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Examples of the geological past: evolution of coastal sedimentation sequences during Holocene sea level rise

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Abstract

Future sea level rise caused by the greenhouse effect may have an important impact on the coastal wetlands of the world. A much discussed subject is the the expected changes in the ecology of these wetlands. During the recent geological past, the Holocene, the types of sediment deposited under various rates of relative sea level rise are known through investigations of buried deposits in various coastal basins. These studies of the past may contribute to a better understanding of the changes of the shoreline, the backswamp and its ecology which may occur under future rapid sea level rise as predicted by the greenhouse effect.

In this contribution four examples of coastal basin developing under various rates of past relative sea level changes and sediment input are discussed. The main conclusion is that intertidal conditions can only develop when relative sea level rise and sediment input are in balance.

Introduction

An increasing body of evidence suggests that in the coming decades global warming due to the greenhouse effect may lead to a substantial rise in sea level. There is a controversy about the extent of future sea level rise that can be expected in the coming century. Hofman *et al.* (1983) give an estimate between 56 and 358 cm, Robin (1986) calculated the future rise in sea level as being between 20 and 140 cm and Warrick and Oerlemans (1990) suggested a rise of between 31 and 110 cm with a best estimate of 66 cm. The last mentioned estimate is that in the report of Working Group I of the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990).

These differences in the various estimates are due to the uncertainties concerning the input to the models. Robin (1986) expressed this problem as follows: "*With our lack of knowledge of the hydrological cycle and the dynamics of the oceans and the polar ice sheets, forecasting global changes of sea level involves considerable extrapolation and speculation.*"

The future rise in sea level would have its most severe effects in low lying coastal regions, deltas, estuaries and riverplains. About half of the worlds' population live in these coastal lowlands, and they are zones of intense economic and agriculture activity. Future sea level rise will have serious impacts on the socio economics of these areas and on the remaining natural wetlands.

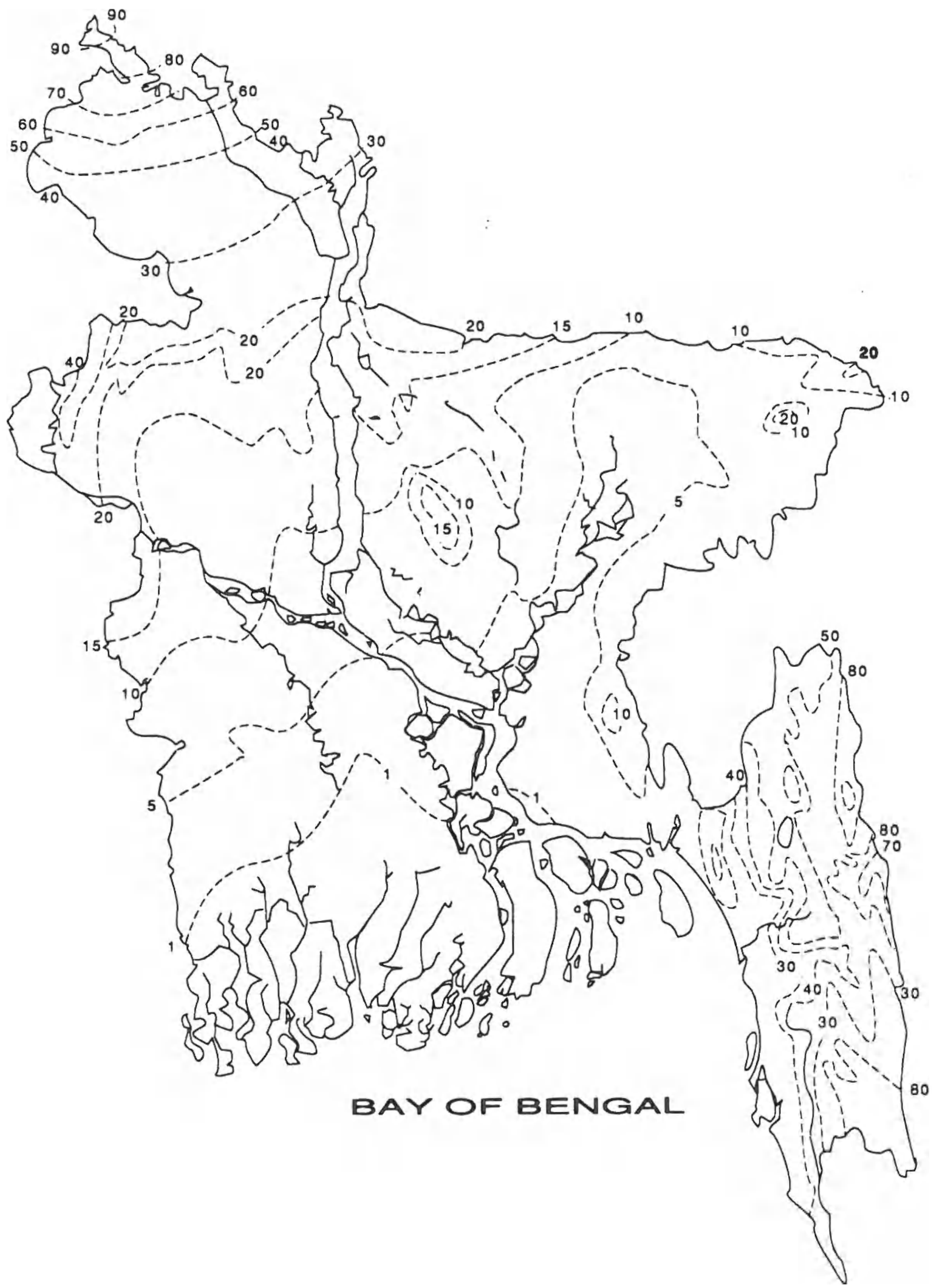
Even without a future sea level rise most coastal wetlands are already endangered habitats owing to human interference. Pollution, land reclamation and human alterations in shoreline processes all pose serious threats to existing wetlands. Even more serious is the decrease in supply of sediments to wetlands caused by the construction of dams and reservoirs for hydropower and irrigation. The best known example is the Nile Delta. After the construction of the High Aswan dam the sediment supply to the delta was reduced to zero. Most deltas in the world are eroding, mainly due to serious sediment reduction caused by the construction of dams and reservoirs. The economic benefit of these constructions for irrigated agriculture, water resource management, electricity generation and flood control are important but the coastal wetlands are being lost.

