SEA-LEVEL CHANGE AND WATER-LEVEL MOVEMENTS IN THE NETHERLANDS DURING THE HOLOCENE

ORSON
VAN DE PLASSCHE

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SEA-LEVEL CHANGE AND WATER-LEVEL MOVEMENTS IN THE NETHERLANDS DURING THE HOLOCENE

A CONTRIBUTION TO

IUGS UNESCO IGCP 124

PROJECT 61

ORSON VAN DE PLASSCHE

I gazing at the boundaries of granite and spray, the established sea-marks, felt behind me Mountain and Plain, the immense breadth of the continent, before me the mass and doubled stretch of water.

The tides are in our veins, we still mirror the stars, life is your child, but there is in me older and harder than life and more impartial, the eye that watched before there was an ocean.

(from: Continent's End, Robinson Jeffers)

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ORSON VAN DE PLASSCHE*

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* Instituut v. Aardwetenschappen, Vrije Universiteit
De Boelelaan 1085
1007 MC AMSTERDAM
The Netherlands

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ABSTRACT

A relative MSL curve for the western and northern Netherlands is presented as one of the Dutch contributions to Project 61 of the UNESCO-IUGS International Geological Correlation Programme 'Sea-level movements during the last deglacial hemicycle, about 15.000 years'. The graph covers the period between 7500 and 2000 14C y. BP. Sections between 7500 and 6000 BP and between 2750 and 2000 BP are given as a radiocarbon time scale, and the intermediate section is expressed by historical age (BC).

The MSL curve was obtained from a comparative analysis of 3 time-depth graphs and available data on phases of fluvial activity. These time-depth graphs are (1) a MSL-trend curve based on critically evaluated data from the literature, (2) a fluctuating MHW curve established for the beach-plain entrances bordering the former Old Rhine estuary on the south, and (3) a fluctuating groundwater-level curve derived from basal peat data collected at Late-glacial/early-Holocene river dunes at Hillegersberg, Bolnes and Barendrecht.

The new graph generally confirms earlier MSL-trend curves for the Netherlands. However, it offers significant refinements, as a result of which it is functional in explaining many features of Netherlands coastal evolution. For example, a noteable decrease in average rate of rise is shown to have occurred around 6500 BP and shortly after 5000 BP which helps to account for earliest, more extensive regressive peat growth in the lagoonal areas and for the onset of western coastline progradation respectively. Furthermore, clear fluctuations in the MSL rise at intervals of approximately 500 or 1000 (siderial) years were established. Negative relative MSL changes could neither be proved nor disproved. These MSL fluctuations correspond in time (not in amplitude) with all sea-level oscillations between 5000 and 500 BC indicated by the eustatic curve for N.W. Europe (Mörner, 1980), and correlate with all but two transgressive/regressive cycles known for the Dutch coastal area over the same interval.

The two exceptions are initial peat growth at the end of the Calais-II transgressive phase when sea level rose rapidly and, conversely, initial clastic deposition at the start of the Duinkerke-0 transgressive period when sea-level rise may have been slow at most. These are respectively explained by shallowing and freshening of the landward part of the lagoonal area due to tidal amplitude reduction in response to a developing and encroaching coastal barrier system, and by high river-discharge values and raised (ground) water tables caused by wet climatic conditions and increased storm activity.

In general, the present investigation has partly resolved the relative importance and interrelationships of factors involved at various stages of coastal development such as: rate of MSL rise, climate, river gradient, coastal and local tidal amplitude, paleogeography (space), and time.

1. INTRODUCTION

In 1973 UNESCO, in cooperation with the International Union of Geological Sciences (IUGS), initiated a scientific enterprise entitled 'International Geological Correlation Programme'. All countries were requested to establish National Committees for the IGCP and were invited to submit project proposals relating to four fields of research covered by IGCP: (1) Time and Stratigraphy, (2) Major geological events in time and space, (3) Distribution of mineral deposits in space and time, and (4) Quantitative methods and data processing in geological correlation.

Early in 1974 dr. A. A. Thiadens, at that time director of the Dutch Geological Survey, submitted to the Board of the IGCP a project under topic (2) called: 'The study of sea-level movements during the last 15.000 years'. Later, after approval of the Project (no. 61) by the Board, the name was ammended to: 'Sea-level movements during the last deglacial hemicycle (about 15.000 years)'. Unofficially it became known as the Sea-Level Project and an initial meeting of countries interested was held at Haarlem (Netherlands) in September 1974.

One of the first tasks to be carried out in Project 61 was the compilation and computer storage of global sea-level data and the initiation of new or additional fieldwork, preferably in areas without or deficient in such information. As far as the Netherlands was concerned, where much sea-level work had been and still was being done, the Sea-Level Project provided the impetus for a critical evaluation and selection of the numerous time-depth data and curves available.

While the Netherlands coastal plain could not be considered as an area deficient in sea-level data, research in this field had reached a state where a relative deficiency in systematically collected high-quality data was apparent. Project 61 thus also stimulated collection of new, additional information.

Execution of the project in the Netherlands was made possible by a full grant from the Netherlands Organization for the Advancement of Science (Z.W.O.), a request for which had been submitted by ir. B. P. Hageman, present director of the Dutch Geological Survey, and prof. dr. A. J. Wiggers, then Head of the Department of Earth Sciences, Free University, Amsterdam. Compilation of Dutch sea-level records began in September 1975 and fieldwork for obtaining additional data was carried out in 1976, 1977, and 1978.

Organization of this thesis is as follows. Chapter 2 discusses the development, objectives, and approach of the Sea-Level Project. Objectives of the national IGCP sea-level project are mentioned in chapter 3, which also deals with the main steps involved in collecting and evaluating sea-level data. As such, it serves as introduction to chapter 4, in which sea-level data and time-depth graphs for the Netherlands, published since 1954, are critically discussed. On the basis of this information the most probable MSL curve for the Netherlands is established. In chapter 5 this curve is used to analyze the significance of published age-altitude data obtained from Late-glacial/early-Holocene river dunes in the Rhine-Meuse delta.

Chapter 6 describes three part-projects initiated for collection of additional sea-level data in the Netherlands. The accuracy and reliability of the radiocarbon and altitude data is considered in chapter 7, while the results of the three part-investigations are presented and discussed in chapter 8. In chapter 9, finally, these results are compared, both mutually as with time-depth data and curves obtained from analysis of published information (chapter 4), and a final evaluation is given.

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I wish here to express my gratitude to all who have been helpful in accomplishing this thesis.

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All who gave permission to carry out borings on their land, yards or in their garden are thanked for their kind cooperation; in particular I should like to mention the office staff of the Dutch Reformed Church at Hillegersberg, Boele's Shipyards and Machinefactory Ltd. at Bolnes, and the administers of the 'Stichting Duivenvoorde' and the 'Stichting Horst en Voorde'.

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Of the 86 samples collected for the present study, over half the number was taken from wide cores acquired by field staff of the 'Boor Technische Dienst', Geological Survey. To the head of this Service, mr. R. Hoogendoorn, and to his staff I am grateful for generous cooperation and excellent work delivered.

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Much of the effort and investment to locate suitable sampling sites and to obtain reliable samples was justified by the fact that radiocarbon assaying was carried out at the Isotope Physics Laboratory of the State University Groningen under supervision of prof. dr. W. G. Mook. My appreciation towards him also regards his cooperation in compiling relevant 14C data and his useful remarks to chapter 7.

