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L'ÉVOLUTION QUATERNAIRE DES BASSINS FLUVIAUX
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THE SOUTHERN NORTH SEA DURING THE QUATERNARY

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RÉSUMÉ

Les facteurs responsables des changements du niveau de la mer et du tracé des côtes sont :

1° les variations eustatiques du niveau marin ;

2° les mouvements verticaux du sol ;

3° les déplacements horizontaux des côtes.

L'influence de chacun de ces facteurs et leur importance dans l'évolution des côtes de la mer du Nord est discutée (fig. 1 et 2).

L'auteur présente ensuite l'évolution des côtes de la mer du Nord méridionale depuis le Miocène supérieur jusqu'à l'actuel (fig. 3). Il souligne les problèmes et les incertitudes qui subsistent pour chaque rivage dessiné sur cette figure.

The paleogeography of the North Sea during the Quaternary has been the object of a number of syntheses during recent years, the latest ones being those of Dechend (1954, 1961), Funnell (1972), Valentin (1951), Veenstra (1970, 1971).

Notwithstanding the great harvest of new facts and interpretations our knowledge on the evolution of sea-level and the situation of coastlines is still hypothetical. Let us here recall the factors responsible for a changing sea-level and coastline.

1. EUSTATICAL SEA-LEVEL CHANGES

The existence of worldwide eustatical sea-level movements is the primordial key to marine beach stratigraphy. Since the introduction of the idea by Deperret it was the object of much applications and discussions.

A glacio-eustatical drop of sea-level during the last glaciation of approximately hundred meters is documented by a large number of facts and accepted by most workers. On the other hand a glacio-eustatic rise of approximately eighty meters is believed probable when all glacier ice would melt. This gives the possibility of

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180 m universal sea-level oscillations, a fact indeed of major and unique importance for worldwide stratigraphic correlations.

However, this use supposes that the curve of the sea-level oscillations is known, which is not at all the case. Indeed even the best documented part of the curve, the Flandrian transgression, is not established accurately enough to prove beyond doubt, for instance, a higher sea-level during the postglacial climatic optimum.

The major reason for this lack of knowledge is the very complicated nature of the curve itself. Figure 1 shows a model for three components of this curve. The major component is the curve of oscillations of sea-level parallel with the climatic evolution of the Northern hemisphere and responsible for the development of arctic and alpine ice. The only certainty is that the 4-glacials system has to be abandoned but it is not clear by how many glacials it should be replaced, with how many stadials, not omitting the cold oscillations during the interglacials.

Such a model can account for a sea drop to -100 m but only for a rise to approximately $+15$ m due to the rather small amounts of arctic and alpine ice that actually still can melt. Higher eustatical sea-levels can be explained by the component of antarctic ice influence. This has developed due to the drifting of Antarctica over the South Pole. It may never have melted totally since, but certainly did fluctuate. It is however not established if these fluctuations have the same rhythm as the northern ones and are in or out of phase with these. It seems more than probable that catastrophic glacial surges did also exist.

Still higher eustatic levels may have existed and ocean-basin deepening (guyots) as a correlative of continental epeirogenetic uplifting (tertiary peneplains) certainly could explain them.

The resultant general curve might show very numerous oscillations (with a wavelength of 21 000 yr?), with increasing amplitude and a tendency of successive maxima to decrease.

