discharge velocity and increased intensity of erosive processes.

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Holocene shoreline migrations in the Puck Lagoon (Southern Baltic Sea) based on the Rzucewo Headland case study

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Abstract: The results of the study indicate that the Rzucewo Headland area – a landform located on the western coast of the Puck Lagoon – has been developing under the terrestrial conditions until the end of the Atlantic period. The headland is constructed from sands and silts with organic beds. The end of the Atlantic period saw the appearance of the first pollen grains of plants which indicate human activity (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*). The sediment age and the then sea level of the Baltic Sea indicate that human activity has been taking place before the development of seal hunter's settlement, i.e. the Rzucewo Culture.

A transformation of the freshwater lake into the brackish/marine Puck Lagoon started not earlier than 5500–5000 years BP. In the Subboreal period, cliffs on slopes of the Puck Morainic Uplands started to develop and the accumulation of sands in the Rzucewo Headland began. The pollen grains of the plants relating to human activity (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*) are more numerous in the pollen spectrum. The occurrence of the plants and the approach of the Puck Lagoon shores to Rzucewo coincided with the development of the Rzucewo Culture (seal hunters) c. 4400–3700 years BP. In the last 4000 years or so, average growth of the Rzucewo Headland was c. 100 m^3/year. In the period 1958 –1997, a land growth of up to 50–80 m (on average 1–2 m/year) was noted on the northern part of the Headland.

The analysis of the geological and palynological data from the Rzucewo Headland indicates that its development has taken place under conditions of a long-drawn-out transgression. No evidence indicative of either a phased transgression or a periodical regression was found. A good compatibility of the relative sea level curve of the Puck Lagoon with the curves of the eustatic changes of the ocean indicates only a small range of vertical movements of the Earth's Crust in this area during the Subboreal and Subatlantic periods.

Key words: Southern Baltic, Puck Lagoon, Rzucewo Headland, palynology, radiocarbon dating, sea level changes, coastal processes

Introduction

The Puck Lagoon (also called Little or Inner Puck Bay) and its coast have been subject of the geological, geomorphological and paleogeographical studies for many years (Pawłowski, 1922; Rosa, 1963; Musielak, 1983; Jankowska & Łęczyński, 1993; Witkowski & Witak, 1993; Kramarska *et al.*, 1995, etc.). However there is little detailed information on the Lagoon's age, sea level changes and the development of the coast. The data relating to sea level change in the southern and south-western area of the Baltic Sea in the Middle and Late Holocene (including relatively new recent information) are not explicit and they are very often contradictory. The published curves of the relative sea level changes sometimes show oscillations of sea level of several meters in only short periods. Occasionally, such changes as have been identified have been attributed to different periods and those changes allocated into short time periods are sometimes of different in directions (e.g. Lampe, 1996; Lampe & Janke, 2000; Rotnicki, 1999; Tobolski, 1989, 1997; Wojciechowski, 1990).

The information on a shoreline displacement in the Puck Lagoon is particularly important to both paleogeographic studies and the interpretation of studies of the archaeological sites located on the shores and bottom of the Lagoon. One of the more controversial issues is whether or not there was a rapid sea level rise of c. 1–1.5 m approximately 1000 years ago (Tomczak, 1995), the potential effect of which would have been the destruction of the early mediaeval harbour in Puck (Zbierski, 1986) and the creation of an erosion platform along the Lagoon's shores (Tomczak, 1995).

Since 1984, an area of the Rzucewo Headland – a promontory located on the western shore of the Lagoon c. 4 km south-eastwards from Puck (Fig. 1) – has been of particular research interest, especially in respect of the latest phase of archaeological studies at the Neolithic site there (Król, 1997). The geomorphological, paleogeographic and palynological studies, associated with the archaeological excavations, have supplied many new data about the region (Gołębiewski, 1997; Miotk-Szpiganowicz, 1997; Bogaczewicz-Adamczak *et al.*, 1999). The Rzucewo Headland is also an important geological site for studies of the postglacial transgression of the Baltic Sea. During the geological work which was carried out on the Puck Lagoon shores, one of the youngest peats presently situated below modern sea level was found on the Rzucewo Headland (*Geodynamic Map*..., 1997). However, to date, published information on the genesis and geological structure of the Rzucewo Headland is both limited and contradictory. Musielak (1983) regarded the Rzucewo Headland as an abrasive platform covered with medium- and coarse-grained sands, in places with pebbles and boulders. By contrast, Jankowska and Łęczyński (1993) state that the Rzucewo Headland is built from sandy formations and its genesis and stability are yet to be elaborated.

The paper describes the geological structure and age of the Rzucewo Headland together with a reconstruction of its flora and environment as well as the processes of the sediment deposition in the context of changes in the shoreline position of the Puck Lagoon during the Subboreal and Subatlantic periods. On account of the continuous peat layers which are well preserved under marine sediments, this study of the Rzucewo Headland area may be an important contribution to our understanding not only of the age, the shoreline migration and the related history of the settlement on the Puck Lagoon coastline, but also of the whole Southern Baltic area.

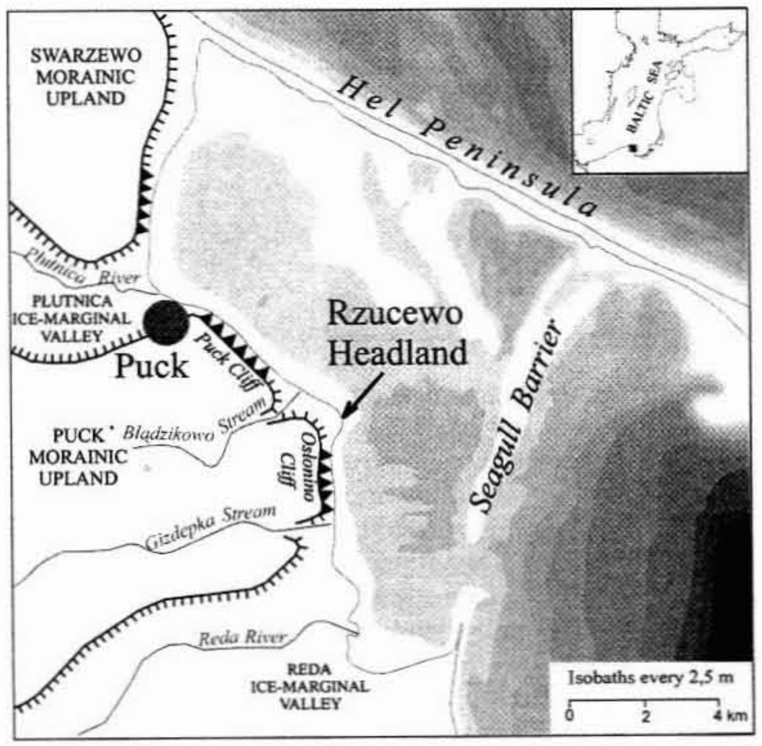


Fig. 1. Location of the studied area

Characteristics and location of the study area

The Puck Lagoon is situated in the north-western part of the Gulf of Gdańsk within the Precambrian platform at the western boundary of the peribaltic syneclise slightly east from the Łeba elevation (Znosko, 1998). The recent vertical movements of the Earth crust on the north western coast of the Gulf of Gdańsk (Puck Lagoon) are c. 0.0 to –0.5mm/year and on its south eastern coast, eastwards from Gdańsk, they are up to –2.0 mm/year. Within the Łeba elevation, uplift of up to 0.5mm/year has been detected (Wyrzykowski, 1985) (Fig. 10).

