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The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution

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Abstract

The Netherlands and the adjoining southern region of the North Sea form part of a subsiding area with a complicated tectonic and sedimentary history. This area was either a shallow sea or a coastal lowland. After a compressional stage at the onset of the Tertiary, tensional forces dominated from the Oligocene onward and induced the formation of an intraplate rift system. The relationship between this system and sediment supply by rivers originating in the hinterland is discussed.

In the Quaternary, depocentres shifted considerably. Here a role was played by changes in sea level due to build up of inland ice and repeated climatic changes, leading to increased sediment discharge. In the later part of the Quaternary, inland ice itself invaded the basin and reshaped the landscape.

Introduction

The area occupied by The Netherlands is of particular interest for the study of coastal lowlands, because it forms part of an intraplate basin with an intricate tectonic history complicated by the presence since Oligocene times of a SE-NW-running rift-fault system. The evolution of the coastal plains during the Miocene and the Holocene (treated in some detail in the original Keynote lecture) has been published elsewhere (Zagwijn & Hager 1987; Zagwijn 1986) and will not be dealt with here.

A general discussion of the tectonic framework is followed by an analysis of the paleogeographic evolution in the Tertiary (which differed between the earliest Tertiary and the Oligocene) and the Quaternary, under changing influences of climate, sediment supply, and position of depocentres.

Tectonic framework

The tectonic framework (Fig. 1) has two main elements: one, the Hercynian Ardenno-Rhenish Massif, which has been subject to uplift since the Miocene and even more so since the Middle Pleistocene (Fuchs et al. 1983); the other, the Graben systems (Upper Rhine Graben, Leine Graben, Lower Rhine Embayment, Rur Graben, and Central Graben), which became active at various times during the Eocene and Oligocene. Toward the northwest this Graben system grades into the intraplate basin of the southern part of the North Sea. The northwestern branch of the rift system, which underlies the southern half of the present Netherlands and shows a NW-SE-trending fault system, is of special interest in the present context. Toward the southeast this fault system is linked to the Lower Rhine Embayment, which was originally part of the Hercynian Massif, and has been subject to considerable downwarping since the Early Oligocene. This occurred later than the formation of the southern branch of the rift system, the Upper Rhine Graben. The northeastern branch of the triple system, the Leine Graben, was active in Oligocene times but is now inactive (Ziegler 1982).

The structural map showing the base of the Miocene (Fig. 2, adapted from Van Doorn et al. 1985) is illustrative of some of the essential features of the rift system underlying the region (Fig. 18). The main structural lows are the deep Central Graben and the Zuiderzee Basin, which extends southeastward into the Venlo Graben. The latter only became a shallow graben very late in the Tertiary, having previously been a relative high with much the same character as the Peel blocks, which still belong to a structural high (Van Rooijen et al. 1984). In the northeastern part of The Netherlands a different tectonic style prevails, one related to salt structures and associated faults.

The structural map of the base of the Quaternary (Fig. 3) shows some additional basins at least partly representing rejuvenations of much older Mesozoic structures, such as the West Netherlands Basin, the Broadfourteens Basin, and the Vlieland Basin (Zagwijn & Doppert 1978).

Paleogeographic evolution during the Tertiary

The Tertiary and Quaternary sedimentary fill in the Lower Rhine Graben system and the southern part of the North Sea Basin is shallow marine (littoral and epineritic) and continental. The continental deposits more specifically belong to coastal plain and deltaic environments. Generally speaking, the relative subsidence and the rate of sedimentation were in equilibrium, but changes in sea level and sudden changes in sedimentation rates produced some extensive hiatuses. However, subsidence never became so rapid that it produced sea depths of considerably more than 100 metres. Thus, the isopach maps presented here reflect mainly differences in down warping.

During the earliest part of the Tertiary, subsidence patterns were very different from those of Oligocene and later times (Letsch & Sissingh 1983; Keizer & Letsch 1963). This is exemplified by the map showing the thickness of the Lower Eocene deposits (Fig. 5). Two basins can be recognized, one situated in the SW part of The Netherlands (called the Voorne Trough) and the other further north. These two basins were separated by a high, the Mid-Netherlands ridge, which had been formed by Late Cretaceous to Early Tertiary inversion of older basins (Heybroek 1974; Ziegler 1982).

During the Oligocene this situation changed completely. First, a large shallow basin was formed that extended over the ancient Mid-Netherlands high and also protruded toward the southeast into the Lower Rhine Embayment, the formation of which had just started (Fig. 6). Faulting was still of little importance. Of the older basin structures, only a remnant of the Voorne Trough persisted for some time. Except in former coastal areas, the marine sediments were fine grained (Boom Clay) and remarkably uniform thoughout the basin (Van den Bosch & Hager 1984).

During the deposition of Upper Oligocene sediments, faulting was already evident (Fig. 7). In particular, the Central Graben of The Netherlands and its southeastern continuation into the Lower Rhine Embayment stands out clearly. In the innermost part of the Embayment, close to the Hercynian Massif, coastal lowlands developed where in places peat and organic lake deposits could accumulate. These deposits are now found as lignites and sapropelic oil-bearing coals. The marine sediments are more variable than they were before, sands dominating closer to the coast and clays further away from it. Remnants of pre-existing basins, such as the Voorne Trough, are no longer active.

The area in which Upper Oligocene marine deposits are preserved is conspicuously smaller than the area covered by Lower Oligocene sediments.

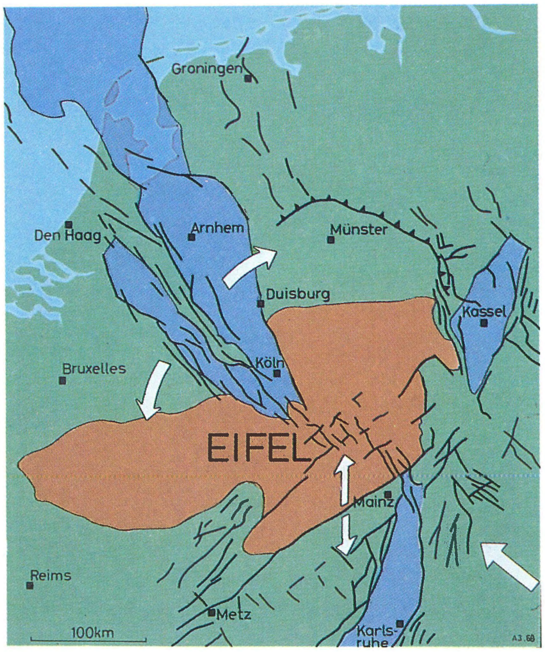

Fig. 1. General tectonic framework of the Western European Cenozoicum rift system (after Fuchs et al. 1983).