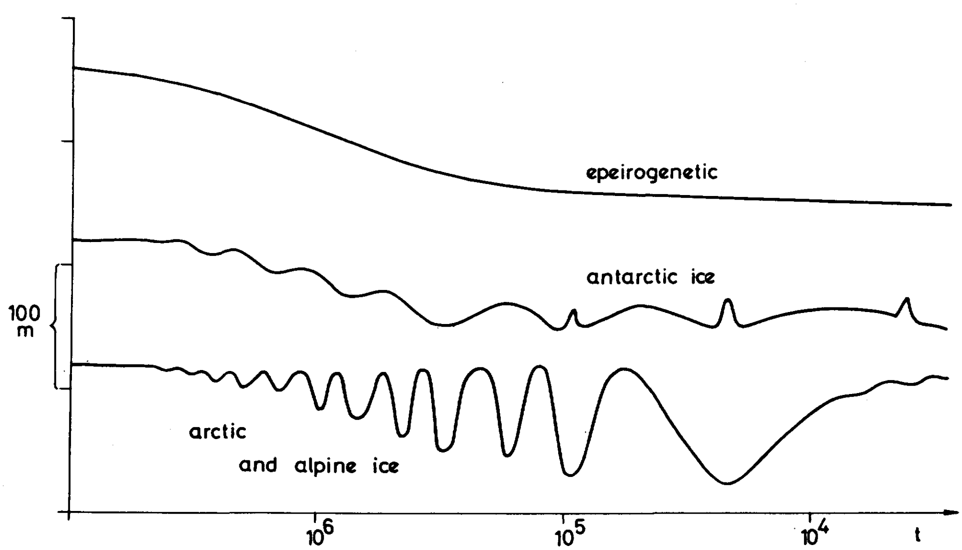

FIG. 1

As a matter of fact sea-level must have been always moving. The rate of change however is rapid in descending or ascending parts of the curve and slows down around minimal and maximal positions. In this way lowest and highest sea-levels will have left most traces, by erosion or sedimentation. This effect is probably reinforced by the greater climatological stability of the equilibrium situations transforming in fact the sinusoidal curve in a block curve and slowing down the rate of sea-level change around maximal positions. Our real knowledge in fact is limited to some of these maximal positions and we should be aware that they represent only a very small fraction of the time and, even without down warping, important parts are only documented under the actual sea-level.

In the lower Pleistocene only the Beersian oscillation (Dricot, 1962) was rather convincingly ascribed to glacio-eustatical movement. In the Cromer Forest Beds, West (1972) sees two eustatically controlled temperate transgression phases. The Holsteinian (~Hoxnian) and Eemian (~Ipswichian) sea-levels are better documented but outside both type areas all modern correlations are made with great precaution and even doubt. In deep ocean cores Sancetta (1972) distinguish however three climatic phases between Weichselian and Saalian and only the oldest one is named Eemian (around 125 000 yr). Correlation of these three events with type Eemian (estimated around 90 000 yr) is completely uncertain.

We mentioned earlier already how postglacial sea-level changes are still not agreed upon. The curve established by Jelgersma (1962) does not show any oscillations notwithstanding the numerous indications of a general Subboreal regression as presented by Godwin (1945).

2. VERTICAL LAND MOVEMENTS

We need not stress that the major reason for all these difficulties is the unstability of the land. A first problem is presented by compaction of sediments, sometimes very important and always almost impossible to quantify exactly. Next comes glacio-isostatic movement, rather well documented for the Holocene, best in the rising areas, least in subsiding parts. The southern limit of this influence is not well established and it should not be forgotten that the British ice reached further south than in Germany and may have had a considerable influence on sea-level in the Southern Bight. The same glacio-isostatic adjustments must have been more important in relation to the greater Saalian ice-extent, but it is not at all evident how much the peculiar indentations of Eemian and Holsteinian transgressions may have been influenced by these earlier glacio-eustatic movements. Most important are tectonical movements on which knowledge has rapidly increased (Heybroek, 1967, 1974). As the picture develops it appears that during the Cenozoic areas of subsidence migrated, the movement even reversing. It is highly probable that uplifting of the adjoining land was also irregular, even outside faulted areas.