There is a lively discussion among ecologists about the changes in morphology in coastal wetlands which may result from future sea level rise. The intertidal flats, the humid tropical mangroves and, at higher latitudes, the saltmarshes are of great importance as fish nurseries and for resident and migratory bird populations. The important question is: can the vertical sedimentation on those intertidal flats keep up with sea level rise? If this is not the case a change to subtidal flats will occur resulting in open water. Another question is whether and how sea level rise will move the various salt and brackish water environments landwards. It should be stated that these future changes in the coastal morphology are highly dependent on the rate of sedimentation which is governed by the input of sediments; by catchment area; by the action of the sea; and by the magnitude of the tidal range which redistribute sediments and; the trapping of sediments such as occurs in the mangrove root system. It is evident that these changes are locally and regional highly variable.

Some investigations which attempt to forecast future shoreline position following sea level rise ignore the fact that vertical sedimentation actually takes place during sea level rise. This approach indicates areas to be lost by a rise of sea level of one, two or three meters (Milliman *et al.*, 1989) as demonstrated in figure 1. The same method has been used in the case studies presented by the Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (1992). This "bath-tub" approach to future sea level rise ignores the rules of sedimentary processes and gives a doomsday picture to people in the areas concerned.

Another approach to forecasting changes in morphology and shoreline position is to study the effects of post glacial sea level rise in coastal lowlands. The deposits related to this important period of sea level rise are present in the shallow subsurface layers of the coastal plains. The types of sediment under various rates of relative sea level rise can be studied by geological investigations in these coastal plains. The recognition of these sedimentary environments in the geological past is the physical, chemical and biological conditions at the site of sediment accumulation. This means that their lithology, sedimentary structure, fossil assemblages (pollen, diatoms and shells) and chemical content are analysed.