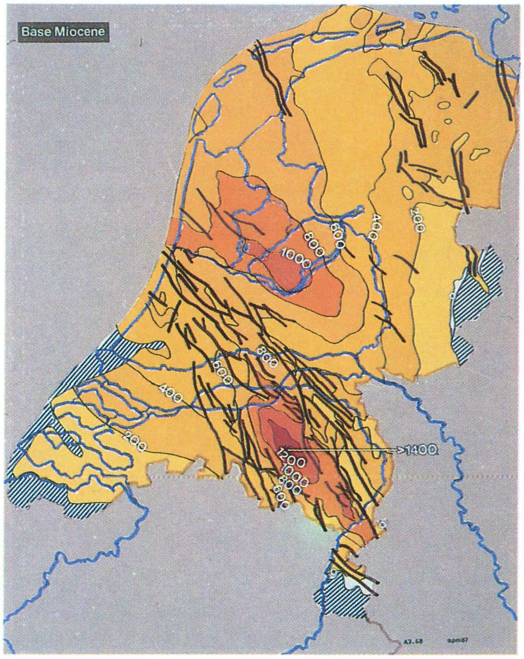

Fig. 2. Structural map and depth contours of the base of the Miocene for The Netherlands (after Van Doorn et al. 1984).

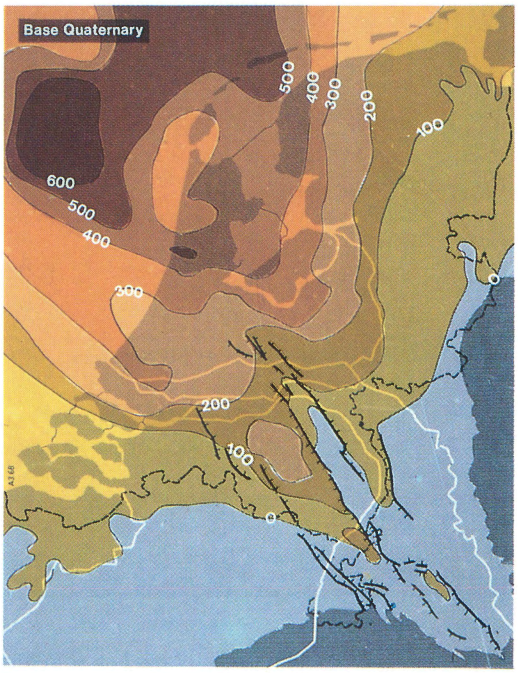

Fig. 3. Structural map and depth contours (below present sea level) of the base of the Quaternary for The Netherlands (after Zagwijn & Doppert 1978).

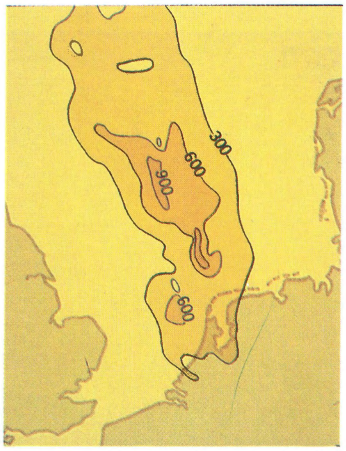

Fig. 4. Depth contours of the base of the Quaternary where it lies deeper than 300 m below present sea level in the North Sea Basin (modified from McCave et al. 1977).

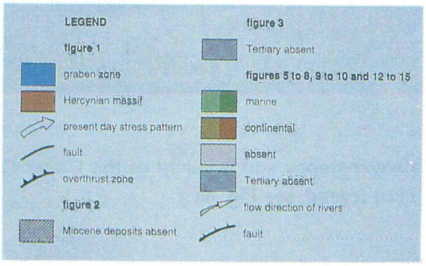

Fig. 4a. Legend for figures 1 to 3, 5 to 10 and 12 to 15

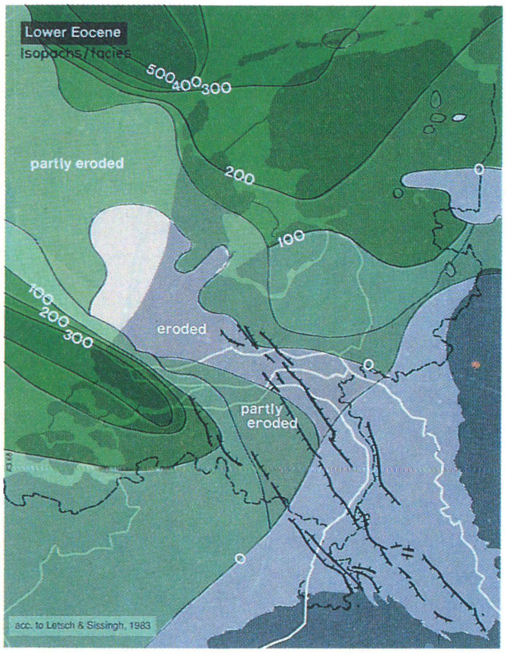

Fig. 5. Paleogeography and isopachs of the Lower Eocene deposits (after Letsch & Sissingh 1983). (For legend, see Fig. 4a.)

Fig. 6. Paleogeography and isopachs of the Lower Oligocene deposits. (For legend, see Fig. 4a.)

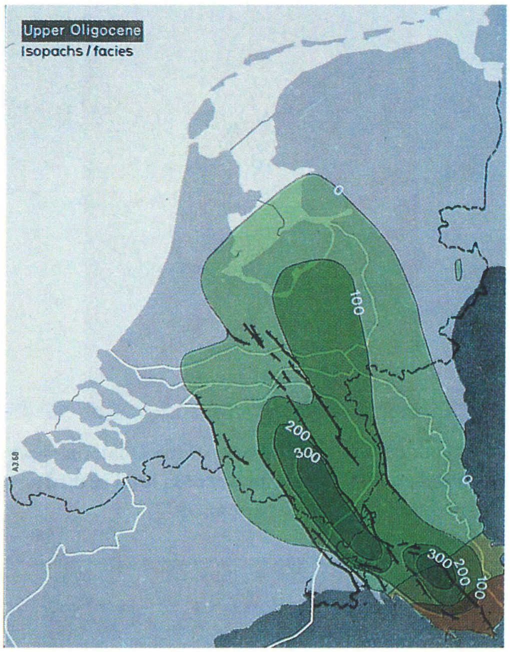

Fig. 7. Paleogeography and isopachs of the Upper Oligocene deposits. (For legend, see Fig. 4a.)

