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Climatic and anthropogenic impulses in the Late Vistulian and Holocene development of the river channels and valleys of the Baltic Coastal Region and Pomerania

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Abstract: Investigations of the postglacial, primarily the Holocene, stage of the development of river channels and valleys in North Pomerania and the Baltic Coastal Region over nearly twenty years have led to the conclusion that the main events in the river channel and valley evolution were conditioned by the climate. It was the Scandinavian glaciations, especially the Vistulian, which determined the fundamental configuration of the sedimentary cover and the topography of this area. Later climatic changes determined both the transformation of the planar channel pattern (braiding, meandering, anastomosing) and the balance between slope and fluvial processes. Changes of thermal conditions and precipitation totals have influenced the nature of the fluvial processes, including the occurrence of floods and the range of formation for the overbank sedimentary covers. It was also found that, until the Middle Ages, the affects of human activity on the environment of river channels and valleys in the Baltic Coastal Region and Pomerania were very limited. The Early Medieval settlement expansion, accompanied by an intensification of deforestation and soil cultivation, was conducive to an increased feeding of the river channels by a fine-grained, fertile load, which affected the extent of overbank cover formation. Yet it was only the 20th century regulation of river channels, the improvement of valley floors, and hydroengineering structures which have brought about significant changes in the hydrology of the North Pomeranian and Baltic Coastal Region rivers and determined the changes in their longitudinal profiles. By incision of channels into the Holocene floodplains, and a basic change in the balance of fluvial processes in individual sections of channels and valley floors, where divided by the hydroengineering structures.

Key words: Holocene, palaeohydrology, fluvial processes, palaeomeanders

Introduction

The larger rivers which flow through North Pomerania and the Baltic Coastal Region formed their valleys in an area enclosed by the southernmost limit of the Pomeranian phase and the marginal zone of the so-called Gardno phase (dated commonly at ca 13 200 BP, or the Oldest Dryas). This area was shaped through degradation of the continental ice-sheet in a very short time interval. The complex deglaciation processes produced a mosaic of morainic and glaciofluvial forms, cut by a network of tunnel valleys, marginal valleys and erosional forms. Complex processes, conditioned primarily by climatic changes, transformed this network of depressions into the present hydrographic network.

Postglacial development of the fluvial network in Pomerania and the Baltic Coastal Region - study status

Until recently, studies of the geomorphology and the geological structure of the river valleys in the northern part of Pomerania and the Baltic Coastal Region were sketchy and fragmentary, and they most frequently appeared in the background of broader works which considered the morphogenesis of this area. In recent years there have been many studies, which can be divided into three groups:

1) Those concerning the Upper Pleistocene development of the river channels and valleys (Galon, 1968, 1972; Sylwestrzak, 1973, 1978a, 1978b; Mojski & Orłowski, 1978; Orłowski, 1981, 1983a, 1983b, 1989), with special preference for the Reda-Łeba ice marginal streamway (Marsz, 1967; Sylwestrzak, 1969, 1978b; Koutaniemi & Rachocki, 1987),

2) Those focusing on the modern development of the river channels and valleys. These primarily relate to the Parsęta (Zwoliński, 1983, 1986, 1987a; Kostrzewski & Zwoliński, 1984, 1985a, 1985b, 1988a, 1988b; Gonera *et al.*, 1985; Kostrzewski *et al.*, 1992), the Radunia (Rachocki, 1973, 1974, 1981) and the Słupia (Florek, 1996),

3) Several attempts have been made to synthesise present knowledge with the aim of devising complex palaeogeographic reconstructions of the postglacial development of river valleys in North Pomerania and the Baltic Coastal Region. Some attempts have focused on the Late Vistulian development of valley morphology (Woldstedt, 1956; Sylwestrzak, 1973, 1978b); others included also the Holocene stage of their

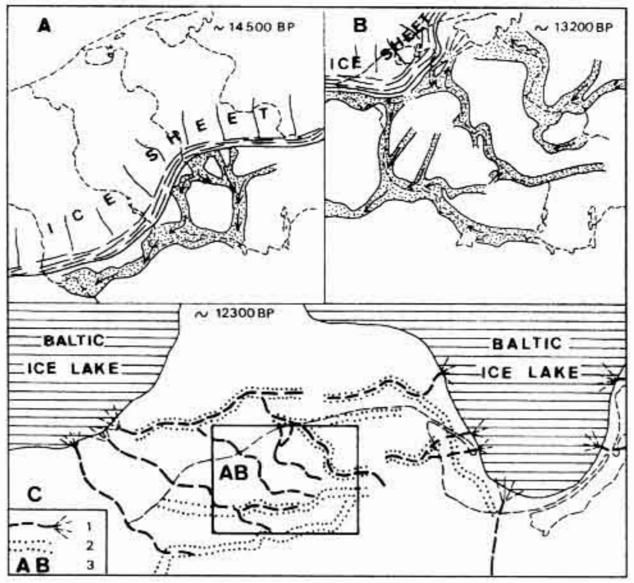

Fig. 1. Development of the hydrographical network at 14 500 BP (C), 13 200 BP (D) and 12 300 BP (A) years.
1 - main rivers with deltas, 2 - Late Vistulian outwash valleys, B - location of the area shown in the parts C and D, (C after Mojski, 1990).

development (Rosa, 1964; Florek, 1984a, 1992, 1994). Zwoliński's work (1987) summarises "the state of the studies of Pomeranian rivers in relation to the fluvial geomorphology".

In the first study dealing with the development of the coastal zone river valleys in the Holocene, Rosa (1964) suggested that the development of accumulation segments was conditioned by the impact of the *Litorina* eustatic transgression. The author also pointed out the polygeneity of the river valleys and the fact that the erosion prevailing in the early Holocene brought about the formation of the erosional valley floors which, today, lie several metres below sea level. He also emphasised how poor our knowledge is concerning the role of neotectonic processes in valley development. He observed that the river channels east of Łeba undergo bottom erosion, while those west of Łeba are being aggradated. He reasoned that this was because the area east of Łeba is rising, whereas the coastal zone west of this area is subsiding.

