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Solid rocks on the nearshore seabed – the distribution and potential impact on coastal processes in the Kołobrzeg region, the Southern Baltic

by

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Abstract

The Southern Baltic seabed is mainly composed of marine sediments situated on glacial and fluvioglacial deposits. In the Kołobrzeg region, however, solid rocks are located at the shallow subbottom. In order to determine the exact distribution of the rocks, some analyses of sonar images, underwater photos, sediment samples, seismoacoustic profiles and bathymetric data have been performed. The outcrops of Jurassic sandstones and mudstones have been documented. The geological structure of the area is presented, while the fact that the present seafloor relief is determined by the shallow uneven top surface of the Jurassic rocks is emphasized. The seabed has been classified as rock platform-constrained. The seafloor is a sediment-poor abrasion platform, within which marine sandy sediments are transported, mainly toward offshore, on the firm, stiff or hard surface of glacial deposits and Jurassic solid rocks. This results in a lack of material for the reconstruction of the beach after storms. Many of the commonly used methods for studying the condition and changes of the coast cannot be used in this type of terrain due to the presence of a thin and discontinuous dynamic layer lying on the erosion-resistant rocks of the geomorphologically complex seafloor.

Key words: seafloor relief and geological structure, Jurassic sandstone and mudstone outcrops, dynamic layer, side-scan sonar, ROV TV, sub-bottom profiling, Polish coast

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Introduction

Previous studies of the geological structure of the seabed in the western part of the Southern Baltic indicate the location of Triassic, Jurassic and Cretaceous rocks just under the Quaternary deposits (Mojski 1995; Kramarska et al. 1999; Uścinowicz 2014). The top surface of the Mesozoic rocks is uneven and many tectonic faults occur there. It is mostly situated between 50 and 60 m b.s.l. within the Polish coast, while its shallowest distribution was observed in the Kołobrzeg region (Kramarska et al. 1999), where the top of the Late Jurassic rocks lied locally even shallower than 40 m b.s.l. (Dobracki & Przezdziecki 2007; Kramarska et al. 1999). On the basis of these data, it was hypothesized that solid rocks are located just under the seabed surface. This feature of the geological structure has not been observed anywhere else in the Southern Baltic coastal zone.

The study area is the nearshore seabed located to the east of Kołobrzeg. The site was selected considering rich survey data sets collected by the Department of Operational Oceanography of the Maritime Institute in Gdańsk as well as the results of previous studies related to the region (Dobracki & Przezdziecki 2007; Rudowski et al. 2011; Zawadzka 2005).

The aim of the study was to recognize and provide documentation for the distribution of solid rocks on the nearshore seabed surface and at the shallow subbottom. The impact of this type of geological conditions on the coastal processes is discussed.

Study site

The study area is the nearshore seabed lying at the depth of up to 12 meters. It is located between 328 and 331 km of the Polish shoreline (Fig. 1), according to the mileage (expressed in kilometers) of the Maritime Offices in Poland. It is situated to the east of the Port of Kołobrzeg, between the beaches of Kołobrzeg and Podczele.

Only one, mostly of natural-origin, low sandy foredune occurs along the shoreline. Its abrasion is a serious problem for the people, hence the efforts to prevent and respond to abrasion have been undertaken in this section of the shore since 1887 (Marcinkowski et al. 2008), though without much success. In view of the current coastal protection methods and the onshore land use, the shore section can be divided into two parts.

In the first part (328.0-330.3 km), the width of the beach ranges from a few to several tens of meters and the height is below 1 m a.s.l. in the most. The shore is protected by groynes (up to 100 m long), situated 80 or 100 m apart from each other. A 50 m long pier is located at 328.67 km. The longshore dune is on average 20-30 m wide and 4.5 m a.s.l. high. The dune is protected by a riprap (rock armor) in the western part of this section. The inland area is a peatland called Solne Bagno, situated on average at 1.5 m a.s.l. Despite the use of the coastal protection system (groynes, riprap), the shore still erodes, which is reflected in, inter alia, the wave-cut seaward slope of the dune.

In the second part (330.3-331.0 km), many coastal protection methods are applied (Marcinkowski et al. 2008; Łabuz 2012). The beach is artificially nourished to the width of about 70-80 m. Submerged breakwaters (built in the period of 2010-2012) are located 40-60 m from the waterline and their top is at 0.7 m b.s.l. The coast is also protected by groynes (60 m intervals) and a seawall including tetrapods situated at the dune base. An 80 m long pier is located at 330.3 km. The dune is on average 4 m a.s.l. high and up to 6 m a.s.l. in the eastern segment of this part. However, the dune does not occur within the segment of 330.85-330.65 km where the beach directly abuts on hotel grounds situated at 2.5-3.0 m a.s.l. The hotel buildings are located there even less than 40 m from the beach.

The surface of the inland area adjacent to the study site is composed mainly of the Holocene peat and silt. In addition, the adjacent region is composed of the Young Quaternary glacial and fluvioglacial deposits (till, sand with mud) (Dobracka 1987; 1988). The thinnest layer of the Quaternary deposits in the Kołobrzeg region occurs between 328 and 331 km of the Polish shoreline (Dobracka 1987, 1988), where the top surface of the Jurassic rocks is located at various depths, mainly about 40-45 m b.s.l., however, it was drilled at a depth of 34.5 m b.s.l. in the borehole Kołobrzeg 19N (CBDG no. 884171) (Dowgiałło & Szymańska 1966). The above-mentioned data indicated tectonic deformations and the erosive nature of the top surface of the Jurassic rocks. Consequently, it can be presumed that the distribution of the Jurassic rocks is visible both in the relief and in the geological structure of the nearshore seabed in this region (Dobracki & Przezdziecki 2007; Rudowski et al. 2011).

