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Geological Development of the North Sea and the Baltic Sea

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Contents

1. Introduction

Coastal evolution and coastal processes depend to a certain extent on the geological composition of the ocean basin. Tectonic structures in the subsurface as well as sinking or uplift rates of coastal regions may control the exposure and delineation of the coastline. The thickness of sedimentary layers, their texture and mineralogical composition have a strong influence on compaction and resistance against erosion. On the other hand, sediment availability is essential for the formation of all soft rock coastal elements such as e.g. barrier islands, spits and bars.

Sedimentary rocks can be sources for mineral resources such as oil and gas. Recently, they are considered as possible sinks for technical CO_2 – sequestration (LACKNER, 2003). Moreover, the installation of offshore structures such as oil rigs or foundations for wind turbines, cable routes and the high demand for offshore aggregate resources to compensate coastal erosion and to be used for coastal protection and for construction purposes require a good knowledge of the geological evolution of the basin (HARFF et al., 2004). The North Sea and the Baltic Sea are geographically close together, just separated by the geologically very young, only 60–80 km wide and 450 km long N–S extending Jutland peninsula, which consists mainly of quaternary deposits. Nevertheless, in parts they underwent a different geological evolution since the Palaeozoic period. For this reason, we describe the geological development of the North Sea and the Baltic Sea separately.

2. North Sea

The North Sea is a shallow continental shelf sea with an average water depth of 94 m. To the West, it is bordered by the British Islands, to the South by the Mid European mainland

and to the East by the western coasts of Scandinavia. It opens into the Atlantic Ocean to the North, via the English Channel to the Southwest, and it has a free connection to the Baltic Sea via the Skagerrak to the East. The sea-bottom of the relatively shallow southern North Sea off the Dutch and German coast shows no distinctive morphological variation. It is composed of young Pleistocene and Holocene soft-rock deposits (ZEILER et al., 2008).

2.1 Palaeozoic to Palaeogene Development

The basement of the North Sea basin consists of more than 543 million years old Precambrian crystalline rocks and faulted metamorphic rocks of Palaeozoic age (for stratigraphy see Table 1). This basement rises towards North and continues in the Norwegian Mountains and the Scottish Highlands. In the North Sea basin, the top of this basement is located in depths of 8–10 km. It is overlaid by terrestrial, lagoonal and liminic deposits into which coal seams are partly incorporated. At the beginning of the Perm Period (Tab. 1), the continental basement was strongly influenced by volcanic activity splitting it into several parts. During the Upper Rotliegend, mainly arid conditions prevailed. Thick series of terrestric sandstones were deposited, which later functioned as reservoir rocks for the economically used North Sea gas. During Zechstein (Perm period), the sedimentary basin was periodically flooded from North-west. As a consequence of repeated transgressions and high evaporation rates, series of siliclastic rocks, carbonates and salt strata, the latter of up to 1,200 m in thickness, were deposited. (RICHTER-BERNBURG, 1972). The maximum thickness of deposits can be found in the south-western-most part of the North Sea basin (Fig. 1).

Tectonic activity and changing shallow marine and terrestrial conditions persisted throughout the Mesozoic period (251–65.5 million years BP). In general, the sinking tendency of the North Sea basin as action at a distance of continental drift, continued, but 'Block-and-Graben' tectonics led to some relative movements with partiallly sinking but also uplifting tendencies. Already at the end of the Triassic period, the sediment load on top of the older salt strata started to deform the salt deposits by thermo-mobilisation, resulting in an early development of salt dome structures (Halocinesis). Later, as a consequence of ongoing salt tectonics and partly other factors leading to vertical dislocations, sills and deep anoxic basins were formed to later become the source areas for the development of hydrocarbons. The mobility of the salt continues until today. In the subsurface of the North Sea, the Northern German und Dutch lowlands, and below the most south-western part of the Baltic Sea, salt diapers in elongated form (Fig. 2), up to 100 km in length, exist. They expand vertically from a depth of up to 8,000 m to the present surface (ZIEGLER, 1990). An obvious example for salt tectonics is the island of Helgoland. Here the characteristic red sandstones were uplifted by more than 4,000 m (SCHMIDT-THOMÉ, 1987). Nowadays, not only the troughs along the salt structures are of economic interest as potential reservoirs for hydrocarbons (e.g. Mittelplate oil field) but huge artificial caverns in the saltdomes can be used for the storage of energy sources such as oil, gas or compressed air and CO_2 as well.

In the German part of the North Sea basin, the sedimentation history of the older Caenozoic period (Palaeogen, 65.5–23 million years BP) is characterised by shallow marine silica-clastic deposits. The subsidence, which already started during the Triassic period (Table 1), continued, giving the North Sea sedimentary basin its typical shape of a shallow bowl in which organic-rich sediments were subsided to depths, which allow the formation of oil and gas (TEICHMÜLLER et al., 1979).

