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The Virgin Sands: a composed barrier fringing the Hel Peninsula

ABSTRACT: The Virgin Sands form the 6.5 km long accumulative bar which is located in the shadow of the Hel Peninsula, within the Inner Puck Bay (Baltic Sea). Its surface is covered with extensive megaripples, the shape of which is similar to parabolic dunes. The bar of the Virgin Sands, as a longshore barrier, was originated in the early stage of the Hel Peninsula development, in the Holocene during the *Littorina* Transgression. The origin of the megaripples is connected with catastrophic breaks of the Hel Peninsula by uprisen waters of the open Baltic Sea. The streams which tore the Hel Peninsula encroached the Inner Puck Bay and transported big masses of the sand, accumulated as the megaripples on the surface of the Virgin Sands.

INTRODUCTION

The submerged barrier of the Virgin Sands located on the southern side of the Hel Peninsula, within the Inner Puck Bay, Gulf of Gdańsk, Baltic Sea (*cf.* Text-fig. 1) was presented for the first time on Swedish map in 1637, but so far has never been the subject of any investigation. The formation of the similar barrier of the Gull Reef and of the Hel Peninsula itself are well documented in the literature. It was Pawłowski (1922) who first recognized the processes responsible for development of the Hel Peninsula and the Gull Reef. The Holocene history of the Southern Baltic coast was discussed by Rosa (1967, 1968, 1972) and Rudowski (1978); Zenkovich (1962) presented the analysis of hydrodynamic conditions of the Puck Bay. The geological structure of the Hel Peninsula and the Gull Reef were recognized by Bohn & Sokół (1972), Dmoch & Wilczyński (1972) and Rudowski & Tobolewski (1973). The distribution and analysis of the bottom sediments in the Inner Puck Bay was presented by Musielak (1978, 1979).

The field investigations of the Virgin Sands were carried out by the Author in summer 1978 and winters 1978 and 1980.

GENERAL CHARACTERISTICS OF THE PUCK BAY

The Puck Bay (area 439.6 km^2) is the eastern part of the Gulf of Gdansk, and it is separated from the open Baltic Sea by the Hel Peninsula (*see* Text-fig. 1).

The basin of the Puck Bay is divided into two parts of different hydrodynamic conditions, depth and bottom configuration: the Outer Puck Bay in the east, and the Inner Puck Bay in the west. These parts are separated by a submarine sandy ridge, the Gull Reef (in Polish: *Rewa Mew*) being a barrier about 11 km long and 200 to 300 m wide. This ridge sometimes emerges above sea level as a row of a few barrier islands. In the south, the Rewa Spit (*Cypel Rewski*) is a border between these two basins; it reaches 1 km in length and it is 100 m wide near its base.

The both parts of the Puck Bay are connected by an artificial channel (*Dypka*) dredged out between the Rewa Spit and the Gull Reef; this canal is 80 to 100 m wide and 6 to 7 m deep.

The bottom of the Outer Puck Bay takes shape of a trough with a morphological axis running from NNW to SSE and the bottom slope oriented towards the Gulf of Gdańsk into depth of 57 metres. The bottom configuration of the Inner Puck Bay is more varied with many shallow parts (0.5—1 m) over accumulative forms and some deeper parts (about 10 m). The shallows with a few accumulative forms dominate along the shore of the Hel Peninsula. The most distinct is a 6.5 km long sand bar, the Virgin Sands (*Piaski Dziewicze*); another one is that of the Western Sands (*Piaski Zachodnie*).

Deposits of the Inner Puck Bay are much differentiated. The finest sands cover the central part of the Bay. To the south, they change into fine-grained ones with an admixture of organic slime. Fine- and medium-grained sands compose near-shore shallows and accumulative forms, while silts fill depressions between bars. Abrasion platforms along cliffs are covered with coarse-grained sands, gravels and blocks eroded from the glacial till. In several places of the bottom there occur layers of fossil limnic-paludal deposits. In a depression to the north of Puck there are exposures of peats, and in a marginal part of that depression the peat detritus is mixed with sand and organic slime.

Nearly 2/3 of the bottom of the Inner Puck Bay is covered with seagrass *Zostera marina,* algal mats and organic detritus (Witkowski 1979). The benthic organisms on the examined area are represented by pelecypods, gastropods, worms, and crustaceans.

The hydrodynamic conditions in the Inner Puck Bay depend on direction and force of wind. Currents and waving created by wind do not play an important role in the dynamics of waters. The system of weak currents in shallow water is complicated and depends on position and configuration of the accumulative forms. One current that runs along the eastern side of the Virgin Sands has its speed from 10 to 17 cm/s (Urbański & Stepko 1976), too small to transport the sediment.

Waves in the Inner Puck Bay are not higher than 50 cm (Musielak 1979), and they may transport the sediment only in the near-shore zone. The main hydrodynamic feature is connected with changes of sea level caused by wind. Sometimes, during the month of March the winds cause either the lifting of sea level to about 2 m a.s.l., or its lowering down to 0.9 m b.s.l. (Musielak 1979). The mean depth of the Inner Puck Bay is only 3 m and such as these changes of the sea level are responsible for main hydrodynamic processes.

