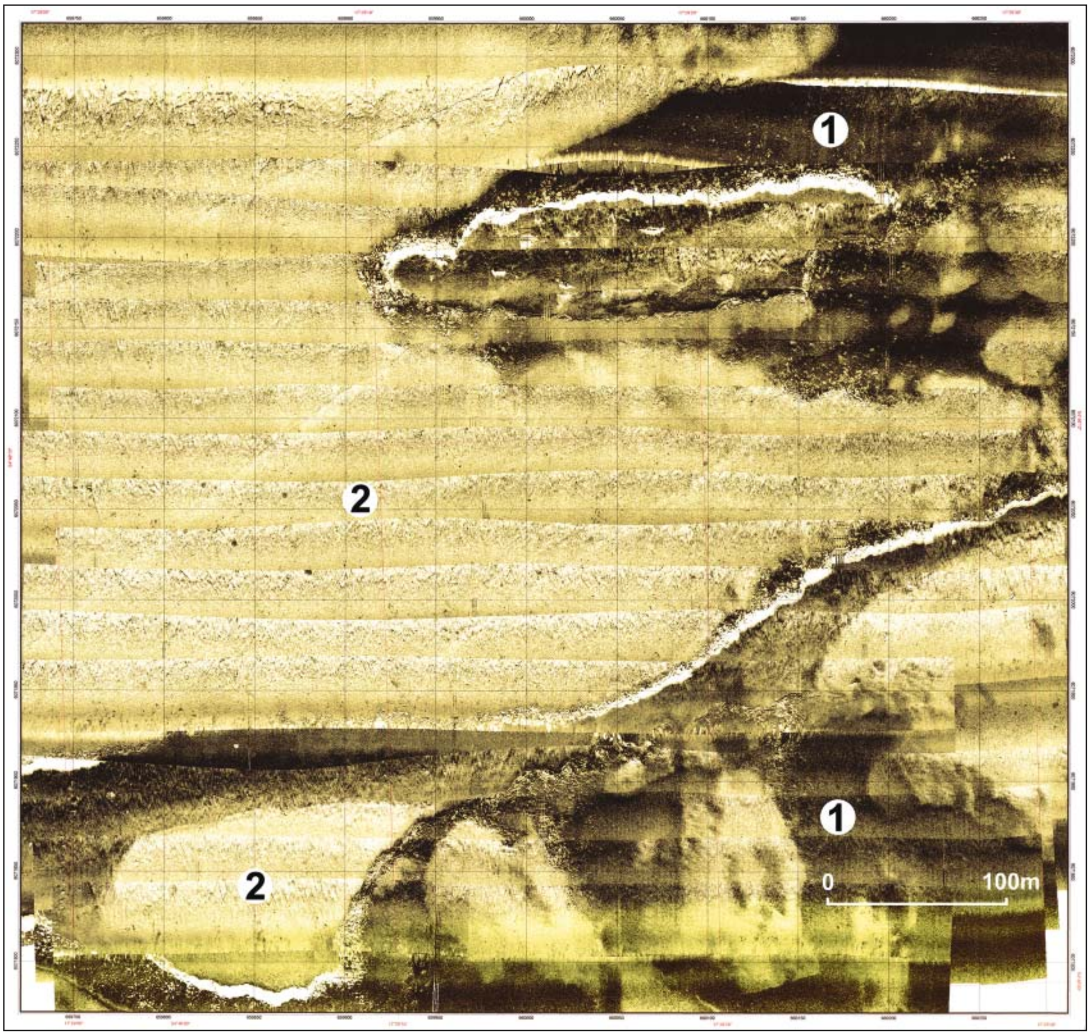

Fig. 9. Sonar map of abraded sea bottom in the Łebsko barrier WGS 84, UTM 33 (Operational Oceanography Department, Maritime Institute in Gdańsk, 2003): *1* – clayey gytja, *2* – marine sand

9 pav. Lebsko nerijos eroduoto jūros dugno sonarograma: *1* – molinga gitija, *2* – jūrinis smėlis