Since 1979, the valleys of North Pomerania and the Baltic Coastal Region have become the subject of investigations by a multidisciplinary group led by the author of this study. The findings have been published at various stages, either as single papers or monographs (Florek, 1989, 1991). However, it should be emphasised here that the programme of these investigations was integrated, to a large extent, with the International Geological Programme No. 158 "Paleohydrological changes in the temperate zone in the last 15 000 years", sub-project B "Fluvial environment", supervised by L. Starkel. This programme is constantly expanding; in recent years it has been enlarged by investigations of quantitative palaeohydrologic reconstructions, investigations into the effect of Prehistoric and Early Medieval colonization on the river valley development, and also by studies of the chemistry of the channel and overbank fluvial deposits. The investigations carried out to date have confirmed the thesis that the Late Vistulian and Holocene climatic changes were the main factors which shaped the river network of Pomerania and the Baltic Coastal Region and the river channels. We have not succeeded in documenting the role of glacioisostatic and neotectonic movements in the development of the river network in this area. But we now know something of the diverse role of anthropo-pressure in the transformation of valley floors and river channels. The material collected so far is presented in this paper.

Climatic changes in the Late Vistulian and Holocene conducive to fundamental changes of river channels and valleys

There is a widespread and growing awareness among researchers of the important role of climate in the evolution of river channels and valley bottoms; with regard to Pomerania and the Baltic Coastal Region this can be found primarily in the works of Florek (1989, 1991) and his team (Florek & Florek, 1986; Alexandrowicz *et al.*, 1989).

The effect of climatic changes on the river valley environment is manifested in:

- changes in the vegetation composition and its density,
- proportions and functional limits of mechanical and chemical weathering,
- changes in the slope processes, resulting from weathering and vegetation,
- position of the ground water level,
- changes of the water level in seas and lakes.

The fundamental event caused by the global climatic changes which had any influence on the development of North Poland's valley system was the Vistulian Glaciation. The initially erosional and then accumulative activity of the ice sheet, and also the erosional and depositional activity of its meltwater, resulted in the formation of subglacial tunnel valleys, outwash valleys, marginal valleys and other depressions which produced a hydrographic network, the shape of which was almost identical to that of today, during the relatively short time of some thousand years of the Late Vistulian (Fig. 1) (Galon, 1972; Sylwestrzak, 1978b; Florek, 1991). The rapidity of those transformations is confirmed by the configuration of the highest (outwash) terraces in the valleys of modern rivers (Fig. 2). They constitute systems inclined approximately towards the NNW, and modern rivers use them only in short segments, running almost parallel.

Rapid Late Vistulian changes of the drainage system took place with a changing regional erosion base, which was the ice-sheet front and after the formation of large water reservoirs in the floor of the Baltic trough - the Baltic Ice Lake. Scarcity of the vegetation cover or its almost complete absence in the cooler periods of the Late Vistulian (Dryas) (Hjelmroos-Ericsson, 1981; Tobolski, 1987) were conducive to the mobility of the surface layers of the postglacial deposits. During the short summers, the active permafrost layer melted and fed the valley bottom with water and sediment load. This favoured the preservation of braided channels and, in the valley segments, temporarily blocked by the dead-ice blocks or by the residual marginal forms, lakes developed in which varved clays were deposited (Vierke, 1937; Florek, 1989, 1991; Fig. 3).

Classic braided channels of the bed-load type (type 5 after Schumm, 1981, or model 2 after Miall, 1985, see Figure 2) existed where there was extraglacial runoff. Such channels,

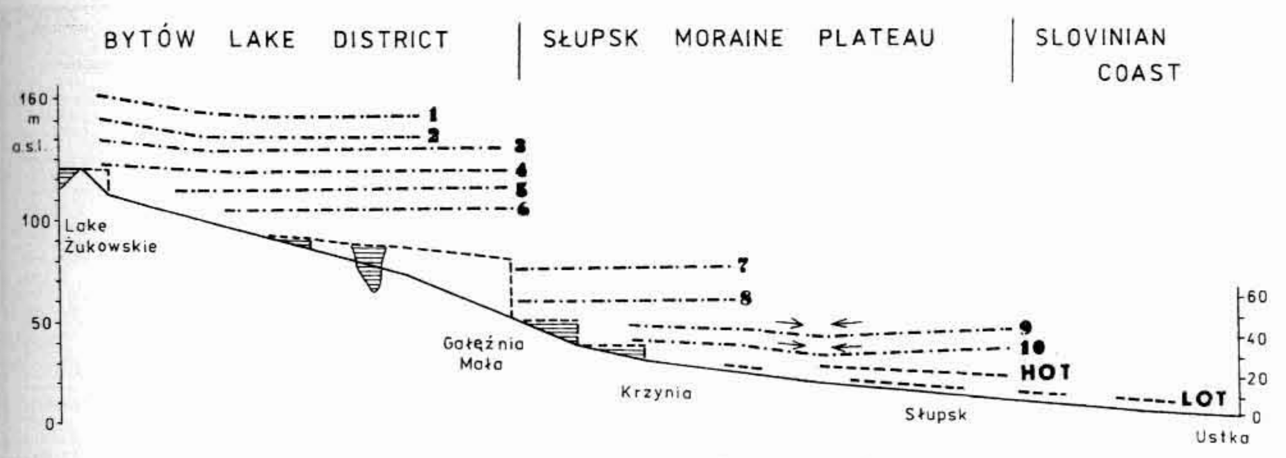

Fig. 2. Longitudinal profile of the terraces in the Słupia valley between Żukowskie Lake and the Baltic Sea.
1-6 - the outwash levels, 7-10 - the outwash valley terraces, HOT, LOT - river terraces; the floodplain is not marked (after Orlowski, 1983).

split into several shallow branches, quickly changed their position as a result of bank erosion, transporting and depositing gravel and sand formed as the highest outwash terraces. The outwash deposits and the valley outwash deposits are characterized by the presence of a few cyclic deposits and a relatively small quantity of sandy deposits of the bar subfacies over the coarse-grained and pebbly deposits of the channel bed subfacies. The coarse-grained deposits are poorly or very poorly sorted, whereas the bar deposits are fine-grained and moderately sorted.