Table 1: Geological Time Scales. *Ma = Abbreviation for mega-annum (10^6 years); a million years. Note on the Tertiary and the Quaternary: The Tertiary and Quaternary have been eliminated from the most recent International Stratigraphic Charts. The Quaternary was formerly considered to be made up of the Holocene and the Pleistocene. The Paleogene and older Neogene were defined as the Tertiary (INTERNATIONAL COMMISSION ON STRATIGRAPHY – ICS, 2003)

	Eon	Era	Period	Sub-Period	Epoch	Ma*
	Phanerozoic	Cenozoic	Neogene		Holocene	0.01
					Pleistocene	1.8
					Pliocene	5.3
					Miocene	23.0
			Paleogene		Oligocene	33.9
					Eocene	55.8
					Paleocene	65.5
		Mesozoic	Cretaceous			145.5
			Jurassic			199.6
			Triassic			251.0
		Paleozoic	Permian			299.0
			Carboniferous	Pennsylvanian		318.1
				Mississippian		359.2
			Devonian			416.0
			Silurian			443.7
			Ordovician			488.3
			Cambrian			542.0
Precambrian	Proterozoic					2500
	Archean					not defined

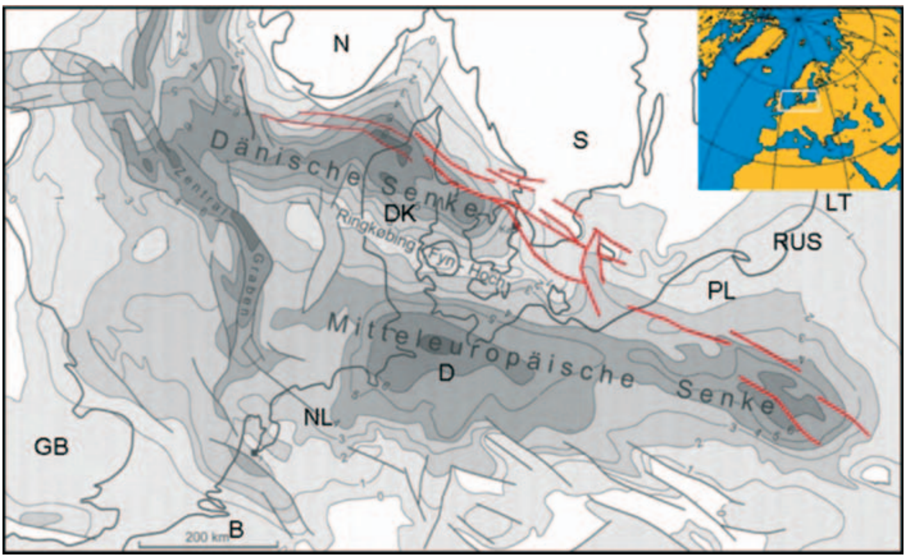

Fig. 1: Total thickness of sediments deposited in the Middle-European and Danish Depression since middle Perm. The red line marks the more than 2000 km long "Sorgenfrei-Tornquist-Teisseyre-Zone" (ZIEGLER, 1990, modified)

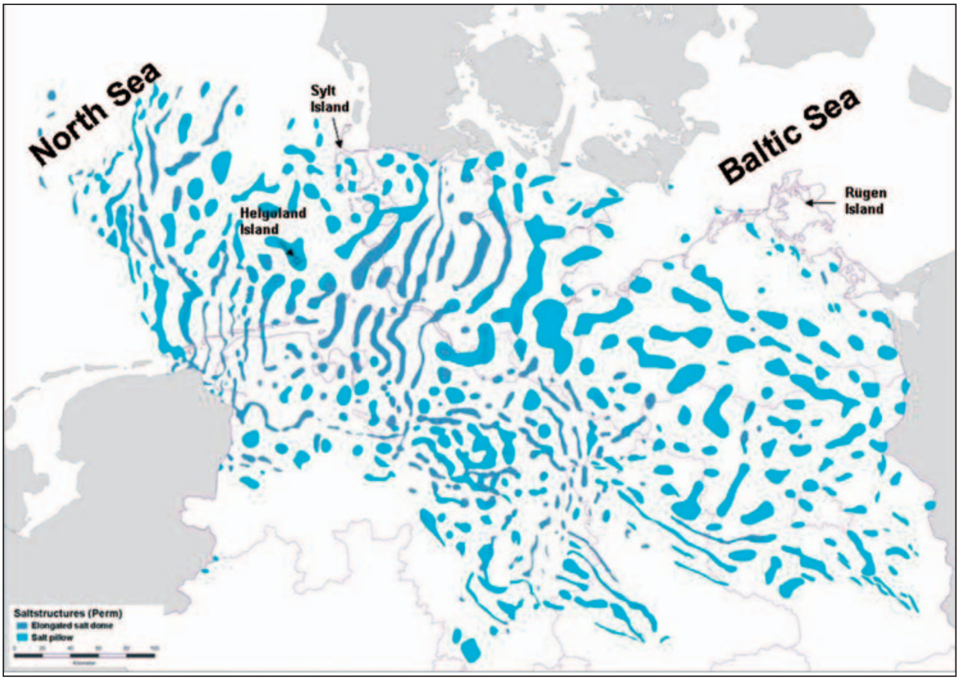

Fig. 2: Salt structures in Northern Germany (BUNDESANSTALT F. GEOWISSENSCHAFTEN U. ROHSTOFFE, 2008, modified)

2.2 Neogene

At the beginning of the Neogene (23 million years BP), the climate was still moderate. However, it changed to lower temperatures, starting approx. 5.3 million years BP, when the formation of ice caps on both poles began. Deposits of this phase are either of marine, terrestric/fluviatile or deltaic origin with partly incorporated brown coal seals. In the present coastal zone, sandstones of Miocene age are important aquifers while younger deposits, thick layers of Pliocene/early Pleistocene delta sands, are often used for coastal protection purposes such as beach nourishments.

