Invited paper

The evolution of the southern Baltic coastal zone

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Abstract

This article discusses the formation and evolution of the coastal zone of the southern Baltic from the decay of the last Scandinavian ice-sheet, which took place some 14 ka BP. During the first 4 ka, the shores of the then southern Baltic basins were shaped under the dominant influence of considerable variations in water level and the young, post-glacial topography emerging from under the ice. Later, until the beginning of the Atlantic transgression, the shores were also unstable, because sea level changes resulting from periodic connections with the World Ocean followed one another in rapid succession. Since that transgression destroyed much of the former shoreline, its reconstruction is at best highly problematical, and in some places no longer possible. The maximum range of the Litorina Sea gave rise to a coastal zone that in many places is to this day quite conspicuous in the local topography and sediments. During the last 4 ka, the shoreline has changed relatively little, thus the present shoreline is largely redolent of the original one. In the coming 100 years or so, the abrasion of the cliffs along the southern Baltic shore will probably accelerate, as will the retrogradation of certain sections of the shoreline, with the result that the shoreline will be less of a straight line than it is at present. Land up to a height of 1 m above sea level will be inundated. The greatest changes in the lie of the shoreline are to be expected in the River Wisła (Vistula) delta and around the Zalew Szczeciński (Oderhaff, Szczecin Lagoon).

1. Introduction

The title of this article is both unequivocal and misleading: unequivocal, because it is self-explanatory; misleading, because evolution, if examined from the time of the last Scandinavian ice-sheet decay, *i.e.* the Late Glacial and the Holocene, from some 14 ka BP to the present day, cannot refer to the southern Baltic (Polish) coastal zone, because at that time, of course, the Baltic did not exist. Neither for that matter did Poland. A basin did exist, but it was twice filled by an extensive lake. Finally, it is not entirely clear what we mean by 'coastal zone', despite numerous attempts at a definition (*e.g.* Rotnicki 1995). None the less, it is this concept that will be used in the present article. The frequently used term 'coastline' is applicable to regional or global assessments, and in such contexts is synonymous with 'coastal zone'. However, where we are talking about inundated coastlines and, moreover, in a basin as small as the Baltic, we should use 'coastal zone'. Solely the term 'southern Baltic' is beyond doubt here, assuming it is meant to coincide with the Polish economic zone. That, indeed, is how it should be understood in this article.

Despite these rather provocative comments, we have got no farther than the title. Yet they are largely justified: it is often the case in natural sciences that attempts at a precise definition require additional comments and explanations. Furthermore, factors understood to varying degrees, usually too poorly, have to be taken into account. These words also apply to the whole of the present article. In order to outline the evolution of the coastal zone of the southern Baltic during such a short geological time, we need to comprehend a large number of factors influencing that evolution. With some of them we are quite well acquainted, about others we have little information, and there are yet more about which we know hardly anything or have only some vague imaginings. The considerable store of knowledge about coastline variations testifies that this is one of the more difficult fields of research in dynamic geomorphology. And this is also the case with regard to Baltic coasts. We know that the principal factors affecting them were vertical movements of the Earth's crust, due on the one hand to the mobility of deep tectonic structures, and on the other to the isostatic uplifting of the crust once this had been relieved of the several-kilometre-thick mass of ice that was the Scandinavian ice-sheet. The evolution of this coastline was also affected by glacio-eustatic changes in the World Ocean level following the melting of the ice-sheets and mountain glaciers, not to mention the rapidly changing topography of the Baltic Sea bed itself and adjacent areas.

Generally speaking, it is easier to follow geological processes, especially endogenic ones, on a geological time scale of millions of years. Now the 10–15 thousand years that we are discussing here would seem to be too short a period for the effects of those events to have been recorded. But this is not so. At the end of the Pleistocene, geological processes occurred with an unprecedented violence. Suffice it to mention the Younger Dryas (Goslar *et al.* 2000, Mojski 1999), the final cold climatic swing of the Pleistocene, when for about one thousand years, the front of the Scandinavian ice-sheet straddled the Oslo, Stockholm and Helsinki regions. It took a mere two thousand years for this ice-sheet to disappear entirely from the face of Europe.

The intention of this article is to discuss the changes in the southern Baltic coastline from the time the first aquatic basins were formed around the front of the receding Scandinavian ice-sheet (Fig. 1) in the light of the evolution of these basins. The history of these events can be divided into three periods. The oldest covers the so-called Late Glacial, that is, the time when the ice-sheet's recession had halted at the Gardno end-moraine (Gardno Phase) up till and including the Younger Dryas. The second period covers the older Holocene; in the Baltic region this will have been from the start of the Holocene until the maximum extent of the Litorina Sea. The third period is the younger Holocene, *i.e.* in the Baltic, from the maximum extent of the Litorina Sea to the present day.

This division of the evolution of the Polish coastal zone of the southern Baltic only partially resembles the one by Tomczak (1995a, b). She distinguished four phases in this evolution and named them as follows: the pre-transgression phase, older than 8 ka BP; the Atlantic transgression phase, between 8 and 5.5 ka BP; the post-transgression phase, between 5.5 and 1 ka BP; and the contemporary phase, that is, the last 1000 years. While the two youngest of these phases correspond to my third period, the others do not fit in with my conception.