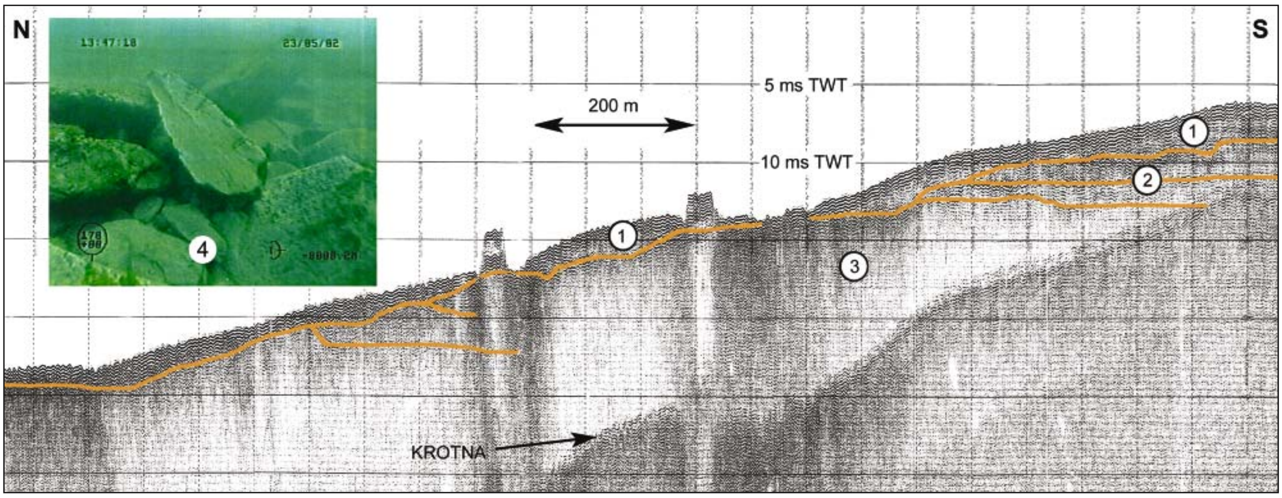

Fig. 10. Interpretation of sejsmoacoustic records of barrier Łebsko, 187 km.: *1* – marine sands, *2* – fluvial-limnic deposits (clayey gytja, silt and fine sands), *3* – substratum: fine-grained sands and silts of marginal lakes, *4* – abrasion of clayey gytia on the sea bottom, 10 m b. s. l. (underwater camera photography)

10 pav. Lebsko nerijos seismoakustinių duomenų interpretacija (187 km): *1* – smėlis, *2* – fliuvialinės-limninės nuogulos – molinga gitija, aleuritas ir smulkus smėlis, *3* – substratas: kraštinių ežerų smulkiagrūdis smėlis ir aleuritas, *4* – molingos gitijos abrazija jūros dugne, 10 m gylis (povandeninė nuotrauka) dissipation, resulting in an increased shore abrasion. The western part of the spit, bordering on a cliff in Jarosławiec, has an abrasion platform in the nearshore zone, below the bar zone. The impact of the platform on the development of abrasion / accretion systems on the shore varies. Between the bottom zone of untransformed forms of the post-glacial relief and the slope formed by wave processes, there is a lowering of the bottom to a depth of 14 m, running at an angle of 20–30° to the shoreline. Like in other shore sections, the trough generating the local circulation system in the nearshore zone intensifies the processes of shore abrasion during waving from NW and N.

Lake Kopań Spit. In the area Darłówek and on the spit of Lake Kopań, sedimemts of the Vistula glaciation occur 5–15 m below sea level (Zachowicz, 2003). Glacial sediments are covered by river sediments, lake-delta sediments, sandy sediments of the spit and organogenic sediments. Near Darłówek, glacial till is covered by a series of silty-clayey lake sediments. Over the silts, at a depth of 4.75 m, there is a layer of peat from 4515 ± 110 years BP. The lacustrine and organogenic series are covered by marine sediments building the spit of Lake Kopań (Krzymińska, Dobracki, 2005). The peats found at a depth of 5.5–5.8 m in their basal part are dated to 5415 ± 110 BP (Zachowicz, 2003). The accumulation of lacustrine sediments in the area of the present littoral zone of Lake Kopań occurred in a melt-out hollow, after melting of dead ice blocks within the zone of a ground moraine. The beginning of the sedimentation occurred in the preboreal period (Krzymińska, Dobracki, 2005). The area of Darłówek is an alluvial lowland of the mouth sections of the Wieprza and Grabowa. The eastern border of the Wieprza fan is delimited by the edge of the morainic plateau of Cisowo (Zachowicz, 2003). East of Darłówek, there is a lowland of Lake Kopań at an altitude of 0.1–0.4 m. Situated to the west, the lowland of Lake Bukowo was connected in the early Holocene with the lowering of Kopań. The lowland was filled with sediments of the delta fan of the Wieprza (Filonowicz, 1987). Under the sediments of the fan, there are sediments of a river-marshy plain. The spit of Lake Kopań, like many Southern Baltic spits, was formed on the base of Plaistocene sediments or on peats and lake gyttjas (Rosa, 1987). The section under discussion is divided into several distinct parts according to the exposure of the shoreline. The eastern part is related to an abrasion platform of glacial sediments. The area of the Wicie cliff in the central part of the spit of Lake Kopań and the area of the plateau of Cisowo, situated east of Darłówek, are made of glacial sands and tills as well as of stagnation formations. The shape of the nearshore zone, depending on the resistance of sediments to abrasion, has varying slopes which influence the course of lithodynamic processes in the nearhsore zone and on the shore (Figs. 10, 11).

