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Barrier island on the Gull's Reef (Puck Bay, Polish Baltic Coast)

ABSTRACT: The paper deals with structure and stages of development of a short--lasting barrier island in the Puck Bay on the Baltic Coast. This form originated exclusively from wave processes acting together with changes in level of the Puck Bay waters, related to wind and atmospheric pressure influence, and without a contribution of longshore currents. Its deeper part, formed by waves under constant submersion conditions appears to be structurally different from surfacial parts, which are genetically related to action of waves and surf on the emerging barrier. Morphology, structure, and ripple marks formed along the inner side of the barrier island appear very close to those of tidal flat environment.

INTRODUCTION

In the Puck Bay there occur a few banks, genetically related to the previous, Late Pleistocene and Holocene stages of development of this part of the Baltic Coast (*cf.* Rosa 1968). The Gull's Reef (*Rewa Mew* in Polish; *cf.* Figs 1—2), the largest of these banks, runs across in the Puck Bay; it represents an old, submerged bay bar, formed during the great Holocene transgression of the southern Baltic (*cf.* Rosa & Wypych 1972b).

At present, ephemeral barrier islands are frequently formed on the Gull's Reef, and they result from wave action and changes in water level of the Puck Bay. The latter changes are related to wind effects and changes in atmospheric pressure; maximum difference in water levels approximates herein 1.2 m (Janik 1962).

The discussed barrier island is the only large-sized form, which originated in the last years. It was formed in spring 1968 in the part of the Gull's Reef situated close to the Hel Peninsula (Fig. 1); it attained its maximum size in August and underwent destruction by storm waves and ice-floe fields during autumn and winter. The forms, which occurred in subsequent years were much smaller in size and lasted much shorter, which precluded any supplementary observations.

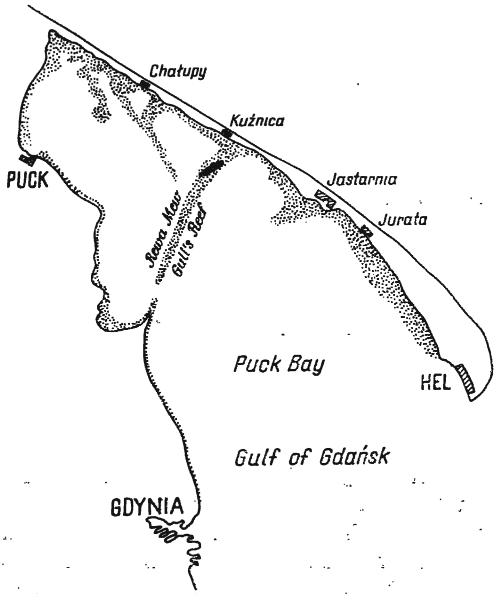

Fig. 1

Sketch map of the Puck Bay; dotted areas — parts of the bottom situated above 2 m isobath, in black — area of the barrier island emerged in August 1968

Although studies on barriers are rather numerous (*e.g.* Johnson 1919; Thompson 1937; Evans 1942; Zenkovich 1946, 1962; Mc Kee 1953, 1957; Botvinkina & *al.* 1954; Leontev 1955, 1961; Ulst 1957; King 1959; Gierlöf-Emden 1961; van Straaten 1961, 1965; Longinov 1963; Hoyt 1967; Davis & Fox 1972; Davis & *al.* 1972), their inner structure is still poorly known (*cf.* Botvinkina 1962, Price 1968, Allen 1970). This primarily results from the lack of opportunities to study the barriers which are commonly submerged or covered with beach or eolian sediments. When their inner structure was exposed, it appeared highly complex (*cf.*, e.g., van Straaten 1963). In the latter case, besides waving, littoral currents and tidal processes contribute to barrier formation; this makes it difficult to estimate the actual contribution of particular factors.

Such difficulties were not encountered in the case of the barrier island from the Gull's Reef. Small dimensions and almost complete emersion of the form remarkably facilitated studies of its inner structure in particular stages of development. Moreover, as it was stated above, this barrier originated exclusively from wave processes acting together with changes in water level of the Puck Bay.