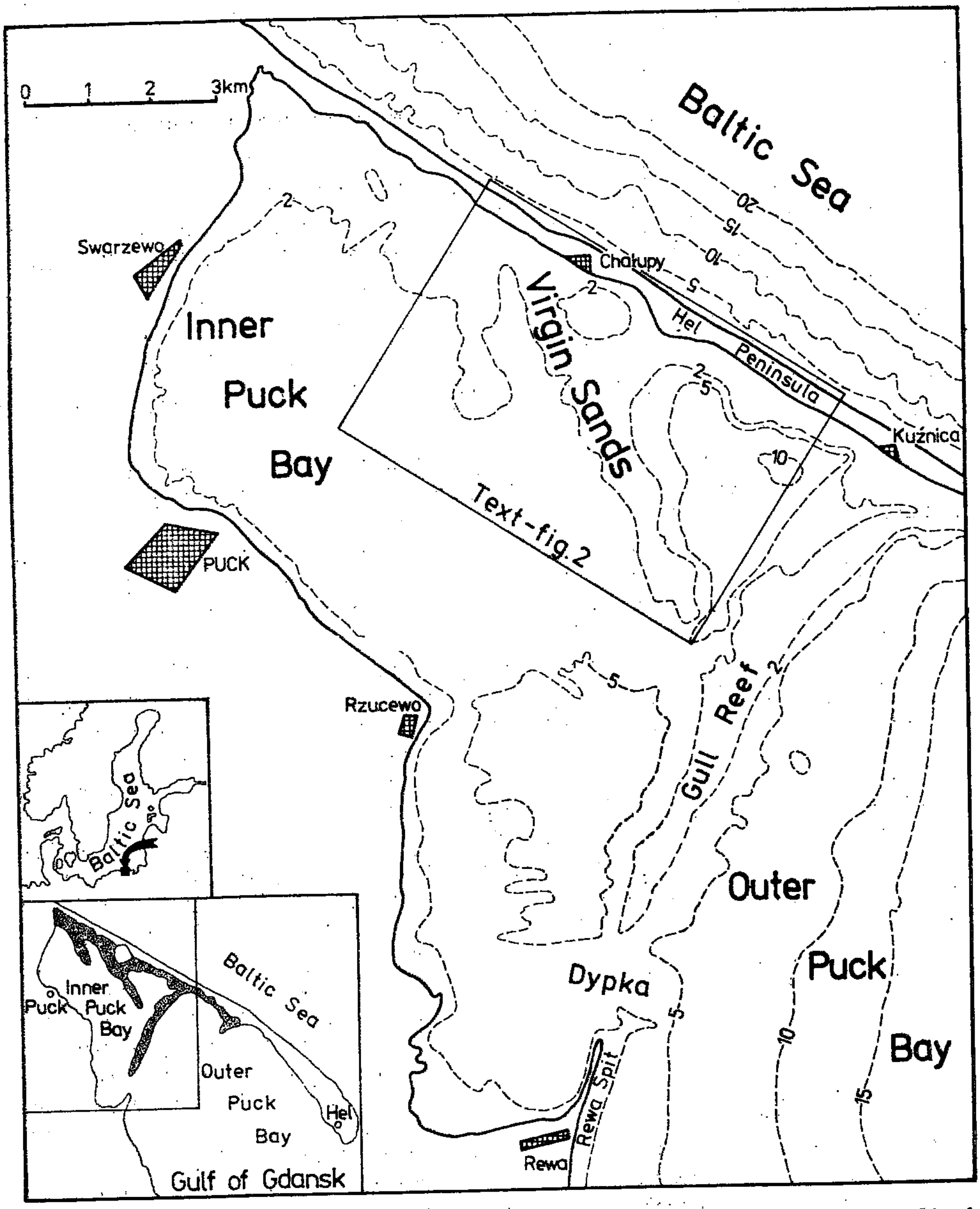


Fig. 1. General map of the Inner Puck Bay and its location within the Gulf of Gdansk and Baltic Sea

Uprisen waters in the open Baltic Sea many times tore the Hel Peninsula and encroached the Bay, as it happened for instance in 1899, 1904 and 1914 (Pawłowski 1922), and in 1939. In all these cases the strong streams of the water transported big masses of the sand from the open Baltic Sea into the Inner Puck Bay.

Waters in the Inner Puck Bay are desalted and their temperature in winter oscillates about 0°C. That is why the surface of the Bay for nearly two months in the year is covered with ice.