2.2.1 Pleistocene Development

The subsequent Pleistocene epoch of the Neogene period (Table 1) is characterised by several climatic changes, related fluctuations of the sea level and resulting depositional conditions. Especially the advances of inland ice masses from Scandinavia and the British/Scottish highlands during the Elsterian as well as the Saalian glacial stage (Fig. 3) left striking, still distinguishable traces such as terminal moraines in parts of the North Sea basin (STREIF, 2002; ZEILER et al., 2008). The depositional processes related to the Saalian glaciation also lead to the recent S-N orientated course of the river Weser (STREIF, 1999), and to morphological high point (shallows) in the North Sea such as *"Borkum Riffgrund"*, *"Sylter Außenriff"* or *"Horns Rev"* (Denmark). During the interglacial stages of Holsteinian and Eemian, which followed

Fig. 3: Maximum extent of the inland ice sheets during Saale- and Weichselian glaciations in middle-Europe. The lower courses of the rivers Ems, Weser and Elbe were forming a common spillway into the North Atlantic via the North Sea (BERNER and STREIF, 2000; modified)

the Elsterian and the Saalian glaciations, respectively, typical marine-brackish coastal sediments were deposited. With the exception of some deep embayments into the mainland, the spatial distribution of these sediments almost describes the recent Southern North Sea coastline (STREIF, 1990).

The ice cover of the subsequent youngest cold stage, the Weichselian glaciation (117,000–10,200 BP), did not reach the German Bight (BERNER and STREIF, 2000, Fig. 3). During the last glacial maximum (LGM), when the Weichselian ice cover had a thickness of approximately 3,000 m and its maximum extent, the global sea level was approximately 120 m lower than the present sea level (see Fig. 4). The entire North Sea area was exposed, the coastline was shifted approximately 600 km to the West (STREIF, 2002), and periglacial processes left their traces in the deposits. In the hinterland, huge amounts of meltwater eroded a wide valley along the southern glacial front (SCHWARZ, 1999) which today is the stream bed of the River Elbe. Together with the rivers Ems, Weser and Eider it formed a glacial spillway which emptied into the North Sea basin (Fig. 3) forming the wide Helgoland glacial valley (FIGGE, 1980; ZEILER et al., 2008). Its outline is still recognizable in the present bathymetry of the German Bight whereas most of the smaller channel structures are buried below younger deposits (SCHWARZ, 1996).

2.2.2 Holocene

After the LGM, melting of the inland ice caps led to a global sea level rise (Fig. 4). At the end of the Pleistocene and in the early Holocene, the magnitude of the sea level rise was approx. 2.1 m/100 years (STREIF, 2002). The southern North Sea basin was flooded around 9,000 to 8,000 BP, which is documented by tidal flat deposits from that time (EISMA et al., 1981). The depositional evolution along the German North Sea Coast began between 8,600 and 7,100 B.P, when the sea level rose from –45 to –15 m below the present German chart datum NN (see Fig. 4). At that time, the coastline was presumably located 5–10 km seaward of the present one (SINDOWSKI 1973; FLEMMING and DAVIS, 1994). During this period, tidal currents and waves penetrated further into the hinterland and eroded the exposed higher parts of the former submerged Pleistocene landscape. Large quantities of reworked sediment were shifted landward, building up a wedge-shaped body of Holocene coastal deposits. This sediment body, striking parallel to the coastline, has a width of 10 to 25 km. In the Weser- and Elbe estuary, its length goes up to 80 to 100 km. While the accumulation wedge tapers off towards the mainland, it can reach a thickness of more than 40 m (AHRENDT, 2006) at its relatively steep seaward slope. Here it mainly consists of fine- to medium-grained sand.

With a decelerating sea level rise from 7,000–3,000 BP (BEHRE, 2003) coupled with an increase of the tidal range from 1.3 m to 2.2 m (FRANKEN, 1987), the coastal zone was formed by salt marshes, tidal flat deposits and in parts by barrier islands with dunes of a height of up to 30 m. With the phase of a slower sea level rise of only 0.11 m /century (BEHRE, 2003) over the last 3,000 years BP, the Wadden Sea area was formed. This area is characterized by a complex pattern of marine and terrestrial deposits, reworked postglacial siliclastic drainage material of the underlying Pleistocene drainage deposits as well as several peat layers, which were deposited between tidal, brackish and lagoonal sediment layers. In the "drowning" landscapes, an also rising ground water table resulted in wide-ranging water logging and the formation of peat bogs. Although subsequent frequently eroded by the transgressing sea, these basal peat layers often mark the beginning of the Holocene depositional history of an area (STREIF, 2004).

Although regional differences exist, which are e.g. due to the palaeo-geomorphology, the characteristic series of Holocene deposits consists of strata of fine-grained sand, silt, clay and intercalated layers of peat (Fig. 5). Within this alternating sequence, marine and brackish deposits overlying peat mark phases of transgression. On the other hand, regressive overlaps with peat overlaying brackish and marine sediments indicate a seaward shoreline displacement (STREIF, 2004) due to phases of a dropping or – more likely – stagnating or slowly rising sea level.

The surface of the Holocene accumulation wedge is almost flat. Its elevation only varies between –1 m to +2 m in relation to the German reference datum NN. This also holds for the North Frisian islets (Halligen), which are relicts of a former very much wider marshland that was partly destroyed by storm surges in the 14th and 17th century. On the barrier islands along the German North Sea coast, the land elevation is often higher. This is either related to the presence of Holocene coastal dunes (East Frisian barrier islands) or to a combination of Holocene deposits combined with elevated cores of Pleistocene (Amrum and Föhr Island)

