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Seismic architecture of the tip of the Hel Peninsula, Poland

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Abstract The article presents results of a pioneering research on the main geological features of the Hel Peninsula based on the analysis of seismic profiles and their comparison with geological cross-sections made on the basis of drillings. The following three parts of the tip structure have been identified: barrier basement (1), barrier core (2) and barrier upper part (3). Seismic facies distinguished therein were subsequently geologically interpreted as follows: Cretaceous marl and limestone (1.1), glacial till and diamicton (1.2), silt and clay of limnoglacial/limnic/marine origin (1.3), barrier sand of the core (2), and sand and peat of the barrier upper part (3). Geological cross-sections covering the geological structure of the tip of the Hel Peninsula underwater slope and the surrounding seabed. The slope base and the distal sand colluvium extent on the seafloor were determined. This paper is the first to present a crosswise section in this part of the Hel Peninsula.

Keywords *• Seismic profiling • Seismic facies • Sandy barrier • Gulf of Gdańsk*

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INTRODUCTION

The Hel Peninsula is a large, 35 km long sand barrier, whose width increases from 150 m (at the base) to nearly 3 km at the tip (Fig. 1). The Hel Peninsula progrades into the deep water of the Gulf of Gdańsk where it ends with the so-called Hel Promontory. The area of our research included the submarine slopes of the tip of the Hel Peninsula with the surrounding open sea floor (Fig. 1).

The first data on the geological structure of the Hel Peninsula come from the late 19th century, when the first drilling was made in the town of Hel (Tomczak 2005). Several other boreholes were made during the following years, which were subject to a thorough lithological and biostratigraphical analysis (Samsonowicz 1935; Sandegren 1935; Bogaczewicz-Adamczak 1982; Bogaczewicz-Adamczak, Żukowska 1990; Tomczak *et al*. 1990; Tomczak 1995a,

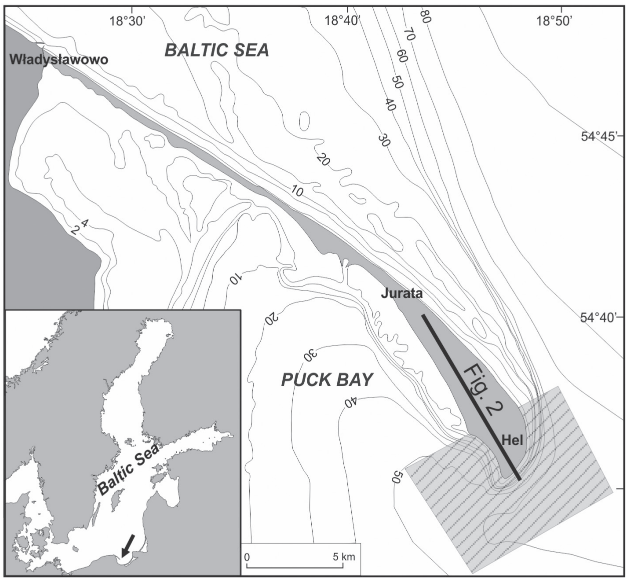

Fig. 1 Location of the study area

2000). The analysis revealed considerable differences in the geological setting between the eastern and the western part of the peninsula. The research that followed was based on more drillings and contributed to a better understanding of the peninsula geology and resulted in more precise concepts of its origin (Bączyk 1963; Pazdro 1948; Rosa 1963; Rosa, Wypych 1980; Musielak 1989; Tomczak, Kramarska 1990; Tomczak 1993, 2005). In addition, detailed geological cross-sections were developed (Bączyk 1963; Rudowski 1979; Sadurski *et al*. 1987; Tomczak 1995a). The most frequently emphasized feature in the geological description of the Hel Peninsula is the different lithologic structure of the barrier basement (Tomczak 1993, 1995b, 2005). Between the village of Kuźnica and the town of Jastarnia, clear differences in the lithologic structure, thickness and arrangement of the sediment layers can be observed in the NW and SE parts. The deeper basement consists of Mesozoic deposits (Tomczak 1995a, 2005). The roof of the Jurassic formations occurs at a depth of nearly 200 m below sea level. The Cretaceous formation roof, which is relatively levelled along the entire length of the peninsula is present at a depth of *ca*. 100 m b.s.l. The Eocene and Miocene sediments, represented primarily by mudstone, silt and sand occur only in the NW part of the peninsula. The Cretaceous sediments are directly overlain by Pleistocene deposits represented by till, clay, silt, sand and gravel. The Holocene sedimentary series are fully developed in the SE part of the peninsula where their thickness may reach nearly 100 m. On the basis of the lithologic and biostratigraphic features, individual parts of the series may be correlated with the successive phases of the Baltic Sea evolution, i.e. the Yoldia Sea, the Ancylus Lake, the Mastogloia Sea, the Littorina Sea and the post-Littorina Sea (Bogaczewicz-Adamczak 1982; Tomczak 2005). In the NW part, the Holocene sediment thickness reaches nearly 10 m. The deposits of this area represent solely the Littorina Sea and the post-Littorina Sea phases.