Figure 1.
Topographic contours (in meters) of Bangladesh



The various deposits can be dated by radio carbon techniques and their relation to former sea level fixed. Such studies of the past can contribute to a better understanding of future changes of the shoreline and its ecology caused by a future rapid sea level rise resulting from the greenhouse effect. In undertaking analysis we have to realise that human interference in the coastal zone and in river areas represent new and very important inputs that were not present in the geological past. Accordingly care has to be taken in translating the "key to the past as a key to the present. These problems were recognised and formulated during the European Workshop on Interrelated and Bioclimatic Land Use Changes, Noordwijkerhout, The Netherlands, Oct. 1987 (Tooley & Jelgersma, 1992).

Four examples of coastal plains developing under various rates of past sea level changes and sediment input are evaluated in this paper in the light of the following short outline of Holocene sea level changes.

Sea level changes during the last 18,000 years

During the last glaciation, the Weichsel or Wisconsin cold period, the build up of ice caps on land caused a drop in sea level of more than 100 m. The lowest position of sea level was reached during the maximal extension of the icecaps; about 18,000 years ago. Shortly afterwards these enormous ice caps started to melt down resulting in a rise in sea level.

Post glacial sea level changes can be subdivided into three time periods: from 18000 - 6000 BP; from 6000 BP to recent times; and over the last 100 years. During the time period 18000 - 6000 BP the restoration of ocean level was dominated by the melting of the continental ice sheets which can be inferred from the geological mapping of retreating ice margins and from the marine oxygen isotope record. The rate of sea level rise during this period was very high: > 1 m/century levelling off to ca. 60 cm/century at end of this period. (Fairbanks, 1989).

After 6000 BP sea level changes are dominated by movements of the earth's crust since the continental ice caps had disappeared. Nakade *et al.* (1988) however mention the possibility that during the last 6,000 years three metres of sea level rise may have resulted from glacier melting in Antartica. The tectonic component seems to have been the most important factor influencing sea level curves over the last 6,000 years which consequently show great regional variation.

Sea level curves of SE Asia and Australia indicate a higher sea level about 6000 BP levelling off to the present level (Figure 2) other curves from the east coast of the USA and The Netherlands show a slow continous rise of sea level after 6000 BP (Figure 3).

During the last 100 years, tide gauge readings have given indications of sea level changes but more precisely of movement of land relative to the sea. These measurements provide evidence of land surface uplift in former glaciated areas due to isostatic rebound. In areas of plate tectonics abrupt shifts in the earth crust in horizontal or vertical directions have been observed. In other areas, especially deltas, slow subsidence of the land relative to the sea is measured. Tide gauge readings have been used to detect eustatic sea level rise by scientific analyses of trends and patterns. After carefully filtering the data, a mean global figure of 1.2 mm/year sea level rise over the first half of the 20th century was obtained by Gornitz *et al.*, 1987. Warrick and Oerlemans (1990) suggest an average rise of mean sea level of 1.0 - 2.0 mm/year due to thermal expansion of the ocean and increased melting of mountain glaciers caused by global warming of the greeenhouse effect. Other scientists (Pirazolli, 1989) have noted that tectonic subsidence and compaction may be included in this global sea level rise figure. Consequently it is questionable if the observed sea level rise is indeed a real signal of the greenhouse effect.

Case histories

Holocene sedimentation sequences from four different areas are discussed below: The Netherlands, the three Guianas, N. Australia, Papua New Guinea and SW Florida, USA. In all investigated areas rapid rise of sea level occured in the period before 5000 BP. The climatic circumstances show important differences between wet tropical and temperate, between areas of macro or micro tidal range and important differences in sediment input either from the rivers or from the sea.