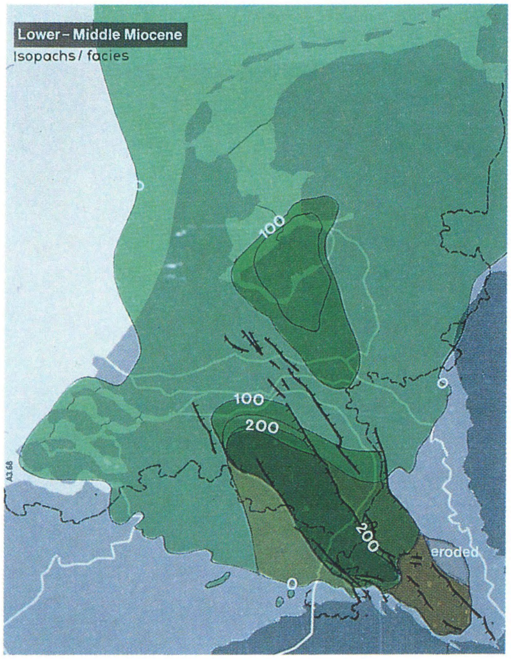

Fig. 8. Paleogeography and isopachs of the Lower to Middle Miocene deposits. (For legend, see Fig. 4a.)

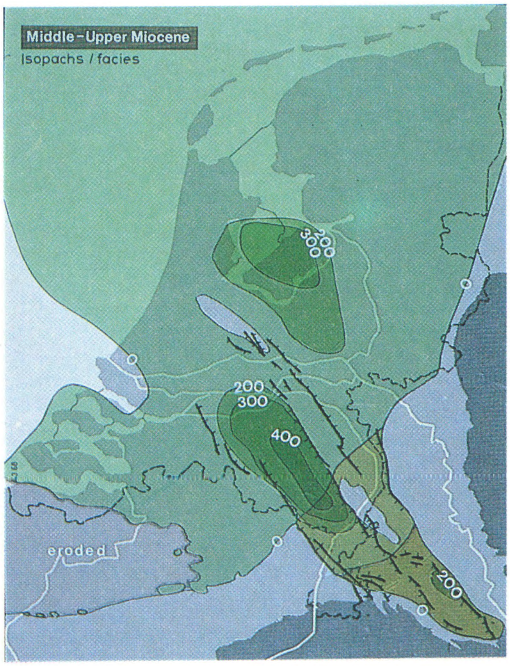

Fig. 9. Paleogeography and isopachs of the Middle to Upper Miocene deposits. (For legend, see Fig. 4a.)

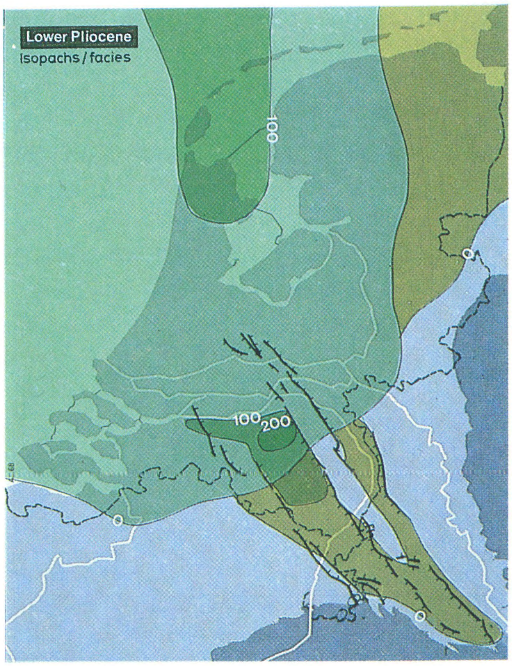

Fig. 10. Paleogeography and isopachs of the Lower Pliocene deposits. (For legend, see Fig. 4a.)

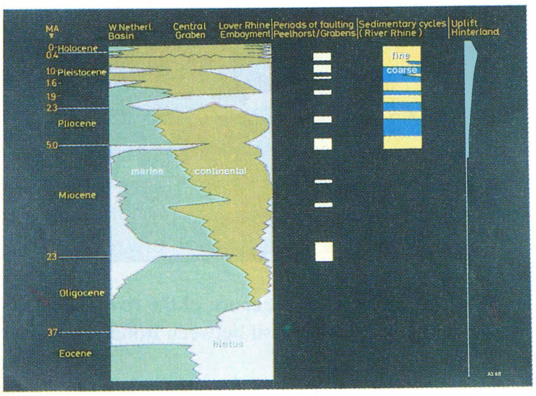

Fig. 11. Generalized distribution of Tertiary and Quaternary deposits in relation to time in the Graben zone between the Lower Rhine Embayment and the western part of The Netherlands, with emphasis on facies distribution and unconformities.

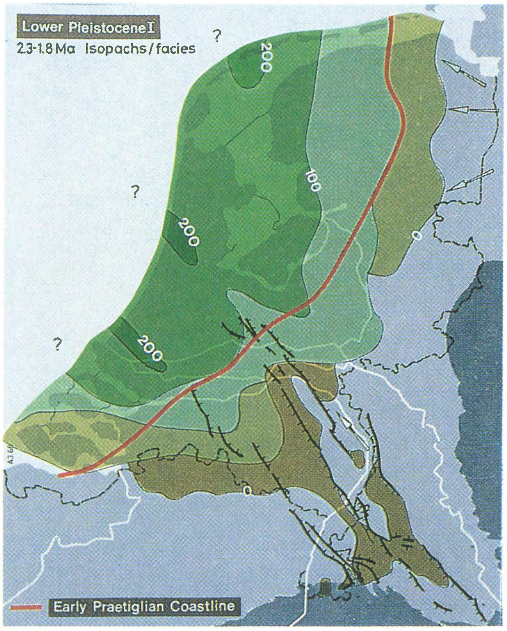

Fig. 12. Paleogeography and isopachs of the Lower Pleistocene (Praetiglian and Early Tiglian, dated between 2.3 and 1.8 MA). (For legend, see Fig. 4a; the coastline during the Praetiglian regression is shown by the red line.)