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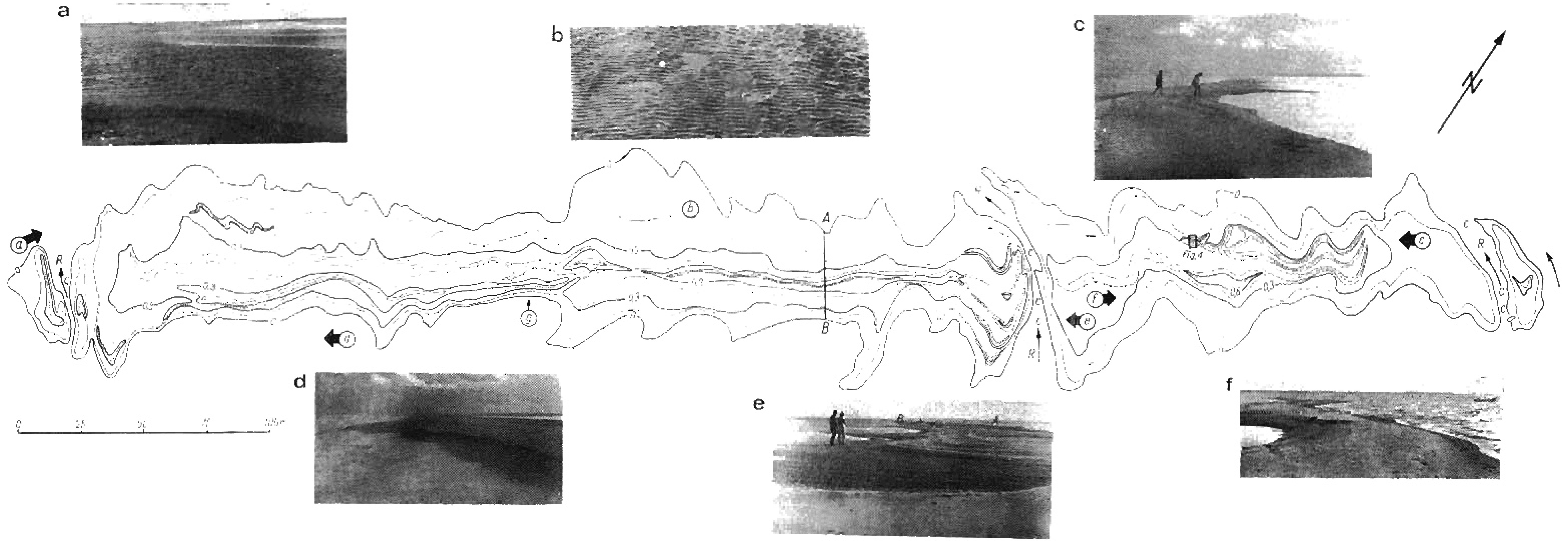
MORPHOLOGY OF THE BARRIER ISLAND

The barrier island [1] (Fig. 2), in its stage of maximum development, attained *c.* 600 m in length, 80 m in width and was rising up to about 1 m

[1] Terminology concerning littoral zone forms and processes is accepted after referenced papers (Rudowski 1962, 1970; Shepard 1963; Price 1968; Allen 1968; Davis & Fox 1972).

Plan of the barrier island on the Gull's Reef

(taken by simplified photogrammetric methods on August 10th, 1968)



Continuous lines — isohypses (heavy lines every 30 cm, thin lines every 15 cm). Beach-ridge crests dotted; arrows indicate direction of currents in inlets; *R* — rhomboid ripples, *C* — current ripples (ordinary and linguoid), *A-B* — line of cross-section in Text-fig. 3; rectangled is the trench, a part of which is presented in Text-fig. 4

