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Aggregate resources and extraction in the Baltic Sea: an Introduction

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ABSTRACT

There is no water body within the European Union which is surrounded by more countries than the Baltic Sea; likewise no water-body is more diverse regarding geological, environmental and ecological conditions. In response to postglacial development, there is isostatic uplift in the northern part of the Baltic Sea with rates of up to 9 mm/year; the southern part is sinking, at rates up to 2 mm/year. Crystalline rocks in the area of uplift and soft glacial and postglacial deposits in the area of sinking result in erosion and coastal retreat along the southern Baltic Sea coastline, whilst the northern countries are gaining land. Additionally, the marine resources of raw materials such as sand, gravel and stones are of limited extent and volume in the most south-westerly and southerly part of the Baltic Sea, due to the late glacial and Holocene development. Such conditions, combined with the predicted sea level rise, will lead to an increasing demand of aggregate resources in the future due to a higher demand for shore protection measures, as "soft" solutions like beach and dune nourishment are favoured in many countries. At the same time, restrictions due to EU and national directives are increasing, limiting the number of resources which can be used. This introduction gives both, an overview about the environmental conditions of the Baltic Sea which are controlling the availability of sand and gravel resources and as well a short summary about the exploitation and use of sand and gravel in the countries surrounding the Baltic Sea.

ADDITIONAL INDEX WORDS: *Baltic Sea, sand and gravel extraction, aggregate resources, Holocene coastal evolution*

INTRODUCTION

Since the trading route of the Hanseatic Lounge, which was established in 1250, the Baltic Sea stands for the exchange of culture, goods and knowledge. This was interrupted only by the "Cold War", separating the eastern and western world for more than 40 years. The political separation, which finished at the end of the last century, led to different developments regarding the demand, exploitation and use of mineral resources from and below the seafloor. Such resources are of limited extent and volume in the Baltic Sea.

Mismanagement of the extraction of sand and gravel resources may cause unacceptable consequences for society and the environment (Boyed *et al*., 2004; HELCOM, 1999). Hence, it is important to aim at sustainable development, whereby dredging is carried out, but with maximum consideration for the needs of nature protection; at the same time ensuring societal benefits from the extraction of the raw material. For this reason, it is necessary to improve our knowledge of the real extent, volume and quality of the resources, likewise to adapt extraction procedures to the development of new techniques, knowledge, laws and guidelines, to ensure minimum impacts on marine habitats.

Sedimentary deposits of economic importance such as sand, gravel, stones and boulders are resources of limited extent and volume; they are either non-renewable or they renew very slowly. Knowledge of the physical characteristics of the seafloor is essential for the identification, delimitation and exploitation of marine resources. Locating sand and gravel mining areas and a sustainable exploitation approach requires a profound knowledge of the palaeogeographic and geological evolution of an area, the spatial extent of the raw material resources and the environmental conditions and consequences, during and after extraction. For beach nourishment and land reclamation, sometimes in connection with harbour construction, extraction of material from offshore is the only environmentally - and economically - realistic alternative. Geological mapping using state of the art mapping technology (side-scan sonar, multibeam, 3-D seismic), is an appropriate approach to explore offshore resources; this enables the accurate delineation of deposits of the required quality.

Within the European Union there is no water body which is surrounded by more countries than the Baltic Sea (Figure 1). Likewise no water-body is more diverse regarding geological, environmental and ecological conditions. All riparian countries of the Baltic Sea have some offshore sand and gravel resources at their disposal, even Sweden in its southern part (Harff *et al*., 2004a; HELCOM, 1999). In some countries, mining is on-going today, due to the increasing demand for aggregates for industrial use, construction purposes and especially coastal defence. This paper provides a short introduction to the evolution of the Baltic Sea, with information in relation to sand and gravel resources; these have been exploited from the Baltic Sea for more than a century (Nielsen *et al*., 2004), but exploitation became very modest until the beginning of the 1980ties (Dybern and Fonselius, 1981).