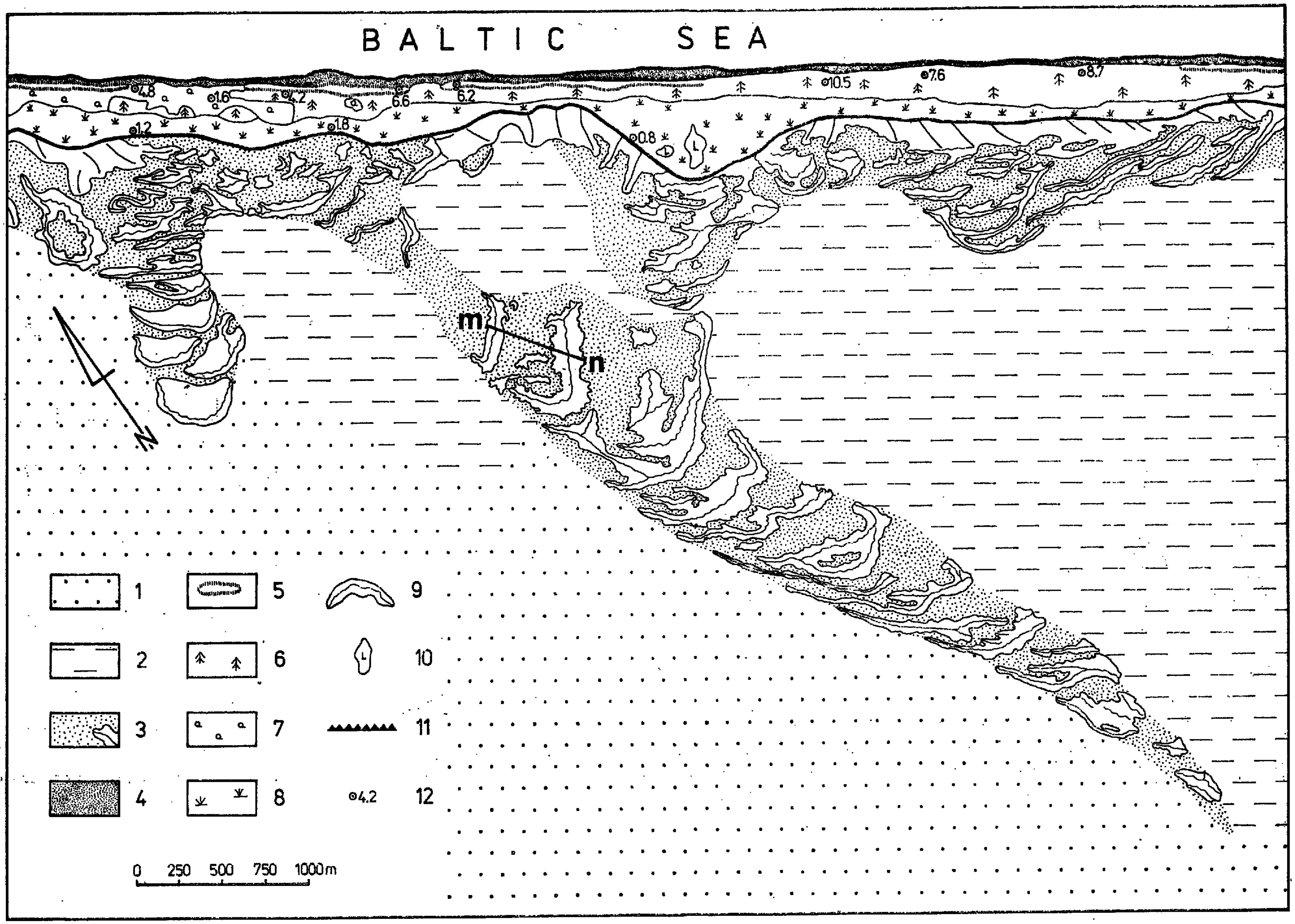
SEDIMENTOLOGICAL FEATURES OF THE VIRGIN SANDS

The Virgin Sands create a sand bar with a morphological axis running from NNW to SSE (Text-fig. 2). The north-east border of the Virgin Sands is very distinct: the slope is steep and 50 m from the edge the depth increases from 2 to 5 m. The south-west border is poorly visible, in many places eroded, and conventionally situated along the isobath 2 m b.s.l. On that side the depth increases very slowly and often several hundred metres from the axis of the bar the depth is less than 3 m.

The surface of the Virgin Sands is covered with extensive megaripples (Text-figs 2—3). In the aerial photograph, there were distinguished 15 big and several smaller mesoforms, the shape of which is similar to that of parabolic dunes, with one or two horns far behind the frontal part. The crests of megaripples are at a depth of 0.5—0.8 m b.s.l., and parts between them are rarely deeper than 1.5 m. Generally, the depths above these mesoforms in the northern part of the Virgin Sands are smaller and increase along the axis of the sand bar to the south.