Having broken through the marginal forms, the longitudinal profiles of the rivers underwent a levelling out process. This started in the Bőlling and continued until the early Atlantic period (Florek, 1991, 1996; Fig. 2). In some valley segments, the meltwater reservoirs were of great importance at this stage (Koutaniemi & Rachocki, 1981; Florek, 1991); subsequently, they were filled by fluvial deposits. The thickness of the fluvial cover over the top of these melt-out holes ranges from 6 m (Łosino) to 10 m (Leśny Dwór). Such a rapid straightening of the longitudinal profiles of the river valleys was favoured by the ice-sheet retreat to the Baltic consequent upon the markedly improved climatic conditions. By then, the main Pomeranian rivers were already flowing through much the same valleys as today, extending into the bottom of the present Baltic, which, at that time, had a water level about 50 m lower than that of today.

The braided channels of the rivers flowing into the Baltic from the Pomeranian area were then characterized by an increasing outflow, a smaller number of branches and their greater stability (type 4 after Schumm, 1981, or model 3 after Miall, 1985, see Figure 3), which resulted from a lesser supply of slopewash caused by an increased vegetation cover which had already developed into park tundra (forest-tundra; Hjelmroos-Ericsson, 1981) in the upper river courses. Despite

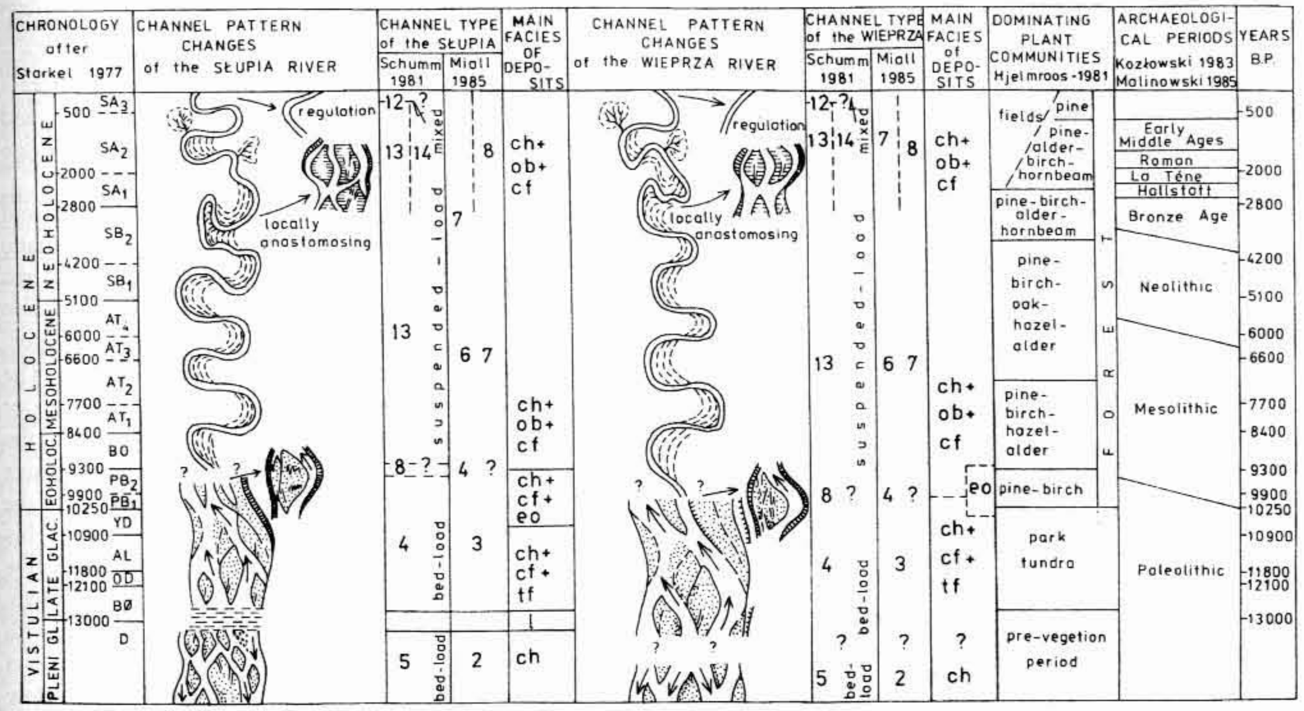

Fig. 3. Chronology of the postglacial changes of the Słupia and Wieprza river channels and valleys; the main sediment facies: ch - channel, ob - overbank, cf - paleochannel infillings, tf - alluvial fans, eo - eolian sands (after Florek, 1991).