THE BALTIC SEA

The Baltic Sea is a non-tidal intracontinental shelf sea with a free connection to the North Sea through the Kattegat and Skagerrak (Figure 1). It is the second largest brackish water body in the world, comprising an area of 412,560 km^2, a volume of 21,631 km^3, extending 1,300 km in

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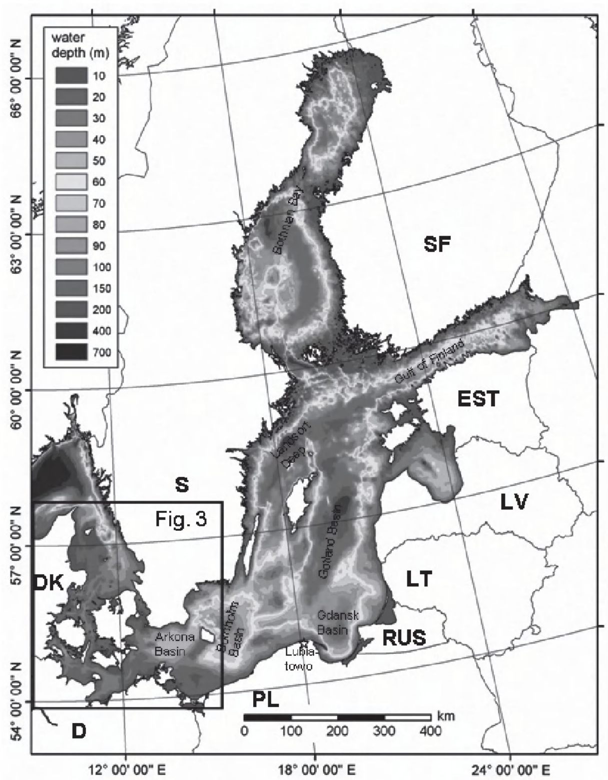

Figure 1. Bathymetry of the Baltic Sea (based upon data abstracted from SEIFERT, TAUBER and KAYSER, 2001).

S – N direction (54° - 66°), 1,000 km in E – W direction (10° - 30°) and has a maximum width of approximately 300 km. Various values ranging between 52 m (HELCOM, 1990) and 55 m (HARFF *et al.*, 2005), are given for the average depth of the Sea; the deepest part, Landsortdeep, is 460 m in depth. The bathymetry is controlled by the presence of sills and deep basins, which developed during the last glacial period. These basins increase in size from west to east (Mecklenburg Bight, 25 m deep; Arkona Basin, 45 m deep; Bornholm Basin, 100 m deep; Gotland Basin, 250 m deep).

Geological development

During the last glacial maximum, approx. 21.000 years[1] ago (FLEMING *et al.*, 1998), the world's continental shelves were widely exposed to sub-aerial processes. Their subsequent flooding was at its highest rates between 15,000 and 7,000 years ago; then was followed by a pronounced retardation during the last 7,000 years. Due to this relatively short time-span, the continental shelves contain presently a lot of relict features, which are inherited from past glacial times (EMERY, 1968; ROY *et al.*, 1994). Typical examples in the higher latitudes are till, deposited by glaciers, and river valleys, which are sometimes deeply incised in the shelf sequences, due to the formerly lower-lying sea-level. The veneer of marine sediments, deposited since the post-glacial flooding, is on many shelf platforms still relatively thin, e.g. the German part of the North Sea, where it does not exceed a few metres (ZEILER, FIGGE and SCHULZ-OHLBERG, 2000) or is even absent, except in areas of high sediment input, e.g. adjacent to river mouth systems or within deep basins.

[1] When not explicitly mentioned all data are given in conventional ^{14}C dates.

The northern and central parts of the sub-surface of the Baltic Sea are dominated by crystalline rocks and Palaeozoic sediments. The whole south-eastern to south-western part, the coastal areas of Latvia, Lithuania, Russia, Poland, Germany and Denmark, are built up of Quaternary deposits (WINTERHALTER et al., 1981), mainly of Weichselian age, with only a few exceptions, e.g. parts of Rügen Island (Germany) or Møns Klint (Denmark), where cretaceous deposits have been pushed by the last glaciation. This observation is at least consistent for the upper layers exposed in shallow waters and at the coastlines.

The basin of the Baltic Sea was carved out over the past 2.4 million years, by several ice advances; of these, the latest formed the specific geomorphological shape of the basins, bays and coastal areas, on a larger spatial scale. The distances between the different ice-marginal lines of the latest ice advance, increase from west to east. Between these ice-marginal lines, melt-water sediments (composed of silt, sand and gravel) have been deposited. As such, the amount of sand and gravel below the veneer of the modern, post-littorina sediment increases from west to east.