Fig. 13. Paleogeography and isopachs of the Lower Pleistocene (Late Tiglian, 1.8–1.6 MA). (For legend, see Fig. 4a.)

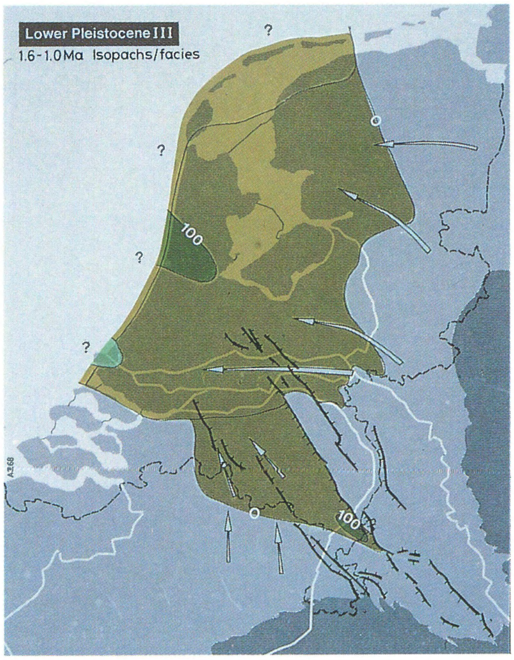

Fig. 14. Paleogeography and isopachs of the Lower Pleistocene (Eburonian to Menapian, 1.6–1.0 MA). (For legend, see Fig. 4a.)

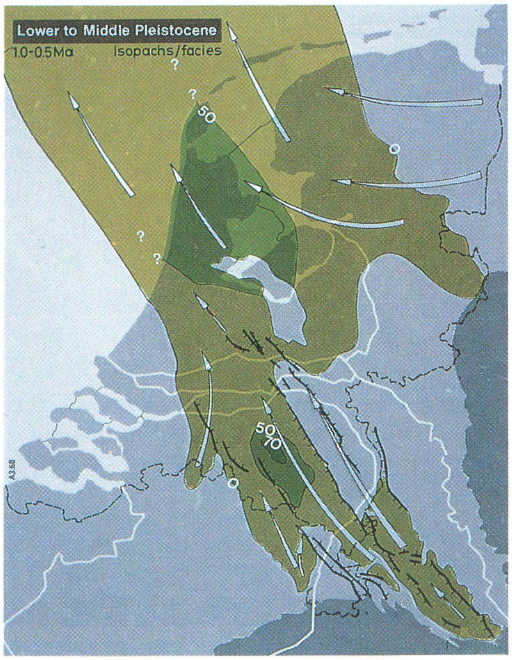

Fig. 15. Paleogeography and isopachs of the Lower to Middle Pleistocene (Bavelian and early Cromerian, 0.9 to 0.45 MA). (For legend, see Fig. 4a.)

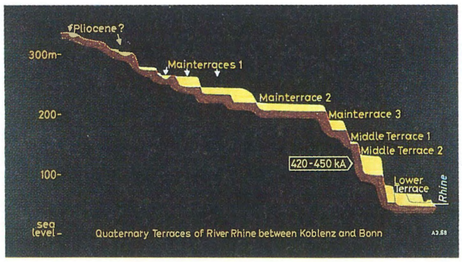

Fig. 16. Quaternary terrace sequence of the river Rhine in the uplift area of the Rhenish Massif between Bonn and Koblenz.

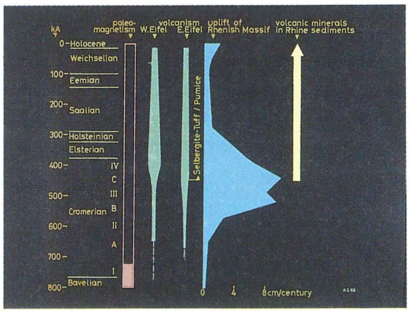

Fig. 17. Table showing the relation between the uplift of the Rhenish Plateau, Eifel volcanism, and the Quaternary stratigraphy of The Netherlands.

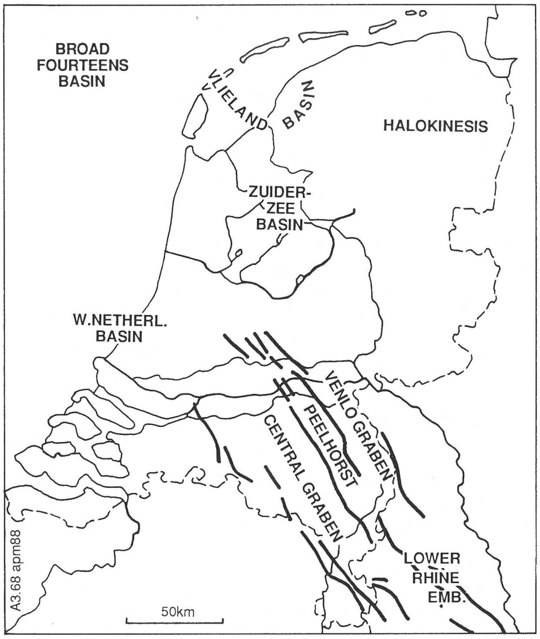

Fig. 18. Nomenclature of tectonic units in The Netherlands and adjacent areas.

This may be partially due to later erosion, but to a large extent the pattern seems to be original and to have been created by non-deposition (synsedimentary erosion) and to the formation of condensed sections outside the area of stronger subsidence. At the transition between the Early and Late Oligocene the sea level dropped sharply (Vail et al. 1977), and it is conceivable that outside the area of strongest subsidence the sea became so shallow that bottom currents and wave action could easily remove any sediment.

In the Miocene the area occupied by coastal lowlands increased considerably (Figs. 8 and 9). Particularly during the Middle Miocene and the early part of the Late Miocene, peat formation was widespread. The position of the coastline, and thus the area of the coastal lowlands, varied considerably. However, in the inner part of the Lower Rhine Embayment peat accumulation continued for a very long period, at least 6 million years, and was not interrupted by either marine or fluvial sedimentation (Hager 1986). The result was a continuous accumulation of peat, originally to a thickness of about 300 m and now compressed to a 100 m thick seam of brown coal. This main seam and its associated seams together form the largest single brown coal occurrence in the world, the total geological reserve amounting to 55 billion tons of coal. Several special conditions contributed to this peculiar peat accumulation: the coastal lowland environment, the sea level fluctuation, a warm and moist climate, and very slow tectonic subsidence with little faulting during that particular part of the Miocene. For further details, reference is made to Zagwijn & Hager (1987).