The once-existing shorelines or coastal zones of the Baltic are discussed against the background of its entire Late-Pleistocene and Holocene history, and the decay of the last Scandinavian ice-sheet. One of the sources for this work were the maps in the Geological Atlas of the Southern Baltic, especially Table XXVII, which was compiled by Uścinowicz (1995). Many of my conceptions have been presented in earlier publications (Mojski 1989, 1995, 1997), but have had to be revised.

2. Ways of delineating former shorelines on the Baltic Sea bed

So far, former shorelines on the Baltic Sea bed have been sought with the aid of constantly upgraded techniques and information on sunken cliffs and abrasion surfaces provided by continuous seabed mapping. For a long time, the geological structure of these formations was completely or almost

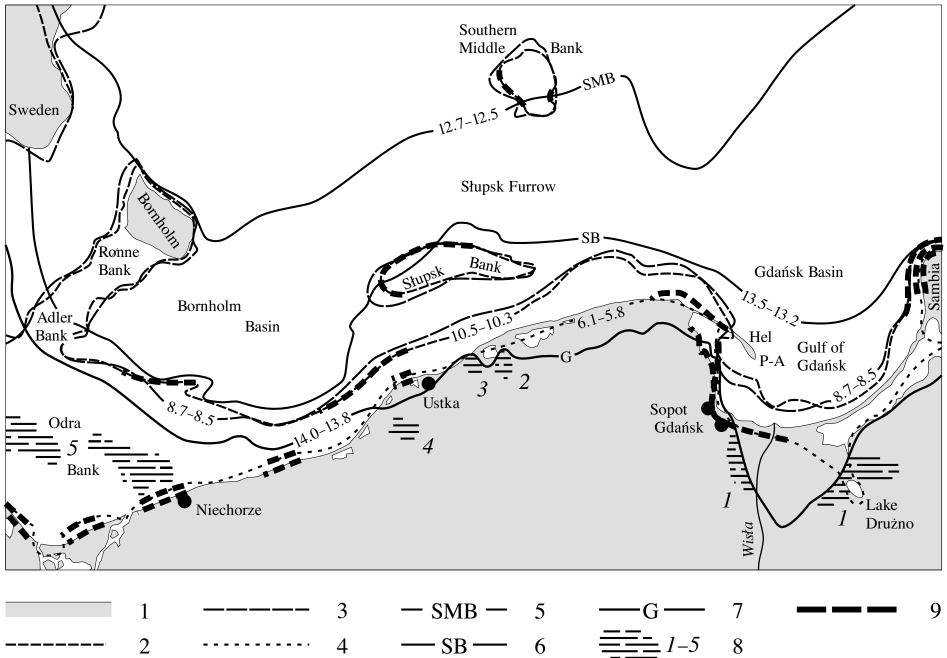

Fig. 1. Selected Late-Glacial and Holocene shorelines along the southern Baltic: 1 – present, 2 – during the Baltic Ice Lake Phase, 3 – during the Ancylus Lake Phase, 4 – during the Litorina Sea Phase; Ice-sheet limit during: 5 – the Southern Middle Bank Phase, 6 – the Słupsk Bank Phase, 7 – the Gardno Phase; 8 – proglacial lakes or lake areas: *1* – Gdańsk, *2* – lower Łupawa river, *3* – Wytowno, *4* – Sławno, *5* – Odra Bank; 9 – cliffs. Ages in ^{14}C ka BP

unknown. The mid-1960s, however, witnessed the first attempt to define onetime coastlines in our part of the Baltic seabed (Rosa 1967), not only cliffs coasts but also accretion shores. Those former shores were delineated on the basis of accurate bathymetric charts, quite simply at locations where the isobaths cluster together and using what little information on sediments was available.

During the next stage in this research, initiated over 20 years ago (Rosa 1987, 1989, 1991), the initial concepts had to be revised. This was perfectly understandable: seabed topographical criteria could no longer be sufficient. The time had come to carry out a regular geological survey of the seabed in the whole area. Undertaken by the Branch of Marine Geology of the Polish Geological Institute, the fruits of this task were a Geological Map of the Baltic Sea bed on a scale of 1:200 000, and subsequently a Geological Atlas of the Southern Baltic. Both publications, together with the rapidly rising number of papers on the origin and evolution of the Baltic during the Late-Glacial and Holocene, have become a mine of information on former coastlines which on the one hand has not yet been utilised to the full, but on the other has stimulated much further research.

A significant inference to be drawn from these investigations is that the earliest shorelines were mostly washed away by subsequent marine transgressions, particularly during the Litorina transgression. In some places, however, fragments of cliff coast have survived; these can be regarded as remnants of earlier shorelines, especially if abrasion platforms are present. Elsewhere, the preserved littoral facies of the sediments could indicate a former seashore. On the other hand, narrow, steeply sloping sections of the seabed could have arisen in a variety of ways: they might be the slopes of former valleys. This has been well known for a long time (Rosa 1963, 1967).