Dr. L. P. Louwe Kooijmans (State Archaeological Museum, Leiden) and prof. dr. W. Roeleveld read the larger part of the manuscript. Their constructive criticism is gratefully acknowledged. Dr. Roeleveld, I highly valued your readiness to function as objective sounding board; dr. Louwe Kooijmans, your enthousiastic interest and your own sea-level work inspired me much.

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The cover (photo) is by Els Tammes, my Friend, who gave so much of her time and energy during the years of this study, yet managed to become the artist she now is.

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2. PROJECT 61 OF THE IGCP: THE SEA-LEVEL PROJECT

2.1. BLUEPRINT FOR AN INTERNATIONAL SEA-LEVEL PROJECT

Initiation of the International Geological Correlation Programme in 1973 could hardly have been more timely. It provided the necessary international stage to begin the performance of the global play concerning relative sea-level changes, the scenario for which had been written one year earlier by Walcott (1972).

Walcott, inspired by the idea of Daly (1925) that changes in waterload over the oceans would deform the earth, computed for simplified earth models the elastic deformation of the globe and the glacio- and hydro-isostatic movements of the crust that accompanied and followed the sudden and rapid melting of large ice sheets about 16.000 years ago. The first response of the earth's crust to the shifting of a very concentrated ice load to a less concentrated water load over the ocean basins is an instantaneous elastic deflection of the entire globe. Computation of this elastic response gives an uplift of the glaciated and immediately surrounding regions which is equal to 20-40% of the eustatic[1] sea-level rise. Farther away the positive elastic displacement decreases and passes into negative elastic crustal movement. In the central parts of the oceans maximum values of 20-30% of the eustatic rise are attained. For example, for a 100 m average global sea-level rise a relative change of sea level of 122 m is predicted in the central Indian Ocean.

The time-dependent glacio- and hydro-isostatic relaxation movements begin later but continue much longer than the elastic response, which terminates as soon as the changes in loading end. The isostatic movements involve viscous flow of upper mantle material. To account for this flow Walcott assumed an earth model having a thin asthenosphere, in which viscous flow can take place, sandwiched between a strong, elastically deformable lithosphere and a mesosphere that is also only deformable elastically.

In the case of glacio-isostasy the unloading of a glaciated area causes a gravitational disequilibrium that is restored by inflow of material through the asthenosphere from a zone surrounding the area of ice melt. As a result (further) uplift can be expected to take place in the deglaciating/deglaciated region and downwarp of the crust in the peripheral zone of material depletion within the asthenosphere. In the case of hydro-isostasy the ocean floor is depressed under the weight of the added meltwater and mantle material is forced to flow from underneath the ocean basins to under the continents which, as a consequence, will rise. Walcott's calculations for these relaxation movements show: (1) that the glacial unloading response will cause a considerable uplift of the deglaciated areas accompanied by subsidence of the crust in the surrounding zone, and (2) that the water-loading response results in a rather complex up- and downward movement of the ocean floor, but with ultimately little net subsidence, accompanied by a relatively large rise of the continents.

Walcott assumed that no further meltwater was added to the oceans after 6000 years BP. He therefore favoured the second of three competing schools of thought on sea-level change (Jelgersma, 1966). The first school advocates a continual eustatic sea-level rise up to the present time. The second maintains that eustatic sea level reached its present height about 4000 years ago and has remained stationary since that time. The third school holds that several times during the last 6000 years eustatic sea level has been higher than at present by about 2-3 m. Evidence for a continuously rising sea level comes mainly from a wide zone surrounding the formerly glaciated areas. Higher sea levels during the last 6000 years have been reported from many coasts in the southern hemisphere. The geographical position of data on which the second school is based, is roughly intermediate to those of the first and third school. Whereas emerged shells, dated between 5000-2500 BP, are found both in deglaciated regions and along most of the continental coasts in (sub)tropical latitudes, submerged peats of similar age are found at coastal sites within the zone of subsidence surrounding regions of glacial rebound (fig 6 in Walcott, 1972). Within the limits of his assumption that no meltwater is added to the oceans after 6000 years BP, Walcott explains this consistent pattern of emerged shells and submerged peats in terms of earth deformation by relaxation within a thin asthenosphere. Although an objection may be raised to the inclusion of emerged shell data from a tectonically active region such as Japan, this is the first time that an explanatory framework had been offered within which the three contradictory opinions about eustatic sea-level change during the last 6000 years could be united.

Walcott, aware of the potential of this model approach for studying sea-level movements and the properties of the earth's crust and mantle (but also of the fact that much remained to be improved: more complex models, more soundly based parameter values, better distribution of data), suggested three objectives for future investigations:

1. establishment of a reliable curve of the world-wide average sea-level rise (in order to '. . .ensure reliable measures of the actual vertical movement of the load'.);
2. study of the earth's rheology on a time-scale of thousands of years; and
3. collection of many more sea-level data for areas deficient in such information, in particular from mid-oceanic islands which should have been subject to elastic deformation only.

These suggestions for further research are largely reflected in the objectives and working programme of the Sea-Level Project.

2.2. SCOPE OF THE SEA-LEVEL PROJECT

The primary objective of Project 61 is to establish a world-wide valid graph of the trend of mean sea level during the last deglaciation and continuing to the present time. This graph will be an expression of the changing hydrologic balance between ice and water in response to climatic changes. Other objectives of the Project are: (1) to draw conclusions about local crustal movements along the coast and about the fundamental parameters of strength and elasticity of the earth's outer layers, (2) to establish the rates of response of sea-level movements to climatic changes on different time scales, and (3) to predict future sea-level movements, in particular for low lying countries.

In a general sense these objectives do not differ significantly from those of many sea-level studies in and before the early sixties (see Jelgersma, 1966, for references). At that time, to determine the one, world-wide valid (eustatic) sea-level graph was also a major goal. Not only did one expect the eustatic curve to be largely a reflection of the deglaciation history – and as such of importance in the study of climatic changes – but also to be a most useful reference for measuring glacio-isostatic and tectonic movements. The results could then be used for testing models of elasticity and plasticity of the earth's crust and mantle. It was considered feasible to arrive at an approximation of the eustatic rise by collecting many sea-level data along all of the so-called stable coastal areas of the world (Fairbridge, 1961). However, Walcott has confirmed earlier doubts about the stability of any coastal sector (e.g. Newman and Munsart, 1968) by convincingly demonstrating that presumed stable coasts far away from rebound areas also experience (d) vertical movements caused by the changes in ice/water loading on the earth. Consequently, the eustatic rise cannot be measured anywhere. In addition, the results obtained by Walcott confirm an earlier conclusion reported by others (e.g. Wellman, 1964; Bloom, 1967; Mörner, 1972), that is: eustatic rise is the net result of changes in ocean-water and ocean-basin volumes. Furthermore, he made it very clear that given the scale and complexity of the factors and processes involved, the information contained in relative sea-level data must be retrieved by means of global physical-mathematical models.

The two practical goals that followed from the Project's objectives were:

1. compilation of existing and collection of new sea-level data, the latter particularly in areas deficient in such information; and
2. prediction of relative sea-level movements by means of physical-mathematical models (which, as it happened, were largely developed outside IGCP).

The Netherlands contributions to the Sea-Level Project fit the first of these two complementary lines of activities. First, however, a brief qualitative discussion should be given of the main factors involved in relative sea-level movements, and of the model (-testing) approach to this phenomenon.

2.3. RELATIVE SEA-LEVEL CHANGE

Vertical ocean-level changes, as recorded at a given coastal site, can be either real or apparent. A change of sea-level is real when the land is known to be stable, and apparent when sea-level is known to be fixed while the land is rising or subsiding. The net result of real and apparent ocean-level changes is called relative sea-level movement. One can also speak of relative change if, for a given record of sea-level change, it is either not known or uncertain whether real and/or apparent ocean-level variations are or have been involved. These changes are thus considered as relative to land level or relative tc sea-level.