Materials and methods

The study is based on the data collected in the course of various research carried out by the Department of Operational Oceanography of the Maritime Institute in Gdańsk. The fieldwork was performed aboard the research vessel IMOR and the

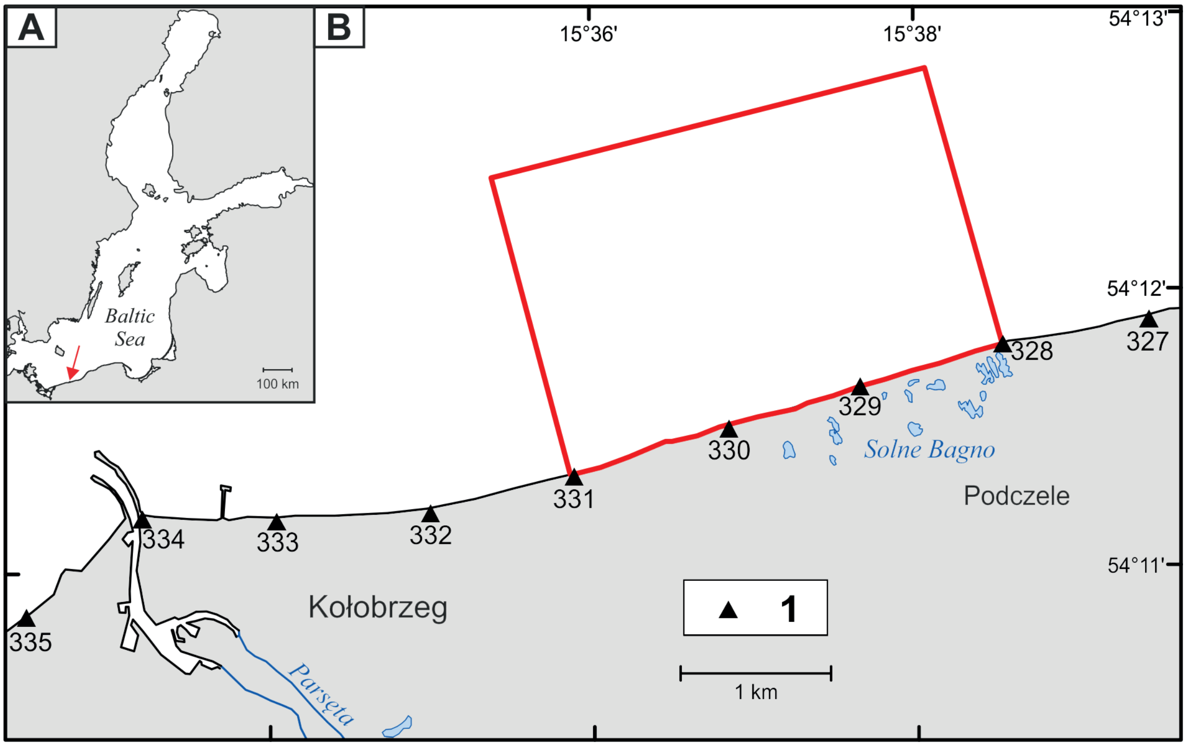

Figure 1

Location of the study area: A – marked by the red arrow, B – sketch by red lines; 1 – mileage (expressed in kilometers) of the Polish shoreline

hydrographic cutter IMOROS in 2006-2007 (Gajewski et al. 2007). The precise positioning was provided by DGPS (AgGPS 132 by Trimble) with the satellite navigation (OMNI STAR), as well as the navigation system (Hydro by Trimble).

First and foremost, non-invasive methods were used to recognize the surface and the geological structure of the nearshore seabed. These methods were complemented by classical analysis of core and grab samples of sediments, which were collected from the sea bottom and the onshore.

A bathymetric survey was carried out using a multibeam echosounder (Seabat 9001). On the basis of the obtained results, a detailed bathymetric map was drawn. In this way, the full spatial image of the seafloor relief was achieved.

The pictures of the seabed surface were performed using a side-scan sonar (Edge Tech DF 1000). Some objects – big stones, boulder areas, hard rock outcrops and anthropogenic objects (ropes, tires, etc.) lying on the seabed surface – were identified. Some of them were selected for further analysis by a remotely operated underwater vehicle equipped with a video camera (ROV TV, SeaEye 600DT).

Fifty six cores (up to 3 m long) were sampled (Fig. 2) using a vibrocorer VKG-4. Forty eight surface sediment samples were collected by a Van Veen grab sampler. Moreover, thirty two sediment samples were collected from various parts of the beach and dunes. Each sample of sediment was examined macroscopically and described.

Thirteen seismoacoustic cross-shore profiles were performed (Fig. 2) using the sub-bottom profiler OreTech 3010s at 3.5 kHz. The resolution of the obtained records is 20-30 cm, while the seabed penetration is 5 m. Wobbling of the vessel was eliminated by the active heave compensation (TSS 320B). Measurement data were collected using the CODA DA 200 system. Seismoacoustic profiles were interpreted considering the results of the sediment analysis, the products of the ROV TV inspection as well as the sonar images and the bathymetric map. The interpretation of seismoacoustic profiles was also based on the knowledge of the method (e.g. Rudowski & Gajewski 1998; Rudowski & Rucińska–Zjadacz 2010; Stoker et al. 1997) and the study area (Dobracka 1987, 1988; Dobracki & Przezdziecki 2007; Dowgiałło & Szymańska 1966; Mojski 1995; Rudowski et al. 2011; Uścinowicz 1991; Zawadzka 2005).