Figure 2 shows a simplified profile along the eastern coast of the Southern Bight. As base of the Pleistocene in the North Sea was followed the proposal of Van Voorthuyzen-Zagwijn (1972) and this limit placed on top of the Poederlee-Formation in Belgium. During the lower Pleistocene a tertiary trend continues with localized strong subsidence in the Voorne trough and the Central Netherlands Basin. The hinge of the uplifting-downwarping movement migrates to the north. Still situated in the center of Belgium in the Upper-Miocene, in the north of

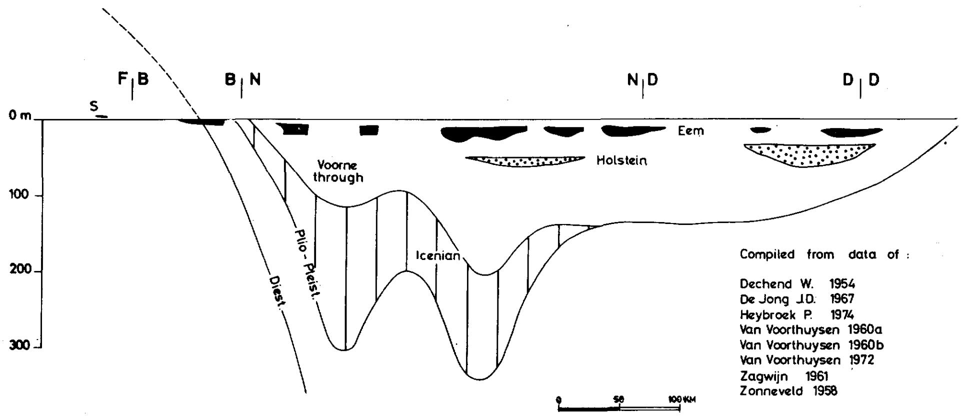

FIG. 2

Belgium at the Plio-Pleistocene boundary, it reached the IJsselmeer during the early Pleistocene. From Holsteinian on the movement reversed and the hinge moves south again. Downwarping is more largescale and certain thicker Holsteinian and Eemian deposits are more due to filling up of glacial reliefs than of local tectonic depressions. The younger interglacial sea-levels are transgressive to the south. While in the Central North Sea marine interglacial sedimentation can be thought of as continuous, the Southern Bight shows an unconformity and is clearly an erosive wedge.

3. HORIZONTAL COASTLINE MOVEMENT

The position of the coastline is the result of the interaction between absolute sea-level movements and absolute land movement as discussed before. These lead to eustatical or tectonical trans- or regressions. This continuously changing coastline has also its own dynamics: a balance between the energy along the coast and the work to be done. The energy is very variable along a seacoast and is a function of waterdepth, of configuration and orientation to the windsystem and of tidal characteristics. The work to be done is the transportation of material eroded by the sea or brought in by rivers. The balance leads either to erosional transgression or to sedimentational regression and is rather exceptionally in equilibrium.

Taking into account all these factors it would normally be easy to explain each coastline configuration. When we try to apply this model to the Southern North Sea immediately big problems arise. We must realize once more that the coastline originated essentially by the drowning of subareal reliefs in casu glacial and periglacial topographies.

During late Pleistocene, periods with depressed sea-level took a major fraction of the time; moreover the subareal processes during these periods had a much greater geomorphological activity. We are used to explain in this way ria's and fjords, but it must be stated in general that the actual coastline is extremely influenced by what happened on land during glacio-eustatical regression periods.

Figure 3 gives an idea of recent coastline evolution. During the Upper-Miocene the erosion of a deep tidal trench parallel to the coast and the sedimentological characteristics of the infilling Sands of Diest necessitate the existence of strong tidal currents very much comparable to those in front of the actual flemish coast. This can be better explained by the existence of a "Straits of Dover," than by a more distant western connection with the Atlantic. During the Pliocene the seacoast migrated to the north and the Straits of Dover closed, both as a result of strong uplifting of the Artois-Weald axis. Maybe a more western Straits continued to exist and was responsible for tidal erosion of the East-Anglian trough (West, 1972).