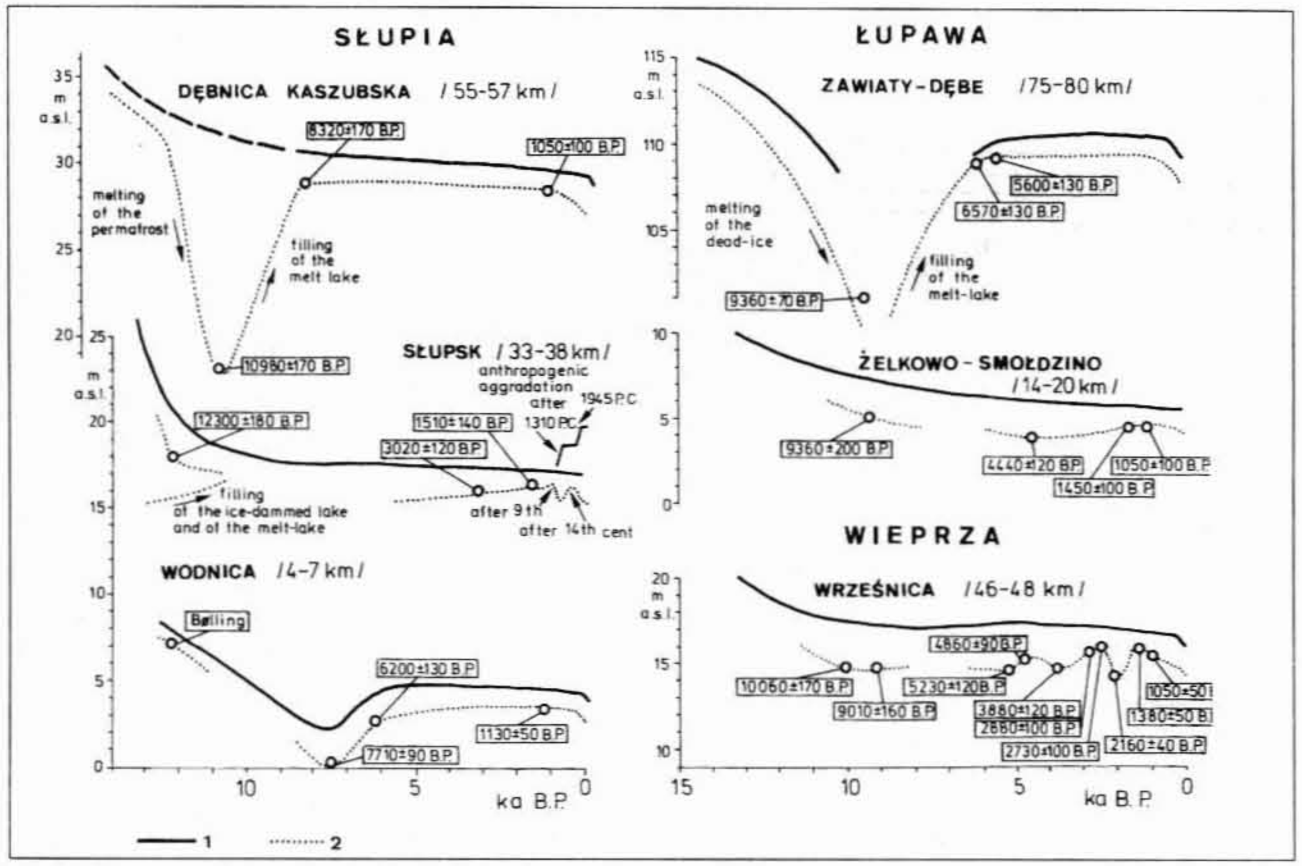

Fig. 4. Changes of the vertical position of the Słupia, Wieprza and Łupawa river valley bottoms from the end of Pomeranian phase, in selected cross-profiles.
1 - floodplain surface, 2 - bottom of the fluvial deposits (after Florek, 1991).

the considerable density of the vegetation, the floral communities were not very resistant to degradation. This is evidenced by the dunes which were formed on the Łupawa alluvial fan near Smołdzino in the Younger Dryas (Tobolski, 1972, 1981), and in the river valleys on the higher river terraces as late as in the Preboreal (Florek, 1989, 1991; Fig. 4). All branches of the channels probably functioned only during the spring floods. Such channels formed the higher river terraces in the valleys of Pomerania and the Baltic Coastal Region. The structure of the terraces is characterised by fining-upwards sequences and the occurrence of only one depositional cycle. The sand transported in the channels at that time was medium grained and poorly or moderately sorted, and a clear division into the deposits of the channel-bed subfacies and those of the bars may be distinguished. The surfaces of these terraces show traces of braided channels, disturbed by later processes relating to the degradation of the permafrost. It should be emphasized that, in the river valleys of North Pomerania and the Baltic Coastal Region, the braided channel pattern prevailed for a long time, due to the proximity of the ice-sheet, therefore a long-lasting inflow of meltwaters in arctic conditions, and organization of the whole runoff northwards was very late (the turn of the Oldest Dryas and Bř lling).

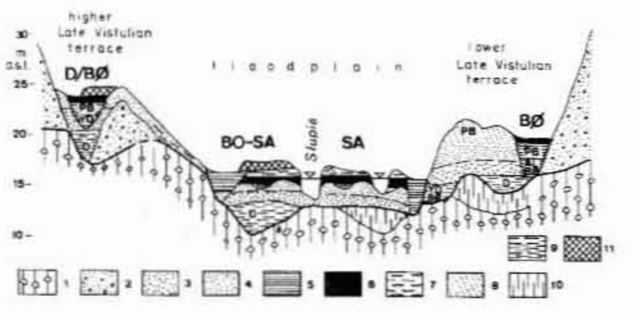

Fig. 5. Synthetic geological cross-section of the Słupia river terraces in Słupsk.
1 - till, 2 - glaciofluvial gravels and sands, 3 - coarse-grained sand of the channel-lag sub-facies, 4 - fine-grained sand of the bar sub-facies, 5 - organogenic and mineral palaeomeander infillings, 6 - Subatlantic peats, 7 - contemporary overbank sediments, 8 - aeolian sand, 9 - varved clay, 10 - clayey till, 11 - earth work.

Decay of the permafrost and the expansion of birch and birch-pine forests followed the radical change of climatic conditions that occurred at the turn of the Younger Dryas and the Holocene. This brought about another threshold situation in the river valleys of Pomerania and the Baltic Coastal Region, after which the meandering pattern started to develop. The Preboreal forest communities seem to have played a major role in increasing the evapotranspiration. The density of the turf covers and changes in their species composition to plants more resistant to mechanical damage were essential in the control of the surface runoff and soil washing processes. This was important, for instance, in view of the possible destructive effect of some animals (e.g. reindeer) on the undergrowth. The gradual increase of temperature, accompanied by growth of the annual precipitation (albeit on a very limited scale at first), contributed to a decrease and compensation of outflow (Gonera, 1986), and, consequently, to a decreased fluvial activity. On the other hand, the circulation of ground waters and the leaching of the aeration zone became more intense,