Glacio-isostatic movement and climatically-controlled eustatic sea level fluctuations have caused transgressions and regressions in the Baltic Sea and its precursors, during the Holocene development. From the early to middle Holocene, the Baltic Sea underwent 4 evolutionary stages: Baltic Ice Lake; Yoldia Sea; Ancylus Lake and Littorina Sea (Figure 2) (BJÖRK, 1995; ERONEN *et al.*, 2001 and LAMPE, 2005), experiencing alternating fresh-, brackish- and marine water conditions as a result of the interaction of uplift rates and changes in relative sea level. Based upon the modelling of large scale palaeo-coastline changes, since the onset of the Littorina transgression 8000 BP the sea-level in the northern part has declined significantly; in some areas by more than 200 m (CATO, 2004). This pattern has been resulted in a regression, out-weighting by far the southern transgression. According to MEYER and HARFF (2005) the aerial extent of the Baltic Sea has diminished by approximately 30 % whilst the volume has decreased from 47,000 km^3 to 22,000 km^3, or by 47 %.

In response to glacio-isostatic rebound, the northern part of the Baltic Sea is dominated still by an uplift relative to the present sea level, with rates up to 9mm/year in Bothnian Bay (MÖRNER, 1977; HARFF *et al.*, 2005); in the southern part, subsidence rates of up to 2 mm/year occur (MEYER and HARFF, 2005). Such subsidence generally causes erosion and coastal retreat, along the whole of the southern Baltic Sea coastline, from Denmark via Germany, Poland, the Kaliningrad area, Lithuania to parts of Latvia, as these coastal areas consist of an alteration of cliffs and lowlands, built up of soft glacial and postglacial deposits, with only the few exceptions of the chalk-cliffs of Jasmund, Arkona and Møns Klint (Figure 3).

Environmental conditions

For the ecosystem of the Baltic Sea, the deep basins are not the most important; rather the two sills, the Drodgen Sill in the Øresund, with a depth of only 7 m below sea level and the Darss Sill between Gedser Rev and Fischland-Darss, with a depth of 18 m below sea level (Figure 1). These sills control the water exchange with the North Sea (JACOBSEN, 1980). Such exchange is not continuous, but depends strongly upon westerly storms, resulting in oxygen-rich North Sea water inflow into the Baltic Sea basin; this, 73 % takes place via the Darss sill, whilst the remainder is controlled by the Drodgen Sill.

The ratio between the Baltic Sea surface and the drainage area is 1:4, the annual freshwater input (rainfall and river discharge) amounts to 660 km^3/year and the brackish water discharge is 950 km^3/year, which is compensated by 475 km^3/year of North Sea water inflow (BJÖRCK, 1995). The difference in the balance is due to evaporation. Therefore the Baltic Sea is dominated by an estuarine circulation. A distinct stratification of the water body with a pronounced halocline and pycnocline leads to oxygen depletion in the deepest parts of the basins where regularly anoxic conditions predominate.