At the beginning of the Pleistocene the Voorne trough was still subsiding rapidly and Rhine sediments were not yet capable of counterbalancing the downward movement, so a wide southern bay still existed. This much smaller Icenian Bay had no more direct connection with the Atlantic and its coastal sediments (Rijkevorsel Clay) show a low energy wadden environment comparable with the actual Deutsche Bucht. Following Zagwijn (1962) this tertiary type of North Sea ended with the Tiglian. As more material becomes available it is highly probable that still later marine incursions will be found at least in the Central Netherlands Basin. Their scarcity however shows that from end Tiglian on Rhine-Meuse sedimentation was predominating over subsidence and that the Southern Bight may have disappeared completely. This situation must have lasted up to the Cromer

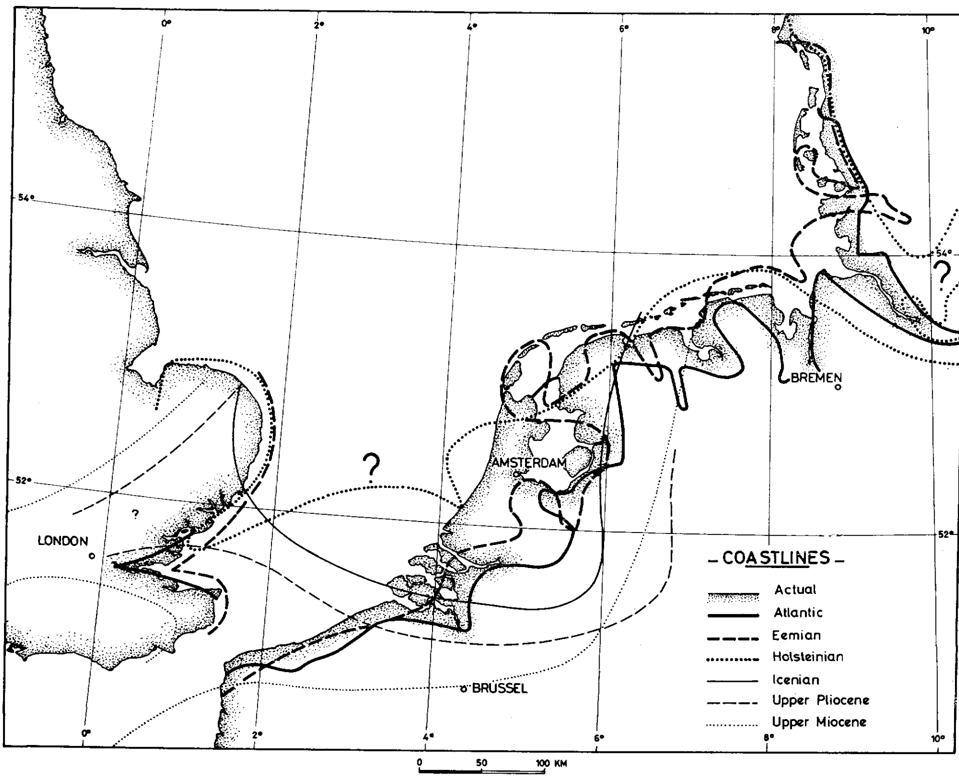

FIG. 3

Forest Beds of which "marine" sediments are only known on the north coast of East-Anglia.

Around this time must be situated the turning point leading to the modern Southern North Sea configuration. Indeed Holsteinian sediments demonstrate a net transgressive behaviour. They penetrate deeply in the Deutsche Bucht. The peculiar form of their indentations may essentially be determined by the drowning of a glacial topography, but their extension nevertheless indicates the development of a subsiding trend which still continues and is responsible for the general form of the Deutsche Bucht. The Southern Bight begins also to develop, the Clacton area showing the presence of at least estuarine conditions deep to the south. Other deposits are not definitely known. The Cardium layers of Lo were tentatively correlated (Tavernier, 1962; Van Hoorne, 1962) with Holsteinian. They are however only covered with Weichselian sediments and the fact that they are not decalcified by later weathering renders such an old age problematic. There is also a modern tendency, not yet proven, to consider as Holsteinian the classical Sandgatte beach thought of as Eemian since Dubois.

The growing penetration of the Southern Bight can be explained by three factors:

1. renewed subsidence of the Roer valley graben after the Sterksel zone;

2. less sediments brought in as the Rhine is lenked to the north at the end of the jungere Hauptterrasse.