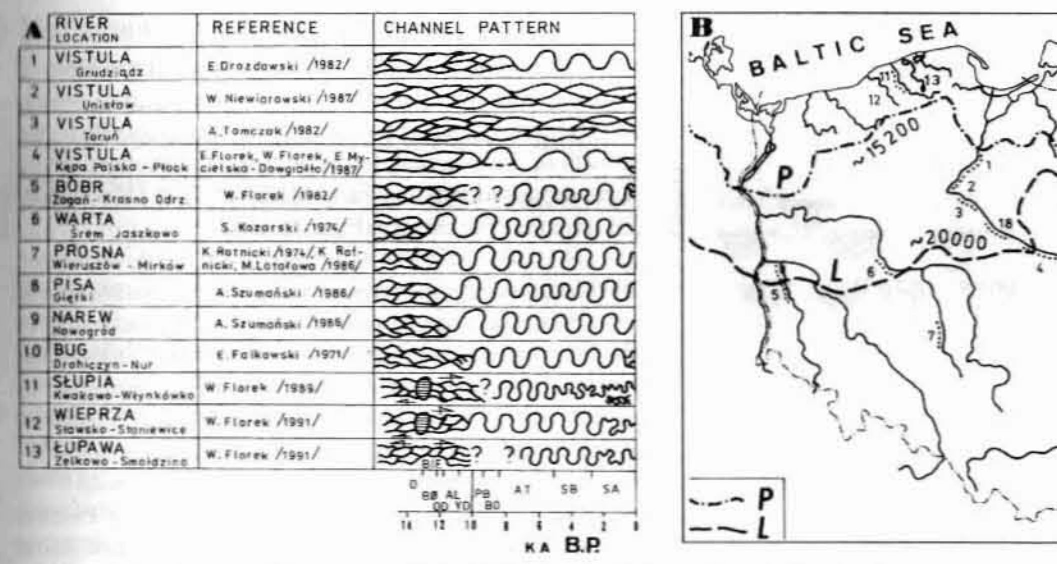

Fig. 6. A - changes of river patterns in the Polish Lowland river valleys during the last 15 000 years (after several different authors); B - location of the research sections of valleys; the maximum limit of the Leszno phase (L) and Pomeranian phase (P) of the VistulianGlaciation.

which was evidenced by a rapid increase of carbonate deposits in the paleochannels and melt-out hole lakes which were common in the river valleys (Alexandrowicz *et al.*, 1989; Florek, 1989, 1991; Fig. 4).

No traces of the so-called "great meanders", reported for the Late Vistulian stage of the Warta, Prosna (Kozarski & Rotnicki, 1977) or San (Szumański, 1986) river development, have been found in the valleys of northern Pomerania or the Baltic Coastal Region. After a presumably short transition period (no morphological or sedimentological evidence is available), with the whole drainage area dominated by mixed forests with higher edaphic requirements (pine forest with hazel in the undergrowth and later, also elm, oak and alder; Latałowa, 1982, 1983), very sinuous meandering channels of the suspended-load type (type 13 after Schumm, 1981, and models 6 and 7 after Miall, 1985) developed in the Pomeranian river valleys. Such channels were characterized by a considerable compensation of runoff, limited transport of load (especially the coarse-grained fraction), small gradients and a low channel width-to-depth index. It is emphasised that classic, sandy meandering channels of regular shapes, with several meander beds and crevasse fans (model 6 after Miall, 1985) are not very common here. Due to the lithological conditions, model 7 is much more frequent; this is defined by Miall (1985) as a meandering channel constraining fine-grained deposits. Meanders formed in such sedimentary conditions have more complex shapes. Coarse-grained deposits appear only in the channel beds and bar bottoms. In the valley of the middle Wieprza their presence is so poorly marked that it is difficult to define the depth to which the fluvial processing of deposits reached. It should also be pointed out that the plant cover density completely reduced the supply of alluvium to the river channels, which, accompanied by a flow concentration in a single channel, caused its erosional incision and initiated the development of a floodplain situated ca 1.5-2 m lower than the lowest Late Vistulian terrace. Generally, its width is visibly smaller than that of the valley floors of the Late Vistulian channels.

In the early Atlantic Period the climate was fairly warm and moderately wet. Pine predominated everywhere, with a birch-hazel-alder admixture in Pomerania (Hjelmroos-Ericsson, 1981), or linden, elm and oak in the morainic plateaus and higher valley terraces of the Baltic Coastal Region (Latałowa, 1982, Zachowicz, 1989). In the very wet localities, the alder prevailed. The change in the species composition of the forests (with its greater proportion of thermophilous deciduous trees) resulted in a considerable decline of the surface runoff, which favoured the decrease and compensation of the outflow, thus the fluvial activity diminished. The latter part of the Atlantic Period saw signs of an increased humidity. In the Łupawa valley this was manifested by the river deposits which entered the overgrown melt-out depressions, dated at 6570 ±130 BP. The river deposits must have been connected with such a marked rise of water level in the Jasień Lake that it overflowed and formed the upper section of this river (Florek, 1991, 1992). At the close of the Atlantic Period, the increased humidity was manifested by the initiation of peat accumulation in the lowest sections of floodplains (Florek, 1991, 1996). The climate humidity was not very clearly marked until the start of the Subatlantic. This resulted in intensification of lateral erosion, and the growth of peat covers in the Late Vistulian terraces (Florek & Florek, 1986; Florek, 1989, 1991; Fig. 4).

The early part of the Subboreal Period saw the expansion of oak forests (*Quercetum mixtum*) and hazel (Latałowa, 1982; Tobolski, 1987). The valley floors were still occupied by alder, sometimes with an admixture of birch (Latałowa, 1983, 1987). At the same time, the proportion of species with advanced habitat requirements decreased, especially that of the elm; also pine decreased (Latałowa, 1982). New components appeared - hornbeam and beech. The latter part of the Subboreal was a period of hornbeam expansion, and, starting from the latter part of the sub-Atlantic, beech woodland predominated (Latałowa, 1982, 1987; Tobolski, 1987). These changes in the species composition of the forests did not produce any significant changes in the functioning of the river channel and valley systems.

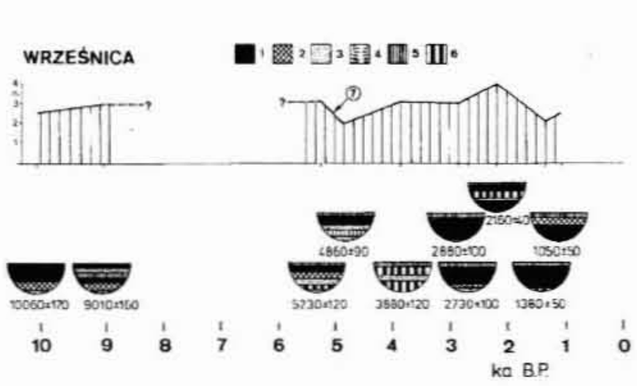

Fig. 7. Diagram of infillings palaeomeander lithology of the Wieprza river near Wrześnica.
1 - peat, 2 - gyttja, 3 - sand, 4 - water, 5 - overbank deposits, 6 - organic silt, 7 - total thickness of fluvial deposits.