The Puck Lagoon is a small and shallow basin which is isolated from the Gulf of Gdańsk open waters by a partly submerged barrier, so-called Seagull Barrier. In the west, the Lagoon is bordered by the Puck and Swarzewo Morainic Uplands and the Reda and Płutnica Ice-marginal Valleys (Fig. 1). The Valley floors in the areas neighbouring the Lagoon lie at 0.5–1.0 m above sea level and they are generally covered by peat. The slopes of the Uplands, which are generally built from two till layers which are often separated by sands, rise to c. 5–15 m above sea level and, on three sections of a total length of c. 5 km, form an active cliff (*Geodynamic Map*..., 1997). The Rzucewo Headland is situated at the foothills of the Puck Morainic Upland and it separates the two sections of the cliffed coastline (Fig. 1). On its north-eastern, the Puck Lagoon is separated from the open sea by the Hel Peninsula, which is approximately 150 to 300 m wide. Here the Lagoon's shores are formed by numerous storm overflow cones.

The total area of the Puck Lagoon is 102.69 km^2. Its average depth is 3.13 m and its maximum depth, 9.4 m; approximately 30% of the Lagoon area is situated at 0 to 2 m depth (Nowacki, 1993a).

The average monthly temperature of the surface waters varies from 1,37°C in February to 19.06°C in August; the average yearly salinity is 7.31‰ (Nowacki, 1993a, b). In the Puck Lagoon, the number of days when the Lagoon is frozen over ranges from 0 to 125, on average it is 73 per year (Szefler, 1993).

In Puck, in the period 1951 to 2000, the average water level was 502.00 cm (2 cm above NN) and monthly average levels ranged from 488 cm in February to 510 cm in December. In Puck, an absolute measured minimum was –83 cm below the average water level and a maximum was +115 cm above. In the period 1951 to 1975, an average sea level rise was 1.1 mm/year in Puck. According to newer data, average sea level rise between 1975–2000 increased to c. 2.8 mm/year.

In the Puck Lagoon area, the winds from the western sector dominate (approximately 40–50%). Strong winds (>10 m/s) occur 60–70 days per year (Cyberski, Szefler, 1993). On the Rzucewo Headland, average wave heights at a wind speed of 15 m/s are from approximately 0.2 m with the winds N, S and W to approximately 0.4 m with the wind E and up to 0.6 m with SE wind (Jarosz, Kowalewski, 1993).

Material and methods

The geological structure of the Rzucewo Headland and its hinterland was examined by the Polish Geological Institute from 1995 to 2000. 11 boreholes were sunk to depth of 1.5 to 30 m, and two seismoacoustic profiles surveyed (Fig. 2). The seismoacoustic profiles were facilitated by a Seabed Oretech 3010-B profilegraph of 3.5 kHz

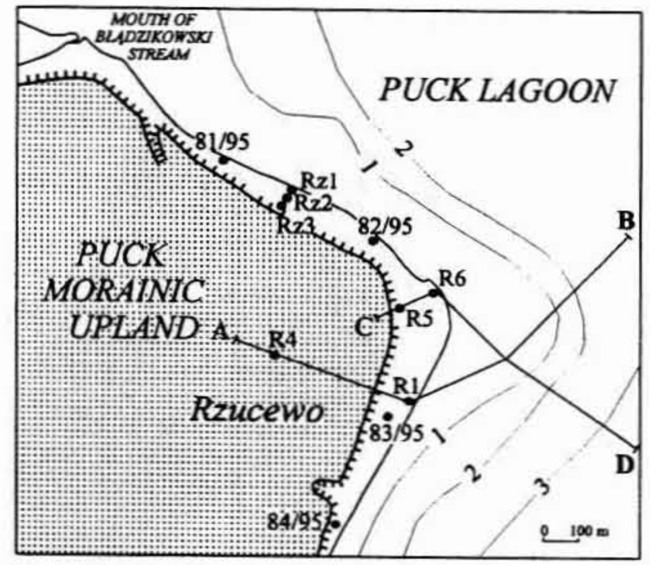


Fig. 2. Location of boreholes and geological cross-section lines

frequency. The seismoacoustic profiles were plotted using the DGPS system and the boreholes with the topographic map of 1:10 000 scale with a geodetic control of the vertical ordinates to momentary sea levels. Only the vertical controls of the Rz1, Rz2 and Rz3 boreholes (Figs. 2, 5 and 6) were determined with a geodetic control to the average sea level.

In the Radiocarbon Laboratory of the Silesian Technical University, five datings of the organic sediments from four boreholes (R1, R6, Rz2 and Rz3) were carried out, using the ^{14}C method (Figs. 2–5). Four peat samples and one sand sample with an organic matter, plant remains and *Cardium* sp. were dated. In the Leibniz-Labor für Altersbestimmung in Kiel two samples of *Cardium* sp. shells and one peat sample were dated using the AMS ^{14}C method (core Rz3). Radiocarbon dates were not calibrated and for shells marine sea water reservoir effect were not taken into account.

Eleven samples from the borehole profile R1 were taken for the palynological analysis. The laboratory analysis of the samples included subjecting them to hydrofluoric acid over 48 hours, boiling in 10% KOH and subjecting to acetolysis (Faegri, Iversen, 1975; Berglund, 1985). Up to 1000 pollen grains of trees were counted in each sample. The total of the pollen grains of trees and shrubs (AP) and of terrestrial herbaceous plants (NAP) were the basis for estimation of percentage values. The fraction of the pollen grains of water plants, telmatic plants, spores and *Pediastrum* cenobia was counted in relation to the total AP + NAP. The obtained results were presented in a percentage diagram of the pollen. Holocene subdivision is based on the work of Mangerud *et al.*, 1974.