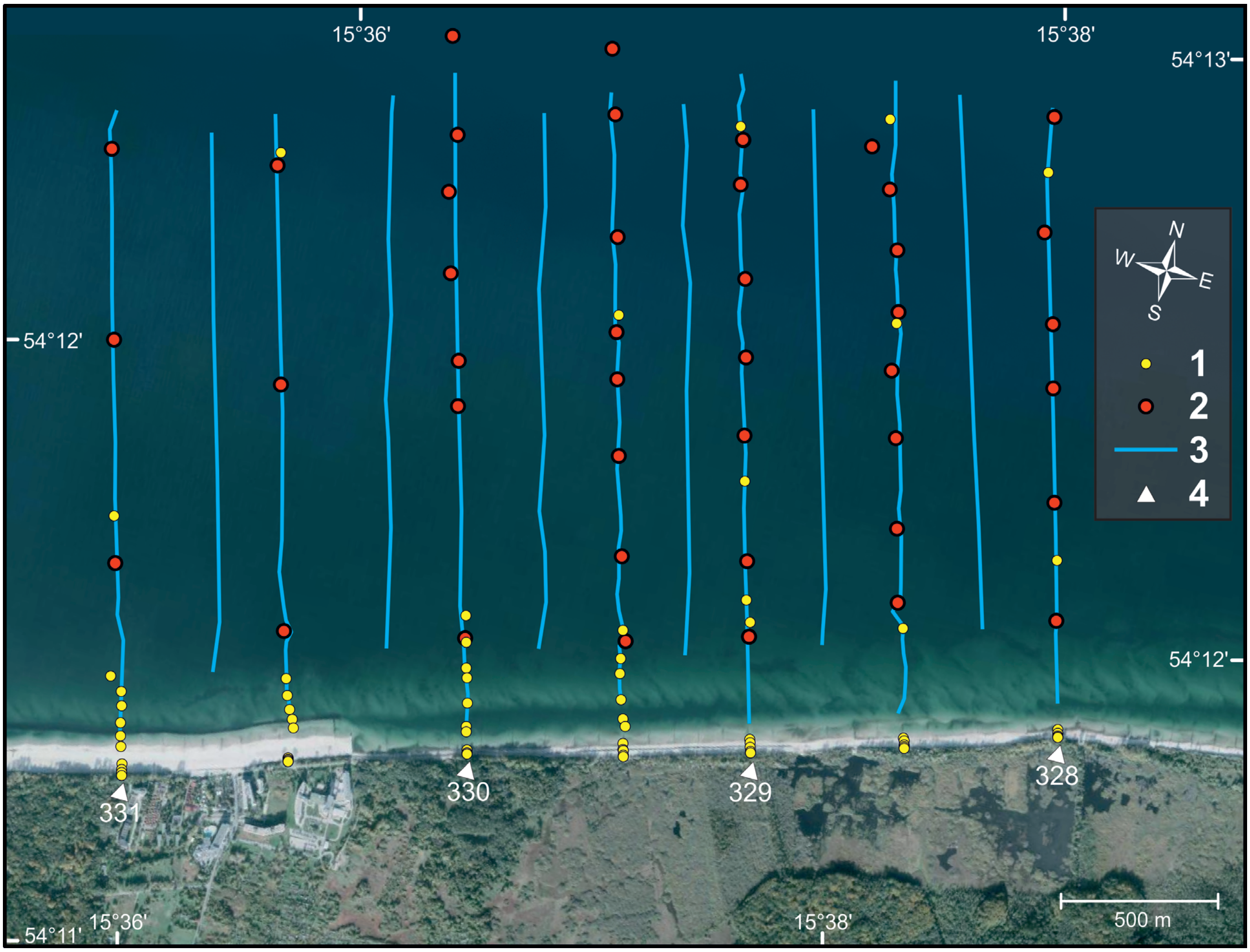

Figure 2

Location map of: 1 – grab sediment samples, 2 – core samples, 3 – sub-bottom profiles, 4 – kilometers of the Polish shoreline. Orthophotomap (by CODGiK, October 19, 2012) in the background

Results

The relief of the study area is varied. Based on its nature and depth, the following morphological units were defined (Fig. 3): I – the nearshore bar zone, II – the shoreface slope, III – the rock platform, IV – the deeper nearshore seafloor.

The nearshore bar zone is on average 250 m wide. Ephemeral and discontinuous bars of various shapes and small sizes (up to 100 m long) occur occasionally near the beach within this zone. One well-developed, but broken in many places, straight bar is situated in the deeper part of the zone. Its ridge is generally at a depth of 2 m in the western part and at about 3 m in the central and eastern part of the study area. The nearshore bar zone is open toward the shoreface, the slope of which is 1-2° and its surface is undulated. The foot of the shoreface slope is at a depth of circa 8.5 m (Fig. 3). This morphological unit is the narrowest (about 300 m wide) in the eastern part, while it widens towards the western part, where it is 500-600 m wide.

A large area with a complex relief is located mainly at a depth of 8.5-10.5 m (Fig. 3). The ridges (up to 1-1.5 m of relative height and up to 100-200 m wide) are clearly visible at the seafloor relief. The main axes of the ridges are generally in W-E or NW-NE direction (Fig. 3). There are also oval hills and, less often, pits about 100-200 m in diameter.

The northern part of the study area is a deeper nearshore seafloor located at a depth of 10.5-12.0 m. The relief is less varied and its forms are less conspicuous.

On the basis of the sonar images, unusual inliers (Fig. 4) were recognized on the seafloor surface between 329 and 330 km of the Polish shoreline. They were identified as outcrops of solid rocks. The validity of this interpretation was confirmed through inspection using ROV TV (Fig. 5). The selected