Real and apparent sea-level movements can be either related or unrelated to climate-induced load shifts on the earth's surface, and may result from the same process (fig. 1). In the situation where a glacial period is terminated by climate amelioration, real variations in ocean level result from changes in ocean-water and -basin volumes and from changes of the geoid. The first is primarily a function of meltwater return flow. For a discussion of other variables reference is made to Pirazzoli (1976). The second results from crustal movements caused by instantaneous elastic and time-dependent isostatic response of the earth to a surface load redistribution. Geoidal modifications are caused by changes in the gravity field corresponding to mass shifts on (water/ice) and within (mantle material) the earth, and by changes in the moment of inertia (Dieke, 1966; Jensen, 1972; Clark, 1976; Mörner, 1976; Farrell and Clark, 1976). Crustal movements of tectonic origin are responsible for the recording of apparent sea-level movements and, to the extent that the ocean-basin volume is affected, also for real variations of sea level. The latter may also result from geoidal changes caused by such tectonic movements and other processes. Satellite measurements have revealed that the equilibrium ocean surface has considerable elevations and depressions (fig. 2). Lack of correlation between this relief pattern and patterns of heatflow or tectonism suggests that the origin of the present geoid must be sought at great depths in the earth, possibly at the core/mantle boundary (Cook, 1972; Mörner, 1976).

It is understood that volume changes in ocean water and ocean basin, and changes in ocean-level distribution (geoid) are intimately related. In this respect figure 1 is incomplete in that no lines representing a feedback effect have been indicated.

The numerical significance of geoidal changes remains to be evaluated (Mörner, 1976, 1981; Cathles, 1980; Kaula, 1980; Newman et al., 1980, 1981). It is important to realize, however, that geoidal changes cause real but differential ocean-level changes as opposed to changes in ocean-basin or ocean-water volume, which are world-wide in effect. Such changes in ocean-level distribution seriously challenge the terms of reference for the primary objective of the Sea-Level Project. It is therefore now generally accepted that the new goal is to define the history of local or regional sea-level variation; not only because of geoidal changes, but also because of the increasingly recognized importance of reliable and accurate relative sea-level data, and of the difficulties that may be encountered in obtaining them.

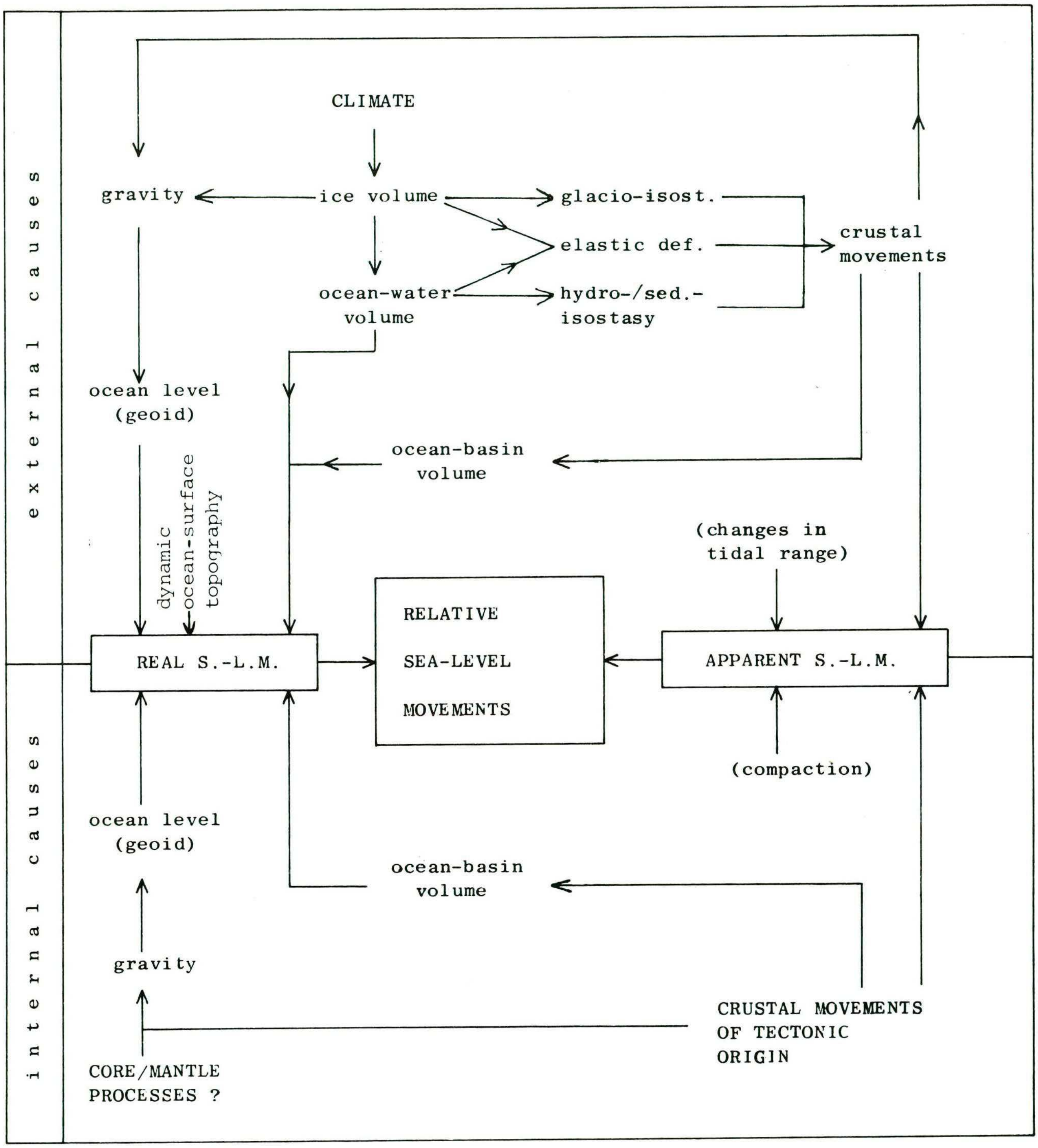


Fig. 1 Diagram showing (interrelationship of) factors and processes which are or can be involved in relative sea-level movements.

2.4. THE MODEL (-TESTING) APPROACH, SOME GENERAL CONSIDERATIONS

Several improved numerical models have been published since that proposed by Walcott (1972), e.g. Chappell (1974), Cathles (1975), Peltier and Andrews (1976). A shortcoming of these models is that deformation of the equipotential ocean surface is not incorporated. This aspect was first considered in a model by Farrell and Clark (1976), and applied by Clark et al. (1978). Recently Cathles (1980) refined his calculations by also including the influence of gravity on ocean levels.