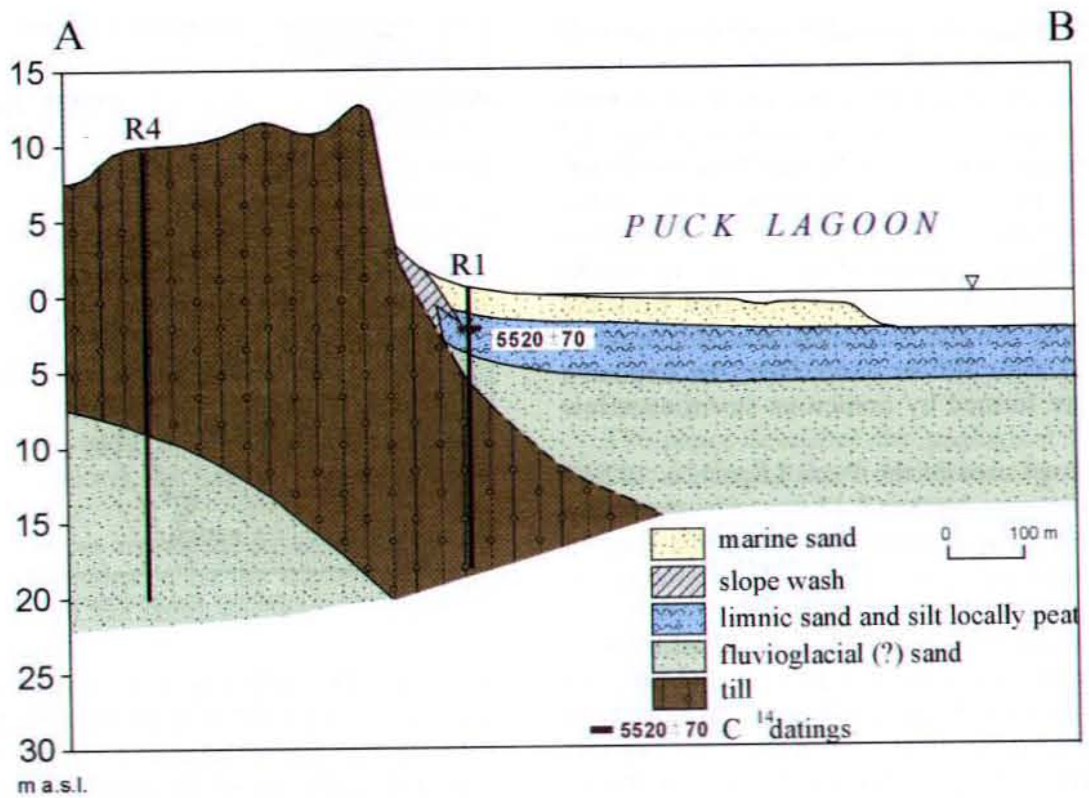


Fig. 3. Geological cross-section A–B

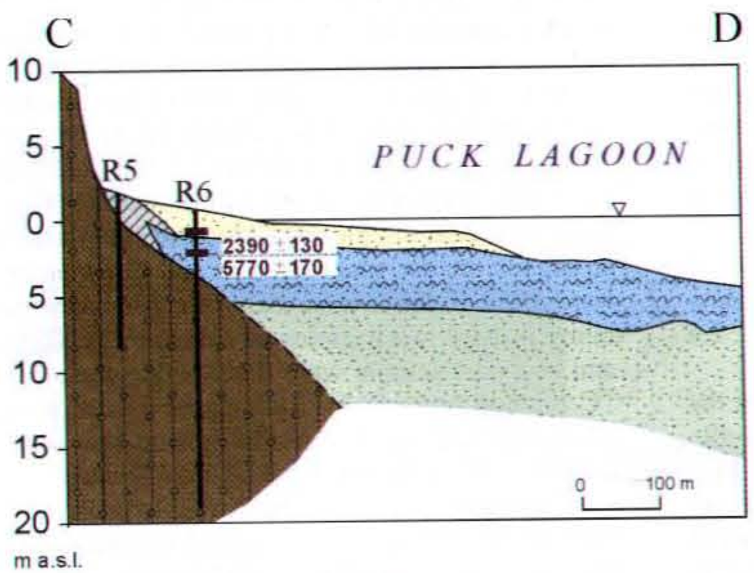


Fig. 4. Geological cross-section C–D

The samples from the R1 core were also analysed for diatoms (Witak) and ostracods (Krzymińska). However, none was found in any sample.

For the analysis of the recent changes of the shoreline, the aerial photographs of a 1:10 000 scale from 1958 and 1997 were used; the photographs were standardised and compared using Adobe Photoshop 5.0 software.

Results of the study of the Rzucewo Headland

Morphology and geological structure

The Rzucewo Headland situated on the western coast of the Puck Lagoon is a landform extending from the foothill of the Puck Morainic Upland. The surface of the Upland in the Rzucewo Headland region rises to c. 10–15 m a. s. l. and it declines towards the coast with a steep slope in till. In places, the Upland is cut by valleys, of which the Błądzikowski Stream Valley is the widest. Both to north and south of the Headland, there are narrow (several to more than ten meters) erosive plat

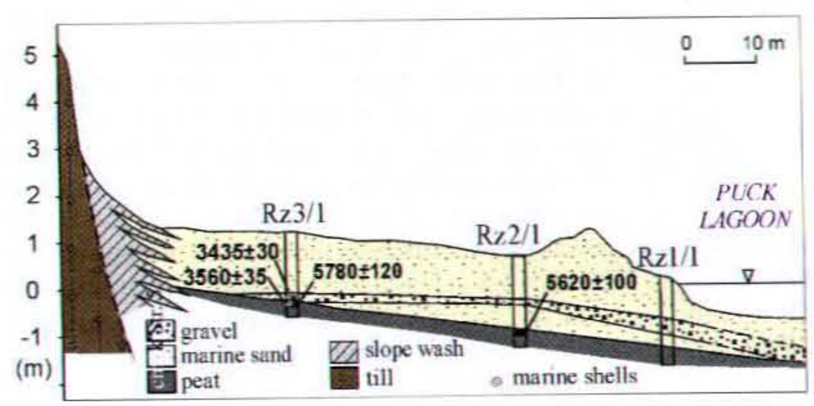


Fig. 5. Geological cross-section across the boreholes Rz1–Rz2–Rz3

forms below the Puck and Osłonino Cliffs. The northern boundary of the Headland is defined by the narrowing of the nearshore shoal southwards from the outlet cone of the Błądzikowski Stream (Fig. 2). The southern boundary is demarcated by the transition between the Headland's accumulation form and the erosive platform at the foot of Osłonino Cliff. The length of the Rzucewo Headland shoreline is thus c. 1.1 km. The landward part of the Headland rises to c. 1.0–1.5 m a.s.l. Its width, as measured from the foothills to the water line, ranges from 50 to 150 metres. A much larger part of the accumulation zone lies underwater at depths of up to 2 m b.s.l. The half-moon shaped sedimentary body is 800 m wide in the N-S direction and 450 m, E-W; its area is c. 250 000 m^2 (25 hectares). The average thickness of the marine sands forming the Rzucewo Headland is c. 1.5–1.6 m (Figs. 3–6) and 375 000–400 000 m^3 in volume.

Based on the boreholes and seismoacoustic profiles in the Rzucewo Headland area, the following sequence of sediments was established (Figs. 3–6):

- Tills, which form the surface and slopes of the Puck Morainic Upland, drop steeply under the Puck Lagoon floor (Figs. 3 and 4). At the foothills of the Upland (borehole R5), the upper surface of the till lies at c. 0.4 m a.s.l. On the Headland shoreline, this surface lies at 3.7 m b.s.l. in borehole R6 to approximately 5.5 m below sea level (borehole R1) (Fig. 6). At the edge of the Holocene littoral, a slope wash was formed; this interfingers with the marine sands.
- Lower (fluvioglacial?) sands underlie the Puck Morainic Upland till (Fig. 3). Upper, most probably also fluvioglacial, sands lie on the till in the Rzucewo Headland area and in the Lagoon (Figs. 3, 4 and 6). The thickness of the upper fluvioglacial sands ranges from 0 m (at the Upland foothills) to over 10 m in the Lagoon.
- Late Glacial as well as Early and Middle Holocene sands, silt and peat deposited in limnic and swampy environments in the proximal part of the Headland lie directly on the till, and in the Lagoon they are underlain by fluvioglacial sand (Figs. 3 and 4). Along the Rzucewo Headland shoreline, the upper surface of the peat occurs at the depth from –0.55 m in the northern part of the Headland (borehole 81/95) to c. –3.2 m in the southern part (borehole 83/95) (Fig. 6). In the northern part of the Headland at the Upland foothills (borehole Rz3/1),