Lake Jamno Spit. In the nearhsore zone of Lake Jamno, the bar zone is limited to the depth of 4–5 m. Below, there are very diverse forms of the bottom relief; their shape depends directly on the resistance of formations transformed in the

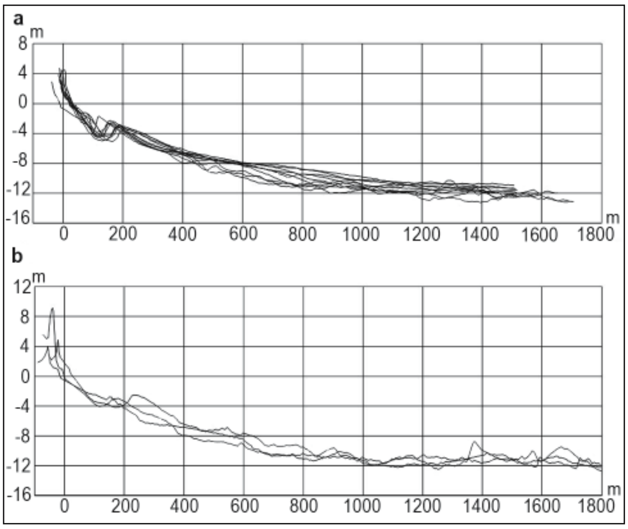

Fig. 11. Types of nearshore profiles at the Kopań barrier with abrasion tendency on the coast: series of bathymetric profiles measured in 2002, performed every 500 m along the shoreline, situated within abrasion bays, shaped in the last century: *a* – 267–269 km, *b* – 260.5–262.5 km

11 pav. Priekrantės profilių tipai ir kranto abrazijos tendencijos Kopano nerijoje (2002): *a* – 267–269 km, *b* – 260,5–262,5 km

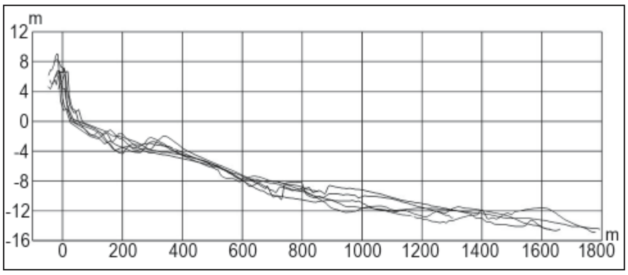

Fig. 12. Types of nearshore profiles at the Jamno barrier with abrasion tendency on the coast during last century. Series of bathymetric profiles performed in 2003, every 500 m along the shoreline, situated within an abrasion bay, shaped in the last century 286.5–291.5 km

12 pav. Priekrantės profilių tipai ir kranto abrazijos tendencijos Jamno nerijoje praėjusiame šimtmetyje (2003): *a* – 286,5–291,5 km

conditions of transgression. At a depth of 6–10 m, there are steps and abrasion remnants. The preserved forms, made of lacustrine gyttjas, provide evidence for the extent of the pre-Jamno of the Boreal period. At a depth of 12–15 m b. s. l. there is a weakly rebuilt surface of Pleistocene sediments covered by a thin layer of sea sediments or lacking them totally. The destruction of lake sediments lowers the altitude of the bottom and increases the profile slope; as a result, offshore transport increases, contributing to the intensification of shore abrasion processes (Fig. 12).