Lettered circles (*a, b, c, d, e, f, g*) indicate places of photographs, the direction of which is arrowed

a — general view on the barrier island from its SW end; small-scale inlet in the front, Hel Peninsula in the background; *b* — asymmetrical wave ripples with space of c. 10 cm; flat-topped ripples observable at lower left; *c* — general view on the barrier island from its NE end; numerous promontories and small embayments on the right side, a few beach ridges in the center, moraine plateau of Gdynia in the background; *d* — margin of the barrier island, seen from the Gdańsk Gulf during backwash of waves: narrow, relatively steep foreshore beach and small beach microcliff; *e* — one of the inlets cutting the island, inlet bottom covered by small, ephemeral linguoid ripples; in the background, a few beach ridges with sinusoidal crest course (Gdańsk Gulf to the left); *f* — NE end of the island (Hel Peninsula in the background); *g* — site of the trench presented in Pl. 4, Fig. 1

above water level and up to 1.3 m above the bottom in its NW part. Its shoreline was highly differentiated, with numerous embayments and promontories (*c* and *f* in Fig. 2) up to 20 m in length. The island was cut in a few places by small shallow inlets, with slow currents, formed by waves and uprush flowing over the island coming from the Gdańsk Gulf.

Foreshore beach belt, delineated by 15 cm isohypse, continued along both sides of the barrier island. Beaches of SE island side were narrow (*d* in Fig. 2) and sloping at an angle from 3° to 5°, 10° at the most. Well-marked beach step, 15 cm in height, separated the beach from the adjoining, gently sloping bottom, with depth up to 0.5 m. Beaches from the opposite side of the island were wider, almost flat (*c* in Fig. 2), and gradually passing into shallow bottom, *c.* 20 cm in depth, sloping at an angle from 1° to 2°.

The beaches were overtopped by gentle slopes, passing upwards into wide, broadly rounded sinuous crest (*f* in Fig. 2). On the island surface there occurred numerous beach ridges (*c* and *e* in Fig. 2), usually with strongly curved crests and short distal slopes, up to 20 cm in height. The beach ridges were distributed in a few belts, stretching at different altitude. Together with small-sized abrasional undercuttings, they marked successive stages of emergence of the barrier.

Inner lagoons (*cf.* Gierlof-Emden 1961) were scattered in the island crest part. Lagoon margins were often covered by accumulation of detritus of plants overgrowing adjoining parts of the bay bottom. These lagoons and lowermost beach ridges relatively quickly underwent modification or destruction when hydrodynamic conditions changed. Consequently, these lagoons were commonly short-lasting and soon infilled by uprush deposits.

Gull pellets

Accumulation of gull pellets was stated in the uppermost part of the barrier island (Pl. 4, Figs 2—3). These pellets were spherical, 3 to 4 cm, and occasionally up to *c.* 5 cm in diameter, and usually built of crushed shells of the mussel, *Mytilus edulis*, innumerous fragments of the cockle, *Cardium edule*, and of sand and small pebbles. Fish remains were represented in these pellets in insignificant amounts. The pellets made almost exclusively of fish bones and vertebres, with minor contribution of sand, were recorded only a few times; however, they are rather not stable, and desintegrate when they get dry.

STRATIFICATION

Inner and upper parts of the barrier island reveal markedly different structure, which appears to be related to particular stages of island evolution. The inner part, being the base of the form, represents a part of an older bar, formed under continuous submersion conditions during high storm water level. This part was built of cross-strata a few centimeters thick and up to 7 m long, slightly convex and gently inclined at an angle up to 3°, usually in two directions. The strata diagonally approached the lower surface of sets, at an angle up to 5°; in sets of cross-strata sloping towards SE, to the Gdańsk Gulf, tangential arrangement was often found.

The sets were in the form of long, weakly concave-convex lens (Fig. 3) and sometimes in the form of elongated, flattened wedges. In the latter case the lower surfaces of the sets were flat and erosionally truncating underlying layers. The sets were *c.* 20 cm thick at the average. Both cross-strata and sets extended at a remarkable distance along the axis of that form. In the cross section they were almost horizontally oriented.