The current state of knowledge of the tip of the Hel Peninsula geology is based on cross-sections drawn on the basis of boreholes that did not reach the tip itself (Fig. 2). The farthermost borehole was made *ca.* 2 km from the present-day, underwater slope of the tip (*i.e.* 2 km from the maximum range of the Hel Peninsula) and thus the structure of the tip is either not shown on the geological cross-sections (Fig. 2a) or is presented as extrapolated continuation of the structure of the preceding stretches (Fig. 2b, c).

The surface sediments of the seabed near the Hel Peninsula tip consist mainly of Holocene sand of a varied grain size composition. The foreshore zone bottom at the seaward side is covered mostly with fine sand. Medium-grained sand occurs around the tip and on the coastal shallows, at the lagoon side of the peninsula. The seabed of the deeper parts of the Puck Bay is covered with sand-silt-clay, silty-clay and clayey-silt. Fine and silty sand on the bottom of the Hel Peninsula tip area is accompanied by sand-silt-clay (Kramarska 1995).

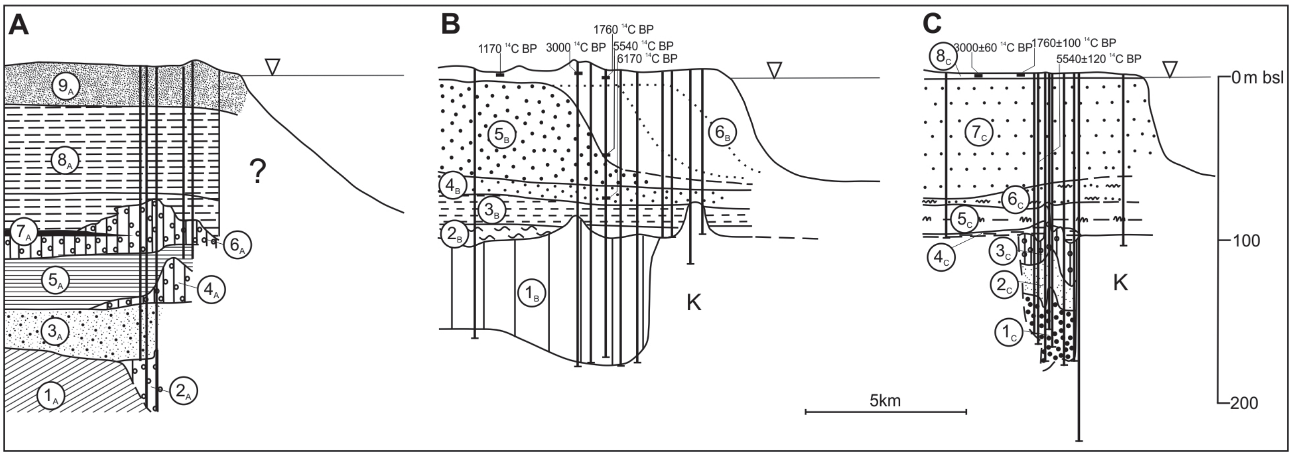

Fig. 2 Examples of the geological cross-sections of the Hel Peninsula (after: A – Rudowski 1979, B – Tomczak 1993, C – Tomczak 1995a) (location in Fig. 1). Explanations: 1_A – Cretaceous, 2_A – oldest till, 3_A – deposits filling older erosional incision, river and fluvioglacial gravel and sand, dilluvial clay, silt, sand and gravel, 4_A – older till, 5_A – deposits filling younger erosional incesion, gravel and varigrained sand passing into ice-marginal lake silts, 6_A – till, 7_A – ice-marginal lake deposits, varved clays, 8_A – Ancylus Lake – Littorina Sea deposits, silts, sandy-silts and sands, 9_A – barrier deposits, bottom offshore, beach, aeolian, sands locally gravel; 1_B – Pleistocene undivided, 2_B – Pre-Ancylus deposits, 3_B – Ancylus Lake deposits, 4_B – Mastogloia Sea deposits, 5_B – Littorina Sea deposits, 6_B – Post-Littorina deposits with accretion lines of the youngest part of Hel Spit, K – Cretaceous; 1_C – Pleistocene coarse deposits, 2_C – Pleistocene sandy deposits, 3_C – Pleistocene tills, 4_C – Pre-Ancylus clay deposits, 5_C – Ancylus silty and clay deposits, 6_C – Mastogloia silty and sandy deposits, 7_C – Post-Littorina and Littorina sandy deposits, 8_C – Holocene terrestrial deposits; the location of drilling sites and radiocarbon dates are indicated

The Hel Peninsula tip forms a "semi-circular" sandy area where the land is covered with dune ridges reaching 20 m in height, surrounded by a wide beach up to 100 m wide at the eastern side. At the western side, the beach is narrow (up to 20 m width) (Rucińska-Zjadacz, Rudowski 2015).