In some valley sections (e.g. the Słupia river near Słupsk, or the Wieprza in the vicinity of Sławno), the low gradient, impeding the transport of both water and load, resulted in formation of an anastomosing channel (type 14 after Schumm, 1981, and model 8 after Miall, 1985). The branches of such a channel develop in consequence of persistent flow in the meandering channels, the necks of which have been dissected, and also through the accumulation of the fine-grained, fertile material in the channel, which is conducive to a rapid invasion of plants on the newly-formed islands. In such circumstances, the significance of lateral accumulation of deposits decreased, whereas that of vertical accretion increased.

The middle part of the Subatlantic saw fluctuations of humidity and intensity of the fluvial processes. The periods of greater fluvial activity were characterized primarily by the growth of the overbank forms of sandy clay; some of these were deposited after the Early Medieval town colonization, i.e. after the 10th century (Figs. 4 and 8).

The last period, that in which there has been hydroengineering interference, is the stage of functioning of the mixed-load channel type, as evidenced by the results of the load movement investigations (quantitative ratio of the bed load:suspended load:dissolved load for the Słupia river in Słupsk is 0.77:1:7.6 - Florek & Florek, 1986). The channel shape, however, is similar to the type 12 of Schumm (1981) - the suspended-load channel of relatively low sinuosity.

The stable climatic conditions of Northern Poland, possessing oceanic features, and the limited agricultural expansion also determined that the planar system of the Pomeranian river channels remained unchanged until the close of the 19th century. It must also strongly be emphasised that the Baltic *Litorina* transgressions affected only the mouth sections of the river channels, i.e. those within reach of the storm backwater - a few kilometres. The sea level rise in some periods, which impeded the outflow of the surface and ground waters, was conducive to the formation of peat bogs, marshes, lakes, as well as lagoons (sections of the Gardno and Sarbsko Lakes). The valley segments which had existed in the early Holocene on the axis below the present sea level were gradually destroyed by the abrasional activity of the sea.

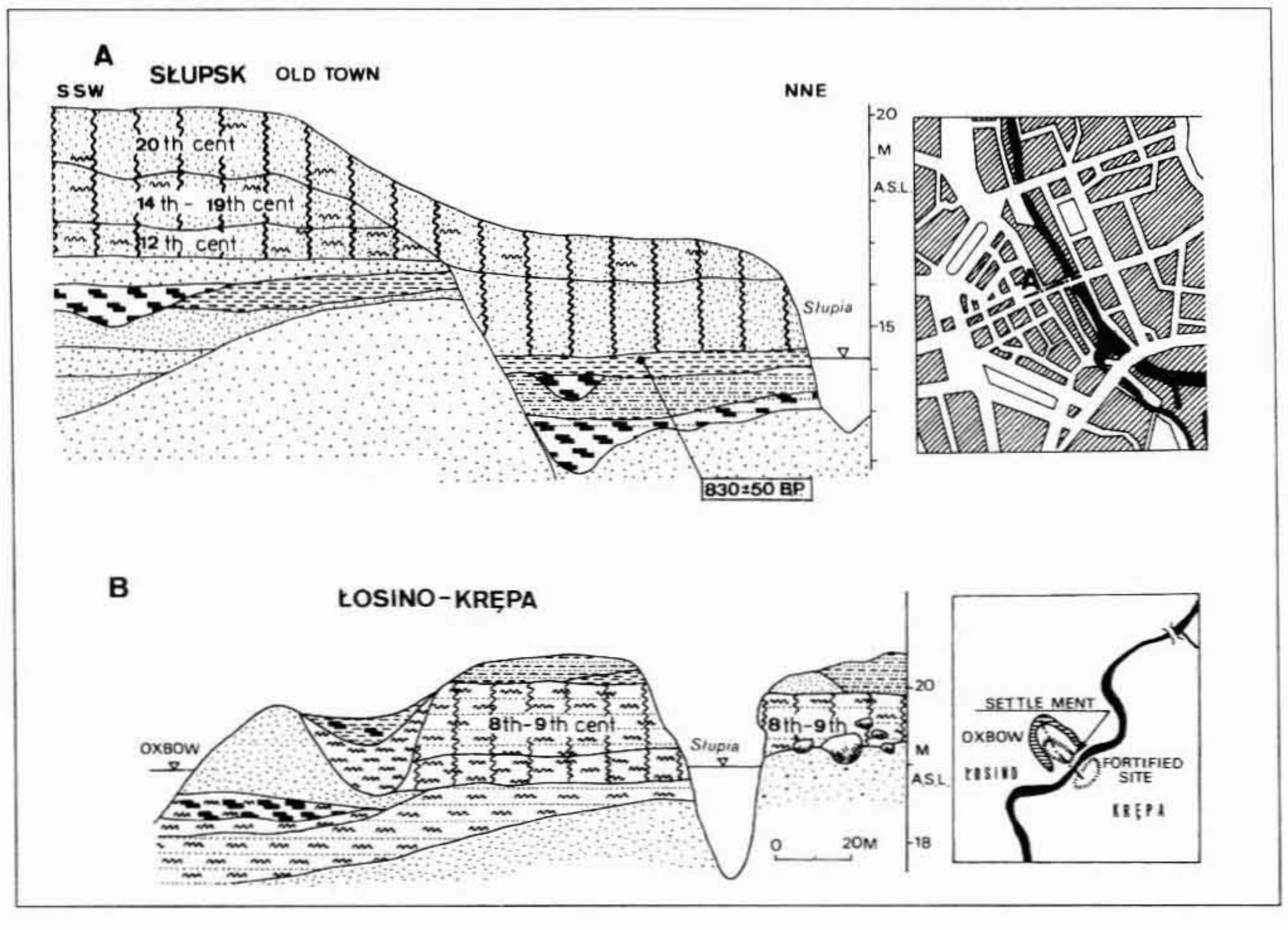

Fig. 8. Anthropogenic aggradation of the Słupia floodplain in Słupsk and Łosino.