The sets were mostly built of fine- to medium-grained, medium-sorted sands. However, they were found some differences in grain-size distribution and sorting, depending on the position of a sample in transversal cross-section of the form. The finest fraction and best sorting were found in top parts of lens-like sets, which correspond to the crest of the originating form. Grain size was progressively increasing, whereas degree of sorting progressively decreasing along with sloping of the strata, towards SE (proximal slope of the form). Lateral, lowermost parts of the sets, and particularly these situated at NW side of the form (distal slope), were built of the coarsest, the least sorted or even unsorted material. Here, coarse-grained sands with scattered pebbles, up to 2 cm in diameter, were found.

Lowering of the water level in the bay enabled emergence of the bar. This was followed by initiation of surf activity on margins of the bar. Shore processes formed the upper part of the island, markedly separated by erosional boundary from its inner part (Fig. 3). In this stage, beaches and numerous beach ridges (Fig. 4 and Pl. 4, Fig. 1) with stratification typical of such forms (*cf.* Thompson 1937, Mc Kee 1957, Botvinkina 1962) originated. The beaches and beach ridges were built of sands of variable size and sorting. Here, also some cross-strata of unsorted coarse sands and fine gravels with single pebbles, up to 5 cm in diameter, were found. Locally, small accumulations of plant detritus were encountered. Stratification of that part of the island differed from that of the former primarily in more steeply inclined

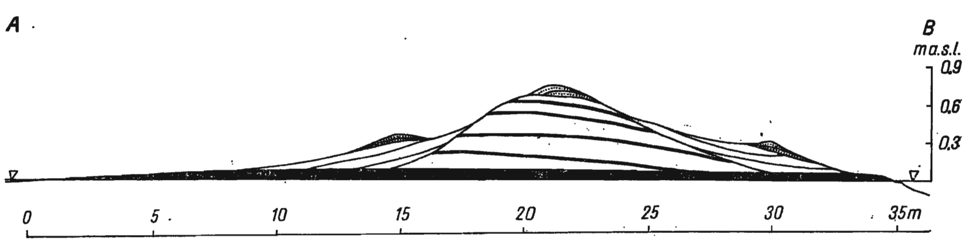


Fig. 3

Sketch section (*A-B* in Text-fig. 2) across the barrier island

Black areas — saturated sediments; haevy lines — boundaries of sets formed in continuous submersion during storms; thin lines — boundaries of sets subsequently formed by waves and uprush; dotted — small beach ridges situated at various height and related to different stages of the barrier emergence cross-strata, generally thinner sets of strata, and in higher variability of both strata pattern and grain-size distribution. Scourings with trough-like lower surface, cor-

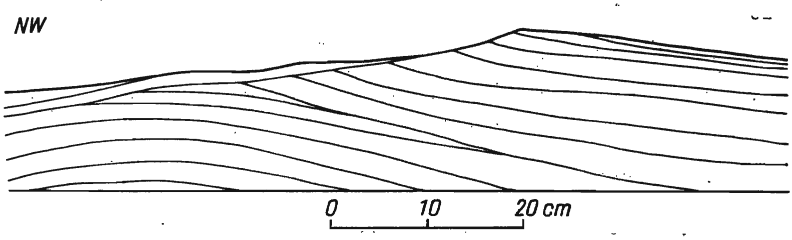


Fig. 4

Stratification of the upper part of the barrier island, from its marginal NW part; exposure in the trench (rectangled in Text-fig. 2). The core consists of small beach ridge, partly washed out by uprush. To the left, erosional surface overlaid by sediments washed out of the shore and deposited herein by backwash of waves

responding to small-scale inlets or axes of small embayments, as well as convex, lenses-like sets corresponding to elongated promontories, were quite common.

The presented barrier island appears highly similar to bars from the coasts of the Black and Azov seas (*cf.* Shurko 1961) both in the structure of inner and upper parts, somewhat differing from the latter in its upper part being proportionally thicker and devoid of layers rhythmically stratified or enriched in heavy minerals. These differences are presumably related to quicker and more intense formation of the form under discussion and its uninterrupted emergence without any longer periods of stabilized conditions (*cf.* Zenkovich 1946, 1962; Leontev 1961; Longinov 1963).