The seabed around the tip is a wide, flat, sand-covered shallow (up to 4 m in depth), separated by a sharp edge from a relatively steep, sandy slope. The submarine slope of the tip of the Hel Peninsula is a unique form when compared with underwater slopes of other sand barriers due to its steep inclination (5–8^o on average, and locally almost 20^o) and its height (*ca.* 50 m) (Rucińska-Zjadacz, Rudowski 2009; Rudowski *et al.* 2016). There are other spits entering deep waters of non-tidal water bodies, for example the Long Point spit on Lake Erie (Davidson-Arnott, Conliffe Reid 1994). However, no mass movements were identified and described on such spits. In the case of such a steep inclination of the tip slopes a variety of forms connected with mass movements developed on the slope surface (Rucińska-Zjadacz 2015; Rudowski *et al*. 2016).

The incentive for the research were the results obtained from the earlier, detailed investigations of the underwater slope of the Hel Peninsula tip (Rucińska-Zjadacz, Rudowski 2008, 2009; Rucińska-Zjadacz 2015; Rudowski *et al*. 2015, 2016). The investigations revealed great impact of the surface mass movements on the structure and the evolution of the tip.

Among the numerous boreholes made within the Hel Peninsula, there are no drillings from the farthermost part of the spit and therefore its geology has been extrapolated so far as a continuation of the preceding part of the peninsula. The research is the first attempt at the determination of the Hel Peninsula tip structure with the use of both the drilling information and the seismic survey results. The paper also is the first to present a crosswise section in this part of the Hel Peninsula. Until now, the crosswise sections have been developed only for the Puck Bay area (Kramarska *et al*. 1995; Uścinowicz *et al*. 2002).

MATERIAL AND METHODS

The article is based on archival high-resolution seismoacoustic and seismic profiles obtained during the last dozen or so years (Fig. 3). The aforementioned archival information consisted of analogue