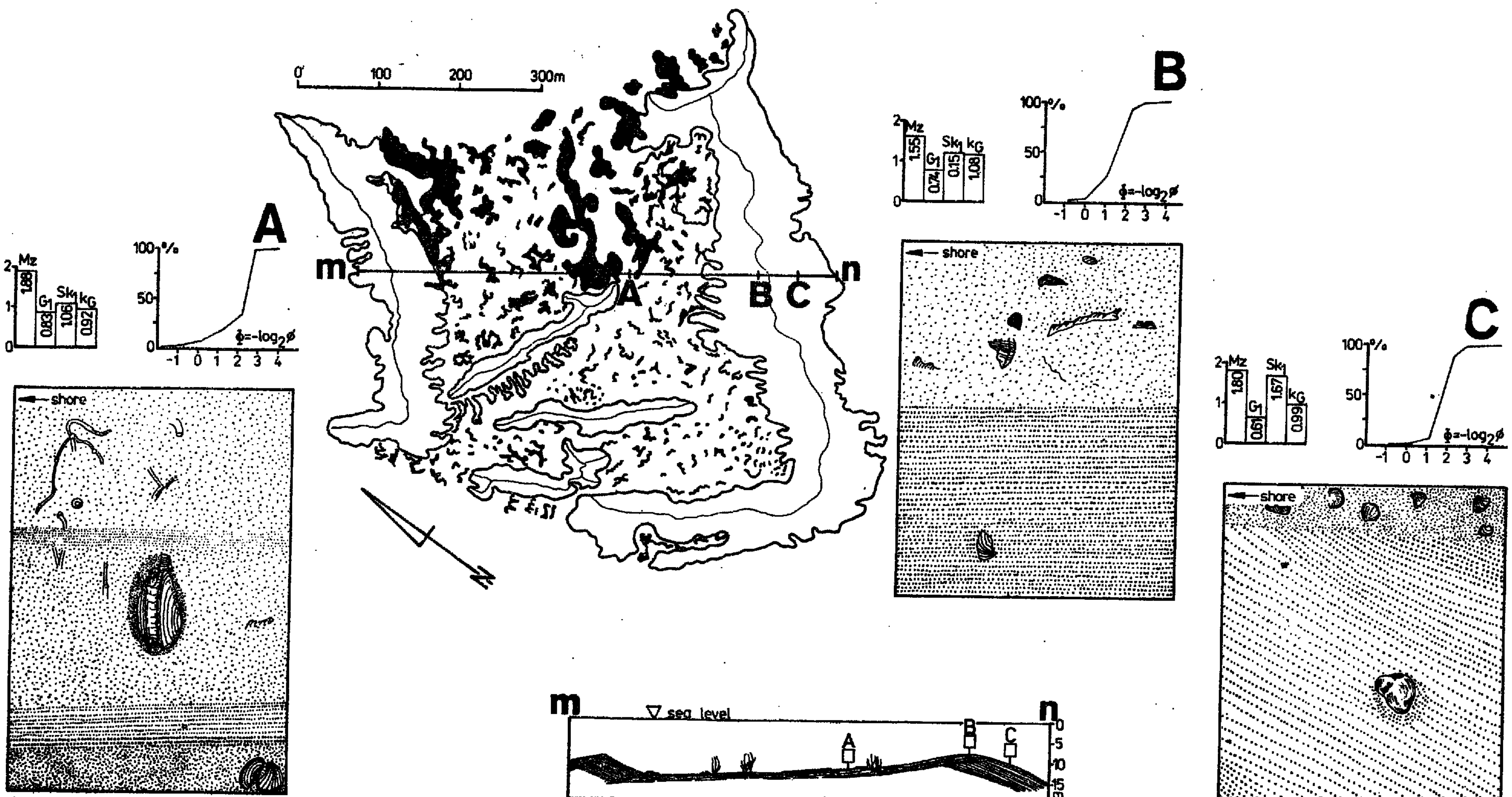
Measurements on stereoscopic photographs and surveyings of depths from the boat show that frontal slopes of megaripples are short and steep (Text-fig. 3). The distal slopes are nearly horizontal, very vast, reaching the frontal part of the next mesoform. On aerial photographs, the distal slopes are covered with dark spots masking their sizes and relief of the bottom. From the direct underwater investigations it is apparent that these areas are covered with organic detritus and shell debris or overgrown with meadows of seagrass *Zostera marina* and algal mats. These mats of thickness 0.5 cm, are composed of fine- and medium-grained sands incrusted with algal filaments and packed with faecal pellets. Roots of seagrass stabilize the sand on the distal slopes of megaripples and the mats compose a screen isolating deposits from an influence of inactive waters. The crests are devoid of vegetation and are well visible against their background. The relief of crests is very diversified, featured by waving and currents which produce wave and current ripples respectivelly. The ripples developed in the marginal parts of crests are usually represented by asymmetrical straight-crested small ripples, which in shallow water change into undulatory sinuous ones. Ripples existing on the surface of the central part often are rebuilt by waves into symmetrical wave ripples with essentially straight crests nearly devoid of bifurcations. They are only few centimetres high, but their crests can be traced for distances up to 6 m. In deeper places on the eastern side of the Virgin Sands, small-scale current ripples (mainly undulatory) or even linguoid-shaped ripples appear.