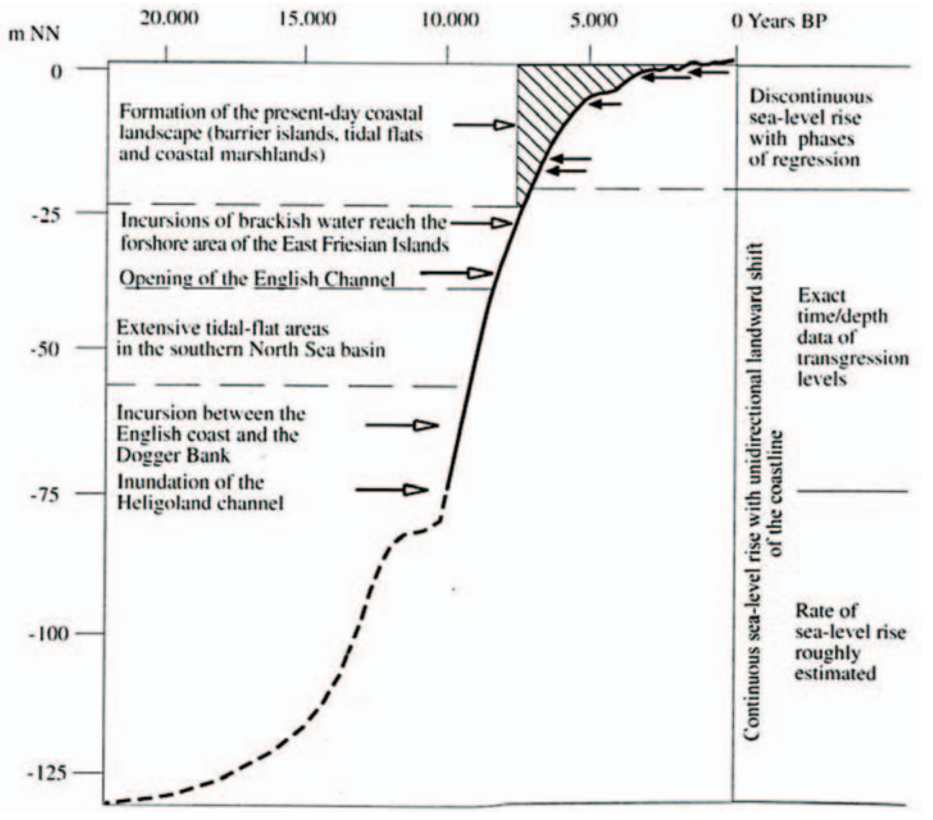

Fig. 4: Relative sea level rise since the last glacial maximum. The age is given in conventional ^{14}C dates. The marine transgression is divided into 3 phases. The last phase, which lasts since 7,100 years BP, led to the development of the present landscape (STREIF, 2004)

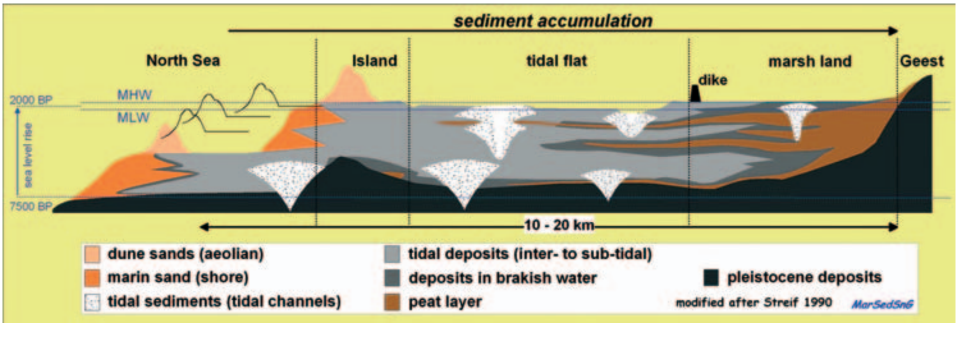

Fig. 5: Schematic cross-section through the Holocene coastal accumulation wedge; example from Lower Saxony (STREIF, 1990; modified)

and/or early Neogene age (Sylt Island), which can be found on the North Frisian barrier islands. The typical elongated shape of the East Frisian barrier islands with sandy foreshores and beach and dune sediments on the coast exposed to high wave energy, and with fine-grained organic-rich deposits on the sheltered lee indicate that their formation is very much related to the ongoing interaction of mobile sediments with currents and waves (DAVIS, 1994). However, the presence of erosional relicts of Pleistocene deposits in depths of only –5 to –10 m NN beneath almost all islands indicates that in a former stage of their geological evolution they also had a core of older deposits. As can be seen on the island of Sylt today, these cores are directly exposed to the forces of the rising water level and at least are partly erode during periods of lower water levels. These cores were finally inundated, and – in their temporarily last stage of island evolution –, they were buried under younger, now sea-born sediments. Under conditions of a presumably rising sea level, the development of these islands is characterised by an almost continuous landward shift of the shoreline.

Likewise elongated accumulation bodies located in Dithmarschen (north of the Elbe estuary) and on the Eiderstedt peninsula, on the other hand, underwent a completely different depositional evolution. Doubtlessly, in a former stage of the Holocene coastal evolution, these gravel and coarse sand accumulations were formed under strong wave and current action (HUMMEL and CORDES, 1996). A subsequent and in some areas still ongoing intensive import of sea-born sediments into this region leads to a pronounced seaward shift of the shoreline. Today these former wave exposed island-like structures are still visible as elongated low elevations in the flat marshlands some 10 kilometres inland.