Today it is clear that former shorelines are extremely difficult to delineate if they are lying below sea level. Paradoxically, it is easier to find flooded shore zones. It is not so much the traces of the shore itself that are important; rather an abrasion platform, a layer of pavement, or better still a concentration of heavy minerals typically found on beaches. In the case of cliff coasts, the presence of accumulated stones and boulders, and a steeply sloping bottom, would be important. Regular studies of this kind aiming at delineating former shorelines have never yet been done along our coast.

3. The Late-Glacial

The southern Baltic Late-Glacial began around 14 ka BP, that is, at the time when the front of the ice sheet was stationary along the line of the Gardno end-moraines (Gardno Phase, Fig. 1), and came to an end during the period when the youngest end-moraines in the Younger Dryas (Central Sweden Moraines – Salpausselkä) were formed, *i.e.* 10.2 ka BP. During these 4 ka or so, the ice sheet disappeared from the whole of the Baltic Proper and the Gulf of Finland, in a band at least 500 km wide and broadening somewhat towards the east. Every year a strip of land about 130 m wide on average was exposed. However, this figure does not say much, since at that time the front came to a halt several times, each time for around one hundred years; moreover, large masses of stagnant ice, and later dead ice, remained in depressions. On contact with water these masses disappeared rapidly.

Numerous small, shallow lakes were formed behind the retreating ice sheet. Their shores will have been flat and marshy, a typical scene in the tundra. The sediments of such basins have been discovered in a few areas (Fig. 1) to the south of the Gulf of Gdańsk. Unlike Roszko's (1969) perception of them, they are merely small, shallow pools in depressions of various kinds. Also of this type are the ice-dammed Lake Wytowno and a similar lake on the lower Łupawa river in the Gardno end-moraine zone. The latter lake (Czerniawska 1999) has visibly encroached into the foreland of the Gardno moraines. The ice-dammed lake near Sławno, farther to the west, is also one of these proglacial lakes. The sediments of similar water bodies on the Odra Bank have been dated to 14.06 ka BP (Kramarska 1993) and on the Gardno Lowland to 13.8 ka BP (Rotnicki & Borówka 1994). Throughout this region the terrain was low and flat, dotted with such shallow lakes. Deeper lakes were formed somewhat farther south in the incipient channels, the best known of which is the Niechorze Channel.

Those proglacial, local, cold lakes can hardly be regarded as the earliest stages of the Baltic Sea. It is more likely that they were part of a system of periglacial lakes that were forming in areas lately relieved of their ice load.

However, what can be seen as the earliest stage is the narrow body of freshwater extending along the edge of the ice sheet from Sambia to Skåne (Uścinowicz 1995). During the Słupsk Bank Phase (13.5–13.2 ka BP), the ice-sheet raised marginal formations – an eastern lobe in the Gdańsk Basin and a western one in the Bornholm Basin. The end-moraines on the Słupsk Bank and in the southern part of the Adler Bank (Eagle Bank), later washed away, were also formed at that time. Large masses of stagnant and then dead ice were left behind in the forelands of those two lobes, which, as time elapsed, were inundated by the waters of the pro-glacial lake. Varvites were formed in the ice-dammed lake lying between the lobes in the Słupsk Bank foreland. The southern shore at the eastern end of this lake as far as Ustka lay very close to the present-day shoreline. At the western end, by contrast, that shore is buried at least a dozen or so metres on average below the present sea level of the Baltic. This is the upshot of at least two factors. One was the westward outflow of meltwaters, the westward slope of the bottom, and the depression of the shore of the proglacial channel that evolved from the narrow ice-dammed lake there. The other factor could have been negative crustal movements, whose amplitude increased westwards.

Not a single shoreline from that time has survived. One has to agree with earlier opinions that if such shorelines did ever exist, they must have been destroyed at some later time, especially by the transgressions of the Litorina Sea.

The retreat of the ice-sheet front from the Słupsk Bank Phase end-moraines caused the further enlargement of the proglacial lake and, in consequence, the formation of the Baltic Ice Lake. As a result, the waters of the Bornholm Basin and the Gdańsk Basin became connected. The Słupsk Furrow was flooded at this time. This whole process lasted until 10.5–10.3 ka BP, when the Baltic Ice Lake reached its greatest extent, its northward spread being held up by the Central Swedish end-moraines and

Salpausselkä. Whereas at the beginning of this period the shoreline lay 55–50 m below the present-day sea level, at the time of the Baltic Ice Lake's greatest extent it lay 30 m higher. This great lake had a very complex shoreline. In the southern Baltic, the highest parts of the bottom emerged first, later the lower-lying parts. At the time of the Baltic Ice Lake's greatest extent, Bornholm was linked to the mainland – the entire Odra Bank – by means of the Rønne Bank and the Adler Bank. In this way a narrow peninsula with Bornholm at its NE tip was formed. To the east there were isolated small islands, outcrops of old, compacted rocks.