Sketch map of the Virgin Sands and a part of the Hel Peninsula



1 central part of the Inner Puck Bay with fine-grained sands; *2* depressions with muddy and silty cover; *3* underwater washover fans and bars (sands); *4* sandy beach of the open sea; *5* present dunes; *6* aeolian sands covered with forests; *7* aeolian sands covered with bushes; *8* marshes on washover fans (sands and/or peats); *9* crests of megaripples; *10* lakes; *11* cliffs; *12* height above sea level in metres; *m—n* denotes the section of megaripples presented in Text-fig. 3

Structure of the megaripples in a part of the Virgin Sands



Morphological scheme presented in the middle; cross-section (*m—n*) the same as indicated in Text-fig. 2

A, B, C — Structure of sediments taken with case-core sampler, and histograms of mean size (*Mz*), standard deviation (*G*), skewness (Sk_1), kurtosis (k_G), and curves of grain size frequency

An important factor in modelling of the mesoform crests seems to be the ice, which during harsh winters is able to freeze into sediment. In early spring, the ice-cover of the Inner Puck Bay is broken by wind into pieces. These pieces of ice, during strong winds, are introduced into the Outer Puck Bay (Rudowski 1972). The ice not only erodes obstacles on its way, but also transports any macroclastic material throughout the Puck Bay. Several samples taken from an area of the Virgin Sands contain pebbles which were brought over by drifting ice-floes (*see* Text-fig. 3C).

Bedding in deposits of the Virgin Sands is poorly visible, and a more distinct picture is received by consolidation of box samples with epoxide resin (*see* Text-fig. 3). These samples were taken by the case-core sampler, undisturbing the structure of the deposits. Where layers are visible, they are very indistinct and made up of homogeneous sands, often with chaotic disposition of grains. The analysis of bedding in samples taken from the distal slopes of mesoforms is obscured by frequent bioturbations. Sometimes, on the bottom or inside the deposits there appear accumulated huddles of pelecypod shells, or specimens of *Mya arenaria* in their life positions (Text-fig. 3A).

The internal structure of the Virgin Sands bar was recognized by a borehole. The core, 12.80 m long, is lithologically homogeneous and composed of greyish-yellow sands, mainly devoid of fauna. Only in one layer (12.05—10.25 m) were found fragments of redeposited fauna of Tertiary age with an admixture of peat detritus. In the top part of the core the pebbles and debris of recent fauna were stated.

The megaripples on the surface of the Virgin Sands were examined to recognize whether there is any movement of them as a whole. The aerial photographs of the Virgin Sands bar, taken at interval of one year, as well as underwater investigations which show that the megaripples are overgrown with algal mats and seagrass stabilizing the sand, and finally the size of the megaripples in comparison with the depth and hydrodynamic activity in the Inner Puck Bay, suggest that at present the megaripples are stable. Only the crests of the megaripples are modified by the ice and weak currents or waving.

ORIGIN AND DEVELOPMENT OF THE VIRGIN SANDS

There are two different stages in the development of the Virgin Sands. The first stage, of a longshore barrier (Text-fig. 4A), is closely connected with the development of the Hel Peninsula, and its origin is very similar to the origin of the Gull Reef. The second stage concerns in development of megaripples on the surface of the Virgin Sands.

In the Preboreal time during the lowest level of the sea (*Yoldia* Sea), and at the beginning of the *Ancylus* Lake, the area of the present Puck Bay emerged above the sea surface as an area of swamps. The peat layer of that time is known over the whole bottom of the Inner Puck Bay, and its age is assessed at about 8000 years BP (Rosa & Wypych 1972).

This peat rests upon the Pleistocene deposits and is covered by silts and sands, sometimes mixed with peat.

From the borehole drilled in the Hel Peninsula it is known that on the layer of a Pleistocene till there rest fresh-water deposits of the *Ancylus* Lake. The foraminifer fauna (Dmoch & Wilczyński 1972) and the diatom flora (Bohr & Sokół 1972) date these deposits to the youngest