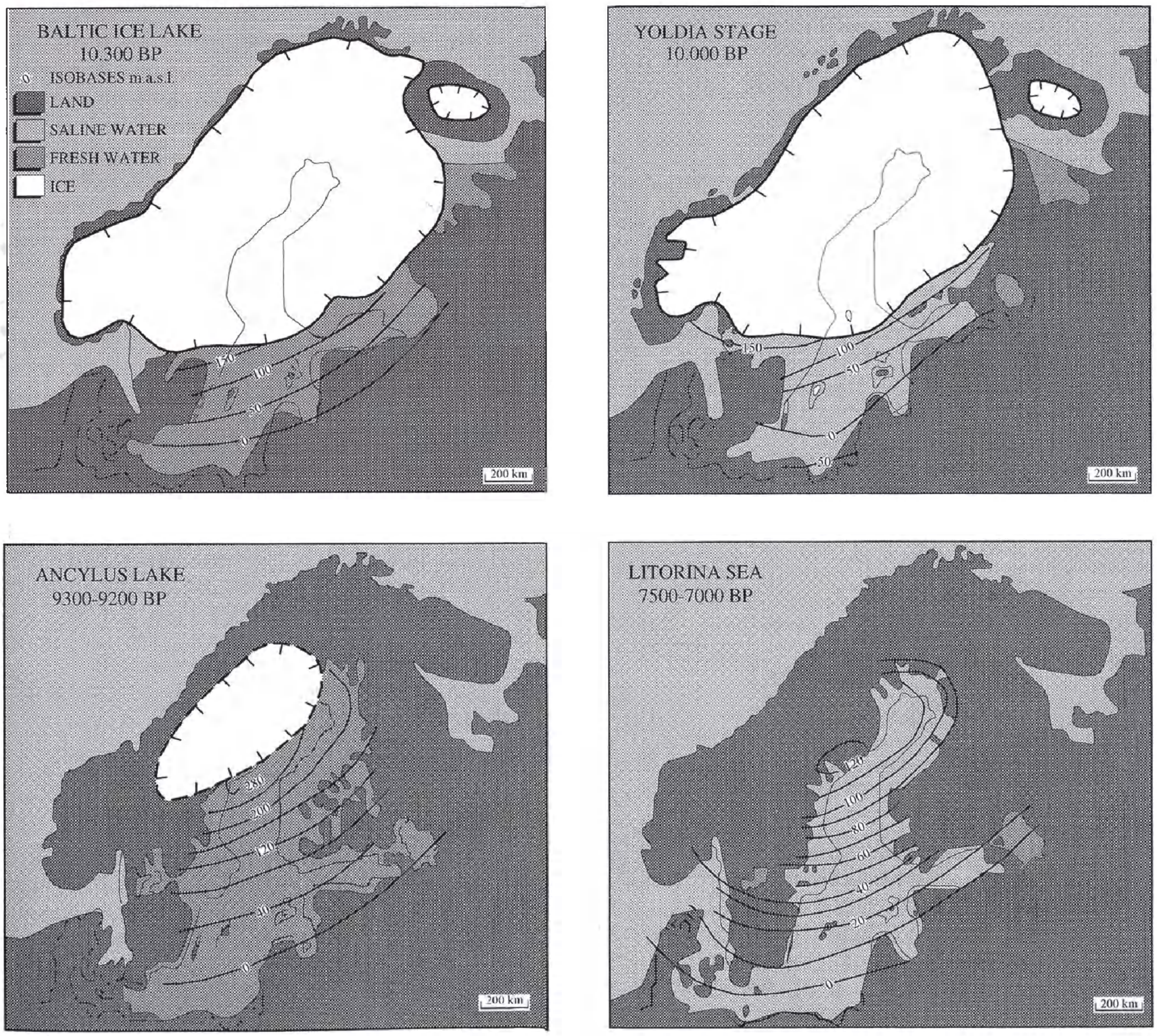

Figure 2. The development of the Baltic Sea during the late- and post-glacial (from ERONEN *et al.*, 2001).

Besides the vertical stratification of the water-body, there is also a strong salinity gradient from full marine conditions in the Skagerrak area to only approx. 3 – 5 ‰ in Bothnian Bay and the Gulf of Finland; this influences strongly the faunal and floral distribution within the entire Baltic Sea. As the Baltic Sea extends up to 66° N, it is affected also by different climatic zones. Sea ice develops in the northern and north eastern parts (e.g. the Gulf of Finland has an ice cover of up to 100 days/year), which is dominated by continental climate. The southern and southwestern parts are mostly free of ice, even during the wintertime. However, several times since 1742 the entire Baltic Sea, including its southwestern part, has been covered with ice (HELCOM, 2007; TINZ, 1995).

Wave conditions and sediment transport in shallow coastal waters depend upon exposure to the main wind and wave direction. Within this context, the southern Baltic Sea coast is exposed to both north easterly and westerly winds. For comparison, within the western Baltic Sea (Germany and Denmark) where fjords and bays are common (Figure 3), the most effective wind direction inducing coastal currents and sediment mobilisation varies considerably; it includes all directions, even south for some stretches of the Danish coastline. However, no long term-trend in increasing storminess indices over southern Scandinavia has been observed (HELCOM, 2007).

Large sections of the German Baltic Sea coastline are retreating, at an average rate of 0.2 – 0.3 m/year and maximum rates of up to 1.5 m/year (SCHWARZER *et al.*, 2003). East of Rügen Island (Figure 1) the coastline turns towards a formation which looks as if equilibrium conditions between erosion and accumulation predominate; however even here coastal retreat dominates. Approximately 70 % of the coastline of the