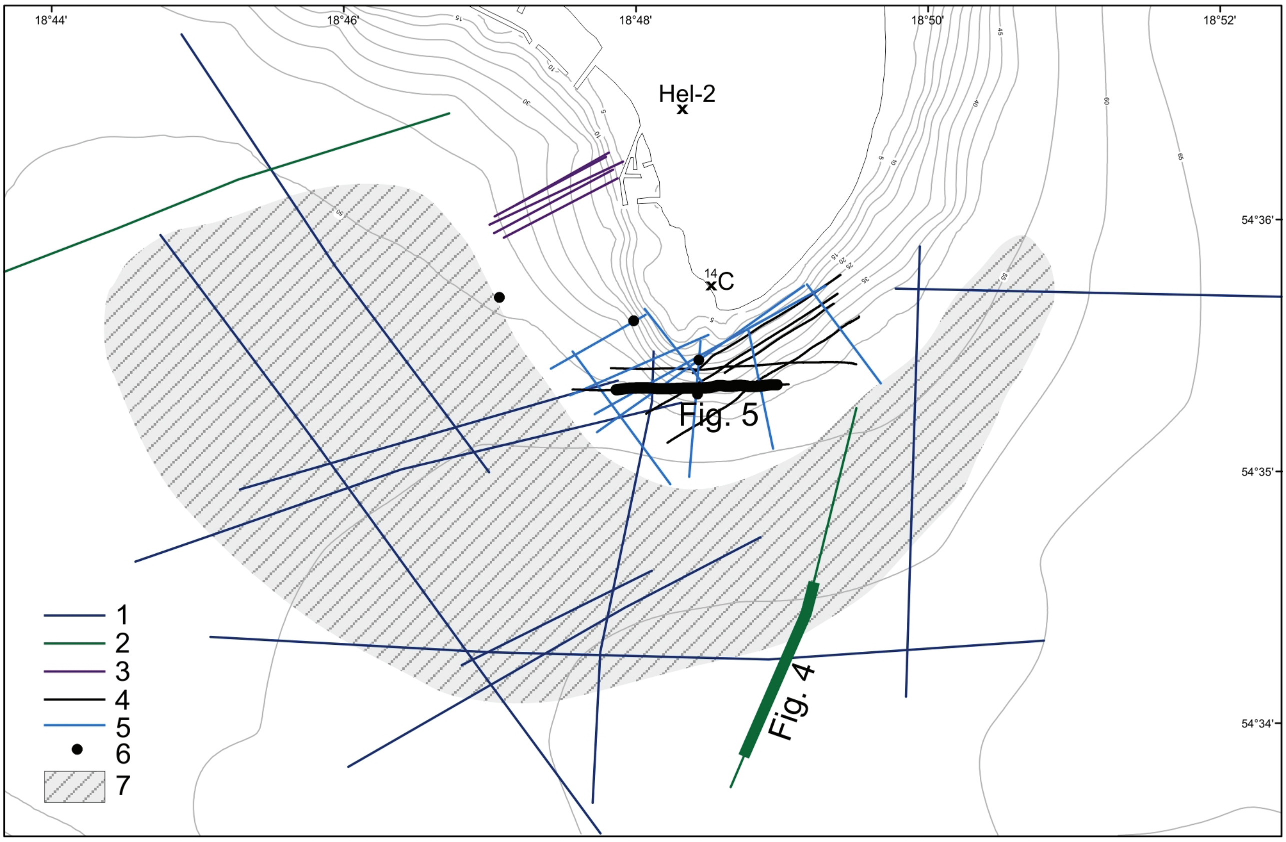

Fig. 3 The study area. Seismic profiles location: 1 – Boomer, 1977 r.; 2 – Boomer, 1990 r., 3 – subbottom profiler, 2004 r.; 4 – Boomer, 2006 r.; 5 – subbottom profiler, 2007 r., 6 – vibrocores, 7 – the area of temporary occurrence of the gas curtain. Location of dated soil (^{14}C) (Rucińska-Zjadacz, Rudowski 2015) and the southernmost drilling site Hel- 2 (after Tomczak 1995) are indicated

seismoacoustic profiles obtained with the Boomer system (frequency of up to 600 Hz) between 1977 and 1978 from the deck of the vessel Horyzont by the team from the Institute of Meteorology and Water Management – Marine Department in Gdynia. Positioning was carried out with the Decca Navigator system using a single-beam echo sounder without depth correlation (the precision of a point location amounted to about 100 m and that of a depth about 5 m). In addition to that, analogue profiles were obtained; they were made in 1990 and 1995 (Jankowska *et al.* 1992) using the Boomer system by the Department of Polar and Marine Research Polish Academy of Sciences (frequency range 600–1000 Hz and positioning with GPS). Photocopies of archival records owned by their authors were used. Furthermore, the authors of the present article used high-resolution seismoacoustic profiles obtained with the subbottom profiler (frequency 3.5–5 kHz) using precise positioning with the DGPS RTK system in connection with the appropriate navigation systems Hydro and Track Point. The profiles were made between 2004 and 2013 by the Operational Oceanography Department of the Maritime Institute in Gdańsk (Rucińska-Zjadacz, Rudowski 2008, 2009; Rucińska-Zjadacz 2015; Rudowski *et al.* 2015, 2016).

Other data used in the present research included side-sonar measurements and sea-floor viewing with the ROV TV system on the tip slopes (Rucińska-Zjadacz 2015; Rudowski *et al.* 2016) and information from the analysis of sparse shallow core samples with a length of 3 m (Rucińska-Zjadacz 2015; Rudowski *et al.* 2015, 2016).

The structure of the underwater tip slope (*i.e.* its deep structure below the seabed surface) was determined on the basis of a detailed analysis of seismoacoustic recording (high-resolution seismic profiling). The record quality is generally good, however, some interference can be observed. The occurrence of multiple waves reflected from the pycnocline surface was reported or of side-by-side multiple waves reflected from adjacent sections of the inclined seabed and its distinct denivelations imposed on the image of the depths and the sea bottom structure.

The precision of the geological cross-section location is in the range of about 50 m, while that penetrating to the depth is close to about 5 m. This is attributable to the variety of methods used and the measurement capabilities available in the previous studies. The cross-sections were based on the entire available set of data related to the seismic profiles. Significant clarity reduction in the sea floor recording may result from the gas curtains (Fig. 3) and other phenomena, widespread pockmarks and for instance "mud volcanoes" connected with a common presence of gas in the clayey deposits of the seabed.

RESULTS

The thorough analysis of the seismic profiles led to the identification of seismic units of various types and reflection patterns, combined in groups with defined lower and upper boundaries. The geological interpretation of these units was made on the basis of the knowledge about the method (Wypych *et al.* 1982; Clay, Medwin 1997; Przezdziecki 2004; Rudowski, Rucińska-Zjadacz 2010) and the study area (Pikies, Jurowska 1992; Uścinowicz, Zachowicz 1992, 1994; Tomczak 2005; Zachowicz *et al.* 2006).