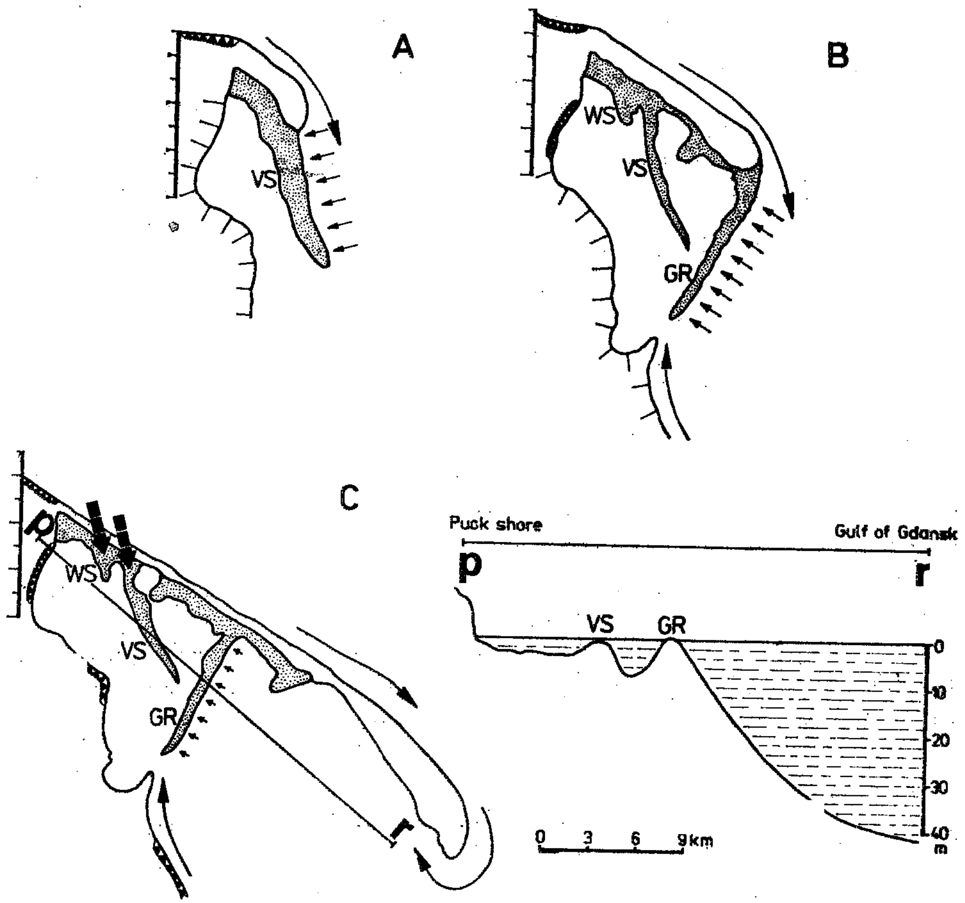


Fig. 4. Development of the Hel Peninsula and its sandy longshore barriers in the Holocene

A — Origin of the Virgin Sands as a longshore barrier; early phase of the *Littorina* Transgression; sea level about 8 m below present sea level
B — Origin of the next longshore barrier (Gull Reef); ended before the maximum of the *Littorina* Transgression, more than 3000 years BP
C — Origin of the younger part of the Hel Peninsula during the maximum of the *Littorina* Transgression, resulting in the present-day situation

Cross-section (*p*—*r*) presents the bottom configuration in the Puck Bay

VS — Virgin Sands; **WS** — Western Sands; **GR** — Gull Reef; long solid arrows — longshore currents; short solid arrows — waving; heavy dashed arrows — places where uprisen waters flow over the Hel Peninsula period of the *Ancylus* Lake in the Boreal time. Over the *Ancylus* deposits there rest deposits of the Atlantic time connected with the *Littorina* Transgression, and these are well documented by marine fauna and flora. In the layer at 40 m depth, both the diatom flora and foraminifer fauna disappear entirely and character of deposits changes, what is sometimes explained by the emersion of that initial part of the Hel Peninsula. At 14 m depth, there is a layer of peat and since that point undoubtedly the initial part of the Hel Peninsula has been emerged. The borehole was situated 6 m above sea level, what means that the Hel Peninsula started to emerge when the sea level was 8 m below present sea level.

In that early stage of its development, the Hel Peninsula was created as a longshore barrier on the edge between very shallow part of the sea in the south and a part, where the bottom steeply dipped to the north toward the open Baltic Sea. When a spit of the Hel Peninsula reached a place where the edge divides into two branches, one which dips slightly to the east and second nearly horizontal running to the south, a barrier of the Virgin Sands started to develop on that southern edge (Text--fig. 4*A*).

When the *Littorina* Transgression progressed and the sea level rose up, the further development of the Hel Peninsula to the east cut off an influence of hydrodynamics from the open sea in the region of the Virgin Sands and stopped their development.

At the moment, while the spit of the Hel Peninsula reached the next point where the main edge divides into two branches, one is running to the south and on that was built the longshore barrier of the Gull Reef (Text-fig. 4*B*). It was originated mainly by the shore transport and accumulation of sands and gravels washed away from the southern coast, but also with sand delivered by longshore drift along the Hel Peninsula. The second branch of the edge on which developed the Hel Peninsula rapidly dips in that point to the east and finally disappears completely.

Towards the maximum of the *Littorina* Transgression, about 3000 years BP with sea level 2 m b.p.s.l. according to Wypych (1974), or about 4000 years BP with sea level 2 m a.p.s.l. (Rosa 1967, 1968), the youngest part of the Hel Peninsula began to develop. The sand carried by the strong littoral drift toward the Gulf of Gdansk was accumulated on the submarine slope, forming the present-day state of the Hel Peninsula (Text-fig. 4*C*). This development put the end of dynamic system in the region of the Gull Reef and gradually stopped its development. In the post-*Littorina* period, when the sea level became stable again, the Hel Peninsula continued to grow only by aggradation (Rosa & Wypych 1972).