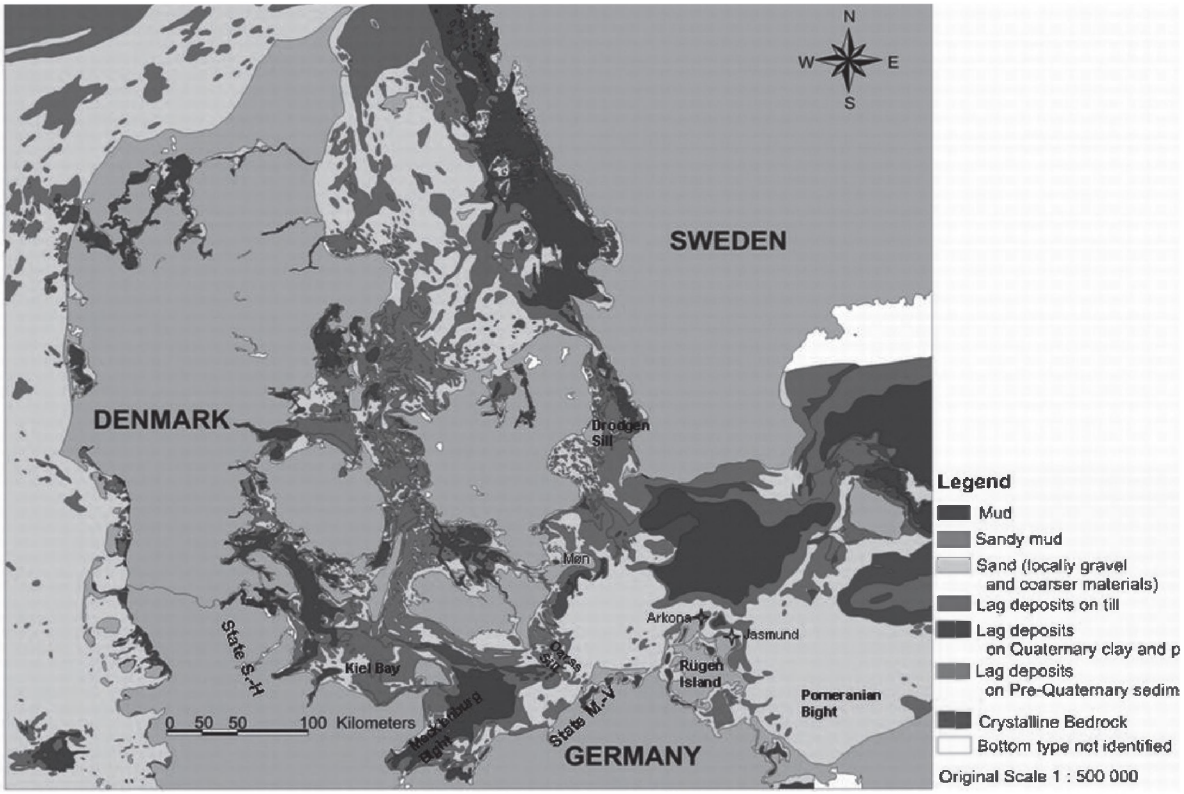

Figure 3. Seabed sediments around Denmark, the German part of the Baltic Sea and parts of the Polish coast. Source: HERMANSEN, B. and JENSEN, J.B. 2000.

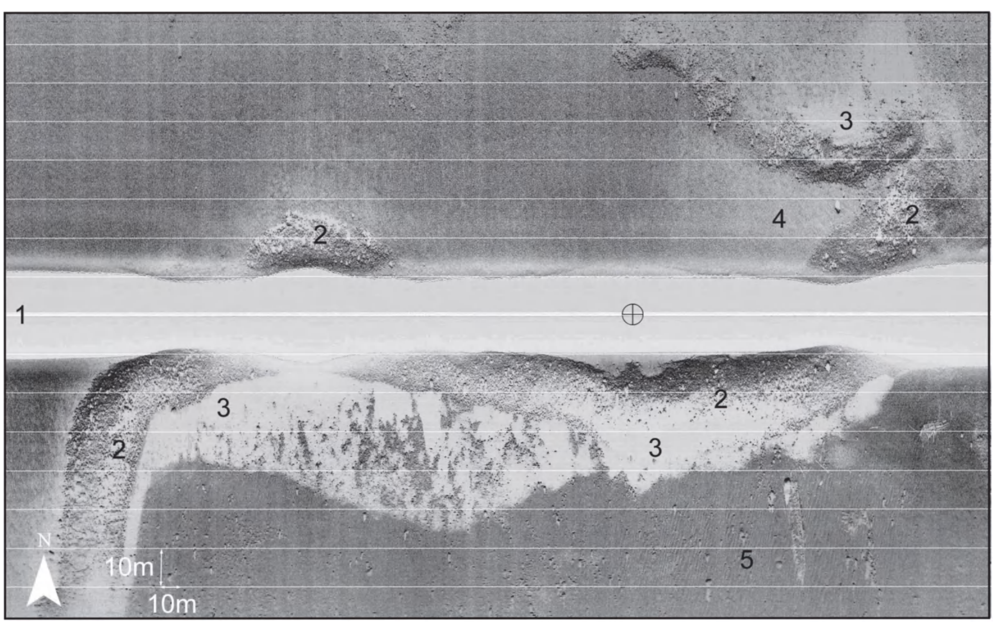

Figure 4. Side-scan image from Adlergrund / Baltic Sea (54° 44,433' N, 14° 17,533' E). To get a better impression about the relief, there is no slant range correction of the image. 1 – water-column, 2 – ridges, 3 – acoustic shadow, 4 – sand, 5 – wave induced ripples (FELDENS, DIESING and SCHWARZER, 2007).