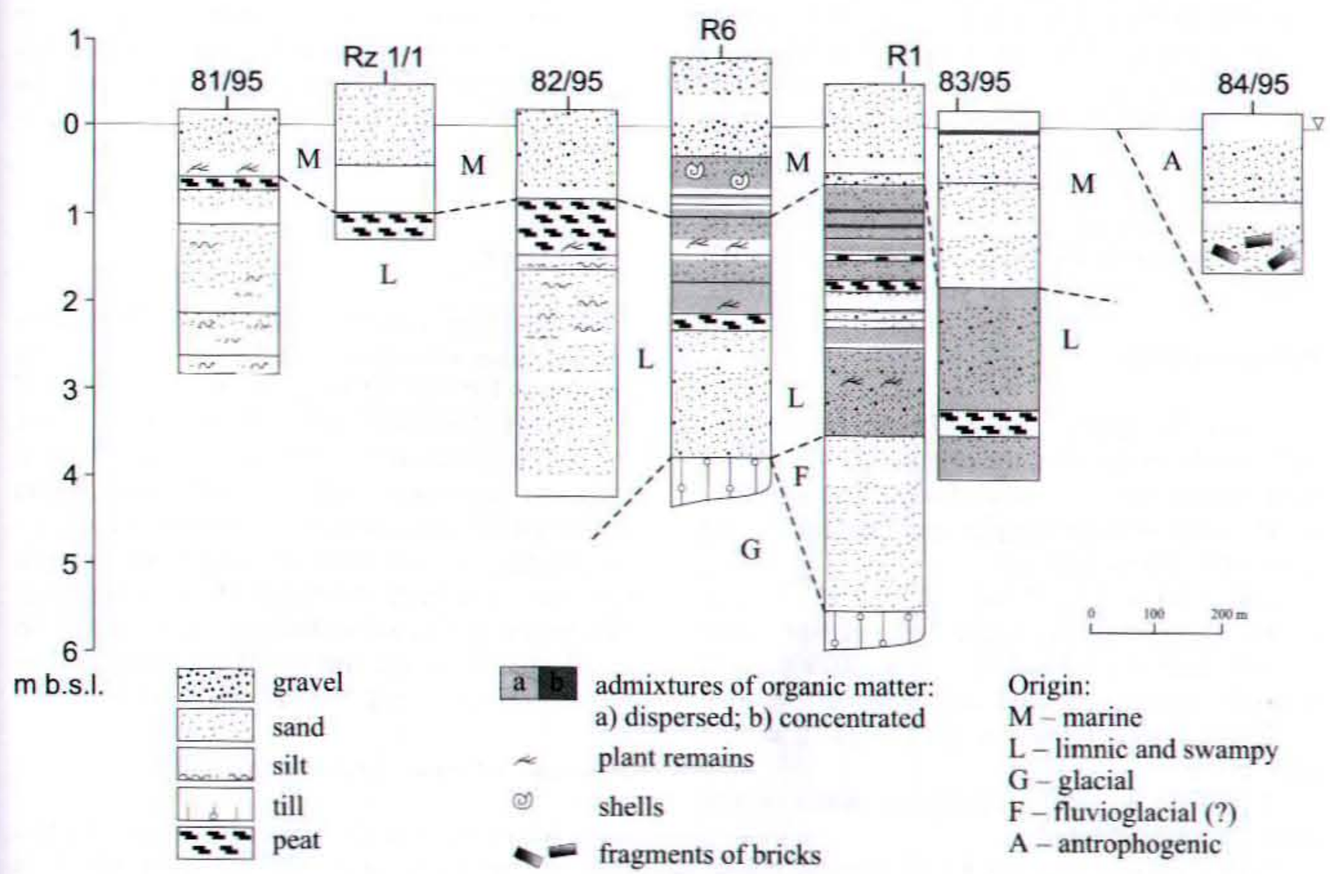


Fig. 6. Geological cross-section along the beach of the Rzucewo Headland

the upper surface of the peat layer lies at 0.35 m below sea level (Fig. 5). Radiocarbon dates for samples taken from close to the upper surface of the peat are as follows:
5830 ±45 years BP (GdA-159), borehole Rz3, 0.35 to 0.40 m b.s.l.
5780 ±120 years BP (Gd-15209), borehole Rz3, 0,54 to 0.59 m b.s.l.
5770 ± 170 years BP (GD-14023), borehole R6, 2.1–2.15 m b.s.l.
5620 ±100 years BP (Gd-15231), borehole Rz2, 1.01–1.06 m b.s.l.
5520 ± 70 years BP (Gd-7698) borehole R1, 1.72–1.85 m b.s.l.
The marine sands are frequently pebbly especially near their base, the gravel sometimes yields shells of *Cardium* sp. and *Hydrobia* sp. and other shell fragments. The upper part of the marine sands is variable. Medium- and coarse-grained sands, often with a gravel admixture are present on the beach. Medium- to fine-grained sands, which are partly eolian, are present between the beach and the Upland foothill. The thickness of the marine sands ranges generally from c. 0.75 m to c. 2.2 m in the shoreward parts of the Headland but this feathers out is less than ten centimetres at the edge of the underwater outcrop. In the borehole profile R6 (0.9–1.0 m below sea level), radiocarbon dating of the marine sand base containing an organic matter gave a figure of 2390± 130 years BP (Gd-10836). Radiocarbon dates for samples of *Cardium* sp. shells taken from the base of marine sand (0.24–0.34 m b.s.l.) and upper surface of the peat layer (0.35–0.40 m b.s.l.) in borehole Rz3 are 3560±35 years BP (GdA-171) and 3435±30 years BP (GdA-169).

Pollen analysis

From the core R1 (Fig. 7) eleven samples collected from the peat, the organic mud and sand with organic matter were analysed palynologically. The depths of the samples and lithology of the sediments are as follows:

1.42–1.44 m; 2.02–2.04 m; 2.13–2.15 – inserts of the organic matter (sandy peat) in fine sands

2.22–2.25 m; 2.35–2.36 – peat, dark brown, strongly compacted, well decomposed

2.45–2.46 m – organic mud slightly sandy, grey black

2.58–2.60 m – inserts of organic matter (sandy peat) in medium sands

2.86–2.88 m – fine sand with organic matter

As result of the pollen analysis, five local pollen assemblage zones (LPAZ) were distinguished, although owing to a non-continuous deposition of the organic sediments their selection was difficult. The zones are numbered from the bottom to the top of the core (Fig. 7).

1 *Tilia – Pinus* LPAZ

The zone was selected on the basis of the pollen spectrum of the lowest layer of the studied sediments (2.88–2.86 m). The spectrum is characterised by high values of the pollen grains of trees (AP – 93%). The most important are pine (*Pinus* – 30%), alder (*Alnus* – 13%) and lime (*Tilia* – 38%). Elm (*Ulmus* – 2%) and hazel (*Corylus* – 1.5%) occur too. The pollen grains of the herbaceous plants do not play any major role. Fern (*Polypodiaceae*) spores reach c. 10% and the eagle fern (*Pteridium*), 1.5%.

2 *Quercus – Corylus – Tilia* LPAZ

The next overlying layer (2.60–2.58 m) contains a very different pollen spectrum, the AP value having fallen to 65%. The most numerous are pollen grains of pine (*Pinus* – 21%), alder (*Alnus* – 10%), oak (*Quercus* – 8.5%), lime (*Tilia* – 6%) and hazel (*Corylus* – 9%). The herbaceous plants (NAP) are mainly represented by grasses (*Gramineae* – 20%), sedges (*Cyperaceae* – 6%) and complex plants (*Comp. S. F. Asteroideae*), the umbelliferae (*Umbelliferae*) and the goosefoot family (*Chenopodiaceae*). The proportion of a fern (*Polypodiaceae*) spores has increased to 18%.

3 *Tilia* LPAZ

The pollen content of this zone, which contains a layer of organic mud (2.46–2.40 m), is similar to LPAZ 1 (2.88–2.86 m). The grains of tree pollen dominate (AP – 95%), among which the pollen grains of lime (*Tilia* – above 40%) are the most numerous. Alder (*Alnus*), pine (*Pinus*) and birch (*Betula*) are less numerous. In comparison to the previous level, the importance of oak (*Quercus*) and hazel (*Corylus*) clearly decreases. The pollen grains of herbaceous plants occur in small quantities and are mainly represented by grasses (*Gramineae*) and sedges (*Cyperaceae*).