Dziwnów Spit. The Dziwnów Spit is made of a complex of sea and eolian sediments. The sediments of the spit include medium- and fine-grain sands with gravels and interbeddings of peat and alluvia (Zachowicz, 2003). In the base of the sediments of the spit, there is a transgressive series of the Littorina Sea and pre-transgressive series of the boreal reservoir represented by silts and clays. Outcrops of the upper level of boulder clays and limnoglacial silts occur 7–8 m b. s. l. (Zachowicz, 2003). The upper level of tills (5–10 m) is formed of sediments of the Vistula glaciation, and the lower level (20–30 m) comprises sediments of the Warta glaciation. Glacigenic sediments are represented by boulder clay laminated with small boulders. Above them, there are varve clays of chocolate colour of a small thickness and small number of varves. Sediments of the late glacial and early Holocene are represented by gravels, sands and silty sands, silts and locally calcareous gyttja. Sediments of freshwater limnic and river environments are 1–2 m thick. Diatom mesotrophic and eutrophic forms indicate the existence of a shallow lake or an old riverbed. The occurrence of oligotrophic forms indicates an environment of a river channel or an old riverbed. In areas of the domination of distrophic forms, a marshy environment occurred. Marshy-lake conditions occurred in the whole area of the Pomeranian Bay (Kramarska, Jurowska, 1991; Kramarska 1998). Holocene sea sediments are 0.1–0.6 m thick. The contact with freshwater sediments has an erosive character. A characteristic feature of the relief of the nearhore zone is the occurrence of convex forms made of glacigenic formations which have a steep seaward slope and gentle abrasion platform, covered by sea sediments of a small thickness. Limnic sediments were shaped as concave nearshore profiles. The groups of bottom forms, carved in sediments of various environments, run obliquely to the shoreline. This causes variable dynamic situations depending on the direction of wave propagation, resulting in the possibility of both accretion and abrasion. Troughs facilitate an intensified abrasion, and convex forms contribute to periodic accretion. The neighbourhood of the Wolin cliff as well as the possibility to supply sediments from sea bottom sources, from abraded deep boulder clays, causes a periodic supply of shoreward transport.

CONCLUSIONS

Semi-stable macro- and meso-circulation systems in the coastal zone of the South Baltic coast depend on the relief of the further and shallower nearshore zone. Due to hydrodynamic factors, in conditions of a permanent system of forms in the outer and inner nearshore zone, a specific coastal system of erosion / accretion forms has developed along the coastline. Coastal shoals with depths smaller than 20 m (the Odra Bank, Czołpino Bank and Stilo Bank) provide good conditions for the alimentation of the shore, change the hydrodynamic processes, and at the same time cause a divergence of sediment transport. Supply of sediments from scoured accretional and erosional platforms on the sea bottom provided favourable conditions for the development of extensive dune fields, where during the last 100 years accretional systems prevailed on the adjoining coasts. In these regions, oscillations of waterline position had large amplitudes typical of areas with high sand resources.

The remnants of the ice margin uplands in the Koszalin Bay and the hilly relief of the seafloor in the Lake Bukowo – Darłówek region were a poor resource of sediments, which did not allow the development of large accumulative forms. However, the presence of the remnants and the uneven seafloor weakens local erosion and limits its range at relatively small amplitudes of coastal changes.

Alimentation of coastal dunes by undersea shoals and banks, as well as sea level rise could limit the action of waves on the convex forms of the seafloor – the forms which are an important source of sediments. This will increase the risk of coastal abrasion since the so-called dynamic layer will have less sand. The general trend of a large group of systems located in neotectonically lowering areas west of the Teyserre–Tornquist line show small rates of abrasion and in rising areas even some accretion. Disappearance of 2–4 km long accretive stretches and the strengthening abrasion of the dune foot reflect in part the decrease of sediment supply from sources in the nearshore zone, caused by the sea level rise.

Valley forms result in permanent abrasion trends on the coast. The Kuźnica-Łeba ice margin valley causes repeating processes in the central part of the Hel Peninsula. Lower order valley forms present in the basal part of the Hel Peninsula and in the regions of Darłówko, Lake Bukowo, Lake Jamno and Lake Resko facilitate the generation of permanent abrasion / accretion bi-structures. On the other hand, abrasion platforms in front of cliffs can, during some periods, cause stabilisation or accretion on the shore. The presence of an abrasion platform is reflected by the generation of a large abrasion / accretion bistructure. Abrasion platforms related to cliffs adjoining dune coasts can influence the development of both accretional and abrasional systems, depending, on the predominant direction of wave propagation and on the difference in the rates of abrasion of both types of coast. Groups of bistructures along the western coast are examples of such a run of lithodynamic processes.