3. Baltic Sea

The Baltic Sea is a non-tidal intra-continental shelf sea with a narrow connection to the North Sea through Kattegat and Skagerrak (Fig. 6). It is the second largest brackish water body in the world, covering an area of 412,560 km², with a volume of 21,631 km³, extending 1,300 km in S – N direction (54°–66°) and 1,000 km in E – W direction (10°–30°). The maximum width is approximately 300 km, the average depth is 52 m (HELCOM, 1990) and the deepest part, Landsortdeep, is 460 m in depth. The bathymetry is controlled by the presence of sills and deep basins, which developed mainly during the last glacial period. These basins increase in size and depth from West to East (Mecklenburg Bight, 25 m deep; Arkona Basin, 45 m deep; Bornholm Basin, 100 m deep; Gotland Basin, 250 m deep).

3.1 Palaeozoic to Palaeogene Development

The geological basement of the northern and central part of the Baltic Sea is dominated by Precambrian crystalline rocks belonging to the East-European-Craton. They have undergone a long term uplift until today forming the Scandinavian mountain ranges. Palaeozoic sediments (older than 251 million years) have been deposited on the southern rim of this craton, forming parts of the East European Platform (Fig. 1). Separated by the huge, more than 2,000 km long "Sorgenfrei – Tornquist – Teisseyre – Fracture Zone" (KATZUNG, 2001), the West- and Middle European Platform is dominated by sediments of Mesozoic age (251–65.5 million years old; EHLERS, 1990). Their basement is formed by deposits of Permian age (see Tab. 1), a period, when arid climate was dominating and the deposition of terrestrial sediments took place. At the end of the Perm period, marine conditions developed due to

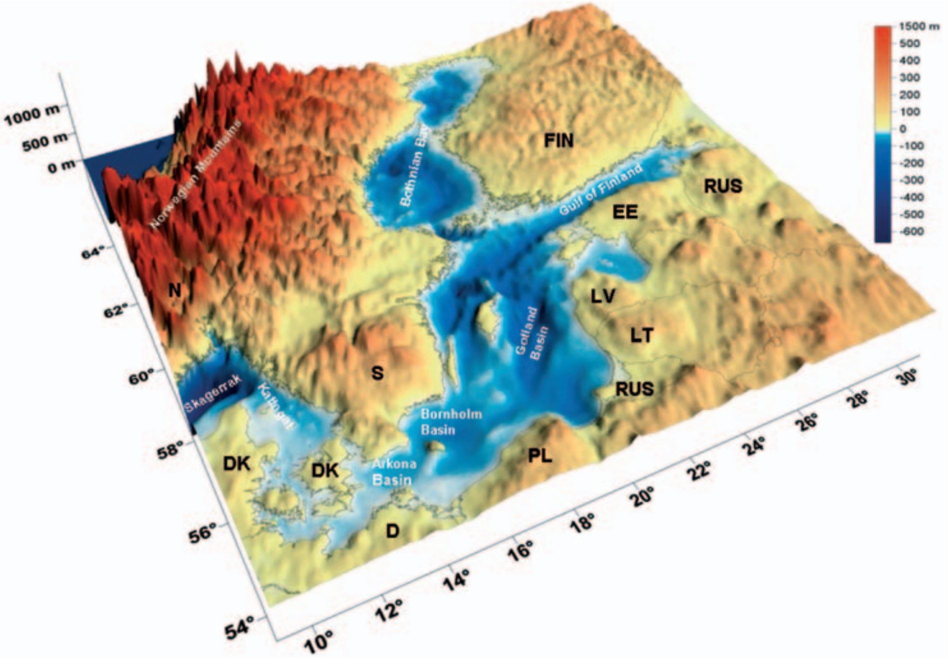

Fig. 6: The bathymetry of the Baltic Sea basin (based upon data abstracted from SEIFERT, TAUBER and KAYSER, 2001)

transgression from the North Sea. At that time, the continent was located approximately 25° north. The climate was subtropical – arid, and as the marine basin was shallow, layers of salt were deposited due to high evaporation. While in the North Sea basin the thickness of salt layers reaches up to 1,200 m, a maximum thickness of only 335 m was observed e.g. 50 km east of Ruegen Island, Baltic Sea (Petrobaltic Drilling K5-1/88; LINDERT et al., 1993). For this reason, the influence of salt tectonics is decreasing from West to East. In the most eastern German sector of the Baltic Sea, salt deposits are rare (see Fig. 2), and their thickness is less than 100 m (DUPHORN et al., 1995). Salt-tectonic was not active here.

During the Mesozoic Era, the general tendency of deposition continued. The thickness of the deposits decreased generally towards North, and close to the Rinkøbing-Fyn-Height (see Fig. 1) the layers are partly tapering off. Due to eustatic water level fluctuations and the exposure to hydrodynamic influence, deposits are ranging from fine- to coarse-grained sediments reflecting their depth of deposition. At the end of the Jurassic period (200–145.5 million years BP, see Table 1), limnic sediments were deposited. The Cretaceous period (145.5–65.5 million years BP) is dominated by a huge transgression reaching its peak during upper cretaceous time when subtropical oceanic conditions prevailed. Typical deposits are chalk layers which can be observed at the cliff-coast of Ruegen and Møn Island. The carbonate content of these layers is 90–98 %. The end of the cretaceous period is marked again by a huge regression. During the Palaeogen (62.5–23 million years BP), several transgressions and regressions took place, covering the entire southern Baltic Sea area during certain periods.

3.2 Neogene

Regression continued during the beginning of the Neogene, 23 million years ago (LOURENS et al., 2004). At the end of this period during the Pliocene Epoch, the climate became colder. The Baltic Sea area was marked by the development of a river system, the Baltic Main Stream, flowing in a NE–SW oriented depression, draining NE-Europe and transporting huge amounts of fluvial sediments which were mainly deposited as Kaolinitic sand in the North Sea basin. This is the material which is dredged offshore in the North Sea today to be used for beach- and dune nourishment.