Figure 2.
Sea level changes over the last 10,000 years in the Western Paciifc

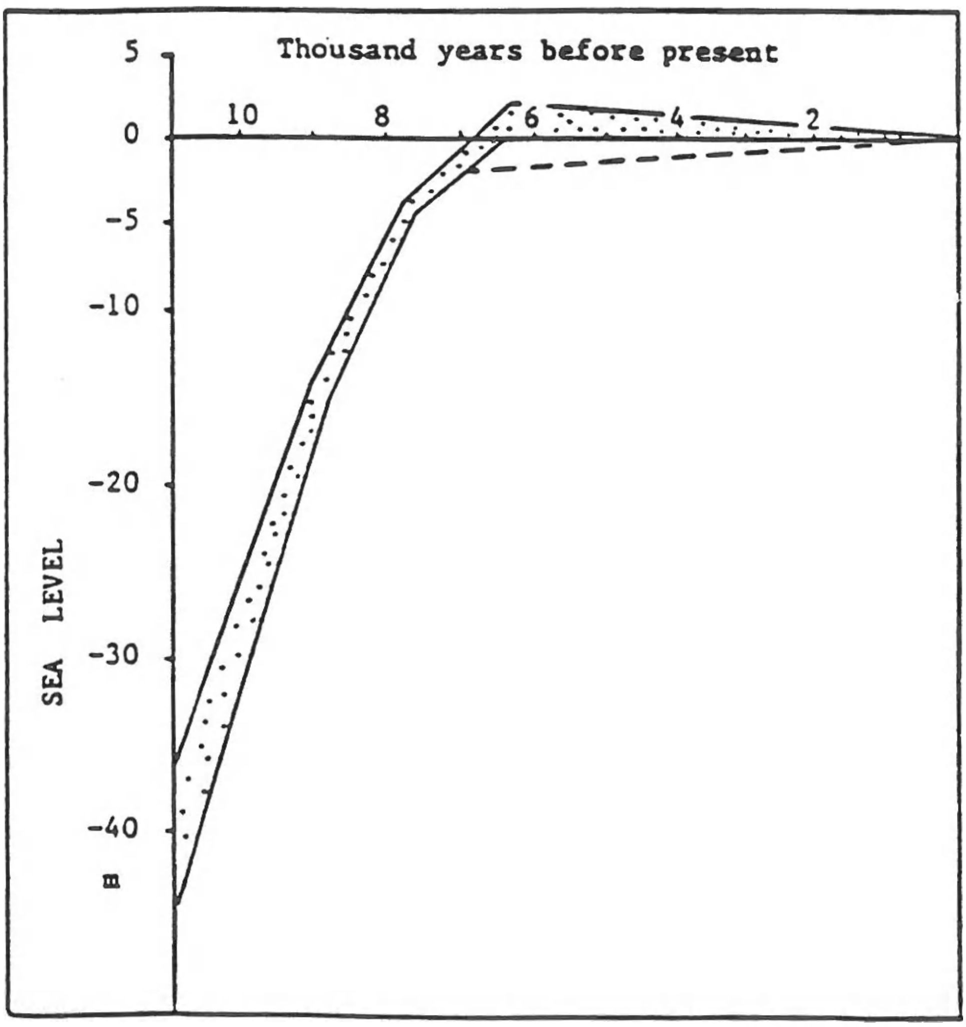
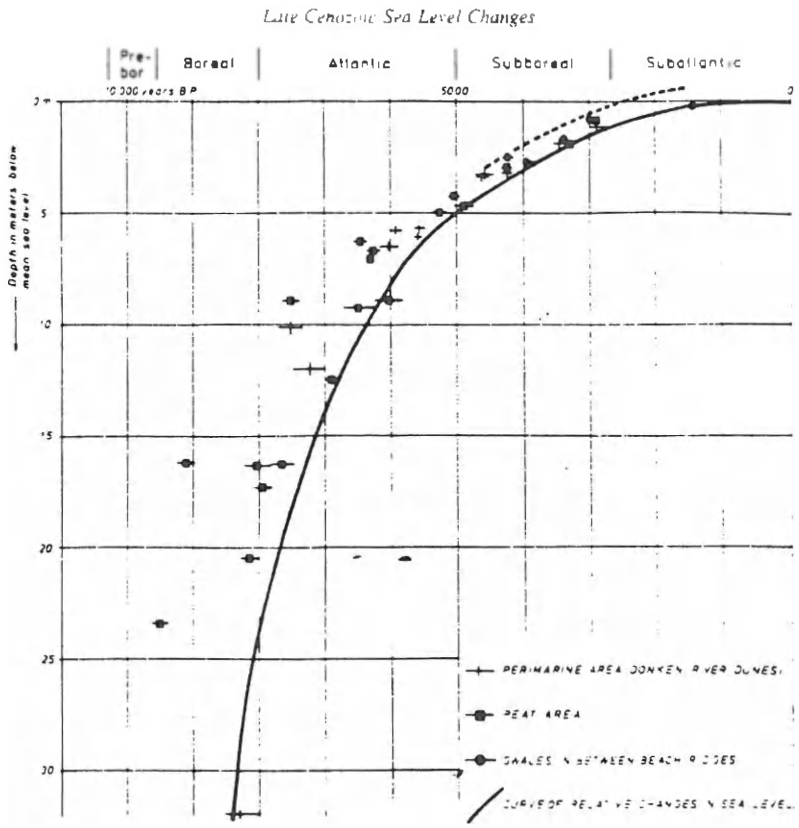