The principle of the model approach is to compare predicted sea-level changes with observational data, and from the degree of fit to draw conclusions about the validity of assumptions made about (1) the deglaciation chronology, and (2) the mantle-viscosity structure and strength of the lithosphere (fig. 3). A useful corrolory of this method is that areas can be indicated where diagnostic field evidence may be obtained. For example, Clark and Lingle (1979), who

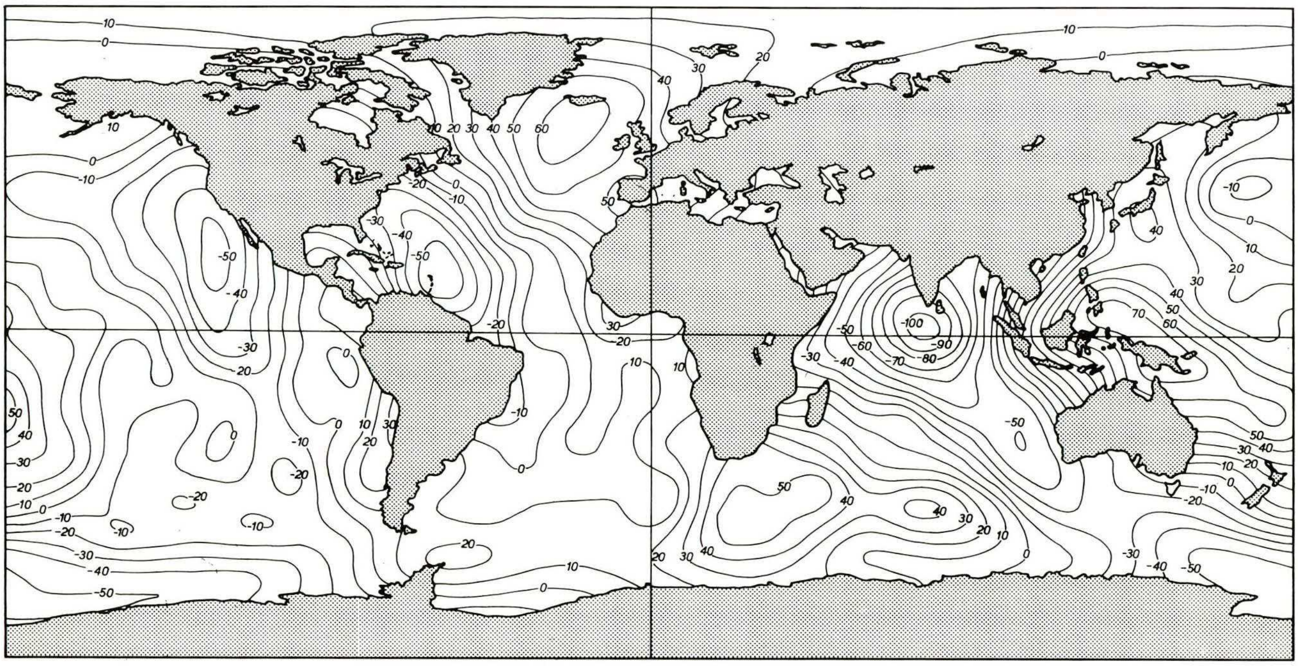


Fig. 2 Geoid map in metres with respect to the best-fitting ellipsoid, f = 1/298.256 (after Gaposchkin, 1973; in Mörner, 1976).

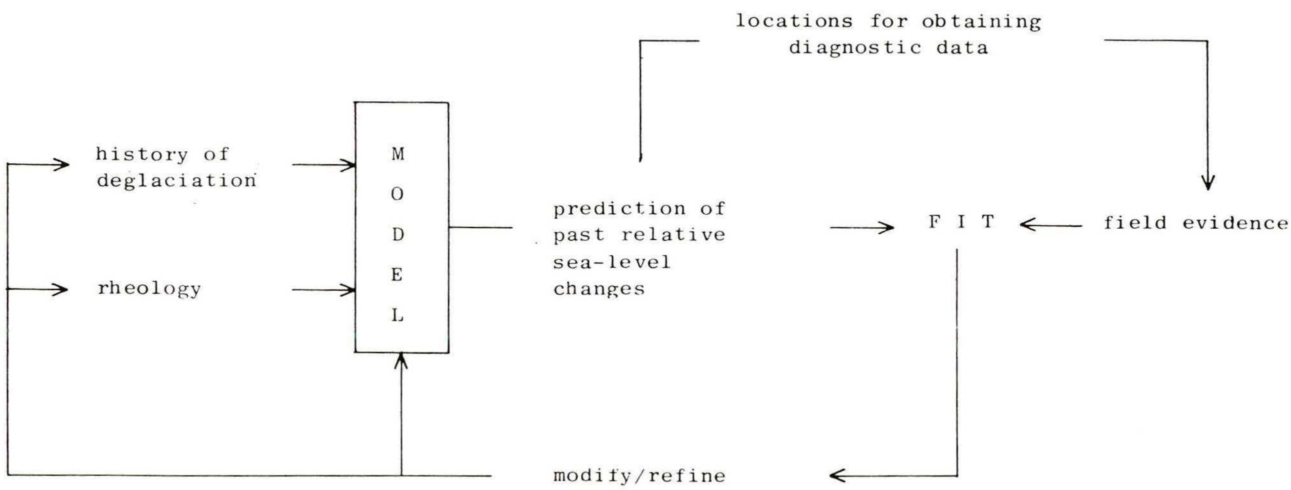


Fig. 3 Flow chart of model approach to the study of global (relative) sea-level change.

computed global relative sea-level changes assuming a contribution of 25 m from the Antarctic ice sheet to the total eustatic sea-level rise, suggested that: '. . . a thorough study of Pacific islands would yield useful information about ocean-volume changes during the past 5000 years, and hence on the glacial history of the Antarctic Ice Sheet.' Close inspection of islands in the central Pacific Ocean is at present in progress (Pirazzoli, pers. comm.). Another example concerns the collection of age-altitude data along a transect perpendicular to a continental margin in order to verify the prediction of a 3-4 m emergence of the 5000 BP shoreline (Clark et al., 1978; Clark and Lingle, 1979; Clark, 1980). Faure et al. (1980) collected sea-level data from a 120 km stretch along the former Senegal estuary. They found that sea level has been within 1 or 2 m of its present position since 6000 years BP. It is concluded that '. . . the tilt across continental margins predicted by mathematical models is less than 1 m from the coast to 120 kilometres inland', and that apparently '. . . the lithosphere is more rigid than has been assumed in models'. A third project that would yield highly informative data is to map the (deformed) ca. 16.000-BP shoreline.

It is outside the scope of this chapter to present an extensive discussion on each of the elements involved in predicting (past) relative sea-level movements. For an up-to-date account of these questions reference is made to the Proceedings of an interdisciplinary symposium on Earth Rheology and Late Cenozoic Isostatic Movements (Mörner, 1980). It suffices here to draw attention to a number of difficulties which arise in comparing model-predicted with observed relative sea-level changes. The predicted changes refer only to the net result of real and apparent variations of ocean level related to exogenic causes, whereas the field record may also contain real and/or apparent changes in level of endogenic origin. Although the isostatic effects on relative sea level are considered to be at least an order-of-magnitude greater than those of vertical movements of internal origin on a 100-10.000 year scale, (which, according to Kaula (1980), should be less than 2 mm/year almost anywhere), this does mean a limitation in assessing the appropriateness of a model. Kaula (see also Chappell, 1981) further stated that prerequisites for testing models and attempts to separate internal from external effects are: (1) refinement of analyses for determining deglaciation trends in time and space (estimating boundaries and volumes), (2) a continuous and reliable dendrochronological calibration curve in order to convert radiocarbon years into historical years, and (3) collection of a large body of reliable relative sea-level data with a wide geographic coverage.

3. THE NETHERLANDS CONTRIBUTION TO THE SEA-LEVEL PROJECT

3.1. OBJECTIVES

Objectives of the Dutch sea-level project carried out within the framework of the IGCP Project 61 were:

1. to establish the relative sea-level curve(s) for the Netherlands; and
2. to prepare a manual for site evaluation and sample collection.