The Słupsk Bank and the Southern Middle Bank to the north made up a large island. Traces of the island's shoreline have survived along the present-day Polish shoreline, but at an average depth of 30 m, and somewhat less around the Southern Middle Bank. Uścinowicz (1995) first interpreted this type of coast, distinguishing cliffs and accretion shores. This picture has to be modified in that the coast east of the then mouth of the river Piaśnica was composed largely of cliffs. Further east still, at the present depth of 40 m, an extensive coastal ridge began to form (Uścinowicz 1995). Later, this was displaced slightly southwards, to become the foundation of the NW part of the Hel Spit (Mierzeja Helska). What is now the Puck Lagoon (Zalew Pucki) was then dry land, the eastern shore of which lay along the line of the Seagull Shoal (Ryf Mew).

It should be mentioned that Rosa (1989) attempted a different reconstruction of the events of those times: he came to the conclusion that a great regression of the Baltic Ice Lake took place during the Younger Dryas. His view is that the water level at the end of the Younger Dryas, when the eustatic minimum was reached, lay 105 m below the present sea level (Fig. 2). There is no evidence for this, or at least Rosa does not provide any. Neither does he offer any evidence for the five coastal flattenings he distinguishes, which he has named 'Allerød I' to 'Allerød V', when the water level in the Baltic Ice Lake dropped from 29 to 55 m below the present sea level. These diametrically opposing views of the direction of sea level change in the Baltic Basin of those times may yet be reconciled if Rosa's hypotheses are supported by datings. It is highly improbable, however, that evidence will be found for the presence of five flattenings during the Allerød period along the coast, or for the eustatic minimum, 105 m below the present-day level of the sea, at the turn of the Pleistocene. At that time the water surface lay at least 80 m higher (Fig. 2; the graph in Uścinowicz 2000).

Uścinowicz's interpretation appears to account for the effect of glacio-isotatic movements. It is well known that once it had been relieved of the pressure of the ice-sheet, Scandinavia began to rise at varying rates, though fastest in the far north, where the ice had been the thickest. In the south,

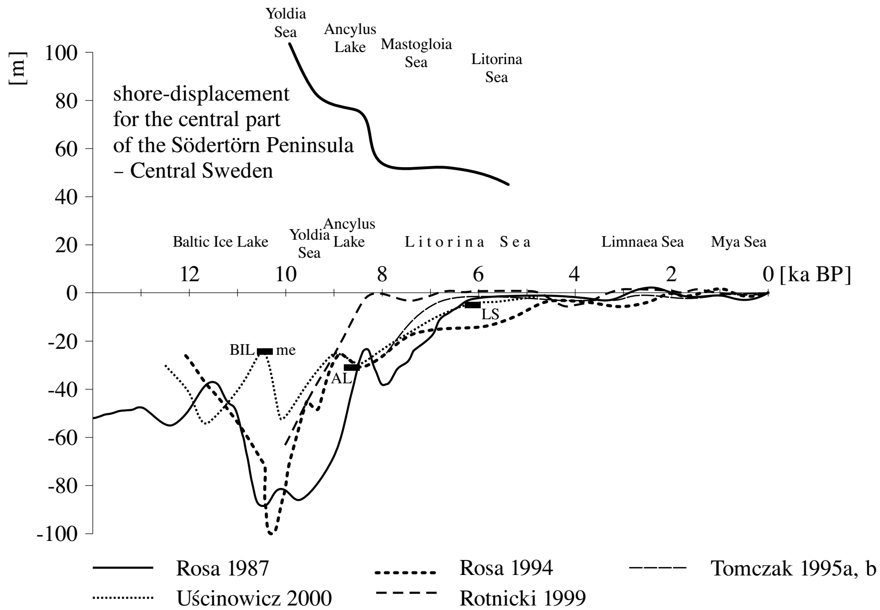

Fig. 2. Late-Glacial and Holocene shoreline displacement in the Polish section of the southern Baltic, according to various authors (see References); Shorelines of: BIL – Baltic Ice Lake, me – maximum extent, AL – Ancylus Lake, LS – Litorina Sea. For comparison – shoreline displacement in Central Sweden (after Hedenström & Risberg 1999). Radiocarbon age not calibrated

where the ice had been thinner, the rate of uplift was slower. The position of zero uplift has been located many times. According to the calculations of Kolp (1987–88), the zero isoline runs just to the north of the Polish coastline. South of this line, the land falls away relative to the north. These calculations and estimates are deciding factors in the reconstruction of the height of former shorelines. Along the Scandinavian coasts of the Baltic, the former shorelines are now 50–60 m above the present-day sea level: the older they are, the higher they lie. An example is given in Fig. 2. In the southern Baltic and on the Polish coast, the former coastlines, relative to the north, now lie much lower than originally. That is why the shoreline of the Southern Middle Bank island at the time of the Baltic Ice Lake's maximum extent now lies only slightly higher than along our present shore.