Table 1. *Offshore aggregate resources and present mining activities of the countries surrounding the Baltic Sea. Resources are given in m³ ·106 (* data taken from HELCOM, 1999, ** Kramarska et al., 2004, ***Nielsen et al., 2004, +M.-V. = State Mecklenburg-Vorpommern, Germany).*

Country	Poland	Latvia	Lithuania	Estonia	Russia (Kalinin-grad and St. Peters-burg region)**	Finland	Sweden	Denmark***	Germany
Aggregate Material	Gravel: 280 Sand: 35	No activity*	No activity*	No activity*	Gravel and sand 400 (33.4+)	< 0,5*	No activities since 1992*	Gravel: 300 Sand: 2510	Gravel: 11.0 Sand: 14.5 (**only M.-V.)

state Mecklenburg-Vorpommern, extending from Mecklenburg Bay to Odra Bay (Figure 3), is under retreat permanently (Harff *et al.*, 2004a). According to HELCOM (2007), 74% of the Polish coast is presently under erosion, but coastal defence structures have only been erected along 26 % of the coast. Along parts of the Latvian coast, cliff erosion has increased from an average of 0.5 – 0.6 m/year over the past 60 years, to 1.5 – 4 m since 1980/81. All of this response is related to the isostatic / neotectonic sinking, sea level rise, frequency of storm surges and the geological architecture of the coastal areas. As such, it requires continuous replacement of the eroded material to maintain a stable coastline in those areas where settlements, different kinds of infrastructures and/or industrial use predominate.

Natural sediment sources within the region are active cliffs and sediment, abraded from the seafloor (Schrottke, 2001). In many cases, the amount of sediment supplied by seafloor abrasion is underestimated, sometimes completely neglected. Depending upon the composition of the Quaternary deposits and the exposure to the main wind- and wave direction, such sediment supply can be of the same order of magnitude as that e.g., from a 10 m high retreating cliff (Schrottke and Schwarzer, 2006). However, in many cases even this is not sufficient to stabilize the coastline.

No precise information is available on wave conditions in the open Baltic Sea, but some measurements are available from the research station in Lubiatowo (Figure 1), which was established in 1974 and belongs to the Polish Academy of Sciences - Institute of Hydroengineering. Records from this research station indicate a maximum wave-height H_{max} of 7.4 m (Paplinska-Swerpel, 2003) and a maximum wave length of around 80 m. During those NE-storm conditions, the depth of incipient sediment movement induced by waves (Wright, 1995) extends down to a water depth of approximately 40 m.

Aggregate resources

Compared to other marine environments in particular to the tidally dominated North Sea, the surficial sediment distribution in the non-tidal Baltic Sea is much more heterogeneous; it is patchy on both, small and large spatial spatial scales (Figure 3). This observation is confirmed by different maps, either covering the whole Baltic Sea (Winterhalter *et al.*, 1981) or just localised areas (Emelyanov, Tauber, and Lemke, 1993; Gelumbauskaite *et al.*, 1999; Hermansen and Jensen, 2000; Tauber and Lemke, 1995; Tauber, Lemke and Endler, 1999 and Uscinowicz and Zachowicz, 1994). The deep basins (Figure 1) function as sinks for fine grained sediment (silt and clay), whilst sandy material is deposited in the more shallow areas. Relict sediment remains, where till or other glacial deposits pinch out at the seafloor (Figure 4) where they are directly influenced by waves.

Dredged material in the Baltic Sea result from both: a) non-renewable fossil resources like glaciolimnic deposits or deposits from a former stage of the Baltic Sea (Bellec, Diesing and Schwarzer, this volume; Manso *et al.*, this volume and Schwarzer, Diesing and Trischmann, 2000); or b) material which originates from coastal erosion or seafloor abrasion, which is transported and re-deposited in shallow marine areas (Kortekaas *et al.*, this volume, and Schwarzer *et al.*, 2003).