Three major units were distinguished in the tip of the Hel Peninsula structure, i.e. Unit 1 – barrier basement, Unit 2 – barrier core and Unit 3 – barrier upper part.

Unit 1 Barrier basement

All the seismic profile sections analysed located deeper than 40 m are very difficult to interpret due to the presence of the so called "gas curtain" (Rudowski *et al.* 2010) (Fig. 3). In the present study, it was only possible to determine the major seismic fa-

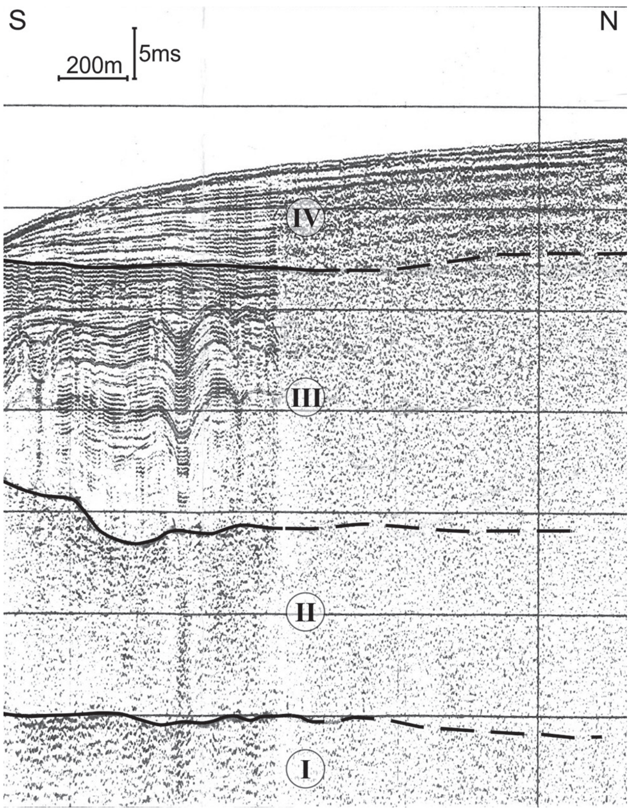

Fig. 4 Part of the ZG 13/90 seismic profile (location in Fig. 3). Explanations: I – Cretaceous marl; II – glacial and fluvioglacial deposits; III – deposits of the suspension sedimentation series; silty sand at the bottom part, silty clay in the higher part, containing disturbances from the buried ice meltdown and gas migrations; IV – silty clay deposits of the suspension sedimentation interbedded with sandy silt deposits of the distal colluvia. On the right: gas curtain

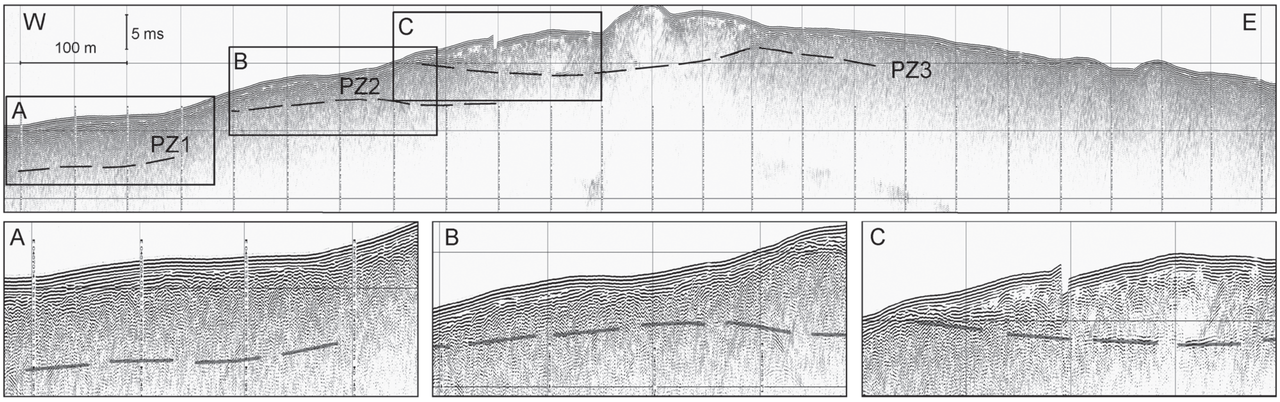

Fig. 5 Seismic profile H14-2 (location in Fig.3). Three levels (PZ 1, PZ 2, PZ 3) corresponding to the three series of barrier's core deposits with erosive tops are indicated

cies boundaries and to interpret them in relation to profile sections without the gas curtain preserved in the vicinity (Figs. 4, 5). The sections of nearby profiles described and interpreted in the papers by Rossa and Wypych (1981) proved to be of much help.