4 *Quercus – Corylus – Pinus* LPAZ

A whole layer of the higher lying peats (2.36–2.22 m) has a similar pollen spectrum, which is characterised by the lower AP values (60–70%) and by a significant, although gradually decreas-

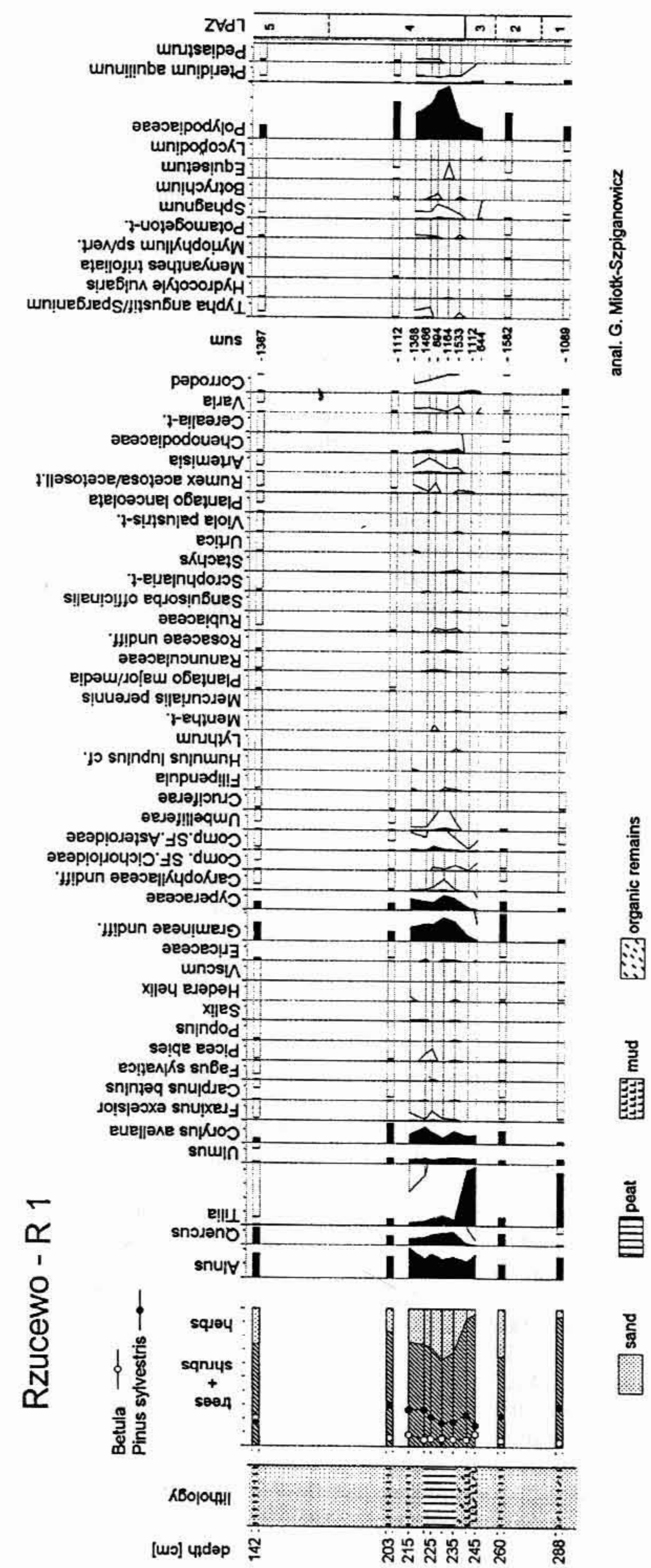


Fig. 7. Percentage pollen diagram

ing content of herbaceous plants (NAP – 40–30%). The trees are represented by pollen grains of pine (*Pinus*), birch (*Betula*), alder (*Alnus*), hazel (*Corylus*), increasing quantities of the oak (*Quercus*) and clearly decreasing quantities of lime (*Tilia* – 3–5%). Among the herbaceous plants, grasses (*Gramineae* – 11–15%), sedges (*Cyperaceae* – 4–10%) and complex plants (*Comp. S. F. Asteroideae*), umbelliferae (*Umbelliferae*) are all represented. The pollen grains of plants related to human activity – the goosefoot family (*Chenopodiaceae*), motherwort (*Artemisia*), sorrel (*Rumex*) – are all present and the first pollen grain of the plantain (*Plantago lanceolata*) appears, a species which is commonly recognised as an indicator of cattle breeding. The proportion of fern (*Polypodiaceae*) spores also increases.

Two younger higher layers of the peat sediments (2.15 2.13 m, 2.04 2.02 m) also belong to this LPAZ. Their pollen spectra are similar, although pine *(Pinus)* and hazel *(Corylus)* increase slightly, resulting in a rise of AP values from 72 to 82%.

5 *Quercus – Betula* LPAZ

This zone is based on the youngest sediment layer studied (1.44–1.42 m). In the pollen spectrum, elm (*Ulmus)*, lime (*Tilia*) and hazel (*Corylus*) are clearly less important whereas the amount of oak (*Quercus*) and birch (*Betula*) increases. The pollen grains of beech (*Fagus*) appear and percentage values of hornbeam (*Carpinus*) occur. Herbaceous plants are mainly represented by grasses (*Gramineae*), sedges (*Cyperaceae*), complex plants (*Comp. S. F. Asteroideae*), and umbelliferae (*Umbelliferae*) as well as by the plants relating to human activity – mainly the goosefoot family (*Chenopodiaceae*) and, to a lesser degree, by motherwort (*Artemisia*) and sorrel (*Rumex*). In this sample of the highest lying peat, the pollen grains of plantain (*Plantago lanceolata*) reach the percentage values. The number of fern (*Polypodiaceae*) spores decreased significantly.

The results of the pollen analysis (Fig. 7) clearly indicate that the sediments studied have mostly originated in a period of absolute domination of mixed deciduous forest (LPAZ: 1, 2, 3 and 4), which can directly be linked to the Atlantic period. Only the highest organic layer (LPAZ 5) originated at the beginning of the Subboreal period when the earlier dominating forests died out and forests with hornbeam (*Carpinus*), typical of the later period had not yet appeared (Miotk-Szpiganowicz, 1997).

Development of the Rzucewo Headland

On the basis of the geological and palynological data presented above, an attempt is now made to reconstruct the palaeogeographical features of the Rzucewo Headland area in the Late Glacial and Holocene and particularly to determine the Headland's age and the morphogenetic processes involved in its construction.

Late Glacial, Preboreal and Boreal Periods

In these periods, sandy sediments no more than 3–5 m thick were deposited and slope-forming processes produced slope-washes over the Upland foothills. Depressions in the area of the present Lagoon were occupied by lakes (Witkowski & Witak, 1993; Kramarska *et al.*, 1995). A lack of organic sediments of that age along the Upland foothills of the Rzucewo Headland indicates that swamps and lakes covered only the lowest parts of the present Lagoon and that the level of the ground and surface waters at that time was not directly related to the water level of the Baltic Sea, which was then at least 20 m lower than at present (Uścinowicz, 2000a, b).

Atlantic Period

During the greater part of the Atlantic period, environmental changes and sedimentary and morphogenetic processes in the area of the recent Puck Lagoon do not appear to have been directly related to the rising level of the then Baltic Sea. In this area, limnic, fluvial and paludal sandy and muddy sediments with organic inserts were formed.