3.2.1 Pleistocene Development

The younger history of the Baltic Sea was dominated by decreasing temperatures over the past 2.4 million years and at least three glacial periods, when ice was advancing from Scandinavia towards NW-Europe. The depression already used by the Baltic Main Stream was carved out further by these ice advances, of which the latest formed the specific geomorphological shape of the basins, bays, fjords and coastal areas as we see it today (Fig. 6). Marginal contours of the ice cover are formed by end-moraines, indicating how far these advances and sub-advances, representing an oscillating ice front, were reaching. The distance between these different contours of the latest ice advance increase from West to East (Fig. 7). Between them 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 marine sediments increases from west to east, namely from Schleswig-Holstein via Mecklenburg-Vorpommern to Poland.

The whole south-eastern to south-western part of the Baltic Sea, the coastal areas of Latvia, Lithuania, Russia, Poland, Germany and Denmark, are built up of soft-rock Quaternary deposits (WINTERHALTER et al., 1981), mainly of Weichselian age. On the other hand, the northern part of the Baltic Sea is mainly composed of hard rock (LAMPE, 1995). There are only a few exceptions where hard rock is exposed along the south-western Baltic Sea, e.g. parts of Rügen Island (Germany) or Møns Klint (Denmark). Here, cretaceous deposits have been pushed up by glaciers during the latest ice advance.

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. From the early to middle Holocene, the Baltic Sea underwent 4 evolutionary stages (Fig. 8).These were the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea (BJÖRK, 1995; ERONEN et al., 2001; LAMPE, 2005). As a result of the interaction of uplift rates and changes in relative sea level alternating fresh-, brackish- and marine water conditions occurred. The Holocene history of the precursor of the Baltic Sea started with the deglaciation and the opening of several drainage channels around 13,000 years BP. Due to these openings, the water-level dropped to at least – 25 m MSL (mean sea level) and caused extensive erosion in the lower river courses. During Alleröd, the waterlevel rose again from –40 to –20 m MSL (see Fig. 9). This phase (Bölling to Younger Dryas) is called Baltic Ice Lake. The opening of the gap at Mt. Billingen around 10,300 years BP due to the continuous retreat of the Scandinavian ice sheet from the southern Swedish mountains caused a drop of the water table to about –40m MSL (BJÖRCK, 1995). The early Holocene incision phase started with the Yoldia Sea (JANKE, 1978). It was the first connection with the Atlantic – North Sea system, which lasted only for some 700 years. By an accelerated isostatic uplift of Southern

Fig. 7: Ice margins of the Weichselian Glacial in the Southwestern Baltic Sea (modified after LANGE, 1984. F = Rosenthal Step, G = Velgaster Step, H = Nordrügen Step, E = margin of Sehberg Advance)

Scandinavia versus the postglacial sea level rise, the corridor to the North Sea was closed initiating a second freshwater phase – the Ancylus Lake period. This freshwater period began with a water level rise to a maximum highstand of –10 m to –8 m MSL (KATZUNG, 2004) followed by a water level drop during the second half of the Ancylus Lake period. For the first time now, the water gradually penetrated into the region of the present-day German coast (LEMKE, 1998). This was due to the slowly subsiding process of this area while Scandinavia is experiencing isostatic uplift (see Fig. 8).

Due to global eustatic processes, the Baltic Sea was again connected to the North Atlantic via the North Sea approximately 7,900–7,200 years BP. It is called the Littorina transgres-

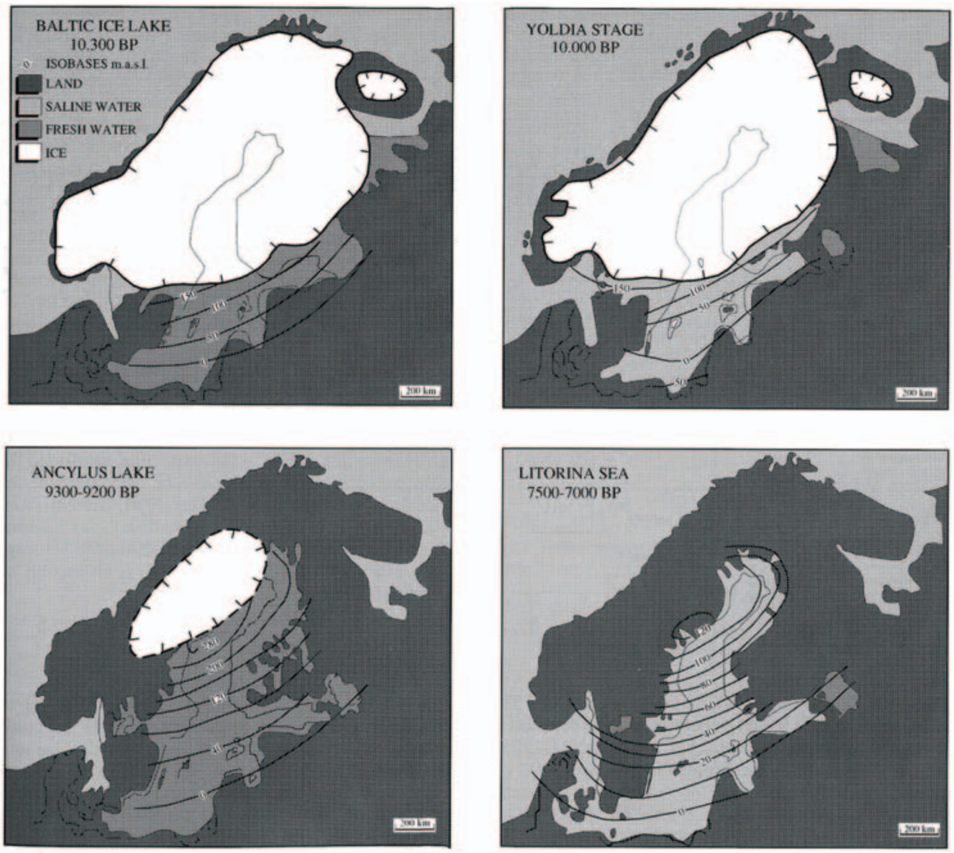

Fig. 8: The development of the Baltic Sea during the late glacial and postglacial (ERONEN et al., 2001)