The following facies were distinguished within Unit 1, Barrier Basement: Facies 1.1. Cretaceous marl and chalk, Facies 1.2. glacial facies with till and sand and gravel mix, Facies 1.3 silt and clay of limnoglacial, lacustrine and marine origin.

The image of facies 1.1. consists of long and intensive horizontal and/or subhorizontal reflections that are acoustically clear and separated by sets of similar but weaker reflections of poor clarity. The facies is characterised by distinct bedding in which a clearly visible arrangement of beds corresponds to the Cretaceous sediments. The facies roof is uneven.

Facies 1.1 is unconformably overlain by facies 1.2 characterised by a chaotic system of short reflections of varied intensity and arrangement, containing numerous *hyperbolic echoes* (Jakobsson *et al.* 2016) and interpreted as glacial diamicton with a rough roof.

Facies 1.3, characterised by long, intensive, slightly undulating reflections, comprises a distinctly bedded deposit assemblage of sand and silt in the lower part and of silt and clay in the upper part, which was interpreted to represent deposits formed as a result of suspension sedimentation and also lacustrine and marine sediments (from the Late Pleistocene to the recent). The upper part of this facies contains interbeddings and inclusions of poorly sorted, sandy-silty deposits related to the deposition of distal colluvia on the foreground of the tip of the Hel Peninsula slope.

Unit 2 Barrier core

The tip of the Hel Peninsula slope structure (i.e. its deep structure below the sea-floor surface) was determined (Rucińska-Zjadacz 2015; Rudowski *et al*. 2015, 2016) on the basis of a detailed analysis of seismoacoustic recording (high-resolution seismic profiling), supported with the side sonar image analysis, underwater TV images and surface sediment samples and obtained from a number of vibrocores.

The seismic record quality is generally good, however, not entirely free from interference. The presence of waves repeatedly reflected from the pycnocline surface was reported, or side-by-side multiple waves reflected from adjacent sections of the inclined seabed and its distinct denivelations imposed on the image of the water column and the seabed structure.

The barrier core structure represents a complex system of colluvia (Rucińska-Zjadacz 2015; Rudowski *et al*. 2016) comprising mainly fine- and medium-grained sandy deposits characterised by a varying content of coarse sand, gravel, shells and different admixtures originating from the surface erosion and coming from the barrier slopes (peat, boughs, debris, rubbish etc.).

An important feature of the barrier core deposits is their strong, lateral and vertical variation attributable to the occurrence of a wide spectrum of landslide forms recorded as sets of reflections of a varied strength, outline and inclination, arranged in the form of humps, undulating tongues, wedges with numerous *hyperbolic echoes* of different size. On the slope surface and erosional boundaries of the reflection sets, pebbles or shells (shell pavements) are frequently observed.

The sediment compaction, medium or poor in the surface parts of the slope, increases with depth and is expressed as a homogenous record in the core centre being indicative of a strong, uniform compaction. The record of seismic profile H 14-2, transverse in relation to the tip axis, contains three very strong and almost horizontal reflections inside the core in the cross-section oriented transversely to the slope axis. These levels were marked as PZ1, PZ2 and PZ3 (Figs. 5, 6).

Distal colluvia that extend far into the barrier slope foreland contain mainly fine silty sands, characterised by moderate to poor compaction, which are also interbedded with silty-clayey marine sediments created by suspension deposition.

Unit 3 Barrier upper part

Unit 3, the barrier upper part, consists almost exclusively of varigrained sandy sediments whose origin is related to the transverse development of the barrier, i.e. the foreshore bottom (3.1), the beach (3.2) and the dune facies (3.3). A detailed description of the structure and the evolution of this facies of the Hel Peninsula near Kuźnica-Jastarnia was presented by Wróblewski (2001, 2003).

Foreshore bottom facies 3.1

Within the tip area, the foreshore bottom is a flat-surfaced coastal shallow (Rucińska-Zjadacz 2015; Rucińska-Zjadacz, Rudowski 2015) (max depth 5 m b.s.l.) with ephemeral, poorly developed sandbanks.

Seismic record of the facies 3.1 was obtained only partly from the upper parts of the landslide niches in the upper part of the slope and supported by data from bathymetric profile analysis and investigations of the surface sediment samples (Rucińska-Zjadacz 2015). The inexplicit seismic record has character of reflections of different length and intensity that are combined to form wedge-shaped sets containing concave parts, and showing mild inclination in different sides. The image with such record was interpreted as compacted sandy sediments with numerous anthropogenic components of varied size (e.g. construction debris, wood logs, turf lumps).