Figure 3.
Sea level curve for the coastal area of the Netherlands (after Jelgersma, 1966)



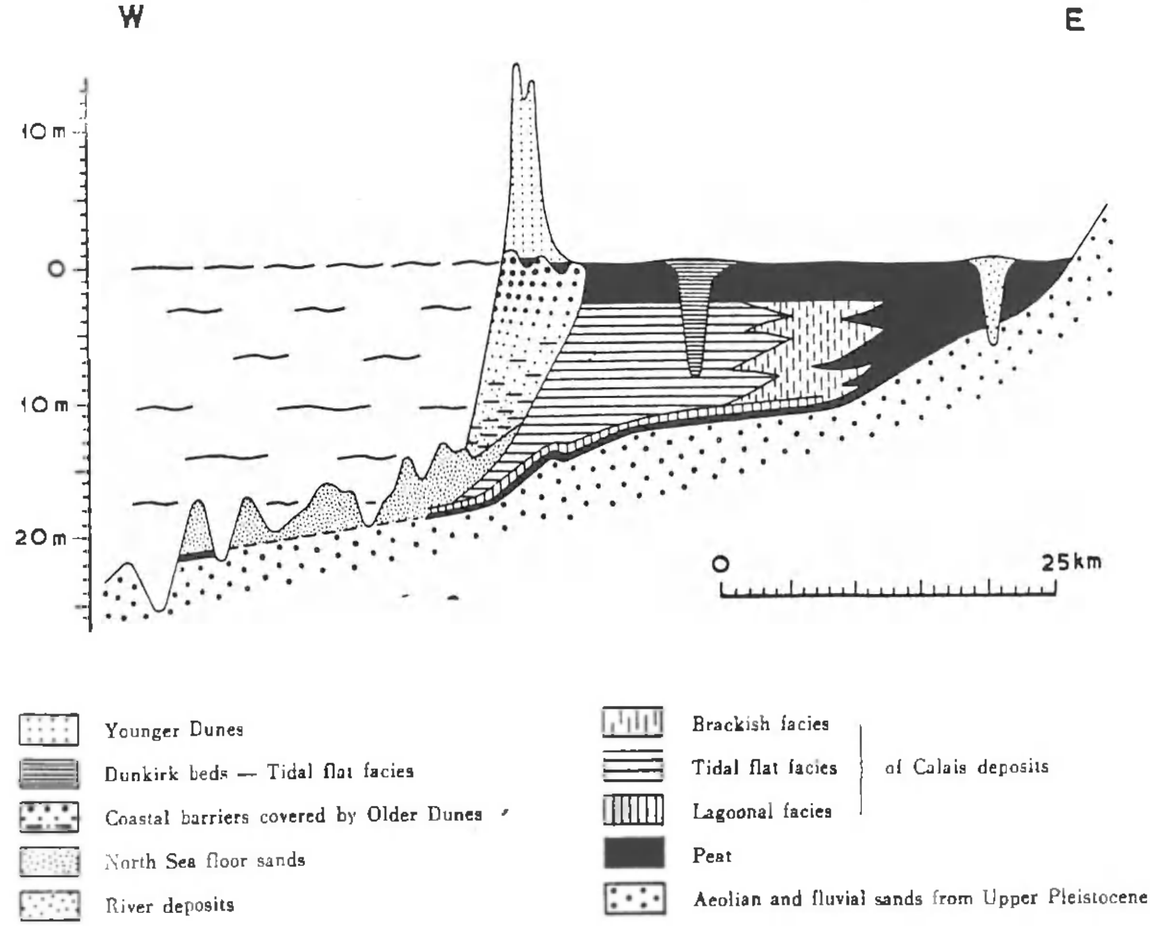
Owing to these variables, the sedimentation rate and the sedimentary environment show great differences in the different case study areas. In all the coastal lowlands, post glacial sea level rise has resulted in a wedge of soft sediments situated on top of the pre-Holocene deposits. The type of sediment in this wedge in the case study areas is discussed below.