Two major cycles of transgression and regression occurred during the Miocene. Around the Oligo-Miocene boundary a general break in sedimentation can be observed in many places, probably with the exception of the deepest parts of the Central and Rur Grabens. Subsequently the extent of marine sedimentation increased, and this was probably related to a marine transgression which penetrated the Lower Rhine Embayment. Later, in Early Miocene to Middle Miocene times, a regression took place and the coastline shifted to the west. At times, peat accumulation in the Central Graben area even extended west of the present city of Eindhoven. (Fig. 8). During renewed transgression the coastline again shifted far to the east, over a distance of more than 80 km during the later part of the Middle Miocene. When regression started once again at the end of that period, it continued throughout the remainder of Miocene and even Pliocene times (Fig. 9).

The evidence from the Miocene makes it even clearer that depocentres lay in marine nearshore environments in front of deltas which were the source of sediment supply (Zagwijn & Doppert 1978). Besides the Central Graben area, a new centre of subsidence stands out, the Zuiderzee Basin. This area strongly subsided during the later part of the Miocene (Fig. 9), a period which is characterized in the Central Graben itself by increased fault activity.

Finally, it is evident that the area of marine sedimentation became considerably larger during the Miocene compared with the situation which prevailed in the Late Oligocene. However, further west, off the present west coast of The Netherlands and in the part of the basin far away from the coast, the Miocene sequence is either absent or strongly condensed. The primary reason for this particular phenomenon seems to be that the sediment brought from the hinterland by a precursor of the Rhine was trapped in the two subsiding areas before it reached the more central areas of the southern part of the North Sea Basin. Only the finest-grained material is found in these areas, and coarser sandy sediments only occur closer to the ancient coasts. A more detailed study of the sediments shows that there were more minor sedimentary cycles than those related to the two major transgression-regression movements. Furthermore, some minor breaks in the sedimentation can be recognized, and these breaks were at least partially related to differential tectonic movements of fault blocks.

During the Pliocene (Fig. 10) the development in the southeastern region continued as in the preceding period: growth of the delta of the ancient river Rhine and, related to this growth, a shift of the depocentre in the Central Graben system toward the northwest. In the northeast the paleogeographic situation had changed, because by now the sea regressed from the North-German lowlands and an extensive delta developed at the mouth of an ancient river system that drained the northern lowlands and the Baltic region. Seaward of this delta there is a depocentre which had shifted northward from the Zuiderzee Basin toward the Vlieland Basin since the Late Miocene.

In sum, the following can be said about the tectonic and paleogeographic evolution since the Oligocene. From then on tensional movements within this part of the European plate led to the formation of a SE-NW-trending rift fault system in the southern part of The Netherlands. Depocentres and areas of maximum subsidence lay in the Central Graben; later on also further north in the Zuiderzee Basin, seaward of ancient deltas that were formed by precursor river systems of the Rhine.

In the last part of the Tertiary a delta of another river system developed in the north. As will soon be seen, the latter system became very important in the Early Pleistocene, that is, in the period between 2.3 and 0.7 million years ago. The data discussed above indicate that rate and pattern of subsidence was primarily steered by sediment loading.

There are several substantial unconformities in the sedimentary sequences of the basin (Fig. 11), i.e., at the base of the Oligocene, at the base of the Miocene, within the Upper Miocene, and at the base of the Pleistocene. The base of the Pleistocene is placed in the North Sea Basin at a time-level of 2.3 million years ago.

The reasons for these unconformities are complex. They are certainly related to changes in tectonic activity, as was the case at the transition from the Eocene to the Oligocene. Sea level changes played a role, too; this certainly holds for the unconformity at the base of the Pleistocene, but probably also for older ones.

Paleogeographic evolution during the Quaternary

During the Quaternary, profound changes took place in the southern part of the North Sea Basin. Whereas during Oligocene and Miocene times the main centres of deposition were situated on the present mainland, the Quaternary depocentre shifted toward the present North Sea (Fig. 4). Thicknesses of more than 900 m have been reported from the Central North Sea, but even further south this series attains considerable thickness, ranging from over 400 metres in the western part of The Netherlands to almost twice that, locally offshore. The second important feature is the increase in the size of the two deltas, one in the south (Rhine and other rivers) and the other in the north (North German-Baltic system) during the Early Pleistocene. Starting about 1.7 Ma ago, this expansion led to the formation of a single large delta which was even much larger than the present area of The Netherlands. In fact, the size of this delta system was similar to that of the largest deltas of the world.

Another interesting feature is that sedimentation rates increased during the Quaternary to about ten times the rate prevailing in the Neogene (Zagwijn & Doppert 1978). The reasons for this are manifold, one being the increasing uplift of the hinterland, but the main reason must have been the climatic changes during the Quaternary with re-

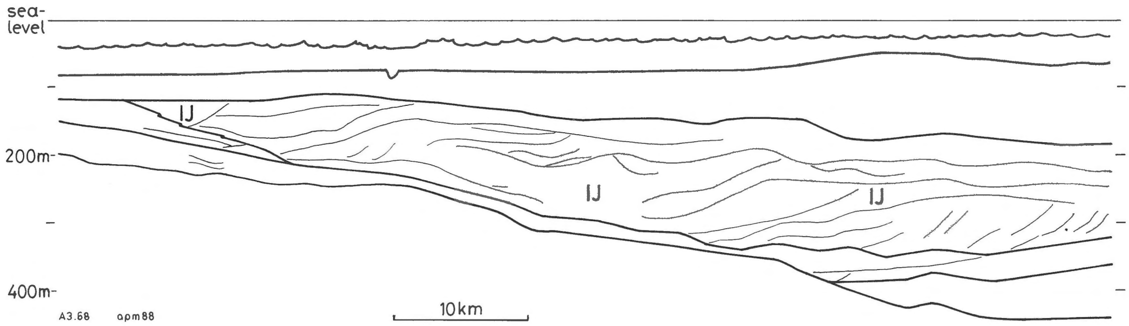

Fig. 19. West-East section situated off the shore of the western part of The Netherlands, based on seismic data and showing Lower Pleistocene delta progradation (IJ = IJmuiden Ground Formation). Source: Cameron et al. 1984.

peated cold intervals. Those were of such intensity that the entire area of Western Europe was north of the tree-line and therefore was not only deforested but also became part of the permafrost region. This pattern is known to have prevailed after the first cold phase of this kind, i.e. the Praetiglien, which lasted from about 2.3 to 2.1 million years ago. Under these deforested and permafrost conditions, erosion of the hinterland and sediment supply into the basin increased enormously.