The cliff sections and accretion shores of the Baltic Ice Lake were identified by echo sounding (Uścinowicz 1995). The bathymetric picture is not accurate enough for this purpose. The cliffs are composed of Quaternary formations, but in the case of the Southern Middle Bank, at least in places, the topographic effects of an older substrate cannot be ruled out. It is also known that the cliffs of this Bank were formed on a substrate of outwash plain sands and gravels. On the other hand, the shore around the Słupsk Bank arose in an area of multifarious Pleistocene deposits. Cliffs arose from time to time where harder formations were present. Similar relationships existed on the shore of the Baltic Ice Lake.

The decay of the ice-sheet, which took place towards the end of the Younger Dryas, released a narrow depression from under the ice near Billingen in southern Sweden linking the Baltic Ice Lake with the waters of the Danish Straits. Vast amounts of water flowed westwards out of the lake, causing the water level in the Baltic area to drop to 55 m below the present sea level. This was the maximum extent of the Baltic's regression at that time. According to Uścinowicz (1995), traces of this low water level can be found in the development of regression structures in the then-existing coastal spits and in the erosion of the sediments at the bottom of the lake.

However, the Billingen connection with the ocean also permitted the rapid flow of oceanic waters into the Baltic area, as a result of which the short-lived Yoldia Sea came into existence. Its southern shore lay from 60 to 55 m below the present-day level of the Baltic Sea. Thus, much of what now lies under the southern Baltic was then dry land. Part of this was the Słupsk Bank, separated only by the Słupsk Channel from the Southern Middle Bank. The Adler Bank peninsula broadened considerably, and to the NE of it islands built of old rocks were still in existence. Unfortunately, we know nothing about the type of coasts here at that time. Very probably they were cliffs, which later eroded away. An accretion shore came into existence in the SE part of the Gulf of Gdańsk, since a shallow lagoon developed behind it (Uścinowicz 1995).

The Scandinavian Peninsula was rising faster than the level of the ocean and eventually cut off from the ocean the body of water in the Baltic Basin known as the Ancylus Lake. The rapid uplifting of the land in the north accelerated the flooding of land in the south, where the level of the Ancylus Lake rose by at least 25 m (25 m below the present sea level). In the west (Jensen *et al.* 1999) the Ancylus Lake reached its maximum extent between 9960 and 9360 years BP. These dates do not correspond fully with the relevant dates from our region. Along our shores, the Ancylus transgression was a time of destruction rather than one of deposition and shoreline sculpting.

The constantly rising level of the ocean eventually opened up the Danish Straits, enabling the rapid inflow of oceanic water into the Ancylus Lake. Thus began the Atlantic transgression, called the Flandrian transgression in the West, and the Litorina transgression in the Baltic Basin. The sea level rose at a rate of 1.0 to 1.5 cm per year (Tomczak 1995a, b). This process began a little over 8 ka BP and came to an end about 6 ka BP, and probably somewhat earlier, as radiocarbon datings from the shores of the Wisła (Vistula) delta have indicated (Mojski, 1983, 1988). Over those two thousand years, the seashore retrograded from 5 to 60 km all along our coast (Tomczak 1992). By the end of this transgression, the shoreline lay for the first time very close to the present-day one (Fig. 1). At first, the islands in the Słupsk Bank and Adler Bank areas managed to survive, since the shores there were mainly subject to accretion, but it was not long before they too were flooded. On the other hand, the shorelines of the maximum extent of the Litorina transgression have been traced out with quite good accuracy. This applies particularly to the shores of the Gulf of Gdańsk. The onetime cliff between Gdańsk and Sopot is clearly visible (Mojski 1983): although in the east it is hardly discernible in today's topography, in the north (Fig. 1), at Sopot, the declivity is clearly in evidence. A dead cliff, it lies somewhat to the south of the Orłowo Headland, which is an active cliff being eroded by the Baltic. It is quite a rare occurrence for one and the same cliff to contain fossil, dead and live sections. This cliff displays continuity, but its constituent parts may be of different ages. In the north, it is definitely a contemporary, active cliff, very obviously retreating at the rate of up to 1 m per year (Subotowicz 1982). Towards the south it fades away, and there it may be of varying ages, partly the maximum extent of the Litorina transgression, partly younger. To the east of Gdańsk (Fig. 1) it is a wholly fossil cliff, reconstructible only from the evidence of core profiles. It lies buried under an eastwards thickening layer of the sediments of the Wisła delta. This last piece of evidence is testimony to the fact that the southern shores of the Gulf of Gdańsk are subsiding, a process which is intensifying eastwards. There, the cliff now lies entirely below the present-day sea level. Whatever its cause, this subsidence could be one of the reasons why depressions have formed in the Wisła delta.

At the foot of this section of cliff there is an abrasion platform. Every part of this now lies below sea level, from which one may infer that the maximum extent of the Litorina transgression in this area never reached the present-day sea level, even though the then shoreline lay farther south than today's. As the abrasion platform was formed, older sediments were uncovered: in some places glacial deposits, in others peat. Their topmost layers have been radiocarbon dated at several sites, the youngest date being 6330 years BP, the maximum age of the Litorina lagoon on the land embracing the Gulf of Gdańsk from the south (Mojski 1988). Rather more to the east, a shallow bay was formed, which extended as far as the present Lake Drużno (Fig. 1), a remnant of that bay. Evidence for this is the dating of bottom sediments from this lake to 6440 years BP (Zachowicz *et al.* 1982). At that time, there was no longer any cliff along this section of the shore.