The pollen spectrum of the lowest part of the palynologically studied sediments in the core R1 (2.88–2.86 m) (Fig. 7) indicates that the sediments originated in a period of forest growth. In the forests, particularly in the fertile mildly wet habitats, lime (*Tilia*) was dominant with elm (*Ulmus*) subordinate and with a small proportion of oak (*Quercus*). The wetter habitats were dominated by alder (*Alnus*) and hazel (*Corylus*). The very few dry areas in the direct proximity of the Rzucewo Headland were covered by a pine forest, in whose undergrowth the eagle fern (*Pteridium aquilinum*) occurred, although the area truly to have been in the more elevated areas. The dominance of lime (*Tilia*) in the forest communities of this region has already been reported (Miotk-Szpiganowicz, 1997; Bogaczewicz-Adamczak *et al.*, 1999).

The higher (2.60–2.58) organic layer probably relates to a slight rise of the water table. This led to the development of the wetland habitats, on which grasses (*Gramineae*), sedges (*Cyperraceae*), lychnis (*Lychnis*), composite plants (*Compositae*), the umbelliferae (*Umbelliferae*) and fern (*Polypodiaceae*) dominated. In comparison to the lower layer, lime (*Tilia*) content in the forest communities decreased significantly. The presence of goosefoot family (*Chenopodiaceae*) and motherwort (*Artemisia*) pollens suggests that the changes in the vegetation may be partially related to human activity in the area. It thus seems possible that man arrived in the Rzucewo region before the development of the "Rzucewo Culture" settlement, the inhabitants of which were seals-hunters.

In the pollen spectrum of the organic mud layer (2.46–2.45 m), grains of lime (*Tilia*) again regains its dominance. A high quantity of lime (*Tilia*) in such sediments has often been reported from archaeological sites (Latałowa, 1989, 1994) and their presence not apparently mean that lime dominated the local flora. However, the area must have provided a habitat suitable for lime (*Tilia*). The less fertile habitats were evidently occupied by pine/birch forests.

At 6 ka BP the Baltic Sea was approximately 7–6 m lower than the present (Uścinowicz, 2000 a, b) (Fig. 11). The then Baltic Sea coast was approximately 5–6 km away from the present Rzucewo Headland. Marshy and swampy areas prevailed in the upland foothills. As in the earlier periods, lakes covered only the floor depressions of what is now Puck Lagoon. By the end of the Atlantic period, c. 6–5 ka BP, sea level rise caused an acceleration of the peat-forming processes in the region of the contemporary Lagoon's shores. The youngest peat layer in that area is radiocarbon-dated at 5520±70 years BP.

At that time, a major change of the vegetation took place. Lime (*Tilia*) was partly replaced by oak (*Quercus*), which co-existed with pine (*Pinus*) in the drier habitats. The more extensive wetlands were occupied by marshy land communities with alder (*Alnus*), hazel (*Corylus*), elm (*Ulmus*), and an admixture of ash (*Fraxinus*). The two consecutive organic inserts (2.15–2.13 m and 2.04–2.02 m) have a similar pollen spectrum, indicating that they originated in the period of similar habitat conditions and are close contemporaries with the lower peat layer. The rapid disappearance of lime (*Tilia)* from the forest communities in the Rzucewo Headland area might be related to the major changes of the water conditions in the area, as suggested by a pronounced change in the sedimentary character. It is also possible that the change was partially related to an increase of the human activity. This is confirmed by substantial amounts of the pollen grains of the ruderal plants such as goosefoot (*Chenopodiaceae*), motherwort (*Artemisia*), sorrel (*Rumex*) and individual grains of plantain (*Plantago lanceolata*) and cereals (*Cerealia*).

At 5.5 ka BP, Baltic Sea was approximately 5–4 m lower than the present (Fig. 11). As earlier, the depression eastwards from the Rzucewo Headland became a freshwater lake, its water level probably being much the same as sea level. The Reda river was flowed through the lake towards the sea though the present data set does not permit the identification of its outlet to the then Baltic Sea. The incision in the Seagull Barrier opposite the present mouth of the Reda (Fig. 1) is an artificial cut made for nautical purposes. At that time, the "Rzucewo Lake" shores were some 1.0–1.2 km away from the Upland edge and the nearest seashore was at a distance of 5–5.5 km.

The Subboreal and Subatlantic periods

At the beginning of the Subboreal period terrestrial conditions still prevailed in the Rzucewo Headland area. The youngest layer of the organic sediments studied (1.44–1.42 m) originated in a period of gradual change in the real forests, the change being related to changes in the climatic-edaphic conditions. This caused a nearly total disappearance of the deciduous trees of higher habitat requirements such as lime (*Tilia*), and elm (*Ulnus*) which became replaced by hornbeam (*Carpinus*) and beech (*Fagus*). The former was especially important in forming new forest communities in the proximity of the Rzucewo Headland (Miotk-Szpiganowicz G., 1997). At that time human activity changed. The increase of the pollen grains of plantain (*Plantago lanceolata*) in these sediments strongly suggests an increase in cattle farming.

Most probably at the turn of the Atlantic and Subboreal periods, c. 5 ka BP, the Baltic Sea level was c. 3–2 m lower than the present, and the freshwater "Rzucewo Lake" became converted into a brackish/marine lagoon. At that time the lagoon was separated from the Gulf of Gdańsk not only by the Hel Peninsula but also by the Seagull Barrier the crest of which could have lain above the sea level. Marine erosion of the morainic upland slopes, cliff development and sand accumulation in the Rzucewo Headland area all started at that time. The occurrence of pollen grains of plants related to the human activity

(*Chenopodiaceae*, *Artemisia*, *Rumex*, *Plantago lanceolata*) coincides with the beginning of a settlement of the Rzucewo Culture, i.e. seal hunters c. 4400–3700 years ago (Król, 1997). The shore of the Lagoon must thus have been close to its present position.

By the end of the Subboreal period, sea level was not lower than 1.0–0.5 m and in the Subatlantic period, with the very slow sea level increase, the Rzucewo Headland quickly became aggraded. The now rapidly-eroding cliffs became main source of the sediments forming the Headland, while as that sea level, sediments from the valleys of the Gizdepka and Błądzikowski Stream were deposited nearshore. Assuming that, as at present time, the winds from the western sector dominated in the Subboreal and Subatlantic periods, then the sediments were supplied to the Rzucewo Headland mainly from the north-west, i.e. from the area of the Puck Cliff and the mouth of the Błądzikowski Stream. Sediment transport from the south, from the Osłonino Cliff and the mouth of the Gizdepka was probably then, as now, insignificant. In the last 4000 years or so, the average rate of the Rzucewo Headland growth is approximately 100 m^3/year.

Recent coastal processes in the area of the Rzucewo Headland

The Rzucewo Headland continues to be an active landform. The present sources of the sediment material for the Headland are: the Puck Cliff (approximately 2 km long and 10 m high) and the Błądzikowski Stream. Transport direction is from NW to SW, whereas the longshore currents easily transport the sandy material and ice floe drift accounts for the gravel and pebbles (Fig. 8).

The recent (1958–1997) changes of the coast were determined on the basis of aerial photographs (Fig. 9). The coast north from the Headland was apparently quite stable over this period; no changes were noted there. In the northern part of the Headland, the shoreline has shifted c. 50–80 m seaward (on average, 1–2 m/year). By contrast the coast south of the Headland has been eroded – a shoreline recession of c. 20 m (on average, 0.5 m/year).