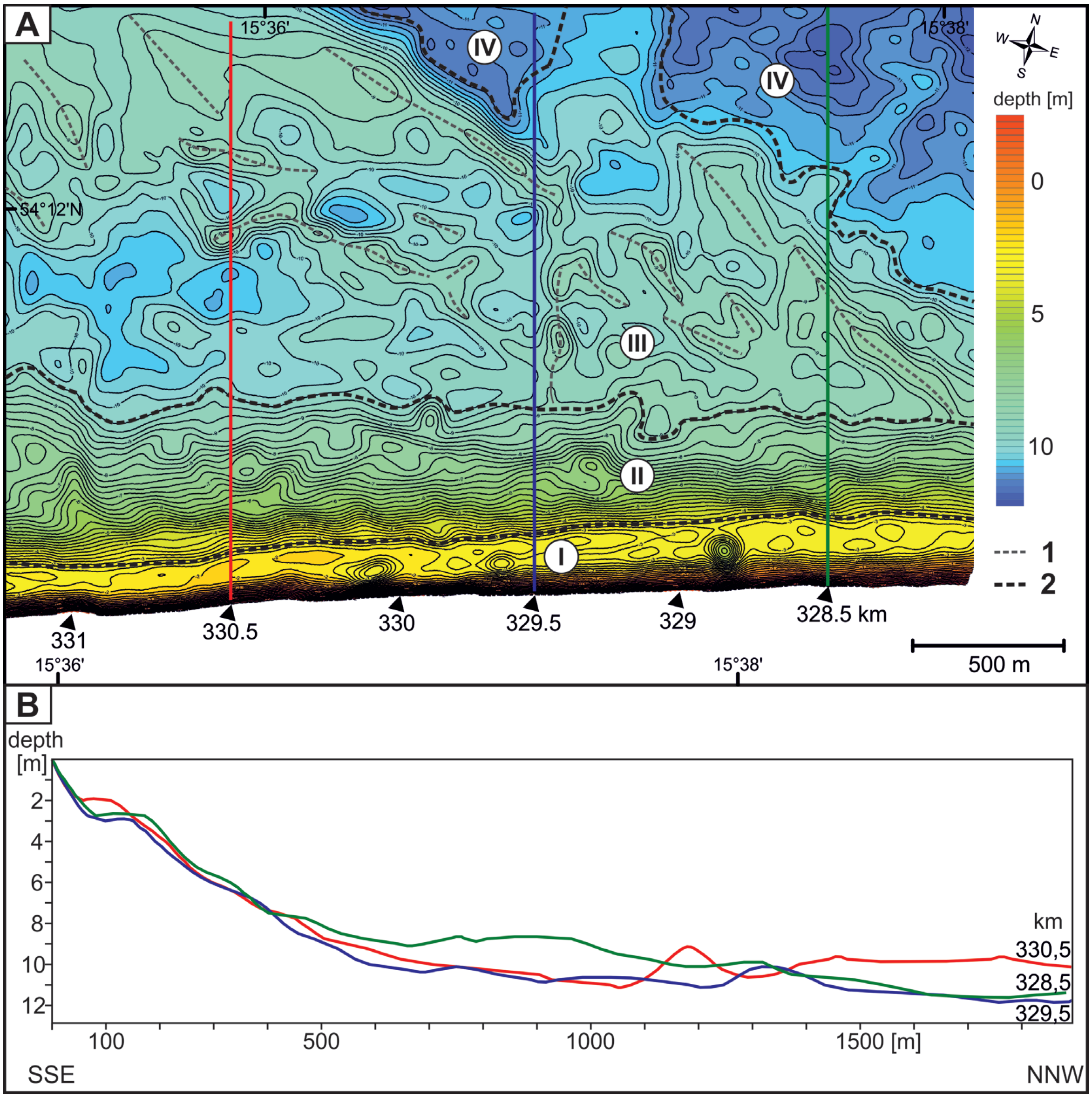

Figure 3

Relief of the nearshore seafloor. A – bathymetric map. 1 – main ridges; 2 – boundaries of the morphological units: I – nearshore bar zone, II – shoreface slope, III – rock platform, IV – deeper nearshore seafloor. B – bathymetric cross-shore profiles (location on the map A)

examples of the outcrops are presented on the sonar images (Fig. 4) and the underwater photos (Fig. 5).

According to the previous studies related to the region (Dobracka 1987, 1988; Dobracki & Przezdziecki 2007; Kramarska et al. 1999), the rocks were recognized as outcrops of Jurassic sandstones and mudstones. They are of varying shapes and sizes, ranging from 20 to 50 m. The outcrops are up to 1.5 high relative to the surrounded seafloor. Their relief and structure indicate significant tectonic deformations. Many folds and faults of these layers are visible (D in Fig. 4). The surface of the outcrops is covered by shells.

The distribution of Jurassic sandstones and mudstones on the seabed surface is shown on the lithological map (Fig. 6). The solid rocks are located on the shoreface slope (II in Fig. 3) as well as on the rock platform (III in Fig. 3).

The seabed within the nearshore bar zone (I in Fig. 3) is mainly composed of medium- and fine sand. The upper part of the shoreface slope (II in Fig. 3) is also sandy. The content of coarse sand and gravel increases with depth. The surface of the deepest part of the slope is mainly composed of gravel, while the thickness of this layer is 0.1-0.5 m (core no. 48 in Fig. 7). Marine