Delta progradation accelerated considerably after the onset of the Pleistocene, as shown for instance (Fig. 19) by offshore seismic sections along the western part of The Netherlands (Cameron et al. 1986; Laban et al. 1984). The first progradational sequence of this kind, which belongs to the IJmuiden Ground Formation, has recently been dated to represent the first cold phase of the Pleistocene, i.e. the Praetiglian.

The discussion of the further history of basin development during the Quaternary must be prefaced by some remarks concerning the significance of the change in climate during this period. Pollen-analytic investigations in particular have provided a detailed picture of this climatic evolution, which was characterized by frequent shifts from very cold glacial conditions to warm-temperate interglacial conditions and vice versa. Comparison of our results with the well-known climatic record published by Shackleton & Opdyke 1976 that are based on oxygen isotope measurements in deep-sea sediments, shows a high degree of correspondence (Fig. 20). In both cases – dated by paleomagnetism – distinctly cold conditions occurred first around 2.3 million years ago and since that time there were several glacial-interglacial cycles. For the last million years a cyclicity of 100,000 years has predominated, but other periods have also been observed. Although discussion of the causes of these cycles may not have led to agreement on all details, the general opinion is nevertheless that the main cause is astronomical and of the Milankovitch type. This means that they are the result of variations in the movements of the earth in relation to the sun, corresponding with variations in the amount of solar radiation received at earth's surface (Berger & Pestiaux 1984; Berger 1985).

Another factor related to the glacial-interglacial cycles is the expansion and decay of large ice-caps, particularly in the northern hemisphere, and the corresponding pattern of falling and rising sea levels. As early as 2.3 million years ago a very large ice-cap covered North America (Easterbrook 1982) and this development must have been accompanied by a considerable drop of the sea level, estimated at 80 to 100 metres. At the same time, during the Praetiglian, a regression occurred in the southern part of the North Sea Basin (Fig. 12, coastline indicated by a red line), followed by a transgression in the next warm stage, the Tiglian (Zagwijn 1975). This regression is related not only to the already-mentioned strong deltaic progradation but also to a hiatus in the basal sediments of the Pleistocene (Fig. 21), representing the oldest of three major Pleistocene unconformities. All of these phenomena can be considered the result of

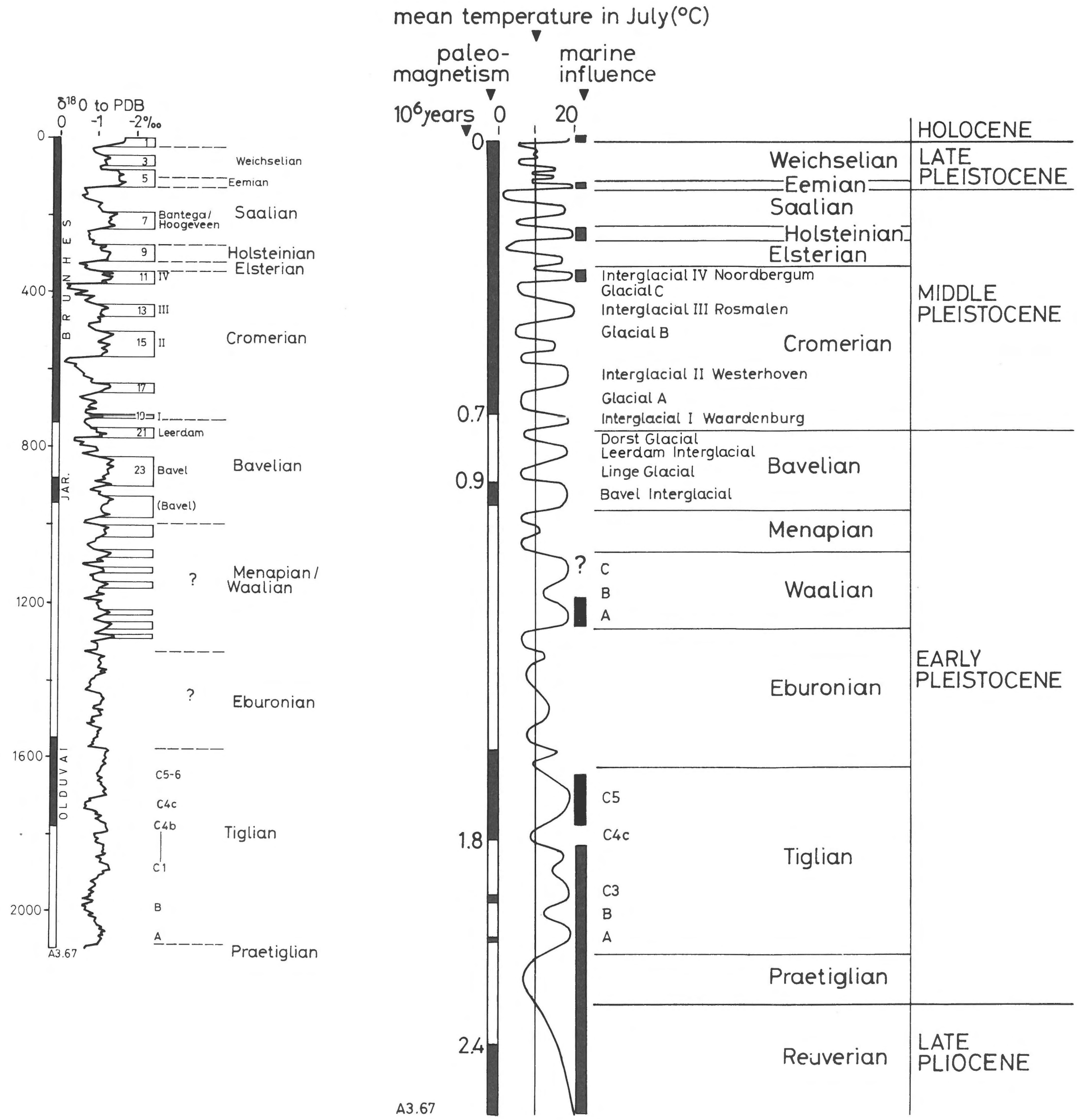

Fig. 20. Comparison of the oxygen-isotope curve of core V28–239 (according to Shackleton & Opdyke 1976) with the Quaternary climatic stratigraphy for The Netherlands (right-hand side). Correlation of the isotope stages (1–21) with climatic stages is tentative.

the first build-up of large areas of inland-ice over the northern continents and the associated drop in sea level. It should be noted that there was a marked change in the pattern of subsidence during that same period. Centres of deposition shifted to the west, i.e., to the West Netherlands Basin, and to the north, to the Vlieland Basin (Fig. 12).