The first objective may seem somewhat surprising in view of the considerable amount of sea-level work already completed in this country during the period 1954-1975 (Bennema, 1954; Van Straaten, 1954; Jelgersma, 1961, 1966; Louwe Kooijmans, 1970/71, 1974; Roeleveld, 1974; Jelgersma et al., 1975). Moreover, a reasonable agreement exists between the results of these workers (see 4.1.). Since the period between 7000 and 2000 BP is well covered by data one would expect that attention be focussed on the time prior to 7000 BP and on the last 2000 years. Furthermore, that attention be given to the, still incompletely understood, position of the time-depth data from the south-western Netherlands two or more metres above curves for the western and northern Netherlands, and to the important question of tidal range variation in time and space. However, in a situation of consensus regarding the trend of the relative sea-level rise it is interesting to attempt an explanation of the differences between the results; in the first place by critically evaluating the published sea-level data and curves (chapter 4) and furthermore, by collecting additional age-altitude data of high quality. Thus, it was decided to further refine the existing Dutch sea-level record rather than to extend it, and to improve our understanding of the significance of the data, and therefore of the relationship between (ground)water level and sea level, and of the factors involved in relative sea-level movements in the Dutch coastal area. A point of importance in this respect was that Roep and colleagues (1975) had just succeeded in obtaining reliable coastal mean high water (MHW) levels from barrier deposits, which would facilitate interpretation of time-depth data from (ground)water-level indicators that originated in various environments behind the coastline.

The second objective was initially of limited scope. Guidelines for sample collection and data evaluation were to be given by way of example on the basis of knowledge and experience obtained in subsiding, alluvial coastal areas such as found along the southern North Sea. However, the structure of a draft Manual for sample collection and evaluation of sea-level data (Van de Plassche, 1977) invited a much broader reference base. As such, there are at present over thirty researchers from fourteen countries participating in the preparation of the Manual (to be published by Geo Abstracts, Norwhich, U.K) that covers sea-level indicators which range from the tropics to the high latitudes.

Structure and contents of the Manual are primarily determined by the main steps (fig. 4) involved in deriving former sea-level stands from fossil sea- or (ground)water-level indicators. The following brief discussion of these steps may serve as introduction to evaluation of sea-level data in succeeding chapters (the order in which they are dealt with does not necessarily represent order in practice).

For the sake of continuity a description of the development of the Dutch coastal area during the Holocene is not included here. A reader not familiar with the depositional history and coastal development of the western and northern Netherlands should refer to Jelgersma et al. (1979) and references therein.

3.2. TWELVE STEPS IN SEA-LEVEL STAND DERIVATION (FIG. 4)

3.2.1. Relationship of indicator to sea level

– Step 1: From indicator to local water level

The interpretation of fossil indicator data in terms of former local tidal level (often MHW) or (ground) water level is, in most cases, primarily based on knowledge of modern analogues (e.g. salt marsh, sedimentary structures in tidal deposits, minimum and maximum water depths of peat-forming plants and trees, depth range of molluscs or other organisms). A correct or accurate interpretation of indicator data often depends on available geo(morpho)logical and paleoecological information.

Indicator data that have been used for sea-level height reconstruction in the Netherlands mainly comprise sediment surfaces and organic deposits, often in combination with archaeological indicators (Bennema, 1954; Jelgersma, 1961; Louwe Kooijmans, 1974, 1976; Roeleveld, 1974). The use of sedimentary structures (Van Straaten, 1954, 1965; Roep et al., 1975; Beets et al., 1981) is becoming increasingly important.

Mature salt marshes along the Dutch coast reach a height of 0.3 to 0.4 m above local MHW (about highest spring tide level) (Bennema, 1954; De Glopper, 1973). Thus, providing a more or less constant tidal amplitude through time (see step 2), a fossil salt marsh surface indicates that former local MHW was at most 0.4 m lower. Obviously, if sedimentological data or information about degree of maturity and/or former distance to the coast is available more precise indications can be obtained.

Marsh bars may be silted to a level of c. 1.2 m above local MHW (Bennema, 1954).

Furthermore, it is assumed in this study that tidal creek levees attained a height between 0 and 0.2 m above local MHW (Zonneveld, 1960; Ente, 1976).

The majority of age-altitude data for the Netherlands pertains to dated peat samples. Depending on the composition and/or the given situation these may represent organic deposition in water depths ranging from a few centimetres to over 1 metre (cf. *Phragmites* peat on sloping Pleistocene surface and on Holocene lagoonal clay). The significance of dated peat samples is dealt with at the appropriate place in the text.

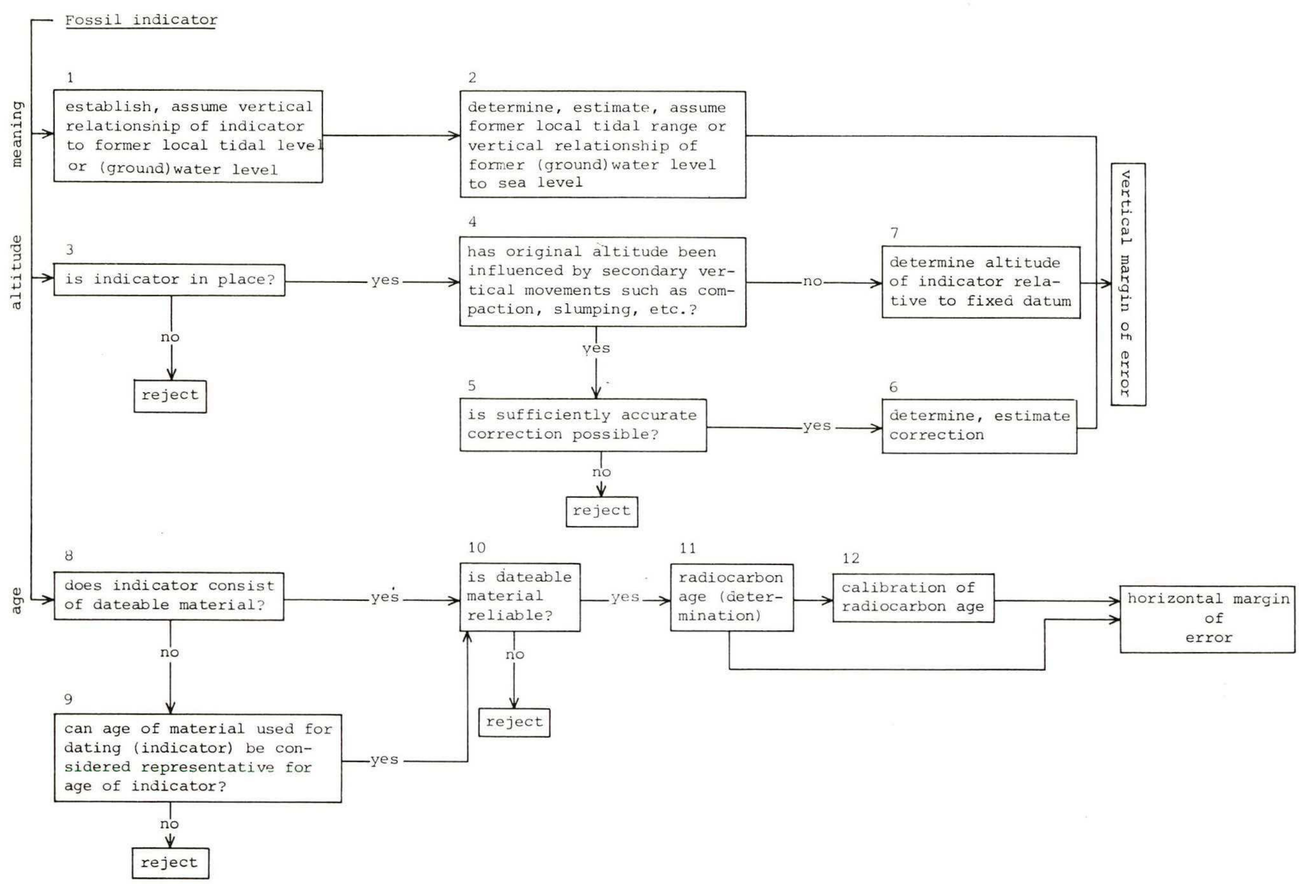


Fig. 4 Scheme of main steps involved in the collection and evaluation of age-altitude data.