The origin of the megaripples on the Virgin Sands is connected with catastrophic breaks of the Hel Peninsula by uprisen sea waters of the open Baltic Sea. There are sections devoid of dunes and cliffs on the northern coast of the Hel Peninsula (*see* Text-fig. 5), and they are potential regions of frequent and big breaks. As a result of rapid overflow, loose sands are taken from the Hel Peninsula into the Inner Puck Bay. The biggest possibility of the great break of the Hel Peninsula is during the early spring storms. At the same time the ice which covers the Inner Puck Bay is broken by strong western winds (Zakrzewski 1979). Ice-floes, transported by wind to the east, meet the Virgin Sands and Western Sands, and form banks 5 m high (Text-fig. 6) creating the corridors along the bars (Text-fig. 5). If a huge break takes place at that time these corridors could help in holding a direction, given to waters with sand by gorge-like canal throughout the peninsula. This sort of current after overflowing and breaking the Hel Peninsula is responsible for the creation of the megaripples on the Virgin Sands. The present-day

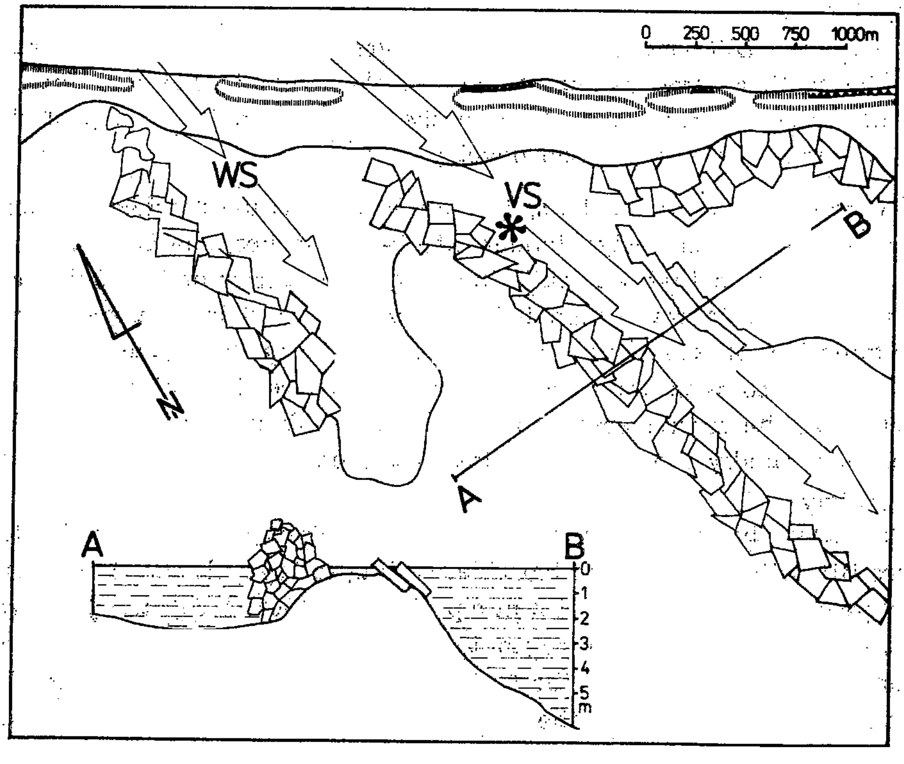


Fig. 5. Formation of megaripples on the surface of the Virgin Sands and of the Western Sands by streams (indicated by arrows) originated by uprisen water in the open sea and encroaching, crosswise the Hel Peninsula, into the Inner Puck Bay where they flow along ice-floe banks (*cf.* Text-fig. 6; the place of taking photos is asterisked)