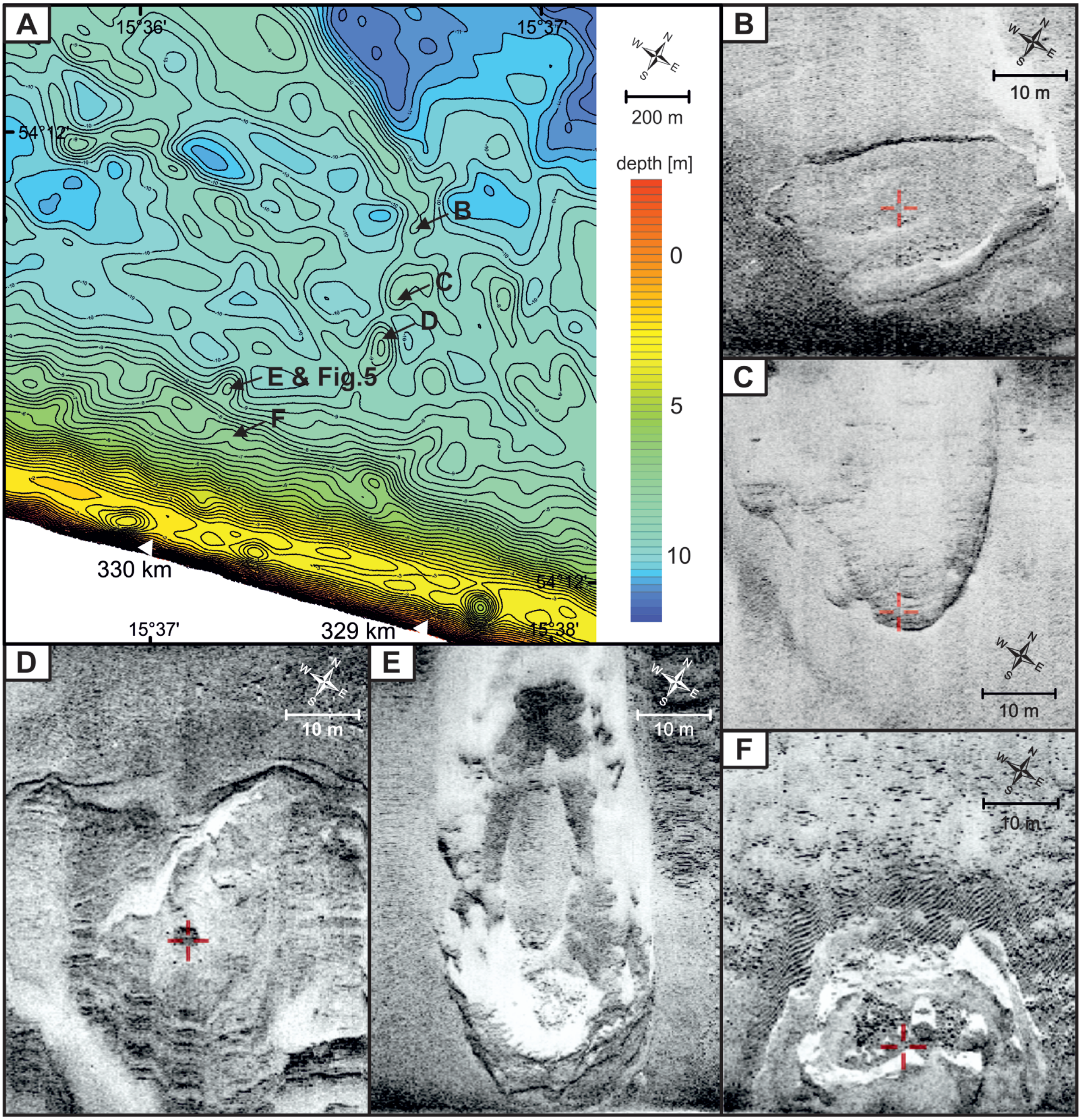

Figure 4

Location map (A) of the presented examples of the solid rocks' outcrops shown on the sonar images (B, C, D, E & F)

sediment is locally absent on the surface of the middle and lower part of the shoreface slope where till, clay and solid rocks cover the seabed surface (Fig. 6). The central part of the study area is also without a sandy cover, while till and clay (core no. 60 & 62 in Fig. 7) as well as Jurassic rocks' outcrops (Figs 4 & 6) cover the surface of the sea bottom there. The rest of the seabed is covered by marine sandy sediments. The thickness of their layer varies (core no. 67 & 74 in Fig. 7), but mostly does not exceed 0.3 m.

The evidence of the distribution of solid rocks in the seabed structure is observed on seismoacoustic profiles (Fig. 8). Considering the previous studies of the geological structure of the region (Dobracka 1987; 1988; Dobracki & Przezdziecki 2007; Kramarska et al. 1999), the rocks were classified as facies of Jurassic sandstones and mudstone. The surface of these rocks is uneven (Fig. 9), eroded and cracked in many places as well as tectonically disrupted. Cuestas, inliers and outliers, rock ridges and furrows can be