– Step 2: From local water level to coastal MHW or MSL

The second step is to relate the height of former local tidal level or (ground)water level, as established in step 1, to coastal MHW or, if possible, to half tide level (= approximately MSL) of that time. Depending on the pertaining situation this may involve determination of the former local tidal range, the influence on (ground)water-table heights of factors such as seepage, hampered drainage, specific weight differences between fresh and salt water, and/or the effect of a sloping water surface in river (-influenced) areas (Louwe Kooijmans, 1976). Special studies are often required in order to quantify these effects and frequently one can only proceed on the basis of estimates or assumptions.

coastal tidal range

Present-day mean tidal range along the Dutch coast varies between 1.36 m at Den Helder and 3.8 m at Vlissingen (Getijtafels voor Nederland, 1981; fig. 5). In sea-level studies prior to 1975 it was assumed that tidal range during the past 8000 years has been more or less constant. Roep et al. (1975) were since able to show from study of sedimentary and burrowing structures and the position of clay seams and shell concentration in Subboreal beach-barrier deposits along the western coastline that this assumption was approximately correct for the western Netherlands and over the past 4800 radiocarbon years (see also Jelgersma et al., 1975 and Jelgersma, 1980).

Present-day tidal range along the northern Netherlands coast has probably increased since about 1200

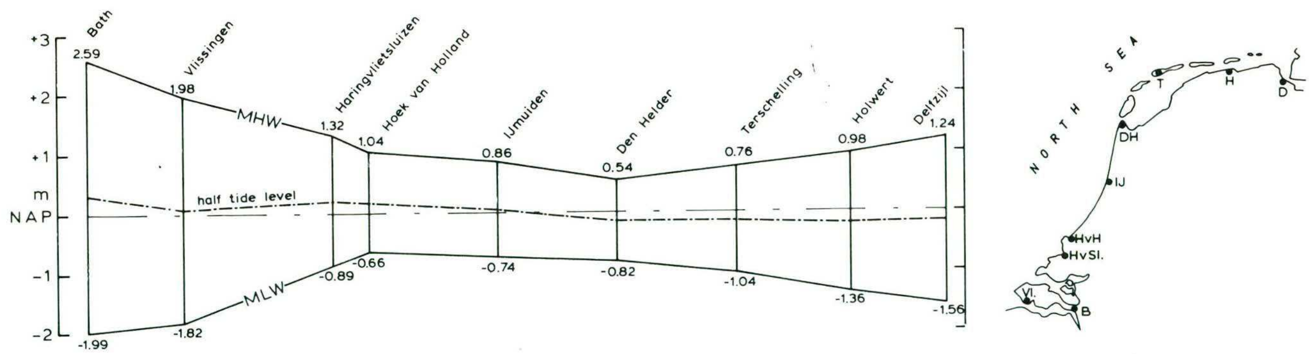


Fig. 5 Presentday variation in mean tidal range along the Netherlands coast. (From GETIJTAFELS VOOR NEDERLAND, 1981).

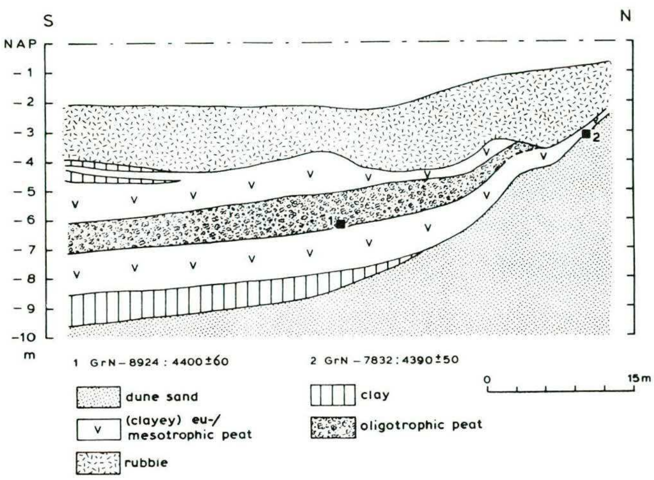


Fig. 6 Section perpendicular to slope of river dune at Hillegersberg. Radiocarbon dates demonstrate the diachronous nature of the lower boundary of the oligotrophic peat bed.

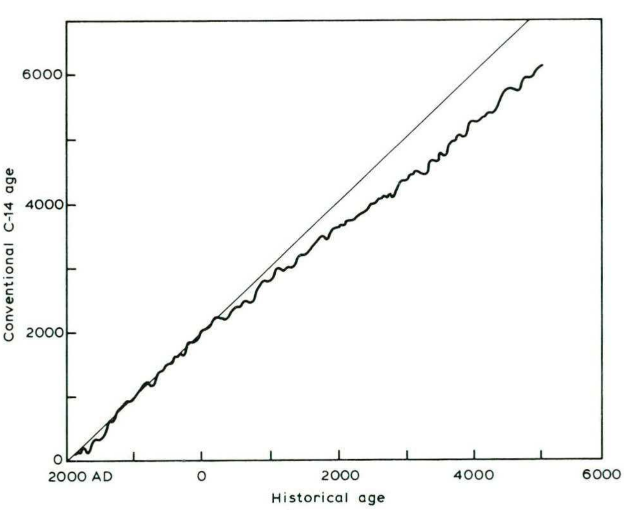


Fig. 7 Dendrochronological calibration curve. Spline function through the best available 14C analyses on dendrochronologically dated wood. (From De Jong and Mook, 1981).

AD due to the building of dikes in this region (Bennema, 1954; Roeleveld, 1974). Thus, when converting former MHW into MSL, a smaller figure for half the tidal range (tidal amplitude) may be used.

It is accepted in this study that MHW in the mouth of the Rhine-Meuse estuary was 0.9 ± 0.1 m above MSL, while further north the mean tidal amplitude was 0.8 ± 0.1 m.

local tidal range

Local tidal range may differ considerably from that at the open coast. A good example is the amplitude increase from Vlissingen to Bath in the Westerschelde estuary (fig. 5), which may be attributed to confinement of the tidal wave in the funnel-shaped embayment (estuary effect, Fairbridge, 1961). A similar effect may occur in wide but rapidly narrowing tidal creeks having natural levees. Conversely, a reduction in tidal amplitude takes place when the tidal wave, after passing through a relatively narrow inlet, enters a basin with a large storage capacity. The resultant lowering of MHW is referred to as a floodbasin or flood-depression effect (Van Veen, 1950; Zonneveld, 1960). Dissipation of tidal energy due to friction also results in a (further) decrease of tidal amplitude (Allen et al., 1980), which may ultimately become zero. In this study, the term floodbasin effect is used irrespective of scale (it may occur locally or regionally) and synonimous with or including the friction effect.

raised water levels in river (-influenced) areas

When a tidal wave migrates up the lower courses of rivers all tidal levels tend to be raised in the upstream direction. This phenomenon is called the (river-) gradient effect (Louwe Kooijmans, 1974, 1976).

raised groundwater tables

When collecting or interpreting age-altitude data from extensive sand bodies (large dune complex, coastal barriers) one should consider the possibility that peat-growth levels were influenced by convex water tables. Peat growth in elongated depressions between barrier ridges may also have resulted in raised groudwater tables (hampered drainage).