3. the glacio-eustatical searise can drown landscapes which have been eroded considerably by periglacial processes. These are most effective on the fine, clayey sands of the Eocene of the London and Flanders Basin. Periglacial conditions become certainly important and long lasting from the Elsterian on. The hypothetical reconstruction on figure 3 of the Holsteinian coast shows an estuarine ria-penetration into the London Basin (Clacton) and one of several which might have begun the inundation of the flemish basin.

The Eemian sediments show a wide advance of the transgressive behaviour and deposits are known in Zeeland and Flanders (Vandenberghe, 1974). They can be associated with a fossil cliff and deeply drowned valleys although the significance of *Corbicula fluminalis* in the Flemish Valley is not clear. The Eemian sediments are essentially wadden and lagoonal environments. It can be expected that they were accompanied by an extensive sandy coastal barrier system, capped with dunes. They are unknown most probably because they lay before the modern coast.

Flandrian sediments show the continuation of the transgressive character, as lagoonal sediments penetrate deeper in land than before. This continuous tectonical subsidence even complicated by the isostatical adjustment interferes with the glacio-eustatical oscillations. In this way the Jelgersma curve may rightly be situated entirely under actual sea-level. However the big extent of transgressive Atlantic Calais-lagoons, the general presence of a regressive Subboreal Holland-peat and the renewed Subatlantic Dunkerque transgressions prove the eustatical oscillation of the sea-level.

This review has stressed that from the Holsteinian on the Southern North Sea is progressively in transgression and that the successive interglacial sea-levels cover one another. The hinge of the subsidence moves again to the south creating the Southern Bight. This is considerably helped by drowning of the periglacially eroded lowlands on relatively weak eocene layers.

The result is different on the British and continental coast. From Denmark to France the transgressive wedge is largely filled up as important rivers bring more sediment than can be disposed off by marine energy, with resultant formation of a wide coastal plain. The coastal barrier, pushed up by the Flandrian transgression, is in destruction in the two weakest stretches. In the Deutsche Bucht the center is destroyed and on both sides the barrier breached into islands. A smaller original sand supply due to the concave coast can be one reason, but the main cause will be the coincidence of tectonic subsidence with the axis of maximal glacio-isostatic sinking. The Zeeland breaches may reflect renewed subsidence of the Voorne-trough, combined with a lack of sediments and high tidal activity.

The British coast is essentially a cliff coast produced by erosional transgression, practically lacking any remnants of the earlier levels. Sea energy, also by tidal currents, is high and longshore transport strong, while stream sediment discharge is very low. The Thames Bay, seaward of the real estuary which begins at Southend, must be explained as a drowned periglacial lowland in the axis of the relatively weak London Basin.

The major problem remains the origin and the dating of the Straits of Dover, as recently reviewed by Prentice (1972). Overflow of an ice-blocked North Sea lake is certainly the most effective trigger possibility. It may have happened during Saale glaciation when British and Scandinavian ice coalesced and as implicitly presented on figure 3. If so some day traces will be found of the higher, very short lived lakelevel, maybe the Cardium layers of western Flanders.

This review shows how many problems remain and how many incertitudes exist for the best known part of the North Sea history, the higher sea-levels. Much more research will have to be conducted in the sea (as Oele, 1969) and in deep bore-holes before its entire history will be understood. The North Sea however occupies a crucial place in quaternary stratigraphy. It can link together marine and continental stratigraphy, scandinavian and alpine glaciations, tectonics and volcanism. This merits certainly a joint effort from the bordering countries.

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DISCUSSION

F. BOURDIER *précise que des recherches récentes dans le Bassin de Paris sont favorables à l'existence d'un interglaciaire plus chaud que le Post-Würm entre le Mindel récent (moyenne terrasse) et le Riss (basse terrasse) ; il est probable que des « hauts » niveaux marins correspondent à cet interglaciaire chaud, tel celui de Sangatte, en France, dans la zone de passage entre la Manche actuelle et la mer du Nord.*