Sand and gravel deposits in the southern part of the Baltic Sea (the offshore areas belonging to Denmark, southern Sweden, Germany, Poland and the Kaliningrad area) have formed mainly as the result of post-glacial erosion and selective transport and deposition processes of glacial and partly postglacial deposits, reflecting the geological settings and the prevailing hydrodynamic conditions. Many of these deposits are of fossil origin and, therefore, non-renewable. They consist of glacio-fluvial deposits, fossil beach ridges and submerged coastal planes, which developed during the former stages of the Baltic Sea (Nielsen *et al.*, 2004 and Schwarzer, Diesing and Trischmann, 2000).

Although the sediment distribution is affected strongly by the subsurface geology, a depth-dependent overall zonation of surface deposits can be found (Seibold *et al.*, 1971). In the southwestern and southern Baltic Sea, coarse-grained lag deposits form a thin veneer (a few decimetres) on top of till deposits, in water depths of 5 to 15 m along the coasts and on the submarine sills and shoals. These sediments result directly from the abrasion of the underlying till deposits. Material with grain sizes within the range of sand is removed by wave- and current action, leaving the coarser constituents behind (Swift *et al.*, 1971; Tauber, Lemke and Endler, 1999). Lag deposit areas are often found to be surrounded by well-sorted fine to medium sands. Apart from the immediate proximity of the coast and abrasion platforms, these sand veneers are relatively thin, for example only 0.5 to 2 m in Kiel Bay (Seibold *et al.*, 1971) and inner Mecklenburg Bay. Significant amounts of marine sediments are found within the deeper basins and channels of the Baltic Sea, where fine-grained, organic-rich sediments (mud) accumulate (Lemke, 1998; Werner *et al.*, 1987). Depending on the water depth, the grain-size decreases from coarse to fine silt while the content of organic matter increases up to 10 – 15 % (Winterhalter *et al.*, 1981).

Exploitation

In the western Baltic Sea, sand, gravel, stone and even boulder exploitation (Karez and Schories, 2005) has lasted for more than a century (Nielsen *et al.*, 2004). For all kinds of usage the most important parameter is grain size; others such as the mineral composition are of minor importance and as such their analyses are mostly not carried out. Gravel is used mainly by the concrete industry; however, sand is used predominantly for coastal protection works, only minor proportions are being used by the glass industry. Natural restrictions regarding exploitation are the water depth, the thickness of mud cover and the distance of the resources from the coast. Around the Baltic Sea, Denmark is the leading extractor and supplier of marine aggregates to other countries, followed by Germany. Minor quantities are dredged in Finland and the St. Petersburg area of Russia (Table 1). No activities are reported from Lithuania, Latvia, Estonia and the Kaliningrad region (Nielsen *et al.*, 2004).

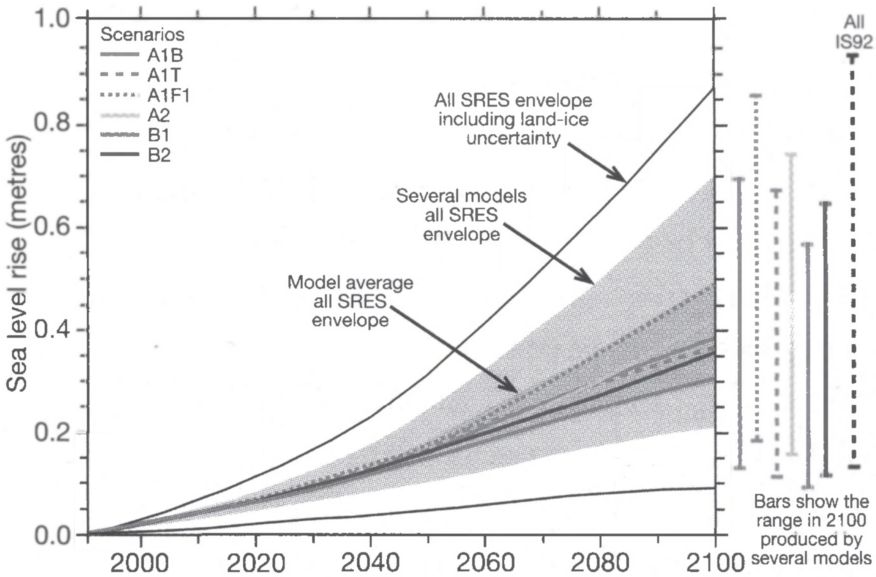

Figure 5. Projected global sea level response related to global climate change in the 21st century as presented in the IPCC Third Assessment Report. Taken from "Climate Change in the Baltic Sea Area, HELCOM Thematic Assessment in 2007" (HELCOM, 2007).