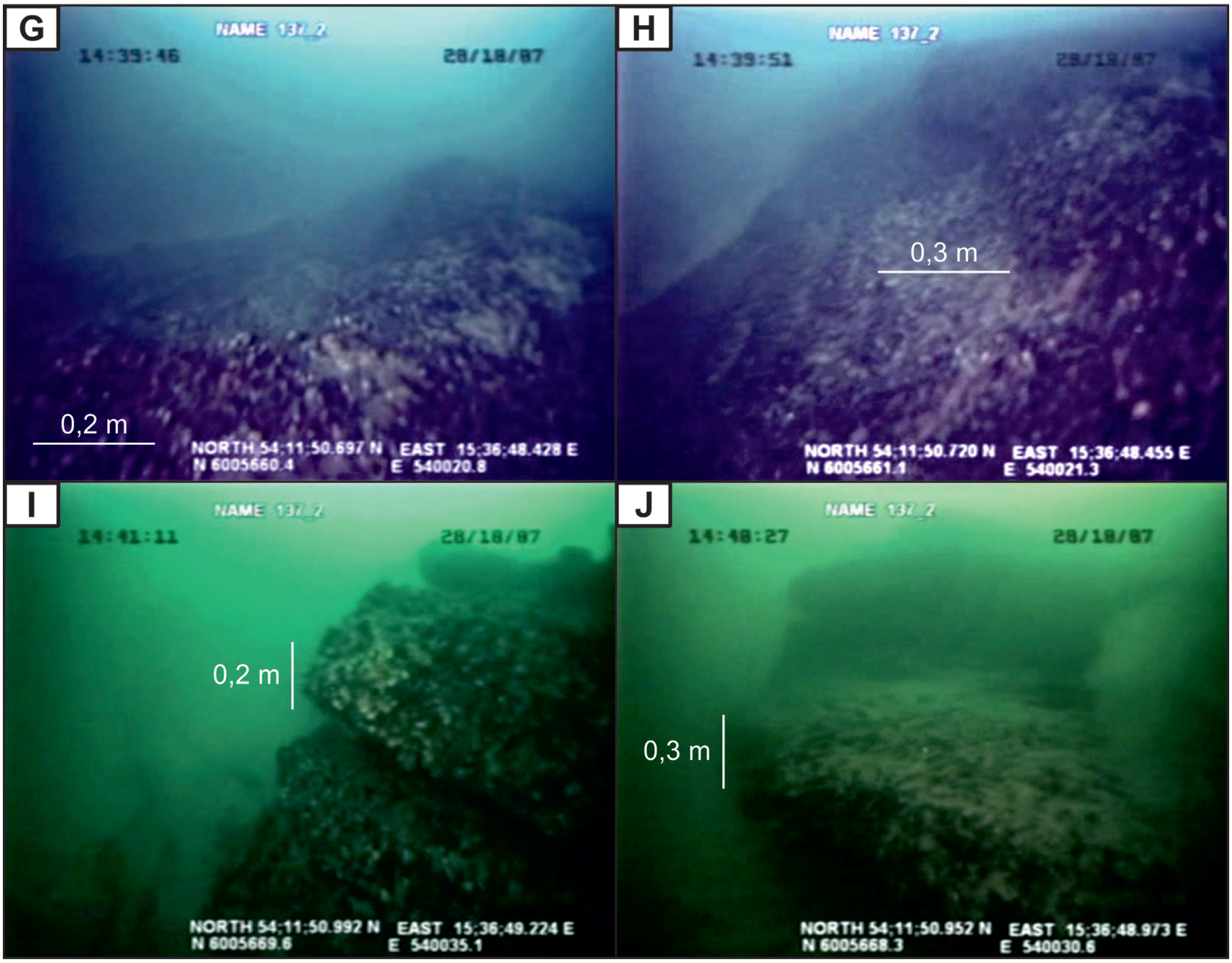

Figure 5

Jurassic rocks' outcrop (E in Fig. 4) presented from different sides on underwater photos (G, H, I & J) taken by ROV TV

observed there. Erosional incisions of the upper part of Jurassic rocks are typically filled with the Quaternary terrestrial deposits (Fig. 9), which were classified as facies of glacial and fluvioglacial diamicton, clay, sand and gravel. In many places, the Jurassic rocks build outcrops (see Figs 4, 5, 6 & 9) or they are located on a shallow sub-bottom (less than 1 m below the seafloor) covered by the facies of marine sandy sediments (Figs 8 & 9).

Discussion

The collected data and the results of performed analyses confirmed the theory that solid rocks are located near the seafloor surface in the Southern Baltic coastal zone in the Kołobrzeg region (Rudowski et. al. 2011). The observed shallow top and outcrops of solid rocks are unique, because this kind of geological conditions have not been observed anywhere else in the Southern Baltic, where a large thicknesses of glacial and fluvioglacial deposits covered by marine sandy sediments is common.

The state of this nearshore bottom is similar to the seabed situated in a microtidal, storm-affected, low-energy environment of the Gulf of Lion, located to the west of Mont Saint Clair in the Mediterranean Sea (Aleman et al. 2015). One or two straight bars are located in the narrow longshore bar zone. The zone opens out into a steep shoreface slope constrained by a rock platform. The seafloor is poor in sediment. Bedrock outcrops are distributed on the shoreface slope and on the abrasive platform. This state of the sea bottom is classified as rock platform-constrained (Aleman et al. 2015). The lack of sediment is characteristic of this geomorphological state of the seabed, while the bedrock – the Jurassic solid rocks in the case of Kołobrzeg – suppresses stronger waves.

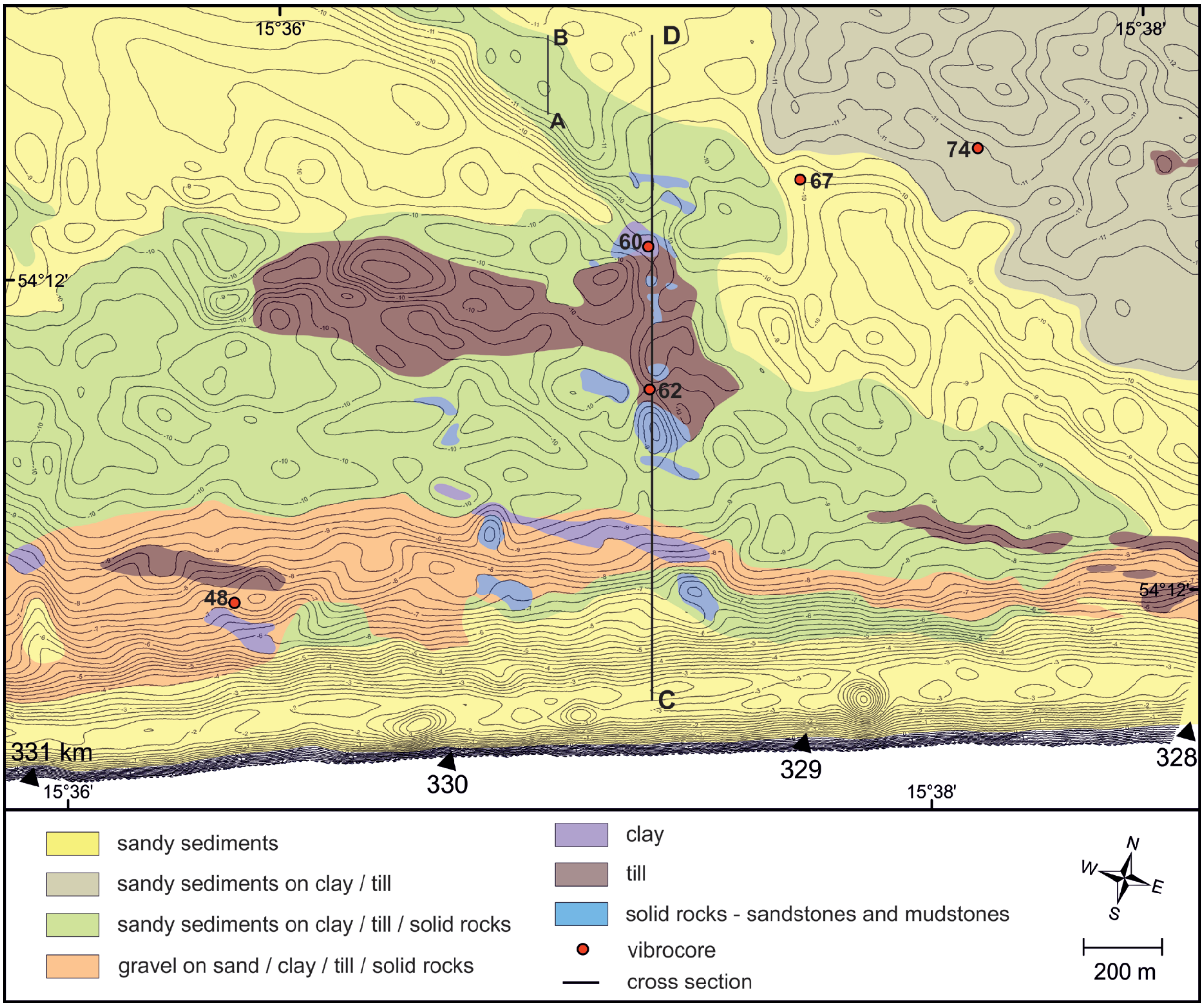

Figure 6

Lithological map of the seabed surface (isobaths every 0.25 m)