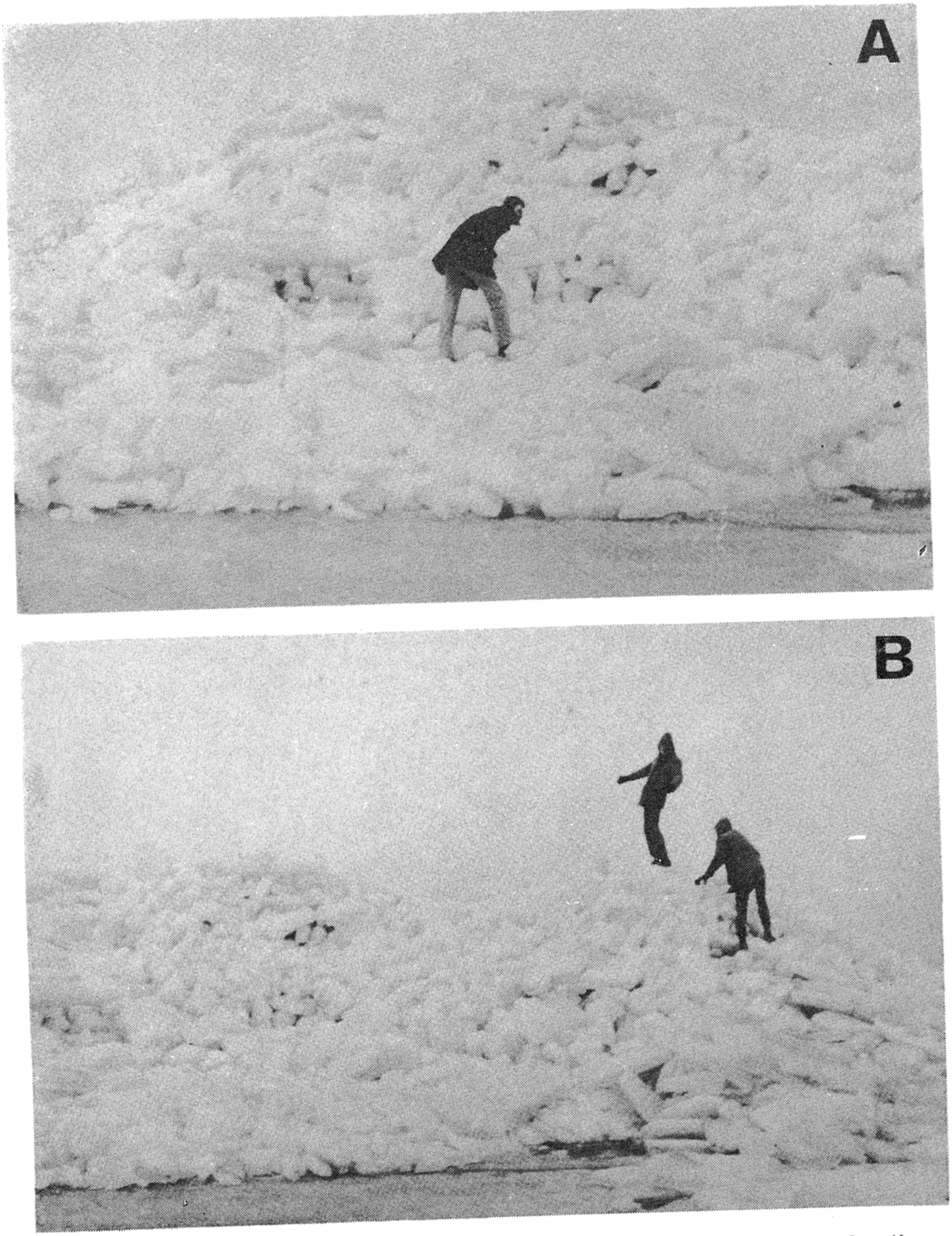


Fig. 6. **A** — View of the ice-floe bank situated along the Virgin Sands (for location *see* Text-fig. 5); **B** — Another view of the same ice-floe bank

state of the megaripples is thought to be the effect of the huge break, which happened a few centuries ago when the sands of the Hel Peninsula were not artificially reinforced.

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C. FILIPOWICZ

ROZWÓJ BARIERY PIASKÓW DZIEWICZYCH W WEWNĘTRZNEJ ZATOCE PUCKIEJ

(Streszczenie)

Praca niniejsza przedstawia charakterystykę sedymentologiczną oraz rozpatruje przyczyny powstania i drogi rozwoju wału akumulacyjnego zwanego Piaskami Dziewiczymi, a zlokalizowanego w Wewnętrznej Zatoce Puckiej (*patrz* fig. 1—3).

Rozwój Piasków Dziewiczych był dwuetapowy. Etap pierwszy, utworzenie wału akumulacyjnego, związany był z transgresją litorynową na południowe brzegi Bałtyku i pozostawał w ścisłym związku z rozwojem Półwyspu Helskiego (*patrz* fig. 4). Etap drugi, to utworzenie pręg poprzecznych (*megaripples*) na powierzcchni wału Piasków Dziewiczych. Odpowiedzialne za ich utworzenie wydają się być spiętrzenia wiatrowe wód przy północnym brzegu Półwyspu Helskiego, w wyniku których następują przerwania półwyspu przez wody wnoszące do Wewnętrznej Zatoki Puckiej znaczne ilości osadu. Okres wiosennych sztormów jest najbardziej sprzyjający takim przerwaniom, a wtedy w Wewnętrznej Zatoce Puckiej spotykane są torosy lodowe (*patrz* fig. 6), zbudowane ze spiętrzonych wiatrem kier lodowych, a ułożonych wzdłuż podwodnych wałów (*patrz* fig. 5). Wkraczające do zatoki wody, wykorzystując takie korytarze, tworzyły prądy osadzające piasek w postaci pręg poprzecznych na całej powierzchni wałów Piasków Dziewiczych i Piasków Zachodnich.