Similar areas that have been studied more extensively include the Łeba Bar, the Gardno Lowland and a few sites farther west, the Świna Gate being a prime example. The sediments of the Gardno Lowland have been both well studied and well dated (Rotnicki 1999). At its maximum extent, a little later than 5090 years BP, the Litorina Sea halted its expansion at the then shore dune, SW of Lake Łebsko. This was a shore lying at the present sea level. The accretion shore had been in existence for at least *ca* 1.8 ka, as the marine deposits were covered with a layer of organic origin that had started to accumulate some 3.3 ka BP. Nevertheless, that shore will have been much younger than the one around the Gulf of Gdańsk, and now beneath the Vistula Bar (Mierzeja Wiślana). This is not difficult to explain: in the west, the sea moved farther inland than in the east.

Due south of Łeba, the extent of the Litorina Sea is thought to be delineated by peat deposits dated to 7.6 ka BP lying under marine sands. According to Morawski (1998), however, these sands were carried to their present position when storms caused the sea to overflow on to the land, so the extent of these formations should be regarded as the extent of these inundations and not of the actual sea shore. Even so, according to this interpretation, the shore of the open sea cannot have been very far away.

The above review of the former shorelines of the southern Baltic shows that they are reasonably well documented with respect to the Litorina transgression and the maximum extent of the Baltic Ice Lake (Fig. 2). All the other shorelines have been more or less destroyed. The destruction took place largely during the Litorina transgression, and like today, and storms will have been the destructive agent. The slightly higher average air temperatures during the climatic optimum of the Holocene – the Atlantic period – may well have contributed indirectly to the increase in the number and intensity of storms.

The maximum extent of the Litorina Sea lasted for about 1000 years. So, taking the annual rate of retreat of the Orłowo cliff of 1 m per year as a yardstick, a cliff coast of this kind will have retrograded a distance of 1 km in 100 years. As a result, 'rough edges' will have been smoothed out, promontories will have been curtailed and accretion shores will have received larger-than-usual supplies of material. At the same time, the Hel Spit and the other sand-bar formations along the southern Baltic coast were growing apace, and the shoreline in places was being displaced slightly southwards.

During the late Litorina period, a shore zone came into existence in those places where brown dunes have survived (Tomczak 1995a, b), the oldest generation of dunes on the Polish coast. The dunes most thoroughly analysed are the ones at the Świna Gate (they were described by geologists employed by the Prussian geological service), and at the landward end of the

Vistula Bar, which separates the Wisła delta from the Gulf of Gdańsk (Rosa 1963), where, in addition, they have been dated (Mojski 1988). Like the two younger generations of dunes, brown dunes are evidence of a relatively stable shoreline. The culmination of the Litorina transgression came to an end 4.5–4.3 ka BP (Tobolski 1989, Rosa 1994), and was followed by the development of the Limnaea Sea, and later the Mya Sea. At that time, the level of the Baltic did not fluctuate by more than 1 m. There was a fairly distinct maximum some 2.5 ka BP and another, less distinct one about 1 ka BP (Tomczak 1992): the maximum range of the Litorina Sea was regained, and in some places overstepped. This may have happened in the Sopot and Gdańsk areas. Following each of these maxima, the sea withdrew somewhat and the shore remained static for a time. It was then that the shore dunes now known as yellow dunes came into existence. They were formed from 2.5 to 1.5 ka BP, with the rate of accretion peaking between 2.2 and 2.0 ka BP (Tomczak 1995a, b). Subsequently, the shoreline became quite stable, although there was a slight tendency for it to be eroded. Presumably, these processes were governed by sea level changes, the amplitudes of which are unlikely to have exceeded 1 m. Recently, however, the conviction has been growing (*e.g.* Uścinowicz 1999, 2000) that the available evidence does not necessarily demonstrate that the present-day formations are the results of gradual processes, as outlined above. Indeed, they may well be the consequence of extreme phenomena such as violent storms, during which the sea destroyed the dune embankments along the shore and poured into the lagoons and other depressions beyond the beaches. The chemical composition of the sediments at such sites would testify to this. Such an event could have occurred, for instance, at Lake Drużno (Zachowicz *et al.* 1982) and on the Gardno Lowland (Tobolski 1989). Taking storm surges into account in the shaping of former sea shores will, of course, make it harder to reconstruct their original positions.

Shoreline smoothing by longshore currents became the dominant process at this time. This is particularly in evidence in the sand-bar sections at the Świna Gate, on the Hel Spit and the Vistula Bar. However, the hypothesis of Mielczarski (1996) that for 500 years these processes smoothed out the shore of the Vistula Bar between Jantar and Krynica Morska is unacceptable: his geological interpretation should be rejected in its entirety.