3.2.2. Altitude

– Step 3

The altitude of an indicator should only be measured when it occurs in place.

– Steps 4, 5, and 6

Indicators whose original altitude has been affected by secondary vertical displacement on a local scale are unsuitable for use unless a sufficiently reliable and accurate reconstruction of the original position can be made. By far the most serious and troublesome cause of secondary vertical movement is, of course, subsidence due to compaction of peat and clay in the profile. Due to many uncertainties with respect to, for example, sedentation or sedimentation rates, history of loading and aeration, and possibilities for pore-water escape, it is, generally speaking, impossible to estimate the effect of compaction with sufficient accuracy. For these reasons few reliable sea-level data were obtained from the intracoastal area, where many good sea- or water-level indicators can be found (and have been dated). The importance of compaction-free samples cannot be overstressed (Jelgersma, 1961; Louwe Kooijmans, 1976).

A procedure sometimes followed in sea-level studies is to relate the age of a sample from the base of a peat bed, that has been lowered due to compaction of underlying deposits, to the altitude of the bed where it is found to rest on non- or much less compactable deposits. Inherent in this procedure is the assumption that the base of the peat bed is isochronous. The following example illustrates that this premise may lead to considerable errors if not supported by evidence. The base of an oligotrophic peat layer, embedded in a body of eu-/mesotrophic peat (fig. 6), was dated 4400 ± 60 BP (GrN-8924) and reaches the surface of a compaction-free sand body at an (extrapolated) altitude of -1.80 ± 0.1 m NAP. A sample from the underlying *Phragmites-Carex* peat, taken at the peat/sand interface at a depth of -3.1. m NAP, gave an age of 4390 ± 50 BP (GrN-7832). These dates show that the base of the oligotrophic peat is diachronous. This conclusion remains valid if the two radiocarbon dates are converted into historical years: $2910 \pm 10 - 3090 \pm 10$ BC (GrN-8924) and $2910 \pm 10 - 3060 \pm 10$ (GrN-7832). The altitude error of the time-depth point, had the age 4400 BP been coupled with the value -1.8 ± 0.1 m NAP, would have been 1.3 ± 0.1 m (too high), and would also have led to an erroneous computation of compaction amount for the column of peat and clay underlying the 4400 BP sample.

– Step 7

In all but a few cases the altitudes of Dutch sea-level data were established by levelling. The elevation of some samples was derived from maps. In evaluating the published data it was assumed that all altitudes obtained by levelling are accurate to within ± 0.1 m, and estimates from maps were considered accurate to within ± 0.3 m. These margins of error include any inaccuracy that may have resulted from establishment of sample depth below surface.

The influence of compaction on the original thickness of dated peat samples was also included in the evaluation.

3.2.3. Age

– Steps 8 and 9

The age of indicators not consisting of dateable material may be obtained indirectly by dating material the age of which can be considered representative for that of the indicator. In most cases dateable material will need to be *in situ* in order to correctly determine its age-relationship to the indicator meant to be dated. An example where this need not be so is the dating of sedimentary structures in beach deposits by means of washed bivalves. The shells cannot be much older than the sediments, since the valves would otherwise have become unhinged by transportation due to decay of the ligaments after death of the organisms. It should be appreciated, however, that the age of the shells need not be representative of the age of the entire sedimentary sequence.

– Steps 10, 11, and 12

The degree to which radiocarbon age of a sample will deviate from its real historical age depends on the specific activity of the primarily incorporated carbon, and on the amount and 14C content of allochtonous carbon added (sometimes lost) during or after formation of the dateable material (contamination).

Processes which may alter the original 14C content during, and particularly after the formation of the dateable material can be grouped under addition, admixture, and carbon-isotope exchange.

Examples of processes which lead to addition of carbon are: infiltration, washing or blowing in, encrustration, precipitating of secondary calcium carbonate, and penetration of roots. A special case of 'addition' is compaction of peat in relation to width of sample interval.

Admixture, a very serious source of error, may be caused by soil organisms and falling trees.

Exchange of carbonate ions can take place in saline, brackish, and fresh-water environments. High-Mg calcite and aragonite recrystallize to stable low-Mg calcite when brought into contact with Mg-free water (e.g. meteoric water) and isotopes may be gained or lost in the process (Bathurst, 1975; Mangerud, 1972).

No attempt has been made in chapter 4 to assess the reliability of published dates in terms of contamination effects. In fact, none of the dates considered have been indicated as obviously erroneous by the authors who published them. However, since none of the dated peat samples have been fractionized (Streif, 1971; Van de Plassche, 1979a), dates may be (somewhat) too young. The younger samples in particular may be affected as the degree of rejuvenation by roots from plants and/or trees that lived on, and contributed to the upgrowth of the peat bed, is primarily a function of accumulation rate. Roeleveld (1974) accounted for this 'Streif effect' by adding (in certain procedures) an extra uncertainty of + (not – !) 50 years to his dates but no such enlargement of the dating errors is applied here. If the autocontamination effect is large it should become apparent from a comparison with assay results obtained for the