The solid rocks and the cohesive deposits are situated on the present seabed surface or are covered by marine sandy sediments. These sediments are components of the so-called dynamic layer that is the most surficial layer of deposits, subjected to redeposition. The dynamic layer is a potential source of sediments to nourish the shore, but also, especially at the bottom with this type of morphological conditions, a symptom of sediment movement toward offshore.

The observed geomorphological conditions are not conducive to rebuild the beach after a storm, while they severely reduce the sediment transport toward the shore. This is one of the main reasons of the shore erosion in the study area, especially given the fact that the sandy cover is absent or only a few centimeters thick in most of the Kołobrzeg study area. The sand is transported on the surface of firm or stiff glacial deposits and the Jurassic hard rocks. Hence, the seafloor is mostly a sediment-poor abrasion platform such as the rock platform-constrained type of coast (Aleman et al. 2015).

The shore and the deeper part of the shoreface slope is abraded in storm conditions. Sediment from these parts of the coast are transported mainly in the offshore direction and deposited bellow 8.5 m depth on the abrasion platform. Subsequently, marine sandy deposits are transported on the abrasion platform surface during a storm toward the deeper part of the bottom. This kind of morpholithodynamic conditions causes that coastal protection is difficult because the material of artificial nourishment is irretrievably taken away to the sea in a relatively short time after the restoration of the beach.

Furthermore, the longshore bars are not an indicator of the accumulation state of the coast. They are built of sediments coming from the erosion of the artificially nourished beach in the absence of longshore sand supply, which is impeded by

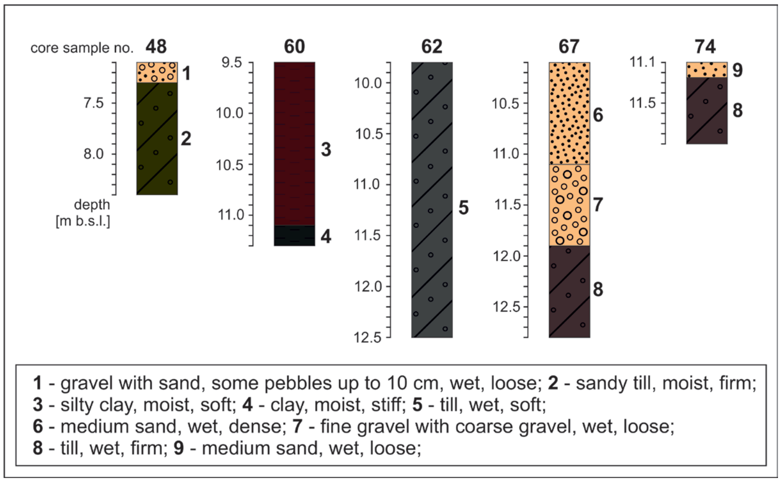

Figure 7

Selected examples of the core sections (for location see Fig. 6)

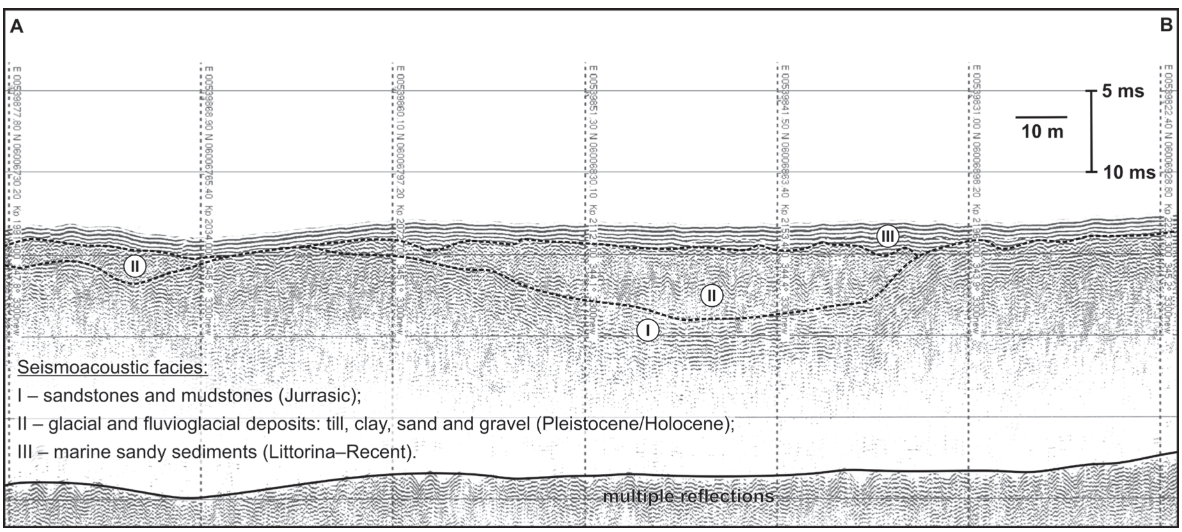

Figure 8

Fragment A-B of the seismoacoustic profile (location in Fig. 6)