The structure of a number of barriers known from the coasts of numerous aquens (Thompson 1937; Mc Kee 1953, 1957; Botvinkina & *al.* 1954; Ulst 1957; Shurko 1961; Reineck 1963; Hoyt 1967; Davis & *al.* 1972) appears highly similar in the structure of their upper parts to the Polish form.

SMALL-SCALE RIPPLES

All the ripples were studied on island beaches and adjoining shallow bottom. No ripples were reported from more elevated parts of the island. Ripple forms formed during earlier stages of development, when water level was higher, underwent destruction due to action of uprush in subsequent stages.

Asymmetrical wave ripples markedly predominated over the area studied. Other ripple types, such as current ripples, ordinary or linguoid and rhomboid ripples, were only found in small areas of small-scale inlets and their outlets from inner, NW side of the island. Ripples from opposite sides of the island appeared to be markedly different (*cf.* Table 1).

Table 1

Measurements of wave ripples within beaches of barrier island and in shallow bottom of the Gull's Reef

Ripples	Dimensions /cm/ s	h	c	Indexes RI= s/h	RSI= l_1/l_2	CI= c/s	SI= l_d/d
Asymmetrical wave ripples /SE part of island/	15–20	2–3	50–10^2	~5	< 5	~5	10–50
Asymmetrical wave ripples /NW part of island/	10–15	1.5–3	50	< 5	2–3	< 5	5–10
Asymmetrical ripples formed by translation waves /NW part of island/	8–10	1–1.5	< 50	5–10	3–5	~5	~5

Dimensions (mean): *s* — space, *h* — height, *c* — crest length. Indices: *RI* — ripple index, *RSI* — ripple symmetry index (l_1 — vertical projection of stoss side, l_2 — vertical projection of leeside), *CI* — continuity index, *SI* — straightness index (l_d — length of bending crest, *d* — radius of bending crest)

Asymmetrical wave ripples

These ripples were represented by small, short-crested forms, with numerous branchings (Table 1) and with crests markedly bent when situated close to shore line. On shallow bottom from outer, SE side of the island, only common asymmetrical wave ripples were recorded. Those ripples appeared indentical with those found in the shallowest parts of the Baltic inshore (*cf.* Rudowski 1970), formed close to shoreline during the lowest water stages.

Asymmetrical wave ripples recorded from the bottom of the opposite side of the island appeared to be more differentiated. They matched the characteristics of shallow water ripple-mark varietes distinguished by Tanner (1960, 1963). Besides common asymmetrical wave ripples, the asymmetrical ripples formed by translational waves were also found (*cf.* Rudowski 1970).

Even a small drop in water level resulted in transformation of the ripples from the bottom of the inner side of the island. This transformation concerned the flattening of crests (*cf.* Tanner 1958), their disruption, and the extension of their shore oriented parts. Progression in lowering of water level often leads to exposition of vast areas of almost flat bottom, already covered by ripples (Fig. 2*b;* Pl. 1, Fig. 2; Pl. 2; Pl. 3, Fig. 1). Ripples, and particularly their furrows, were as a rule covered by a thin silty layer. In places, small, incomplete asymmetrical wave ripples, built of sandy crests were formed on the flat muddy bottom (Pl. 3, Fig. 1).

Current ripples

In small-scale inlets, cutting the barrier island, the currents were stated, the velocity of which was constantly changing in dependence on the intensity of surf effect on the island shores. However, these currents were always directed towards NW part of the island, where the wave action was markedly weaker.

Current ripples originating in the inlets are rather ephemeral and subjected to continuous modification conditioned by a rapidly changing water flow. Here, linguoid ripples (*c* in Fig. 2) at up to 20 cm interval, predominated. Current ripples were usually very rapidly, almost instantly transformed into linguoid ripples. In the inlets, also rhomboid ripples (Pl. 3, Fig. 2), with the longer rhomb axis up to 30—35 cm long, were formed mostly where differently oriented streamlines were crossing each other.