Discussion

Earlier estimates of the age of the Puck Lagoon (i.e. c. 5500 years BP) were based either on dates for the upper levels of the peat layers

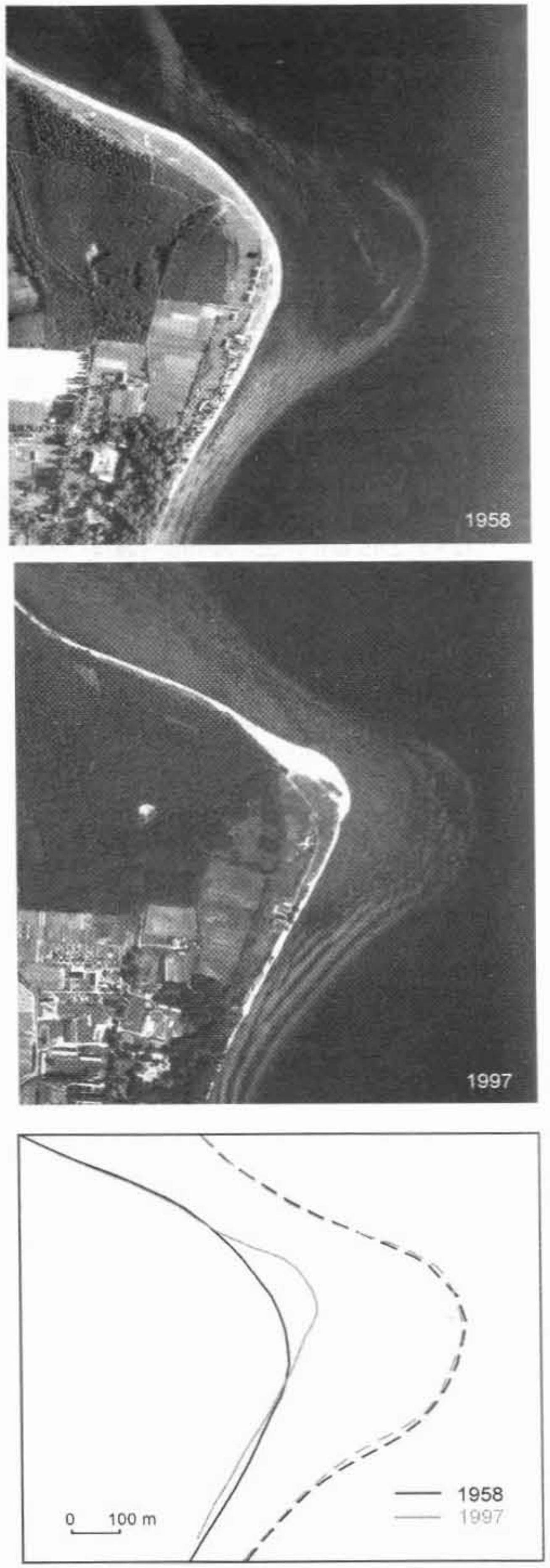


Fig. 9. Aerial photographs and sketch of Rzucewo Headland shoreline changes during the 1958–1997 period

Fig. 8. Banked up ice floes with gravely and pebbly material on the beach of Puck Lagoon near the Rzucewo Headland *(Phot. by Sz. Uścinowicz, 1996)*

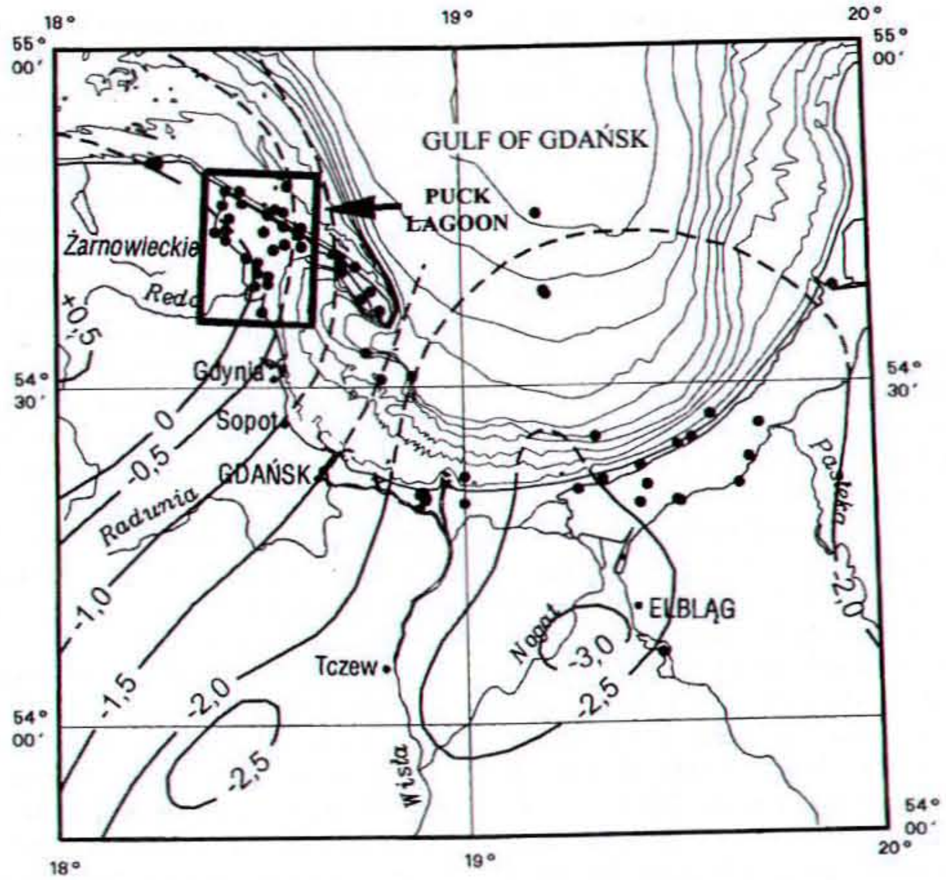
(Kramarska *et al.*, 1995) or on those for the bottom layers of the Lagoon sediments, which contain marine diatoms (Witkowski & Witak, 1993). According to Witkowski and Witak (1993) marine conditions in the Lagoon already existed by the end of the Atlantic period for, in the muddy sediments dated by the ^{14}C method at 5480 ± 130 years BP (Gd-4831), the marine diatoms (*Dimerogramma minor, Grammatophora oceanica, G. marina, Rhabdonema arcuatum, Synedea crystallina)* are present. These diatoms are generally considered to be oceanic species. However, at 5500 years ago the Baltic Sea and the ocean levels were 5–4 m lower than the present and a brackish/marine water basin could exist only into the deepest (>5 m), east and north eastern parts of the recent Lagoon. Conceivably, the radiocarbon date of the lagoonal sediments (Fig. 11) could be made slightly older by the re-deposited older organic matter. Certainly, admixtures of such the matter, which make the radiocarbon datings older, are known to occur frequently in limnic and lagoonal sediments (Winn, 1986; Benike & Jensenm, 1998; Uścinowicz *et al.*, 2000). Neither the few peat datings from the 6000–5000 years BP range, necessarily directly indicate the origin of the Puck Lagoon or beginning of sand accumulation in the Rzucewo Headland area. Either the peat top was partially eroded during the transgression (e.g. core Rz3, Fig 5) or the peat-forming process was interrupted by the deposition (still in a freshwater environment), younger clastic sediments. The pollen spectrum of the highest organic layer in the R1 core from the Subboreal period indicates an intensification of human activity in the area. The results of the pollen analysis and the data of the water level of the Baltic Sea from the period 5000–4500 years BP correlate well with the archaeological data (Król, 1997) which suggest that the seal-huntering settlement at Rzucewo began c. 4400 years ago.