After the Tiglian transgression conditions changed again, because in the Late Tiglian, i.e., in the period between 1.8 and 1.6 million years ago, delta progradation became rapid and the two deltas merged to form one large delta protruding far into

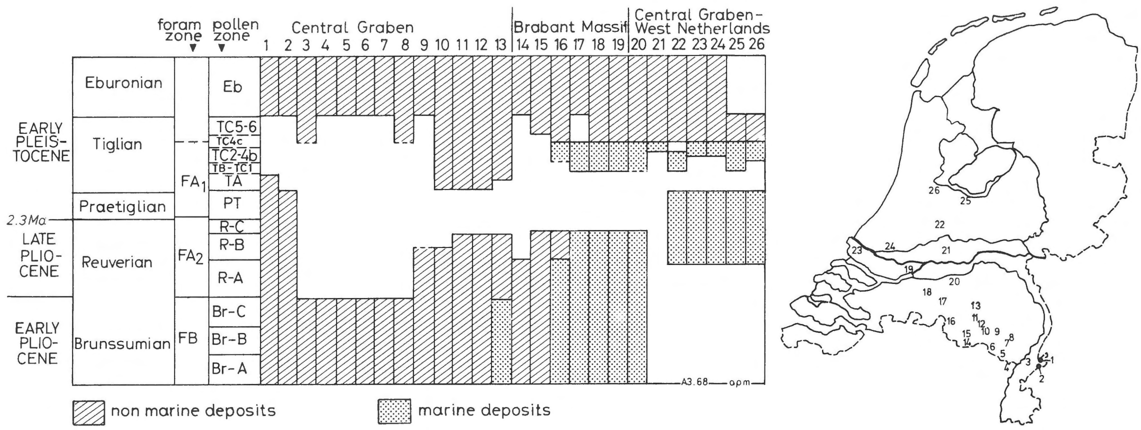

Fig. 21. The basal Pleistocene unconformity in the Central Graben region and adjacent areas. Inset: location of sections 1–26.

the southern part of the present North Sea (Fig. 13). In this period fault activity in the Central Graben area was low and an area of stronger subsidence only occurred in the northern region.

Later, during the Early Pleistocene between about 1.6 and 1.0 million years ago, similar conditions prevailed, but fault activity in the Central Graben region resumed. During this period depocentres lay in the extreme southeastern part of the Central Graben and in a northwestern area whose extension into the North Sea Basin is not yet known (Fig. 14).

The process of deltaic progradation and narrowing of the southern part of the North Sea Basin continued until the transition to the Middle Pleistocene, when the deltaic plain of the two river systems extended far northward and the coastline was probably in the vicinity of the present Dogger Bank (Fig. 15). During this interval, between 900,000 and 450,000 years ago, regression reached a maxi-

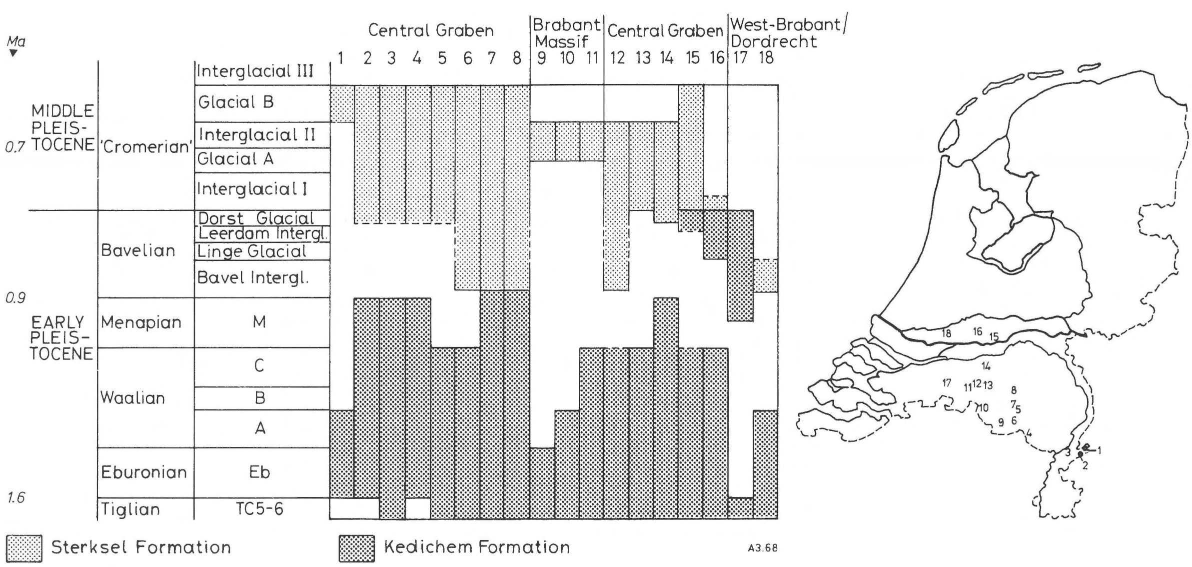

Fig. 22. The unconformity at the top of the Lower Pleistocene in the Central Graben region and adjacent areas. Inset: location of sections 1–18.

mum, not only during periods with a low sea level but also interglacials with a high sea level. The sediments of this period are sandwiched between two other major unconformities, which are related to strong changes in the pattern of fluvial sedimentation as well as to increasing tectonic activity. The oldest unconformity (Fig. 22) can be dated at around 0.9 million years ago. Fault activity in the SE part of the Lower Rhine Embayment led to replacement of local river sedimentation in the Central Graben (Kedichem Formation) by sediments of the river Rhine (Sterksel Formation).