Current ripples of longer duration were found in NW island beaches on the extension of the inlets. There, a drop in water level was followed by the formation of temporary, shallow, poorly-developed "channels". In central parts of these channels numerous ordinary and linguoid current ripples and small-scale longitudinal ripples originated.

FINAL REMARKS

Almost complete emergence of the barrier island from the Gull's Reef gave an opportunity to study the island itself as well as the inner structure of its base. Stratification, found herein, appears the same as that found by Shurko (1961) in similar forms of the Black and Azov sea coast, and may be considered as typical of bars and submerged parts of barriers, mostly formed by wave processes.

In the barrier island studied, remarkable differences between morphology, sedimentary structures content, and structure of shores from the opposite sides of the island were noted. South-eastern shores, facing the Gdańsk Gulf, are generally identical with shores of open sea coasts; whereas, the opposite, NW island shores in their morphology, structure and ripple pattern are similar to the tidal flat areas (*cf.* van Straaten 1961) differing from the latter in much smaller scale of the phenomena found. Thus, it follows that equivalents of tidal environments may also occur, although on a much smaller scale, along non-tidal coasts (*cf.* Leontev 1955, 1961; Davis & *al.* 1972), mostly behind barriers with a cuspate shoreline (*cf.* Zenkovich 1959).

The barrier island in question was formed exclusively by wave processes effecting a sand bank. There is no influence of longshore currents, which could supply material from adjoining coast sections.

Similar origin has recently been accepted for the majority of barrier bases formed on wide sand banks during the Flandrean transgression (Leontev 1969, Gudelis 1972). The Gull's Reef, representing one of such barriers, was previously believed to had formed mostly by longshore currents supplying material from cliffs of the Gdynia area (*cf.* Pawłowski 1922, Rosa 1963, Rosa & Wypych 1972a). However, remarkable accumulations of Pleistocene sands cannot be unequivocally excluded; such accumulations transformed by the waving greatly contributed to the formation of the Gull's Reef.

Destruction of the Gull's Reef, which, except for ephemeral barrier islands, is presently submerged under the Puck Bay waters, resulted from a change in hydrodynamic regime. This change was related to the formation of the Hel Peninsula in the post-*Littorina* period. According to the present authors, this destruction was related to remarkable decrease in wave processes rather than to a break in material supply by longshore currents (*cf.* Rosa & Wypych 1972a, b). Waves in the Puck Bay (presently attaining up to 1.0 m in height and up to 15 m in length — *cf.* Janik 1962) are sufficiently strong to scour a sand bank during storm water level; under suitable conditions, they can only built up small, ephemeral barrier islands on it. Moreover, stress of ice-floe fields during severe winters is another important destructive factor herein.

If the Gull's Reef had been formed mostly by longshore currents, then a break in material supply would have resulted in appreciable change in localization of that form, as it follows from the studies by Castanho (1965). However, this hypothesis has not been substantiated. At present, no lateral shift of the Gull's Reef was found, and only barrier islands originating and disappearing here and there generally move along and not across the form; a similar situation was noted by Davis & Fox (1962) in the bars from Atlantic coast of the U.S.A. and of the Michigan Lake. Also cartographic materials show that the position of the entire Gull's Reef has not changed during the last few centuries (*cf.* Bączyk 1963).