The Netherlands

The coastal area of The Netherlands can be classified as a meso to micro tidal, wind dominated, clastic shoreline. At the present time the rivers Rhine - Meuse deliver mud to the North Sea which was calculated to be 1.5×10^9 kg/year in 1985. Due to engineering work this has been reduced to 0.5×10^3 kg/year at the present time (Visser *et al.*, 1991). The low lying part of The Netherlands has been formed by the sedimentation caused by the post glacial sea level rise.

A cross-section through the coastal plain of The Netherlands (Figure 4) provides evidence of the various sedimentary environments during the Holocene. The decreasing rates of sea level rise during this period are given in Figure 3. The Holocene transgression penetrated through the low lying parts of the pre Holocene surface and gave rise to several tidal basins. The sedimentation in one of these tidal basins, in the NW part of The Netherlands under decreasing rates of sea level rise, has been subject to careful subsurface investigations (van der Spek & Beets, 1992).

Figure 4.
Section across the Holocene deposits of the W. Netherlands (after Van Straaten, 1961)



The recognition of the sedimentary environments encountered in the Holocene has been by cored bore analysis and the studies of lithology, sedimentary structures and the fossil content (pollen, diatoms and shells). The absolute age determinations have been done by the radio carbon method. These investigations have given rise to the recognition of three different stages of sedimentation and sea level rise.

During the first stage, prior to 7000 BP when the relative rise of sea level was more than 75 cm/century, intertidal sediments were restricted to the vicinity of the tidal inlets and channels. Landward lagoons were present, bordered by fresh water swamps. No salt marshes have been encountered in the sedimentary structures and the fossil content. It may be concluded that during this stage the relative sea level rise was greater than the available sediment input in the tidal basin accordingly extensive intertidal flats and saltmarshes could not develop.

During the second stage between 7000 and 5500 BP, relative sea level rise was levelling off to 30 cm/century the sediment supply started to balance the storage capacity created by sea level rise. Intertidal flats increased in size, but saltmarshes were still rare. During the third stage between 5500 and 3500 BP when the rate of sea level rise slowed down to 15 cm/century, the sediment supply was sufficient to fill the basin. Accordingly the lagoons changed into intertidal flats and after 4000 BP saltmarshes became common features.

It may be concluded that during the third period sediment supply was in balance with the relative sea level rise. Van der Spek and Beets (1992) have used the data from the past to forecast the impact of a future sea level rise, more than 60 cm/century, on the Wadden Sea situated in the Northern part of The Netherlands.

The present rate of sedimentation in this important intertidal area is thought to be in balance with the observed relative sea level rise of the last 100 years (15 cm/century). If the sediment supply to the Wadden Sea remains the same in future it seems likely that with a future sea level rise of more than 60 cm/century much of the intertidal flats will become subtidal. The saltmarshes will disappear as the sedimentation rate will be less than the rate of sea level rise, and accordingly much more open water will be present in the Wadden Sea.