Probably the largest known resource of sand and gravel in the Baltic Sea is the NE – SW elongated shoal "Rønne Bank – Adler Ground" (Figures 1and 3), with a potential volume of 1.5 billion m³ of sand and gravel (NIELSEN *et al*., 2004), of which 2000 · 10^6 m³ are located in Danish waters. This shoal extends 60 km from the Bornholm coast, into German territorial waters. Extraction is carried out here to support the Danish, Swedish and German market; it is still on-going but has decreased recently from 700,000m³/year to 250,000m³/year. However, the total volume dredged in the Danish Baltic Sea territories is about 1.5 – 2.0 x 10^6 m³ (NIELSEN *et al*., 2004).

The amount of sand and gravel resources located in coastal waters off Mecklenburg Vorpommern (Figure 3) amounts to 25.5 x 10^6 m³ (Table 1) of which 31 % have been exploited until 2004 (HARFF *et al*., 2004b). In Poland, from 1990 – 2000, 10.9 x 10^6 m³ of sand and gravel were exploited from the Baltic Sea; this approximates to 1 x 10^6m³/ year (KRAMARSKA *et al*., 2004). Approximately 33 x10^6 m³ of sand and gravel exist in the eastern Gulf of Finland; of this, 45% were mined for building in the St. Petersburg and Leningrad districts (MOSAKALENKO *et al*., 2004). The dredging areas are established partly in shallow waters, within a water depth of only 6 m. According to CATO (2004), only 17 % of the Swedish Baltic Sea territories are well mapped. However due to uplift, the highest postglacial shoreline in Sweden is found at an altitude of 286 m above the present sea level: Therefore a huge amount of sand and gravel of former marine origin is found on land at various altitudes (CATO, 2004) and can be mined there. In the past, the demand for marine extraction was not very high; since 1992 there have been no offshore dredging activities offshore Sweden.

CONCLUSIONS

The Baltic Sea is a very 'young' marine environment, which is extremely diverse compared to other oceans regarding geological prerequisites, physical forcing of sediment mobility and environmental conditions. Due to its young geological history and the on-going uplift / subsidence processes, the surface sediment distribution and the upper part of the subsurface, which are of interest as an economic deposit, are very patchy; they are mainly of Quaternary origin. In part, they are primary deposits, such as the gravel sediments in Tromper Wiek (BELLEC, DIESING, and SCHWARZER, this volume), which is the most shallow extraction site in the southwestern Baltic Sea, located in water depth of only 8 m, at a distance of approximately 2 km from the coastline. Partially in some areas deposits are renewing continuously in response to active coastal transport processes (KORTEKAAS *et al*., this volume). In the eastern Gulf of Finland (Kurort District St. Petersburg, Figure 1) deposits formed by wave and current activities, actually are found in water depths of only 3 – 5 m. These deposits have a sediment dynamic linking to beach sands and as such their mining is endangering the coastline (MOSKALENKO *et al*., 2004).

In addition to the risk assessment of aggregate extraction, there are legal and administrative restrictions, e.g. the EU Water Framework and Habitat Directive, together with national laws and restrictions, which differ from country to country. Other conflicts of interest regarding the exploitation of marine mineral resources result from the identification as military exercise areas, archaeological sites, shipping lanes or spawning grounds (CZYBULKA and BOSECKE, 2006).

For the subsiding southern and southwestern parts of the Baltic Sea in particular there might be an increasing demand of sand for beach nourishment in the future; this is related to increasing erosion and coastal retreat, because of the predicted sea level rise (HELCOM, 2007). As these are the areas which have the most limited amount of natural, marin mineral resources due to their Pleistocene and Holocene development, and where shore protection is favoured to be carried out only with natural material, some problems might occur here. In the northern uplift section, where sea level rise is not yet a problem, the available resources are sufficient and dredged material is only used for construction purposes; as such offshore aggregate dredging is not yet identified as a problem. However, by the year

2100, many regions currently experiencing a relative fall in sea level would instead have a rising relative sea level (Figure 5). For example, the past trend of a lowering mean sea level in the Gulf of Finland would not continue in the future because the accelerated rise in global average sea level will balance the land uplift. The combination of high sea levels induced by storm surges, ice-free seas, and unfrozen sediments would enhance erosion and the transport of sediments (HELCOM, 2007).

In summary it is important for each society to maintain environmentally - and economically - sound raw material management, to ensure the fully sustainable exploitation of offshore resources.

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