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BUDOWA WYSPY MIERZEJOWEJ NA REWIE MEW W ZATOCE PUCKIEJ

(Streszczenie)

W pracy rozpatrzono budowę oraz etapy rozwoju niewielkiej i krótkotrwałej wyspy mierzejowej, utworzonej w obrębie bariery zwanej Rewą Mew w Zatoce Puckiej (fig. 1—2). Forma ta powstała w wyniku działania wyłącznie procesów falowych w połączeniu ze zmianami poziomu wód zatoki, a bez udziału prądów idących wzdłuż brzegu. Stwierdzono odrębność budowy partii wgłębnej (fig. 3), utworzonej pod stałym przykryciem wody, oraz partii powierzchniowej (fig. 3—4 oraz pl. 4), utworzonej w rezultacie działania fal i potoku przyboju na wynurzającą się wyspę. Morfologia, budowa oraz inwentarz zmarszczek (fig. 2, tab. 1 oraz pl. 1—3) na brzegach wewnętrznej strony wyspy wykazują podobieństwo do analogicznych cech w środowisku pływowych równi zalewowych (*por.* Leontev 1961, Davis & *al.* 1972). Wyniki przeprowadzonych badań wskazują na istotne znaczenie procesów falowych przy formowaniu barier (*por.* Leontev 1969, Gudelis 1972). Czynnik ten powinien być szerzej niż dotychczas (*por.* Rosa 1963, Rosa & Wypych 1972a, b) uwzględniany przy rozpatrywaniu genezy i poszczególnych etapów rozwoju Rewy Mew oraz innych barier południowego wybrzeża Bałtyku.

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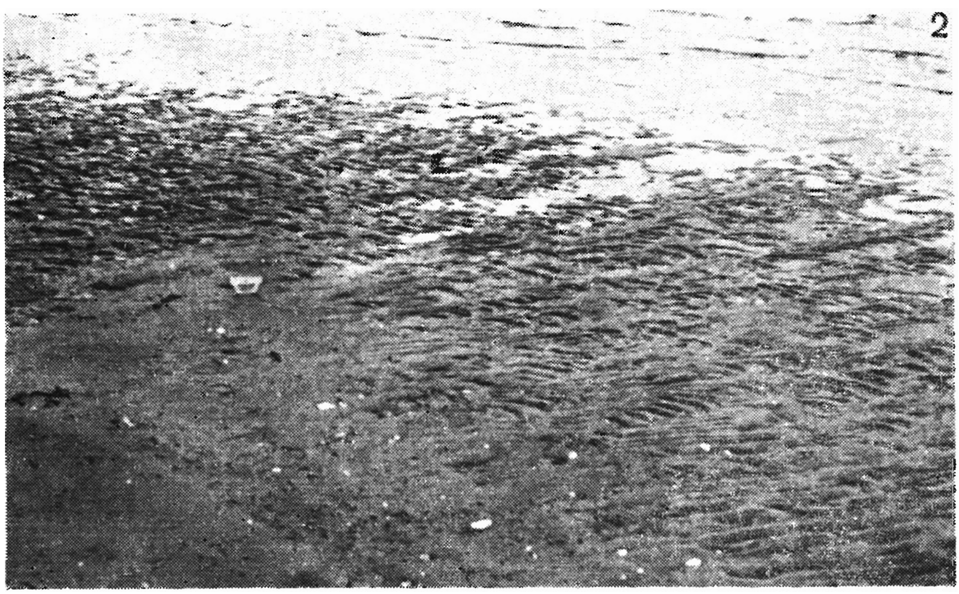
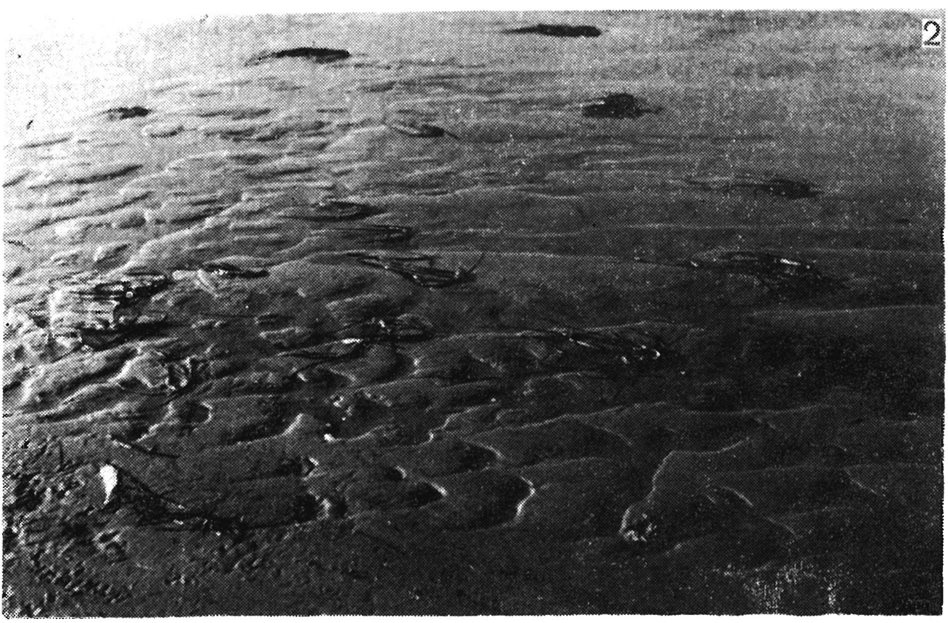