Crosshore profiles in various morphological units, such as spits of coastal lakes, cliff coasts, form the basis for distinguishing coastal structures which, in different ways, influence energy dissipation and lithodynamic processes in the coastal zone. The least advantageous conditions for the appearance of shoreward sediment transport, which could reconstruct the coastal forms, are provided by profiles with slopes larger than 1 : 50 to 1 : 60. Intermediate profiles, with relatively gentle slopes of the nearshore zone and with a large volume of the dynamic layer, cause a gradual dissipation of wave energy on the consecutive bars and during a storm decay provide conditions for the restoration of shore forms as a result of shoreward sediment transport. In the group of intermediate profiles, presence of an inner shoal (bank) with depths smaller than the lower limit of wave influence on the seafloor, can positively affect accretion on the beach. If the inner shoal is located at a depth of 5–8 m, during some periods and independently of longshore sediment transport it can provide sand for the beach and dunes and also cause sanding up of port channels (e. g., the regions of Rowy and Mrzeżyno). Dissipative profiles show a tendency to accumulate sand across the whole coastal zone due to the very gentle nearshore slope and the large volumes of sand collected in the bars, shore slope and shore terrace. In the nearshore zone, there are both convex profiles in the substratum of which cohesive deposits more resistant to scouring occur, and concave profiles the maternal layer of which is formed by peat or sand / gravel Pleistocene deposits. Gyttia results in distinct underwater sills. When a concave profile is formed, the shore is less supplied by the shoreward sediment transport, and during storms, the material from the shore is more easily transported seawards.

In regions of the Polish coast with a shallow maternal bed, small thickness of littoral deposits and large slopes of the nearshore zone, like e. g. along the Lake Kopań Spit, in the present phase, forms on the shore have been destroyed. Along dune coasts with a well developed littoral cover in the nearshore zone, sand reserves accumulated during the Holocene (e. g. Lake Łebsko Spit, Vistula Spit) form a protective layer in extreme storm situations and facilitate the natural nourishment of the shore. The decrease of the volumes of sand in the bars, breaks in the bars, lowering of their crest or complete disappearance of the bars are connected with a strong abrasion of the shore. A clear connection between the lack of the outer bar and abrasion on the shore can be seen on the example of the abrasion bays east of Darłowo and Łeba. Spatial analysis of the number of bars along the Polish coastline shows that abrasion is more intensive along stretches with one bar than with two bars. As a rule, the transition from a 2-bar to 1-bar system is connected with the development of abrasional bays on the shore, especially if this is accompanied by a generally large grade of the shore.

The advancing abrasion of organogenic sediments in the nearshore zone influences the increase in the grade and lowering of the altitude of the bottom in the majority of spits of coastal lakes. This process is one of the main causes of shore abrasion.

The sea level rise during storms reduces the dissipative function of the nearshore zone since a smaller surface of the seafloor comes under wave action. The predicted accelerated sea level rise will result in a reduced dissipative action of the nearshore zone and in a smaller shoreward transport of sediments from the coastal banks. As a result, coastal abrasion will be stronger than in periods of transgression.

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Elżbieta Zawadzka-Kahlau

JŪROS DUGNO RELJEFO POVEIKIS KRANTŲ PROCESAMS PIETŲ BALTIJOJE

Santrauka

Pietų Baltijos kranto morfologijai holocene turėjo įtakos povandeniniame šlaite esančios dugno reljefo formos. Krante bei priekrantėje nuo 0 iki 15 m ir giliau buvo tiriamos mezo- ir makro- reljefo formos. Nustatyta erdvinė dugno sandara priekrantės ruože tarp 10 m izobatos ir sėklių zonos, taip pat sėklių zonoje. Atliktas jūros dugno morfologinis tipizavimas atsižvelgiant į dugno poveikį bangavimui, o bangų – krantui.

Remiantis XX a. dešimtojo dešimtmečio ir 2004–2006 m. reljefo formų kaitos monitoringu, pateikiama Pietų Baltijos priekrantės morfologinių formų tipologija.

Lebos nerijos tyrimų duomenimis, dugno organinių nuogulų sluoksnio abrazija yra viena iš priežasčių, lemiančių intensyvėjantį Pietų Baltijos nerijų nykimą.

Эльжбета Завадска-Кахлау

ВЛИЯНИЕ РЕЛЬЕФА МОРСКОГО ДНА НА БЕРЕГОВЫЕ ПРОЦЕССЫ В ЮЖНОЙ ЧАСТИ БАЛТИЙСКОГО МОРЯ

Резюме

В южной части Балтийского моря в голоцене большое влияние на бероговую морфологию оказывали подводные формы рельефа дна. Мезо- и микроформы рельефа изучались от 0 до 15 м и глубже на берегу и прибрежной зоне. Определено пространственное строение дна прибрежья между изобатой 10 м внутри и возле мели. Осуществлена морфологическая типизация морского дна с учетом воздействия волн на берег.

Также представлена типология морфологических форм в прибрежье южной части Балтийского моря. Установлено, что абразия органогенных отложений явилась одной из причин уничтожения южно-балтийских лагун.