4. The present day

The current state of the Polish Baltic shore and the direction its evolution is likely to take are being thoroughly investigated, not only in order to achieve a better understanding of this evolution, but also to evaluate economic needs and, most significantly, coastal protection measures. Secular changes are governed chiefly by alterations of sea level, but more rapid changes are brought about by storms and coastal management. The two processes overlap and both tend to erode the shore. Nowadays, it is the human agencies that are far more destructive than secular changes. This is especially true along cliff coasts subject to intensive human impact.

The present changes in sea level, and thus the shaping of today's shorelines, are, in the view of most experts, definitely due to the rise in sea levels elicited by the greenhouse effect. The results of this are already visible on 70% of the coasts around the world, including our own one. Between 1971 and 1983 the Polish coast retreated by 0.4–1.6 m per annum (Zawadzka-Kahlau 1999). (The higher figure applies to cliff coasts.) Zawadzka-Kahlau states that the rate of erosion of this coast between 1960 and 1983 was much faster than that recorded during the entire 19th century. She also holds the view that the reason for this heightened erosion is the faster rate of sea level rise and greater storm activity. The mean sea level here has risen by 12 cm in the last 100 years (Zawadzka-Kahlau 1999), 9 cm of which in the 40 years from 1950 to 1990 (Dziadziuszko 1994). Rotnicki & Borzyszkowska (1999) also confirm this very distinct rise in the level of the Baltic. They draw attention to the fact that this rise is faster towards the east, and that it was more intensive in 1971–90 than in the preceding 20 years (Dziadziuszko & Jednorał 1987). The frequency of storm surges in the Gulf of Gdańsk also increased in the same period (Dziadziuszko & Jednorał 1996).

From the geomorphological standpoint, the effect of this sea level rise is the erosion of cliffs, which has been going on for the last few hundred years. The prime example in this respect is the cliff at Trzęsacz which in the last 500 years has receded 1800 m (Dobracki 1999), an average of 3.6 m every year. Elsewhere, cliffs are retreating much more slowly; for instance, the one at Orłowo is retrograding by about 1 m each year.

The effects of coastal erosion are more conspicuous east of Jarosławiec, which, according to Zawadzka-Kahlau, is because the rate of sea level rise there is faster than on the west coast. Her findings have been confirmed by other scientists, who have studied shorter sections of the Polish coast, and should therefore be treated as a basis for making forecasts.

Despite this gloomy picture, there are a few places along the Polish coast where the reverse process is taking place (Furmańczyk 1994, Zawadzka-Kahlau 1999), although these are areas where accretion occurs anyway. This is particularly in evidence along the Hel peninsula where, as the tip is approached, accretion is very much the dominant process, peaking between the 30th and 35th kilometre (Furmańczyk 1994). Accretion has been an on-going process throughout historical times, causing the peninsula to lengthen (Łęgowski 1925, Tomczak 1999). The reasons for this process are obvious enough; it is probably responsible for spit and bar formation elsewhere along the southern Baltic coast. None the less, abrasion is so widespread that sooner or later these features will be eroded away too.

All man-made structures intended to protect the coast exert a great influence on the shaping of the shoreline, but this is not the place for a detailed analysis of them. Suffice it to say that assessments of their value vary in the extreme – from high praise of their undoubted advantages to wholesale criticism. The former opinions are voiced largely in technological circles, where most of the decisions to erect coastal engineering structures are taken. The opposite stance is taken by naturalists, who are better acquainted with the processes of abrasion and have a better realisation of the long-term effects of such engineering projects. Technical operations do indeed provide quick solutions, but only in the short term. Seen over a longer time perspective, their effects always remind us of man's vulnerability in the face of nature's forces. It is precisely these long-term prospects that should be assessed in any forecasting of how the Polish coast is likely to evolve. If the present trend of climatic change continues, it is likely to suffer incalculable damage during the next few decades.

5. Forecasts

The first predictions and computations of such destruction have already been made. Serious attempts have been undertaken in this respect by both engineers (Zeidler 1992, 1995) and geomorphologists (Rotnicki & Borówka 1989, Rotnicki *et al.* 1995). These forecasts assume as axiomatic that the level of the world ocean is rising as a result of the greenhouse effect. The available data is considered proof enough of the intensity of this process and the rise in the world ocean level is regarded as a proven fact. In the southern Baltic, this rise has been recorded in the form of tide-gauge readings. Taken in conjunction with such readings made elsewhere on the Earth, one can predict that the rise in the southern Baltic during the next 100 years will be anything from 30 to 110 cm. Zeidler's (1995) predicted average rise of 60 cm is a very reasonable one. Cyberski & Wróblewski (1999) give a somewhat lower figure, computed from the tide-gauge trend, of 28–35 cm for the year 2100. It goes without saying that the condition for this to happen is that the present rate of global warming remains unchanged.