1 — Inner lagoon from SW part of the barrier island; dark streaks along lagoon and island margins — accumulations of decaying seeweeds; Gdańsk Gulf to the left.

2 — Asymmetrical wave ripple formed by translational waves and strongly modified during drop of water level in the Puck Bay. Small translational waves in the upper part of the photo; protractor 10 cm long; NE side of the island, September 1968.

1 — Asymmetrical wave ripples formed by translational waves; typical, strong bends and flattening of ripple crests in the lower part of photo. Ripple space *c.* 12 cm. Water in small depressions retained since previous, somewhat higher Puck Bay level. NW side of the island, September 1968.

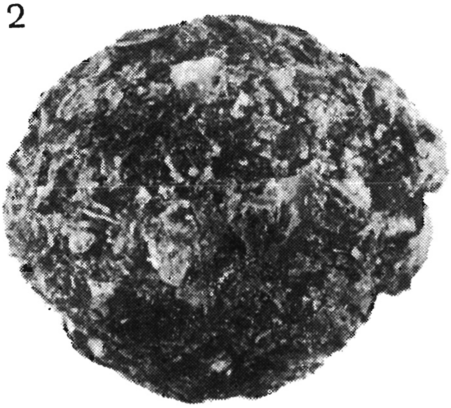
2 — Common, asymmetrical wave ripples somewhat transformed by translational waves. Ripple space *c.* 15 cm. In ripple furrows a few white shells of *Mya arenaria*. Thin layer of mud covers the ripple furrows. NW side of the island, September 1968.



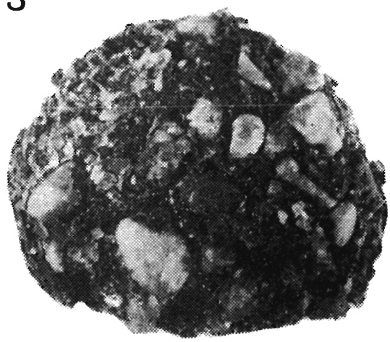
1 — Asymmetrical, incomplete wave ripples formed by translational waves in extremely shallow water. Sandy crests resting on flat, darker-colored muddy bottom; protractor 10 cm long. NW side of the island, illumination from the right; September 1968.

2 — Ripples in the inlets transversally cutting the barrier island. In the lower part, rhomboidal ripples with longer rhomb axis c. 30 cm long, partly transformed by a current; in the upper part, poorly developed linguoid ripples. Clusters of seagrass *Zostera marina* on the sediment surface. Gdańsk Gulf to the left.

2



3



1 — Section across the beach ridge (*cf.* Text-fig. 2g) from the beach facing the Gdańsk Gulf. Thin cross-strata diagonally approaching the lower surface of the set and corresponding to the distal ridge slope. Proximal slope almost completely destroyed by swash. Shovel 20 cm long.

2-3 — Gull pellets consisting of small pebbles, fragments of shells of *Mytilus edulis* and, occasionally, *Cardium edule*. Photo × 2; taken by B. Drozd, M. Sc.