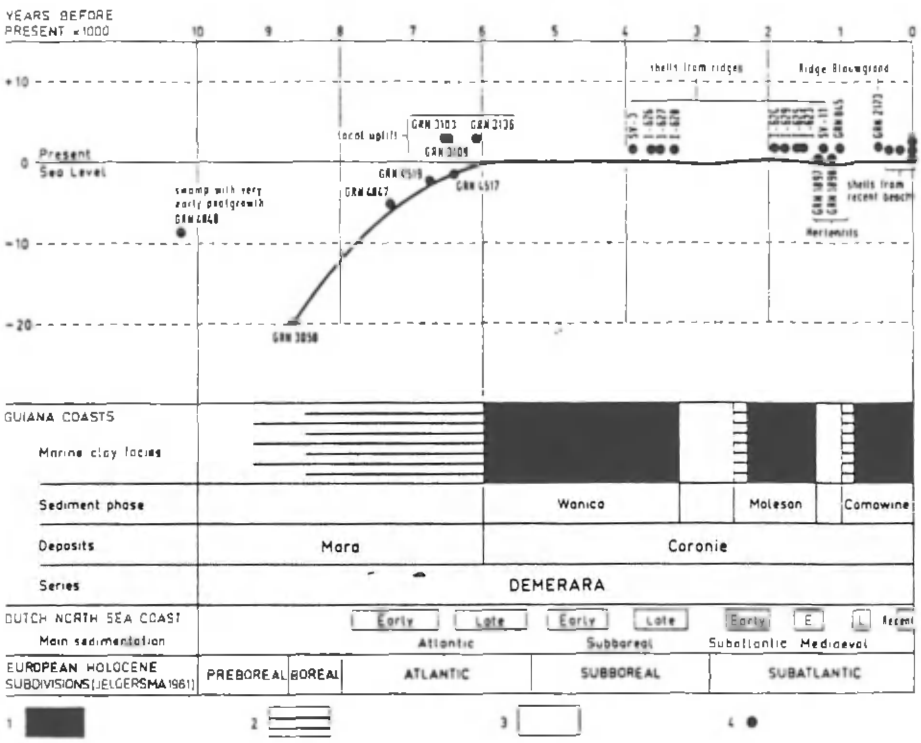
The three Guyanas

Extensive pedogeomorphological and geological mapping has been carried out in the coastal plain of the three Guyanas, northern South America (Brinkman *et al.*, 1968). The coastal landforms of the Guyanas are the product of the post glacial sea level rise and the enormous quantities of silt discharged by the Amazon River and transported by waves and currents. The sediments from the Amazon River form migrating mudflats with associated subtidal mudflats. There is a net transport to the west with a considerable deposit of material in this direction, Wells and Coleman (1977) mention that the near shore waters of the Guyanas are among the muddiest in the world (maximum of 26 - 37 /100 mg/l in near shore muddy coastal waters). The tides are mesotidal, the longshore transport is trade monsoon influenced and shows a westerly drift. The climate is tropical with wet and dry seasons and a high relative humidity.

Palynological studies together with C^{14} age determinations have given indications of the past vegetation, the age of the coastal deposits and sea level changes (van der Hammen, 1963; Roeleveld,1969), together with the work of Brinkman *et al.* (1968) provide the following picture of Holocene coastal development:

In the coastal plain two typical facies of clay sedimentation have been encountered; one at a stable level (Coronie deposits), the other associated with a rapidly rising sea level (Mara deposits, Figure 5). The sediments deposited under stable sea level, dated after 6000 - 5500 BP, are characterised by rapid successive lateral sedimentation of clays low in organic matter and pyrite, colonised by mainly *Avicennia* mangroves succeded by freshwater swamp vegetation as the distance to the sea increased. The sediments formed under a rising sea level, before 6000 BP, accumulated vertically under an actively growing vegetation of almost pure *Rhizophora* extending many kilometers inland from the coast. They contain large proportions of organic matter from the abundant fine *Rhizophora* roots and of pyrite, formed by reduction of sulphates from the brackish water and iron oxide from the sediment. The vertical accretion must have kept pace with a sea level rise of about 0.6 m/century for centuries, with the sediment supply maintained by the long shore current from the Amazon mouths. A thickness of this clay deposit of some 5 m is quite common, *Rhizophora* clays have been found in depressions of up to 40 m in some localities (Van der Hammen, 1963).

Figure 5.
Holocene sea level curve of the Guiana coast near Paramaribo (after Brinkman & Pons, 1968)



LEGEND
1. Deposition of "normal" sea clays at constant sea level
2. Deposition of pyrite clays at rising sea level
3. Erosion
4. C^{14} age determinations

Northern Australia, Papua New Guinea and some remarks on the Mekong, Ganges-Brahmaputra and Choa Phraya Delta

Chappell (1990) describes the sedimentation during rapid sea level rise in two tropical riverine lowlands. In both areas a steep sea level rise is observed until 6000 BP but the sediment input from the land and the magnitude of the tidal range are different. The floodplain of the South Alligator River in North Australia include fresh water wetlands due to the tropical monsoon climate. The sediment input from the land is low, the tidal range is high.

Investigations by mean of boring in the shallow subsurface of the riverine plain give the following data about the environment of sedimentation and the relative sea level movements. The sea level curve, figure 2, indicates a steeply rising sea level until 6000 BP with a level higher than at present, levelling off after that time to the present level. Underneath the recent river deposits in the South Alligator plain, an extensive mangrove clay is present.