The geological cross-sections and core profiles discussed here indicate that the Rzucewo Headland developed under conditions of the mildly ceasing transgression. No data indicative of to either phased transgression or periodic regression were noted. The location and range of the marine (lagoonal) sediments documented in the Rzucewo Headland area indicate that the water level of the Puck Lagoon has never been higher than at present; further that changes of the shoreline location are related either to the accumulation or erosion processes which occurred in the Late Holocene concomitant with the very slow rise of the lagoon level. This is important to any paleogeographical interpretation, particularly in view of the recent vertical movements of the Earth crust in the Puck Lagoon area (0– –0.5 mm/year) (Fig. 10). On the basis of repeated precise levelling and on tide-gauge data as well as mean errors of their determining, the rates determined are –0.8 ± 0.5 mm/year at the end of the Hel Peninsula (in Hel Harbour) and –0.1 ± 0.4 mm/year at the beginning of the Hel Peninsula in Władysławowo (Wyrzykowski, 1985). Over the last 5000 years, the curve of the relative water level changes of the Puck Lagoon (Fig. 11) is in good agreement with the curves of eustatic changes of the ocean (e.g. Mörner, 1976; Blanchon & Shaw, 1995). Thus the destruction of the early mediaeval Puck Harbour (e.g. Zbierski, 1986) and the creation of erosive terrace along the Puck Lagoon shores (Tomczak, 1995) are now shown not to be due to a rapid rise the sea level approximately 1000 years ago.

Blanchon & Shaw's (1995) eustatic curve for the last 5000 years shows a fairly uniform rise of the sea level. However, apart from a long-term trend of the slow sea level rise, the Mörner's (1976) eustatic curve also shows local eustatic oscillations. According to Mörner (1976), the oscillations originate in the Kattegat area due to, among other reasons, periodic changes of climate and oceanic circulation and their amplitudes do not exceed 0.5 metre.

The curves of relative sea level changes from the middle part of the Polish coast (Rotnicki, 1999; Tobolski, 1989, 1997; Wojciechowski, 1990) generally show a series of more or less regular oscillations of amplitude sometimes exceeding 1 m. All these curves are the product of studies of sites located within the same tectonic unit within the Łeba elevation. A similar picture is shown by some curves of the sea level changes in the western part of the Baltic Sea (e.g. Duphorn, 1979; Lampe & Janke, 2000). According to various authors, oscillations were of different values and occurred at different times. The differences among the cited curves and deviations from eustatic curves of the ocean level may be explained by local eustatic oscillations and/or to neotectonic crustal movements within the southern Baltic area.

The agreement of the curves of the relative water level changes of the Puck Lagoon with the curves of global eustatic changes suggests that vertical movements of the Earth crust and local eustatic changes in the Subboreal and Subatlantic periods in the area were limited. If local eustasy and/or vertical movements of Earth crust occurred in the Puck Lagoon area, it fell within the limits of uncertainty when determining the



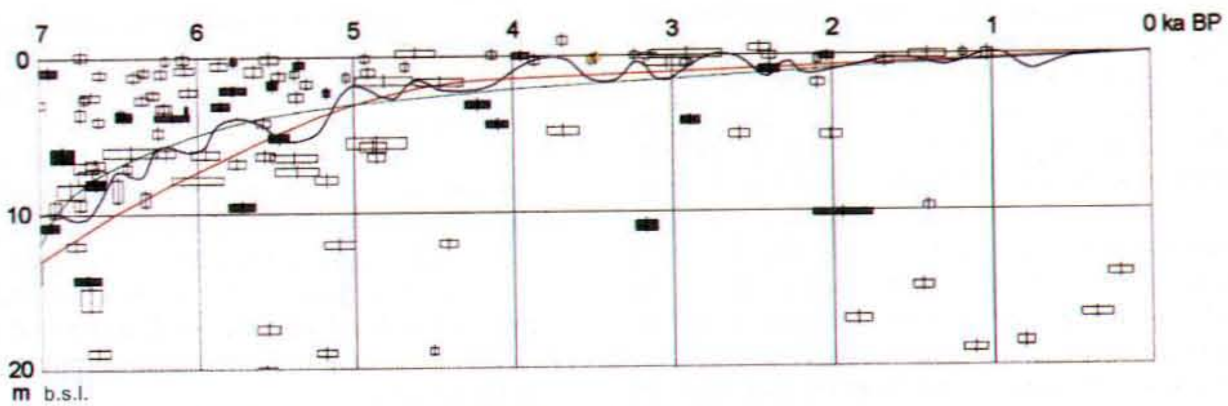
• samples dated by ^{14}C method

—-0.5— recent vertical movements of the surface of the Earth crust (mm/year) after: T. Wyrzykowski, 1985

– – – – recent vertical movements of the surface of the Earth crust (mm/year) extrapolated on the sea

isobaths every 10 m

Fig. 10. Location of the sediment cores dated by the ^{14}C method in the Gulf of Gdańsk area



peat · lagoonal mud · marine shells

data from other parts of the Southern Baltic

relative sea level curve in the Southern Baltic area (after Uścinowicz 2000 b)

eustatic sea level change in the Caribbean - Atlantic region (after Blanchon & Shaw 1995)

eustatic sea level change in the Kattegat area (after Mörner 1976)

Fig. 11. Relative sea level changes in the area of Puck Lagoon

curve of the sea level changes in the area. In order to solve the problems of local eustasy and regional neotectonic movements in the Southern Baltic area, more studies of a high accuracy are needed both at the local and regional scale.

Conclusions

On the basis of geological studies and pollen analysis, the following stages of the sediment deposition and morphogenesis of the Rzucewo Headland and its hinterland have been distinguished:

- **Late Glacial, Preboreal and Boreal Periods**: Slope-forming processes and deposition of slope wash at the foothills of the Upland dominate. No organic sediments dating from that period have yet been found.
- **Atlantic Period**: Sands and silts with organic mud and peat beds were deposited. In the Rzucewo Upland foothills, in marshes and swamps; by the end of that period, the influence of sea level rise was reflected by changes in both sediments and vegetation, the pollen spectrum being distinguished by the more numerous pollen grains of lime (*Tilia*). By the end of the period, the first pollen grains of the plants indicating the human activity appear (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*). The age of these sediments and the water level of the Baltic Sea (5,5 ka BP – approximately 5–4 m lower than the present) suggest that man arrived in the area well before the Rzucewo Culture was established.
- **Subboreal Period**: As the sea entered the Puck Lagoon area, the freshwater lakes were transformed into a brackish/marine lagoon. Cliffs developed on slopes of the Puck Morainic Upland and sand accumulation in the Rzucewo Headland started. The pollen spectrum shows a small proportion of grains quantities of the plants relating to human activity (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*). The occurrence of these plants and advance of the Puck Lagoon shoreline towards Rzucewo coincides with the beginning of the late Neolithic Rzucewo settlement (c. 4400–3700 years ago), which was established by the seal-hunters.
- **Subatlantic Period**: Sands accumulated rapidly around the Headland during a slow rise of the sea level (<0.5 mm/year). The average speed of growth of the Rzucewo Headland in the last 4000 years was approximately 100 m^3/year.
- **Recent coastal processes**: The sources of sediment for the Rzucewo Headland are the Puck Cliff (the actively – abraded section c. 2 km long and 10 m high) and the Błądzikowski Stream. During the period 1958–1997 in the northern part of the Headland, the shoreline migrated seaward c. 50–80 m (on average 1–2 m/year); south of the Headland coastal erosion occurred of c. 20 m (on average 0.5 m/year).

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