The human factor in the transformation of fluvial processes and the development of river valleys in prehistoric and Early Medieval times in respect of the predominant role of the climate

The impact of man's economic activity on the evolution of a plant cover normally consists of the deforestation of the area, a deliberate introduction of plants for cultivation, and fairly accidental stimulation of the growth of some plants, commonly described as "man-accompanying plants". So far, no evidence is available to claim that, in any area of Pomerania and Baltic Coastal Region, the changes in plant cover brought about by prehistoric human activity were drastic enough to disturb the denudation systems, i.e. intensive soil erosion or accumulation of slope and flood forms in the floodplains.

It was not until Early Medieval colonization that a general increase in the rate of accumulation in channel forms was evident (Florek, 1991). This refers not only to Pomerania, but also to the whole of Central Europe (Schirmer, 1973; Florek *et al.*, 1987; Starkel 1987; Starkel *et al.*, 1996). It was associated with a significant increase in the grain size of accumulated material, with a transition from the accumulation of heavy warp soil (clayey-silt) to the deposition of light loam warp soil (silty-sand) (Kalicki, 1991; Pożaryski & Kalicki, 1995).

The Early Medieval period of accumulation of coarse-grained flood sediments synchronized with a period of major hydrological changes, consisting of seasonal variations in the extent and frequency of floods and in seasonal trends of erosion or aggradation. The situation of the lower Słupia valley is characteristic of this. The low location of the fortified site and settlement near Łosino (Fig. 8) suggests that in the 8th and 9th centuries the Słupia channel must have been more incised or it carried less water than now. Also, the Słupia's floods were insignificant at that time. The water level rose after the 9th century, which is evidenced by the sandy-silt deposits covering the material which contains artefacts. A similar situation was observed in the centre of Słupsk (Fig. 8, also Rączkowski, 1989. Florek, 1989, 1991, 1995), and also in the middle Wieprza valley (fortified site Wrześnica; Rączkowski, 1987). Climatic changes, or anthropo-pressure (deforestation of the middle segments of the Parsęta, Wieprza and Słupia drainage areas exceeds 50% - Ślaski, 1951), caused an increase in outflow irregularity after the 9th century, manifested in the greater frequency and extent of floods. The morphological effect was the formation of silt-sand flood covers, which contain archeological material only in their lowest part. Denudation processes were also taking place at that time. Much evidence of river floods in the Middle Ages has been collected over almost the whole of Poland.

The postulated phase of fluvial activity probably lasted until the end of the 12th century. In Pomerania and the Baltic Coastal Region, the 13th and 14th centuries marked a new stage of settlement, manifested chiefly in town locations. In the northern part of Pomerania, the new locations were mainly on the floodplains in the middle (Lębork, Słupsk, Sławno, Białogard), and sometimes also in the lower courses of the rivers (Kołobrzeg, Darłowo). This was, at least to some extent, connected to the preparation of new building ground: filling

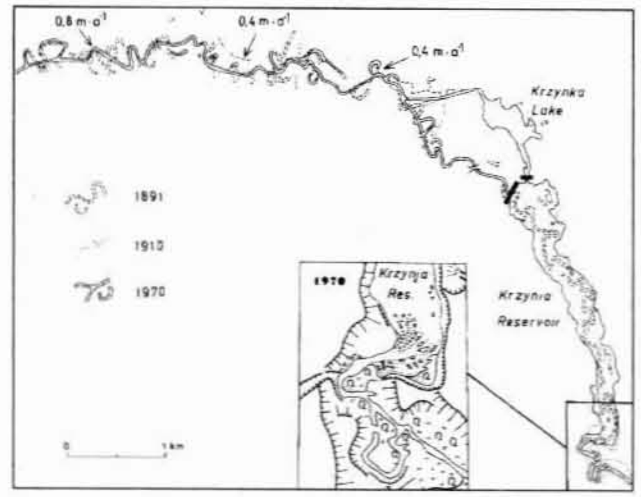

Fig. 9. The Skotawa channel changes from Krzynia to the mouth of the Skotawa in the period 1891-1970.
Average rate of lateral erosion is estimated at some sites (after Florek 1991, 1995).

up the palaeomeanders and flood basins (Florek, 1988, 1991; Popielas-Szultka, 1990). The development of towns was accompanied by the growth of manufacturing structures. There is evidence to prove that small streams were divided by weirs for fish breeding, and water mills and fulleries driven by water energy were constructed. These works did not induce changes in fluvial processes in the main channels, because their construction did not demand partitioning of the whole channel (Florek, 1988). Another factor could have been of more importance: navigation took place on the lower Słupia, which required the constant cleaning of the channel and its banks as boats were drawn upstream by people or animals moving along the bank (Szopowski, 1962). Lower sectors of the main North Pomeranian rivers were probably used at that time for floating timber, necessary as fuel for saltworks and for building fishing boats and warships. Also iron metallurgy was developing elsewhere, e.g. in the Słupia and Wieprza valleys (Rączkowski, 1989), and this involved the exploitation of bog ores and the felling of trees which were later processed into charcoal in kilns.

It is difficult to state exactly whether this significant increase of anthropo-pressure or the naturally occurring climatic changes contributed to another wave of increased fluvial activity in the rivers. Evidence of this period is the flood forms, covering the areas of Middle Medieval settlements (Fig. 8). However, it is difficult to say whether this phase occurred immediately after the 14th century or was associated with a phase of fluvial activity in the 17th and 18th centuries. The latter is usually associated with climatic changes synchronous with the so-called "Little Ice Age", or with the increasing degree of deforestation and beginning of root crop growth (Falkowski, 1967; Starkel 1988). The author is inclined to accept the climatic reasons because the fluvial activation of that time was marked both in the rivers of western Europe (Becker & Schirmer, 1977) and those of northern Europe (Koutaniemi, 1987), where environmental features and standard of management differed significantly. A similar opinion was expressed by Starkel (1977) and Khotinski (1977) and, recently, such an interpretation was also strongly emphasised by Kalicki (1991). Becker & Frenzel (1977) considered that all cool periods in the Holocene had corresponding stages of increased fluvial activity. They are easily correlated with oscillations of glaciers and lake water levels, with periods of landslides and with changes in plant cover (Starkel, 1983; Ralska-Jasiewiczowa & Starkel, 1988).