The mangrove muds, up to 10-14 m thick, are deposited during a steep rise of sea level of about 12 m between 8000 and 6000 BP. It may be concluded that the mangrove clay sedimentation throughout the valley kept pace with the sea level rise during this period. A vertical sedimentation rate of 0.6 m/century seems likely.

As the sediment input of the land is rather low the source of the mud in the plain is thought to be marine muds. The strong sea level rise caused these muds to penetrate in the valley and the strong tidal current redistributed the sediment.

The flood plains of the Sepik and Ramu Rivers in Papua New Guinea are characterised by a high river water and sediment input and a low tidal range. Accordingly tidal currents are insignificant. As the continental shelf is very narrow much of the river sediments disappears to the deep ocean floor.

Geological investigations of the shallow subsurface deposits of the river plain have given the following data about the sedimentary environment during the steep sea level rise before 6000 BP. During this period an island sea developed in this area bordered by mangrove intertidal flats. The maximum extension of this inland sea was mapped and dated at about 6000 years BP. After that time, during stabilisation of sea level, the inland sea was gradually filled up with sediments from the catchment area. This investigation provides evidence that the sedimentation during the steep sea level rise did not keep pace with this sea level rise. Radiocarbon data indicate a sedimentation rate of 30 cm/century, if future sea level rise exceeds this the river plain will be tranformed into an inland sea.

In the Ganges-Brahmaputra, the Mekong Delta and the Chao-Phraya Delta the same Holocene sea level movements are present as in Northern Australia. Extensive subsurface mapping of those deltas is not available but C14 data of *Rhizophora* clays encountered beneath recent fluvial deposits are present.

These *Rhizophora* clays are dated about 5500 BP and are present as far as 100 km inland from the present coastline. (Brinkman & Pons, 1968; Brinkman,1984, 1987; Somboon *et al.*, 1990). Unfortunately insufficient subsurface data are available to indicate the rate of sedimentation in these deltas and to establish the balance between vertical sedimentation and sea level rise.

Mangrove ecosystems on carbonate platforms, SW Florida

Ellison and Stoddart (1991) give an excellent review of the work of Scholl (1964), Scholl *et al.* (1969), Bloom (1970), Ellison (1989) and others, on sea level changes derived from submerged mangrove peats. In this specific area of carbonate platforms like SW Florida mangroves exists in a more or less narrow belt. It is evident (Scholl *et al.*, 1969) that the sediment sources in SW Florida are limited to biological sources; molluscs, algae and rooted vegetation. In the fresh water, calcite mud formation, sedimentation rate is found to have been 1.6 cm/century during the last 4000 years, in the coastal area the sedimentation has kept pace with the sea level rise of 3.5 cm/century during this time. The investigation in S.W. Florida of Scholl (1964) indicates that after sea level slowed down to less than 9 cm/century mangrove systems could develop.

Ellison and Stoddart's (1991) conclusion, based on the geological record of the past, is that the mangrove ecosystem that only derive autochthonous organic accumulation will collapse if future sea level rise is more than 10 cm/century.

Conclusions

These parallels from the past show four important facts:

1. If sufficient sediment is available, vertical accretion can keep pace even with a rapid sea level rise. This means that under favourable conditions of sediment supply the intertidal conditions of our present wetland can be maintained.

2. The magnitude of the tidal current is an important agent in redistributing sediment. Accordingly it influences the rate of sedimentation.

3. A rapid sea level rise can change the inland fresh water environment of a deltaic plain in the humid tropics into an extensive zone of brackish *Rhizophora* clays if enough sediments are available. A lack of sediment can give rise to inland seas.

4. The simple "bath-tub" approach of some authors (Milliman *et al.*, 1989) estimating land loss by comparison of topographic elevations and future sea level heights, exaggerates loss and is inadequate since it neglects the remodelling of the coastal and deltaic plain and the supply and redistribution of sediment.

It must be stressed that construction of dams and barrages has drastically curtailed the sediment supply to many shorelines and deltas, and accordingly the impact of a future sea level rise will not be comparable to the geological data of the past.

In some coastal plains however the shorelines are expanding seawards owing to an increased sediment supply caused by human induced erosion of the hinterland (e.g. N. Java, Madagascar). In these areas the lessons of the geological past are similarly less comparable with a future impact of sea level rise.

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