The youngest unconformity, dating from about 450,000 years ago, is related to even greater changes in pattern. The influx of northeastern rivers into the basin had ceased, probably because the drainage system had been impaired by the invasion of Scandinavian inland-ice. After a period of strong fault activity during deposition of the Sterksel Formation, the Rhine no longer took a northwestern course through the Central Graben but flowed northward from Bonn in its present valley, being replaced in the Central Graben by a local river, the Meuse (Zonneveld 1958). Moreover, far to the north Rhine sediments were carried into the area formerly occupied by sediments of the northeastern-Baltic river system. A striking phenomenon is that from then on the sediments of the Rhine contained substantial amounts of minerals that are derived from the volcanoes of the Eifel, in particular brown hornblende and augite (Brunnacker et al. 1976). Very similar changes in mineral composition have been found in the terrace deposits of the Middle Rhine in the uplift area of the Rhenish Massif (Razi Rad 1975). Therefore, a rather precise correlation can be established between these deposits and the sediments farther north (Zonneveld 1956; Zagwijn 1985).

The change in the heavy-mineral assemblage was related to the onset of the production of selbergite and pumic-ash clouds by volcanic eruptions in the eastern part of the Eifel region, radiometrically dated around 400,000 years ago (Frechen & Lippolt 1965). But this is also the period of strongest uplift of the Rhenish Plateau (Figs. 16 and 17; Fuchs et al. 1983). All of these data made it possible to correlate the oldest sediments of the Urk Formation in The Netherlands with Middle Terraces 1 and 2 of the Middle Rhine. On the other hand, Main Terraces 2 and 3 can be correlated with the uppermost part of the Sterksel Formation of The Netherlands. This means that the unconformity between the two formations in the north is related to the period of strongest uplift in the south. It also means that the two younger unconformities of the Pleistocene are both related to periods of increased tectonic activity (Fig. 17).

In the last part of the Pleistocene, two different lines of geologic evolution can be seen. During warm episodes sea level was high and coastal lowlands developed in the present coastal areas of The Netherlands during each interglacial. During cold periods, Scandinavian inland-ice invaded the lowlands of Poland and northern Germany several times and reached the northern part of The Netherlands at least twice. The first of these invasions was in the Elsterian, around 350,000 years ago. During this stage very deep erosion valleys, locally reaching depths of more than 300 metres, were formed over a very large area (Fig. 23) covering the northern German lowlands and the northern part of The Netherlands as well as adjacent offshore areas in the North Sea. These depressions presumably originated as tunnel valleys under actively moving inland-ice, but the mechanism is not well understood. Other features commonly associated with the action of lowland glaciers, such as ice-pushed hills, tongue-shaped basins, lodgement tills, and glacially transported erratics, are scarce or absent.

In contrast, such ice-related phenomena occurred during the next, Saalian, glaciation (180,000–150,000 years ago) in many places in the northern half of The Netherlands. Much of the landscape of this part of the country was remodelled, and ice-pushed ridges, in places over 100 m high, were formed. These ridges are associated with deep glacial tongue basins reaching more than 100 metres below the present sea level. These depressions were filled in, partly by fluvial and partly by marine sediments, during the last interglacial (Eemian) high sea level episode.

For much of the time during the last glacial (115,000 to 10,000 years ago) The Netherlands lay in the permafrost zone. The greater part of the

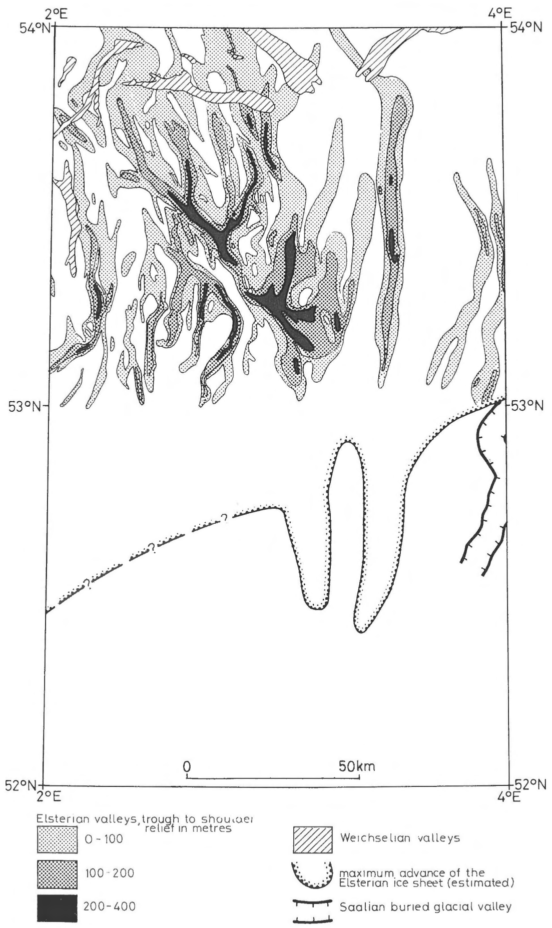

Fig. 23. Deep erosion valleys of the Elsterian glaciation in an offshore area of the southern part of the North Sea. Based on seismic survey. Source: Cameron et al. 1986.

bottom of the southern part of the North Sea was exposed. This time, however, inland-ice did not reach as far south and halted near Hamburg.

Sediments of local and aeolian origin that were formed under a permafrost regime are abundantly present. Thus, much of the old Saalian relief was levelled by erosion and the depressions were filled in by sediment.

For the time being, the story of the geological evolution of The Netherlands ends with the development of the present coastal plains during the last 8,000 years. Many factors have played a role in this evolution, among the most important were the effect of the eustatic rise of the sea level and its interaction with the pattern of the land surface as shaped during the last glacial. Closely related factors include the pattern of the drainage system, its discharge and sediment transport. But other factors have been of importance as well, such as the tidal range, the availability of sediment to build up the coastal plain during rising sea level rise, and the climate. Man's influence increasingly affected the process of coastal lowland building (for the first time in geological history). First in an indirect way, by removing trees and thus influencing the run-off of rivers, and later by draining wet-lands, digging peat, building dikes to control flooding, and, finally, by reclamation of flooded land. For a discussion of this last episode in the geological evolution of the coastal lowlands of The Netherlands, the reader is referred to Zagwijn (1986).

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