These figures can be examined from several points of view. First of all, they ought to be compared with the rates of former changes in sea level. In comparison with the pre-Litorina period in the Baltic's evolution, they are nothing unusual. At that time, the level of the Baltic rose 30 m in 1 ka, that is, by 3 m in a century, and that was several times faster than what is expected to happen in the near future. Again, during the Litorina trangression the level of the Baltic rose by 1.0 – 1.5 m per 100 years (Tomczak 1995a, b), which was twice as fast as the present forecast (Fig. 3). On the other hand, in the period following the maximum extent of the Litorina transgression, that is, the last 5 ka, those 60 cm per century can be treated as an extreme event that would have catastrophic consequences for the whole Baltic coastal zone.

Secondly, if the present trend is maintained, substantial parts of the coastal area will become permanently waterlogged, if not entirely submerged. The requisite computations together with the magnitude of the destruction are given in the literature, so there is no need to go into them here.

Thirdly and most importantly, we should analyse the scenario in which the entire present coast is destroyed and a new coastline comes into existence along the southern Baltic in Poland. In this respect, certain assumptions have to be made. To begin with, hundred-year forecasts are drawn up purely and simply because a century is a convenient, finite unit of time, comprehensible by the human mind. Fifty years all the more so, then. However, this is no way to measure natural processes. There is no basis for assuming that the intensive greenhouse effect will cease after 100 years, and that as a result, the sea level will stop rising, even if the causes intensifying the greenhouse effect are eliminated. The effect will then be delayed with respect to its cause, in other words, the phenomenon of retardation, well known in the Earth Sciences, will come into play. This effect is accounted for in Fig. 3 in that the sea level rise is reduced from 66 to 41 cm.

Any assessment of the position of the shoreline in 100 years' time needs to take three separate phenomena into account. One is the real displacement of the shoreline, another is the waterlogging of the lowest-lying land, and the third is the submergence of land by storm surges.

The real displacement in the shoreline is the easiest to assess and to draw on a suitable topographic map. In this approach, however, soil waterlogging and storm surges can actually alter the line of a shore very considerably. If the present trend is sustained (approx. 1 m per annum, Subotowicz 1995), cliff sections of the coast will have retreated by at least 100 m by the 22nd century. But accretion shores may retrograde even faster, especially if the flooded area now lies below sea level, as is the case in the Wisła delta. The tendency for the shoreline to smooth out, prevalent along the whole Polish coast over the last few millenia, will be halted.

The position of our coast in the near future has already been delineated (Rotnicki *et al.* 1995). However, attention should be drawn to the various behaviours of cliff coasts and accretion shores: their transformation will

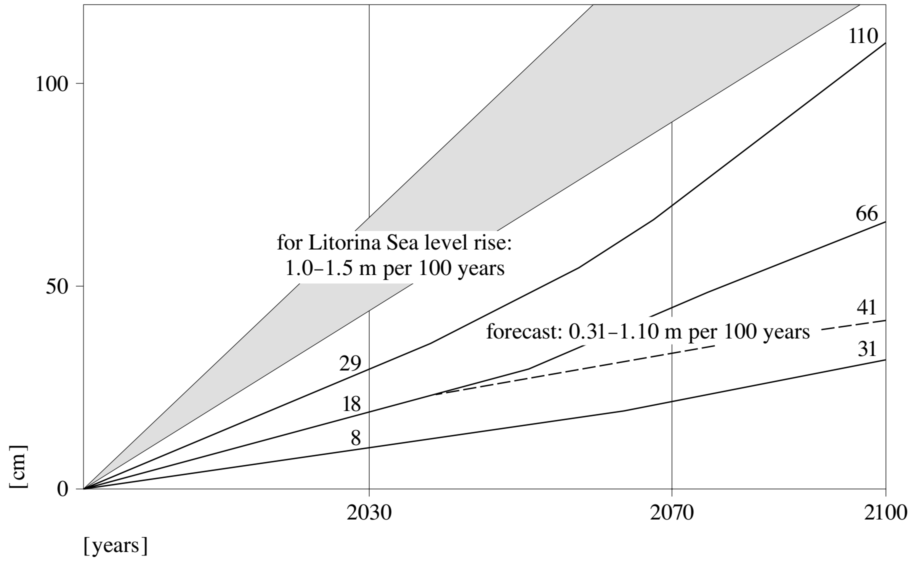

Fig. 3. The Baltic Sea level rise in the 21st century Scenario A 'Business as usual' (Barnett 1984). For comparison – Litorina Sea level rise (after Tomczak 1995a, b). Dashed line – sea level rise if the concentrations of greenhouse gases stabilise by 2030

take place at different rates. The cliff coast will always be more resistant to abrasion, whereas accretion shores will be more readily eroded, which means that newly-forming embankments could be swept away and flooded. Thus, regardless of the on-going smoothing of the shoreline, the submergence of its accretion shores will take place faster than the abrasion of the cliffs. And this is the heart of the matter regarding shoreline displacement. A stable shoreline is therefore a reflection of zero sea level change, whereas a marine transgression leads to coastal indentation. This is nothing new, but when drawing up forecasts it will be as well to keep this most conspicuous effect of sea level change in mind.

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