Human impact on the deformation of the river valleys and the river channel character in modern times

In the middle of the 18th century, major land improvement projects started in Pomerania and the Baltic Coastal Region. As today, drainage works prevailed, which must have contributed to the increasing irregularity of outflow. Increasingly intense floods at the end of the 19th century (the worst was in 1898) increased the pressure for regulation works to be started in 1860. They included dredging of river beds, removing boulders and tree trunks, and sandy bars, and, especially, clearing the meanders, protection of banks and also construction of weirs, dams and water reservoirs. The regulation works were most intense in the first twenty years of the 20th century and coincided with the construction of hydroelectric power plants.

Regulation schemes of the first twenty-five years of the 20th century resulted in significant shortening of channels, in longer sectors by over twenty percent (Fig. 9, see Florek & Nadaczna, 1986), locally even reaching fifty percent. This intensified bottom and lateral erosion was particularly conspicuous in the segment below the weir and hydroelectric power plant in Krzynia (Fig. 9). This was due to the increase of flow velocity resulting from the increased gradient of the channel and the insufficient dissipation of fall energy of the load-bearing water below the power plant. The rate of lateral erosion here generally reaches up to 0.8 m per year.

Construction of hydroelectric power plants, maintenance of weirs and dredging of the river bed are also reflected in alterations of minimum annual water levels, which are closely related to the changes of channel bed position.

The hydro-engineering works also altered the rhythm and range of discharge fluctuations in the sectors below the power plants. This is particularly well marked at the water gauge station at Gałąźnia Mała, where the present ratio of maximum to minimum discharge is 91.5, whereas it is 5.2 at Soszyce, located upstream. The strong fluctuations of discharge rate below the Gałąźnia Mała power plant are gradually weakened in the reservoirs located below Konradowo and Krzynia (Florek, 1989).

As the public utilities and industries, and partly also the agriculture of Pomerania and the Baltic Coastal Region mainly use ground water, the surface water is being fed with extra quantities of water. For instance, it is estimated that the Słupia channel is thus fed with waste waters of 0.5-1.0 m (Florek, 1989). It is now hard to determine to what extent the ground water supplies (this is mainly water from the moraine plateau) contribute to the reduction of underground feeding of the North Pomeranian and Baltic Coastal Region rivers in segments adjacent to bigger towns.

Final remarks

Postglacial climatic changes determined both the transformation of the planar channel pattern (braided, meandering, anastomosing) and the balance of the slope and fluvial processes in the Baltic Coastal Region and Pomerania. Until the Middle Ages, the effects of human activity on the environment of river channels and valleys were very limited. The Early Medieval settlement expansion and deforestation affected the development of overbank cover formation. Yet, it was only the 20th century regulation of river channels and valley floors which have brought about significant changes in the hydrology of rivers which, in turn, determined basic changes of the fluvial process balance in the area studied.

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Polygenesis of the Southern Baltic floor relief

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Abstract: On the basis of its bathymetry, two plains, one deep, the other shallow, may be recognised on the floor of the Southern Baltic Sea. Since the disappearance of the last Pleistocene ice sheet about 12.2 ka BP in the west and 12.5 ka BP in the east and north, the deep plain has remainded drowned, either by the sea or by lakes. In contrast, the relief of the shallow plain is a reflection of three different environments: (1) glacial and fluvioglacial (in the period 14.2-12.5 ka BP); (2) subaerial (12.5-7.5 ka BP) when weathering and stagnant or dead ice conditions predominated and (3) marine (since 7.5 ka BP), i.e. since the shallow plain was covered by the *Litorina* transgression. The processes operating during the later evolutionary phases considerably destroyed the older landforms, i.e. those of glacial, fluvioglacial and subaerial origin. This much modiefied relief was then covered by littoral sediment which accumulated when the Baltic attained its present shoreline. The spits, abrasion platforms and steps and cliffs present in the modern landscape have been created by near-bottom and shore currents.

Key words: late Pleistocene, Holocene, morphogenesis, marine transgression

Introduction

Much new evidence for our understanding of the morphogenesis of the Southern Baltic (Polish Economical Zone) floor has been published in recent years, mainly in respect of the publication by the Polish Geological Institute of two cartographic/text publications which cover the Southern Baltic. The first is the 1:200 000 Geological Map of the Southern Baltic Bottom, published in the period 1989-1995; the second is the 1:500 000 Geological Atlas of the Southern Baltic, published in 1995. In both of them much attention is given to the bottom relief. Each sheet of the Map contains a geomorphological sketch and, in the Atlas, one of the 34 tables is a geomorphological map, and another table presents a synthesis of recent sedimentary processes. In the texts of both publications there are separate chapters devoted to the analysis of bottom relief and to its morphogenesis and evolution.

The new data permit new avenues of investigation, e.g. of the interpretations concerning the origins of the Southern Baltic bottom relief. It has long been known that a significant part of the Southern Baltic area was land during the early Holocene and also partly during the Late Glacial period. The *Litorina* transgression in the Atlantic period (the Flandrian transgression along the western coasts of Europe) converted this area into a sea floor; this resulted in a change of the subaerial relief into a marine underwater relief. The whole complex of these phenomena and processes has recently been firmly dated, using the radiocarbon method, and in some cases also the TL method.

General information on the Southern Baltic bottom relief has earlier been given by Rosa (1967, 1987), Pikies (Geological Atlas..., 1979), Mojski (1989, 1991, 1995), Uścinowicz (1996). The evolution of the contemporary coastal zone was investigated comprehensively by Tomczak (1993, 1995, Geological Atlas...,1995); therefore this zone is not discussed in this paper.

Overview of glacial relief generated after the decay of the last Pleistocene ice-sheet

Bathymetrically, the Southern Baltic area consists of two parts, the so-called shallow plain and the deep plain. These are separated by a more or less well defined shallow plain slope. The latter is located at depths not exceeding 40 m, whereas the deep plain lies below 60 m. Such a division was proposed by Czekańska (1927), and is still used today because it reflects very well the principal bathymetric features.

Glacigenic relief, formed essentially by the decay of the last Pleistocene ice-sheet, has developed somewhat differently in both parts of the bottom. In the deep plain, in the bottoms of the present day basins, i.e. the Bornholm, Gdańsk and Gotland Basins (Fig. 1), the ice-sheet decayed in the presence of