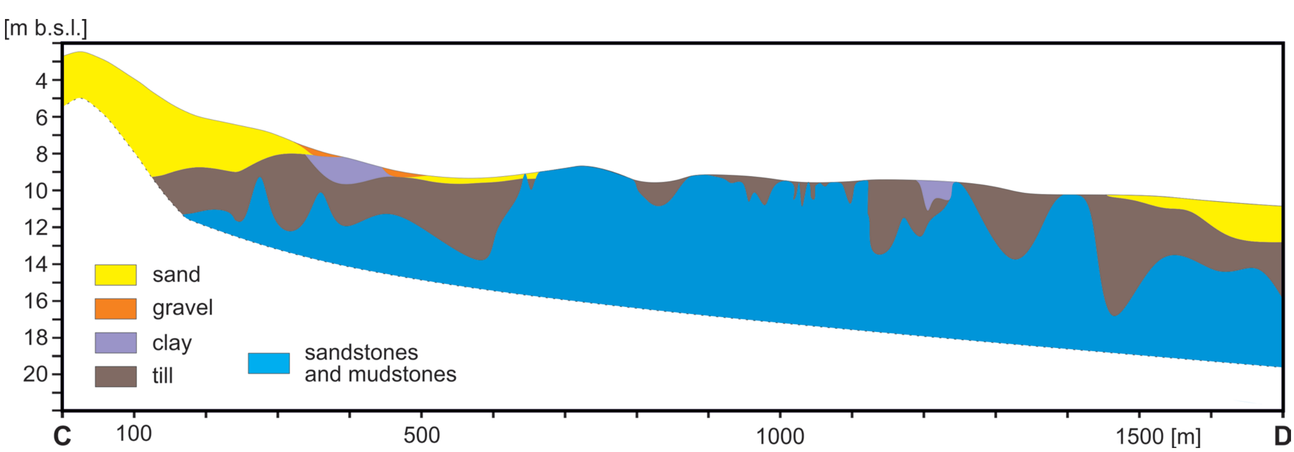

Figure 9

Geological cross section C-D (for location see Fig. 6) the cross-shore hydrotechnical constructions (the breakwaters of the Kołobrzeg port and piers).

Most of the theoretical investigations are based on the assumption that the supply of marine sandy sediments is unlimited (e.g. Basiński et al. 2006; Cerkowniak et al. 2015; Dean & Dalrymple 2004; Marcinkowski et al. 2008; Reeve et al. 2015). The results obtained by numerical modelling of the sediment transport rate ought to be interpreted as the sediment transport ability, understood as the maximum volume of sand that can be displaced in specific coastal hydrodynamic conditions. The efficiency of the models depends on the amount of sandy sediments accumulated in the nearshore, hence they cannot be applied in studies dealing with regions where the dynamic layer is very thin or absent.

Moreover, many of the commonly used methods of surveying the state and changes in the coastal zone, conducted in cross-shore transects only (e.g. Boniecka & Kaźmierczak 2015; Dubrawski et al. 2006; Zawadzka 2005), are unsuitable in geologically and morphologically complex terrains, just like the study area. The execution of the interpolation between the profiles is always vitiated by an error, which is particularly high in the area with such a large spatial variety of landforms. Studies conducted at only randomly located profiles, without the knowledge of the geomorphological positions of all their parts, may yield incorrect interpretation of the results due to the lack of data on the area situated between the survey profiles. Moreover, part of the coastal monitoring methods is based on the wrong assumption (in the case of areas with a thin or absent dynamic layer) that the whole coastal profile is composed of sediments or deposits characterized by low resistance to erosion (Basiński et al. 2006).

Furthermore, the depth of closure concept (Hallermeier 1980; Nicholls et al. 1998), which has just been verified negatively in the sandy and multi-bar Southern Baltic coastal zone (Cerkowniak et al. 2015), could also be irrelevant in the Kołobrzeg region. Significant changes in the profiles, especially on the abrasion platform, cannot be observed due to a small thickness of the dynamic layer and the current relief, thus the shape of the profiles, which is determined by the morphology and tectonic features of hard Jurassic rocks. The shape of the profiles is largely determined by the relief of the top of the solid rocks, which remains unchanged for hundreds of years. Nevertheless, small (but important to coastal processes) changes can be observed at a distance of over 2 km from the shore at a depth of 10 m and more, because of the sediment transport on the surface of hard rocks.

Conclusions

- The distribution of the Jurassic sandstone and mudstone outcrops on the nearshore bottom, between 329 and 330 kilometers of the Polish shoreline, has been documented through the detailed study of the seabed surface using a side-scan sonar and ROV TV. This geological feature is unique on the Southern Baltic coast.
- The seafloor relief is polygenetic in the study area. Its forms are mainly determined by tectonic and morphological features of the top surface of Jurassic rocks, as well as the distribution of partly eroded glacial deposits on the solid rocks.
- In most of the study area, the seabed is mainly composed of erosion-resistant solid rocks and cohesive deposits, moreover the inland area is peaty and silty. As a result, there is no potential local source of sediments.
- The dynamic layer is thin and discontinuous. Sand, which mostly comes from artificial nourishment and abrasion of the lower part of the shoreface slope, is mainly transported seaward. The observed longshore bars are not the indicator of the accumulation state of the shore, but the effect of abrasion of the artificially nourished beach.
- Many of the commonly used methods for studying the state and changes in the coast, as well as most of the classical coastal engineering approaches cannot be applied in studies concerning regions where the dynamic layer of non-cohesive sediments is lacking or very thin. The sediment transport rate, conventionally determined on the basis of bed shear stresses generated by waves and currents, cannot be true for areas where erosion-resistant deposits and rocks occur on the seafloor surface or bellow a very thin cover of marine sand.
- The Kołobrzeg region case study shows the importance of geological structure and geomorphological features of the nearshore bottom for the dynamics of the coastal zone morphology, including as a determinant of the shore erosion.

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Authors' contribution: S.R. – study design, data interpretation, conclusion; P.S. – literature review, data analysis and interpretation, conclusion, manuscript preparation; R.W. – literature review, data analysis and interpretation, conclusion; K.M. – data collection and analysis.

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