sion. Since this time, the connection to the North Sea has been permanent. The first period of the Littorina Sea is marked by a very rapid water level rise with rates up to 2.5 cm/year (Fig. 7). This transgression into the south-western Baltic region led to a widespread inundation of the pre-existing glacial relief without any erosion. The landscape was just drowning. The typical landforms to be submerged were pronounced ridges and terminal moraines, widespread areas of undulating basal moraines and imbedded meltwater channels, all associated with ice- and glacier-tongue shaped troughs and fjords. During the period of rapid sea level rise, all terrain lying below –5 m of the present MSL was flooded.

Approximately 6,000 years BP, the water level almost reached its present position (JANKE and LAMPE, 2000). At this stage, wave impact as well as nearshore sediment dynamics began to effectively modify the coastal profile by intensive redeposition of sediments. Cliff coasts were eroded and cut back; longshore sediment transport led to the development of spits, sandy hooks and beach ridges (SCHWARZER et al., 2003). In the shallow water, small islands, built up of morainic material, were connected by these growing spits, initiating the development of the famous baymouth ("Bodden") coast (the term "Bodden" is the local name for the shallow, semi-enclosed coastal lagoons and backwaters behind the exposed Baltic Sea

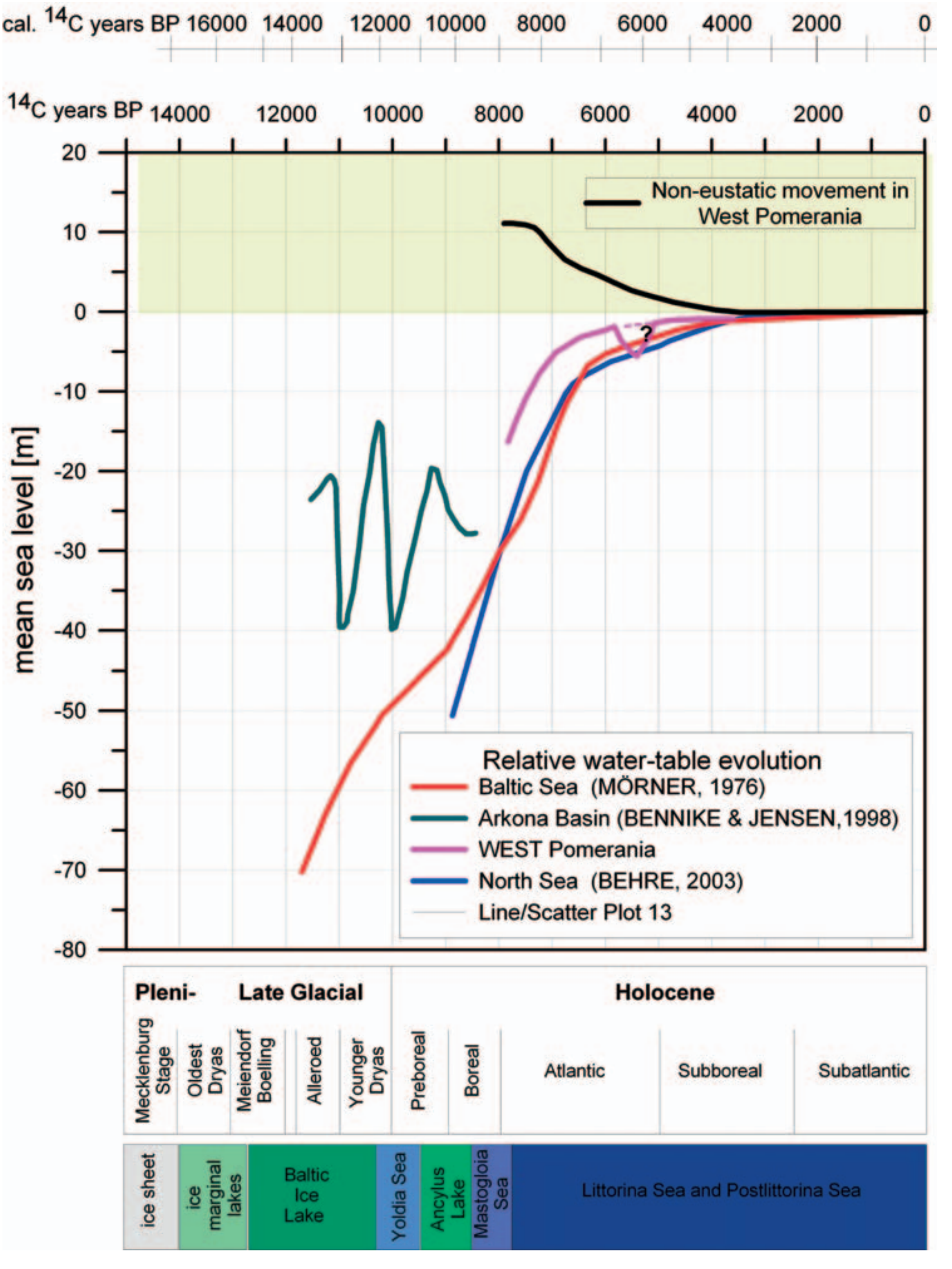

Fig. 9: The relative evolution of the water table in the West Pomeranian coastal area compared with the eustatic curves derived from MÖRNER (1976) and BEHRE (2003) and the relative evolution of the water table in the Arkona Basin according to BENNIKE and JENSEN (1998) and JENSEN (1995). In the upper part of the diagram, the estimated non-eustatic movement component is shown, calculated as the difference between the eustatic and the relative water table (LAMPE, 2005, modified)