Intensive redeposition of sandy sediments is caused here by hydrodynamic factors that include mostly waving subjected to intense transformation due to the direct approachment of deep-water waves onto the coastal shallow. The waves become deflected to a varied degree, which results in a complex interference pattern.

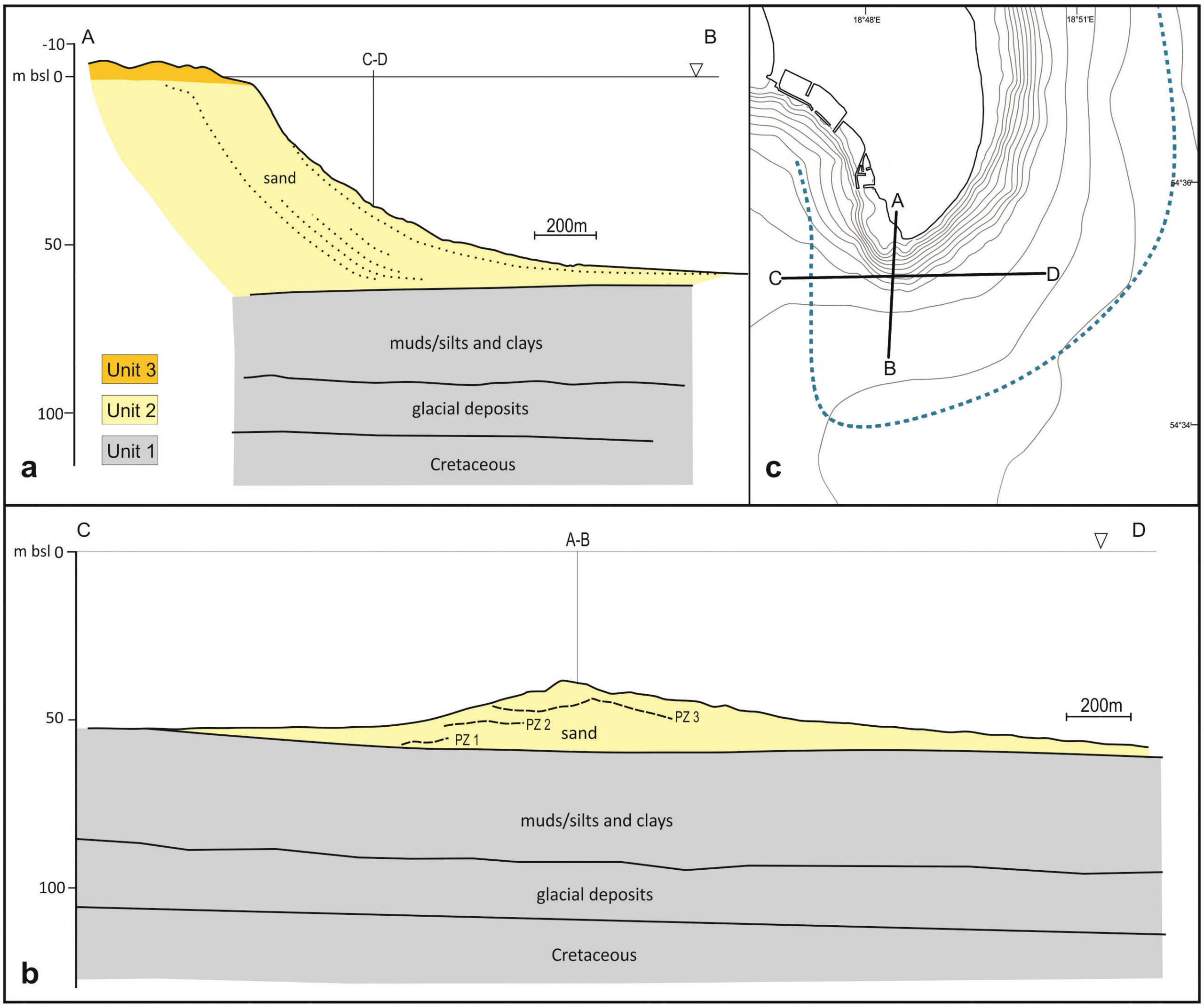

Fig. 6 Seismic architecture scheme of the tip of the Hel Peninsula. a – geological cross-section AB crosswise towards the peninsula axis, levels (PZ 1, PZ 2, PZ 3) are indicated; b – geological cross-section CD along the peninsula axis, dotted lines indicate diagrammatic locations of the slope paleosurfaces; c – location of the AB and CD cross-sections, dotted blue line indicates distal sand colluvium extent

Beach facies 3.2

Sediments of the facies, described in detail by Rucińska-Zjadacz and Rudowski (2015), which are generally similar to those encountered on other beaches of the Hel Peninsula, include sands with fractions of gravel and other constituents of anthropogenic and natural origin (Wróblewski 2003; Rucińska-Zjadacz, Wróblewski 2014).