coast). Rügen Island as well as the Fischland-Darss peninsula are excellent examples where several small islands, consisting of a core built up of Pleistocene deposits, were connected by beach ridges. These ridges are built up of material which is eroded from cliff sections and offshore abrasion platforms: Then it is transported by longshore currents (BELLEC et al., 2008). Rügen, the largest German island, was formed by these cliff falls and abrasions.

In response to glacio-isostatic rebound, the northern part of the Baltic Sea is still dominated by an uplift relative to the present sea level, with rates up to 9 mm/year in the Bothnian Bay (MÖRNER, 1977; HARFF et al., 2005, see Fig. 9). In the southern part, subsidence rates of up to 2 mm/year occur (MEYER 2002; MEYER and HARFF, 2005). Such subsidence generally causes erosion and coastal retreat along the entire southern Baltic Sea coastline, because these areas consist of an alternation of cliffs and lowlands, built up of soft glacial and postglacial deposits.

Based upon the modelling of large scale palaeo-coastline changes since the onset of the Littorina transgression 7,900 ^{14}C years BP, the sea level in the northern part has dropped significantly, in some areas by more than 200 m (CATO, 2004). This process has resulted in a regression, by far out-weighing the southern transgression. According to MEYER and HARFF (2005) the spatial extent of the Baltic Sea has diminished by approximately 30 % since then, whilst the volume has decreased from 47,000 km^3 to 22,000 km^3, or by 47 %.

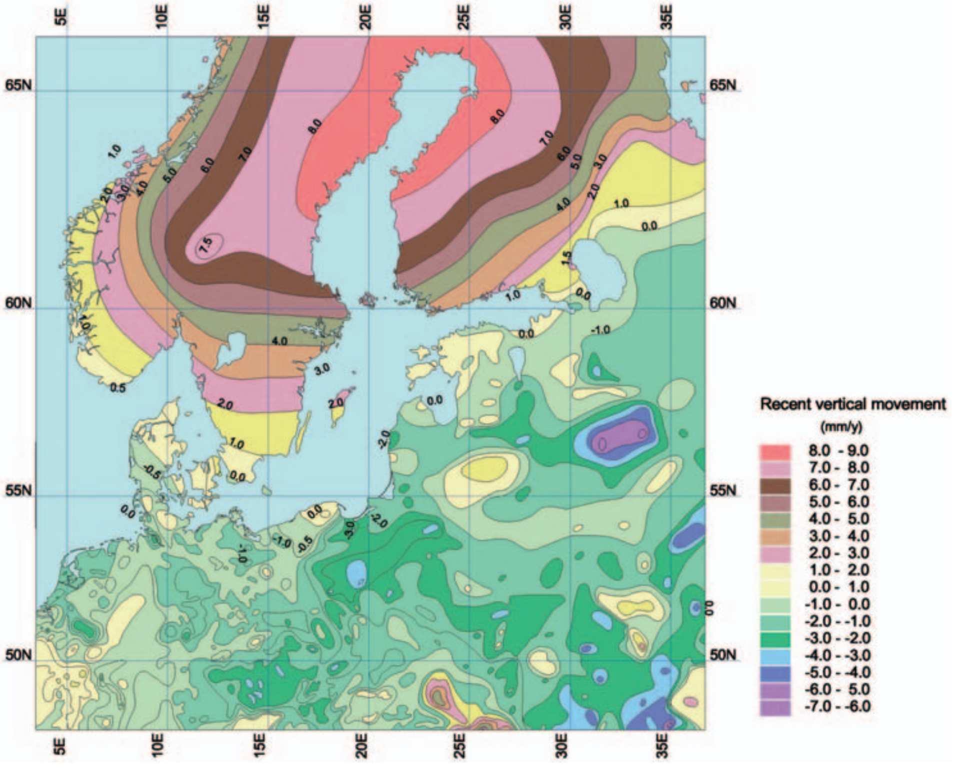

Fig. 10: Present isostatic movements around the Baltic Sea Basin (HARFF et al., 2001)

4. Conclusion

The data presented show well-based facts about the development of the North Sea and the Baltic Sea. However, they also point to numerous remaining uncertainties. From the results presented above, it is obvious, that the correlation of postglacial sea level fluctuations between the North Sea and the Baltic Sea is complicated because of both a lot of local phenomena (compaction, influence of salt tectonics) and far-field factors (gradient in isostatic uplift, neotectonics), which are superimposed. These geologically caused movements have to be correlated with the eustatic water level fluctuations. Up to the present, Holocene sea level curves from the Baltic Sea and the North Sea do not match due to a lack of comprehensive data sets, especially from offshore regions.

The younger geological development of the North and Baltic Sea documents, that the natural coastal depositional system has a relatively high capacity to adapt to a fluctuating – but especially to a rising sea level. This, however, is often associated with a dislocation or even breakup and/or a new formation of morphological elements. Since this does not in any case fit with human interests, coastal engineering efforts have been necessary in the past and will be necessary in the future to manage the coastal anthroposphere.

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