Coastal dunes facies 3.3

The most comprehensive description of the Hel Peninsula dunes was presented by Tomczak (1995b, 2005). Various dune types occur here, including dunes with storm banks and the covering aeolian deposits (Rudowski 1986). Depressions between dunes in this area may contain poorly developed podzolic soil with a weak humus level.

In the abrasive undercut of a dune at the western side of the tip, a poorly developed podzolic soil level containing a humus layer dated at ^{14}C 495±45 years BP was observed (Rucińska-Zjadacz, Rudowski 2015) (Fig. 3). This is so far the southernmost location of the tip of the Hel Peninsula dating.

The sedimentary series of the tip of the Hel Peninsula is not horizontal, but tangentially deposited, oblique according to the development of the underwater slopes and the mass wasting. In this sense, the structure of the Hel Peninsula tip is the sedimentary series deposited on the barrier basement built of fine settled sediments. Barrier core sands cover muddy marine sediments surrounding the tip of the Hel Peninsula. The extent of the colluvium sands can be up 2 km in the adjacent seabed (Fig. 6).

The relief and structure of the tip slope is varied and mainly related to the development of surface mass movements (Rucińska 2015; Rudowski *et al.* 2016) commonly reported in the areas of the continental slope (*inter alia* Hampton *et al.* 1996; McAdoo *et al*. 2000; Canals *et al*. 2004; Baeten *et al.* 2013), underwater slopes of volcanic, tectonic and glacial lakes (*inter alia* Gardner *et al*. 2000; Strupler *et al.* 2017), and of large river deltas (*inter alia* Prior & Suhayda 1979; Nemec 1990; Biscara *et al*. 2012). The inventory and nature of these forms is very similar, although of course the scale as well as the structure of the slope is different.

DISCUSSION

The presented results are a new approach in recognizing the structure of the Hel Peninsula tip and a new sight for the development of this type of forms. Data from non-core drillings did not provide necessary information on the sediment structure. The first seismic profiling of the steep sandy slope of the barrier was carried out in the area of the Hel Peninsula tip (Rucińska-Zjadacz 2015; Rudowski *et al.* 2016) and made it possible to identify the main features of the tip structure. The presented cross- and lengthwise cross-sections are the proposition to depict the structure of the barrier tip with an indication of the units: barrier upper part and barrier core (Fig. 6). The upper part of the barrier is associated with the transverse barrier development due to waves and wind action (Wróblewski 2003, 2009; Rucińska-Zjadacz, Wróblewski 2014; Rucińska-Zjadacz, Rudowski 2015). The barrier core is built by sediments provided by longshore transport and largely discharged down the slope in the form of landslides, as well as by creeping and in suspension. The seismic registry records *i. e.* landslides surfaces, the levels PZ 1, PZ 2 PZ 3 were distinguished within barrier core based on strong reflectors in seismic record (Figs. 5, 6). The levels have a transverse course to the axis of the peninsula. Their origin is related to slides or failure surfaces associated with the development of mass movements on the underwater slope of the tip described in detail by Rucińska-Zjadacz & Rudowski (2009), Rucińska-Zjadacz (2015) and Rudowski *et al.* (2016).

CONCLUSIONS

- The seismic survey records were used for a pioneering research on the main features of the tip structure, *i.e.* its seismic architecture in the area that has not yet been studied with geological drilling.
- The geological profile of the Hel Peninsula was extended by more than 1 km into its land part when compared to the most recent drilling located along the peninsula axis.
- Three major structure units were distinguished, i.e. the barrier basement, the barrier core and the barrierupper part.
  - Seismic facies were distinguished within them:
  - the barrier basement is the sea floor on which the sediments composing the barrier are deposited,
  - the barrier core consists of sediments transported laterally along the barrier axis and deposited mainly on the underwater slope of the prograding tip of the peninsula,
  - the barrierupper part development occurs mainly transversely to the barrier axis and is related to processes of waves and wind action.
- The extent of the slope and the colluvium sands on the bottom around the tip was determined. This is very important for the determination of the mass and the volume of the Hel Peninsula sands and thus for answering the question about the possible sediment supply source.

- The sedimentological interpretation of the commonly used geological cross-section requires revision as the slope is not of erosional origin (*i.e.* formed by erosion of an existing form). Instead it is formed by avalanching, therefore, the age lines should be "tangential", at least to a depth of 30 m, *i.e.* the depth marking the beginnings of the Littorina Sea.

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