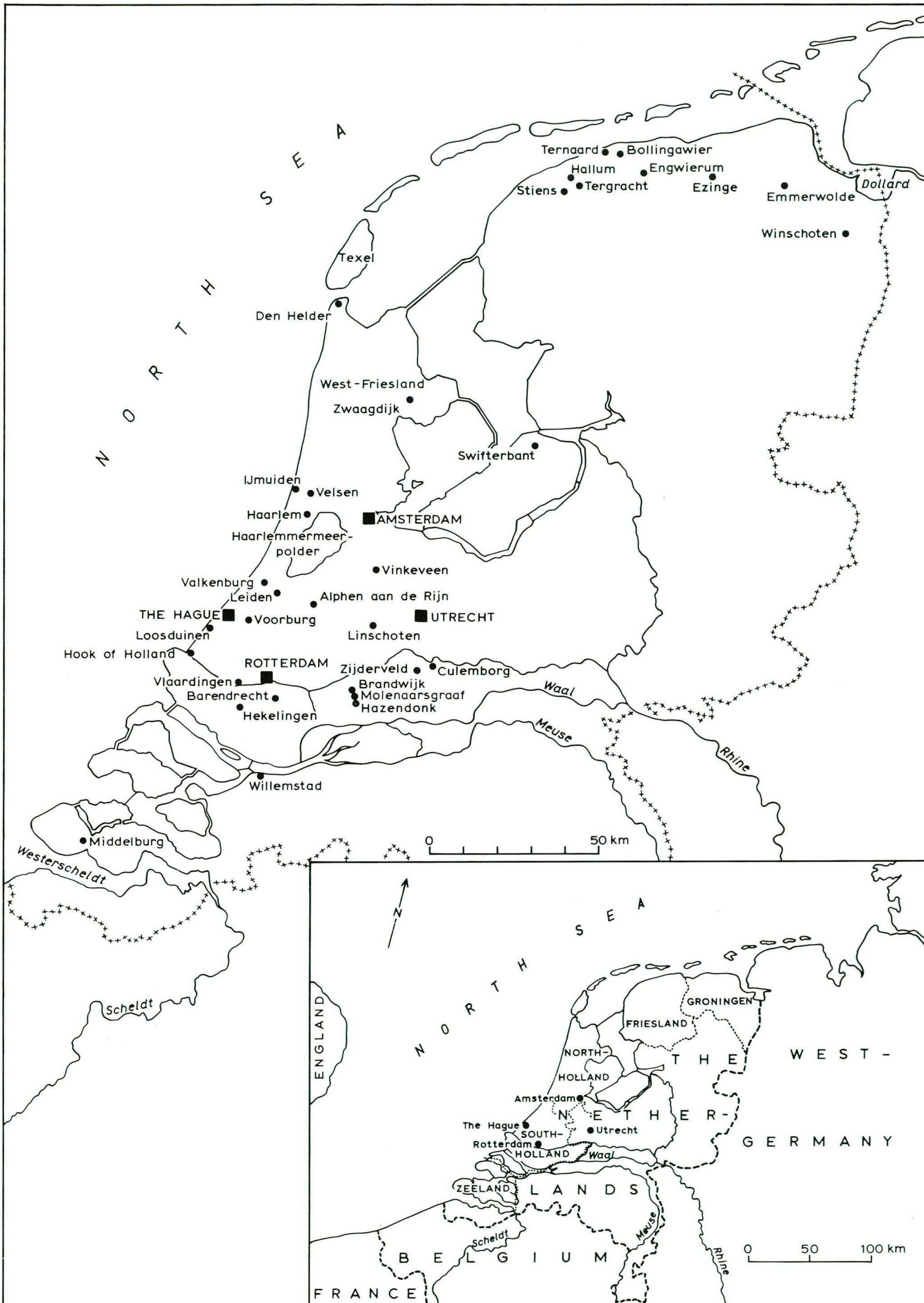


Fig. 8 Map of the Netherlands showing location of areas and sites mentioned in the text.

present investigation, which were performed on peat samples from which all or most rhizomes, roots and rootlets were removed.

With respect to the original 14C content of samples the following factors may be mentioned: past variations in the production of atmospheric carbon-14, isotopic fractionation, and an apparent age of the groundwater from which the plants might have obtained their carbon.

Dendrochronological calibration of radiocarbon-dated tree-rings has revealed both a secular change and, superimposed on it, short- and medium-term fluctuations in the 14C/12C ratio during the Holocene (fig. 7) (e.g. De Vries, 1958; Suess, 1970; De Jong, Mook and Becker, 1980; De Jong and Mook, 1980). The non-linear radiocarbon time-scale requires that radiocarbon years be converted into historical years if phenomena are to be expressed in terms of rates. Due to the medium-term fluctuations in 14C production it is not always possible to unequivocally convert a radiocarbon age into historical age. As pointed out by De Jong and Mook (1981) these medium-term irregularities have a particular bearing on the evaluation of changes in the rate of sea-level rise based on radiocarbon dating.

In the present study, calibration of radiocarbon dates by means of the curve presented by De Jong and Mook (1981) has been applied in only a few cases in order to demonstrate the consequences for interpretation of sea-level data based on radiocarbon dates. A paper is being prepared in which the calibration aspect is taken into consideration more fully.

Calibration of radiocarbon ages presupposes a correction of the dates for isotopic fractionation and, if necessary, for reservoir and/or old water effects. However, earlier radiocarbon dates have frequently not been corrected for isotopic fractionation. In this publication, therefore, 40 years have been subtracted from the age of those peat samples for which no 13C-correction was applied (Mook, pers. comm.).

3.3. MISCELLANEOUS

For the sake of discussion, age-altitude data presented in this study have been numbered 1, 2, 3, etc., beginning with the data published by Bennema (1954) and continuing with those of Van Straaten (1954), Jelgersma (1961), etc. Relevant information pertaining to these numbered time-depth data (in the text often referred to as index points) has been summarized in various tables.

Location maps of areas and sites mentioned in the text, and which are not depicted on other maps, are given in figure 8.

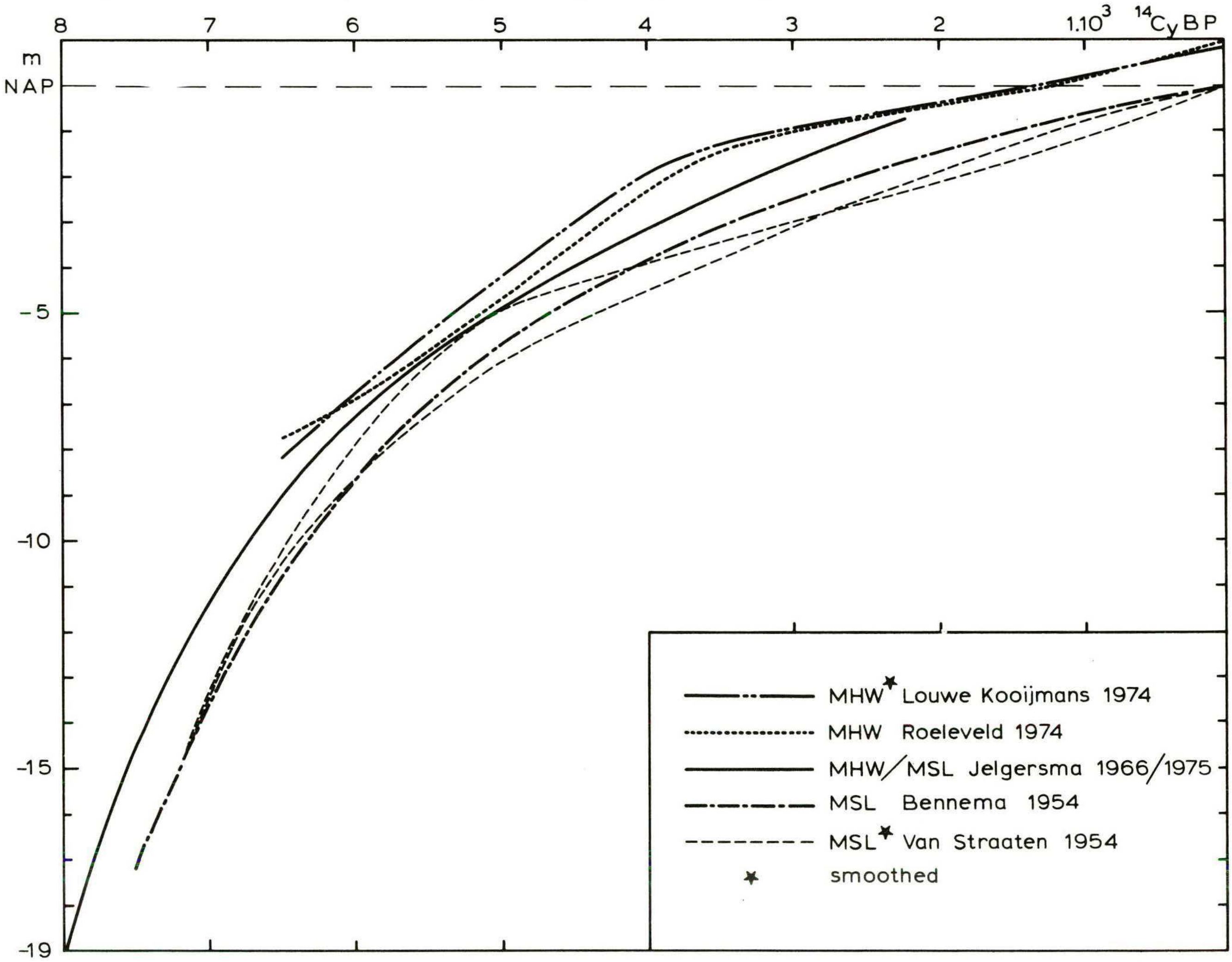


Fig. 9 Relative sea-level curves (MHW and MSL) for the Netherlands published in the period 1954-1975.

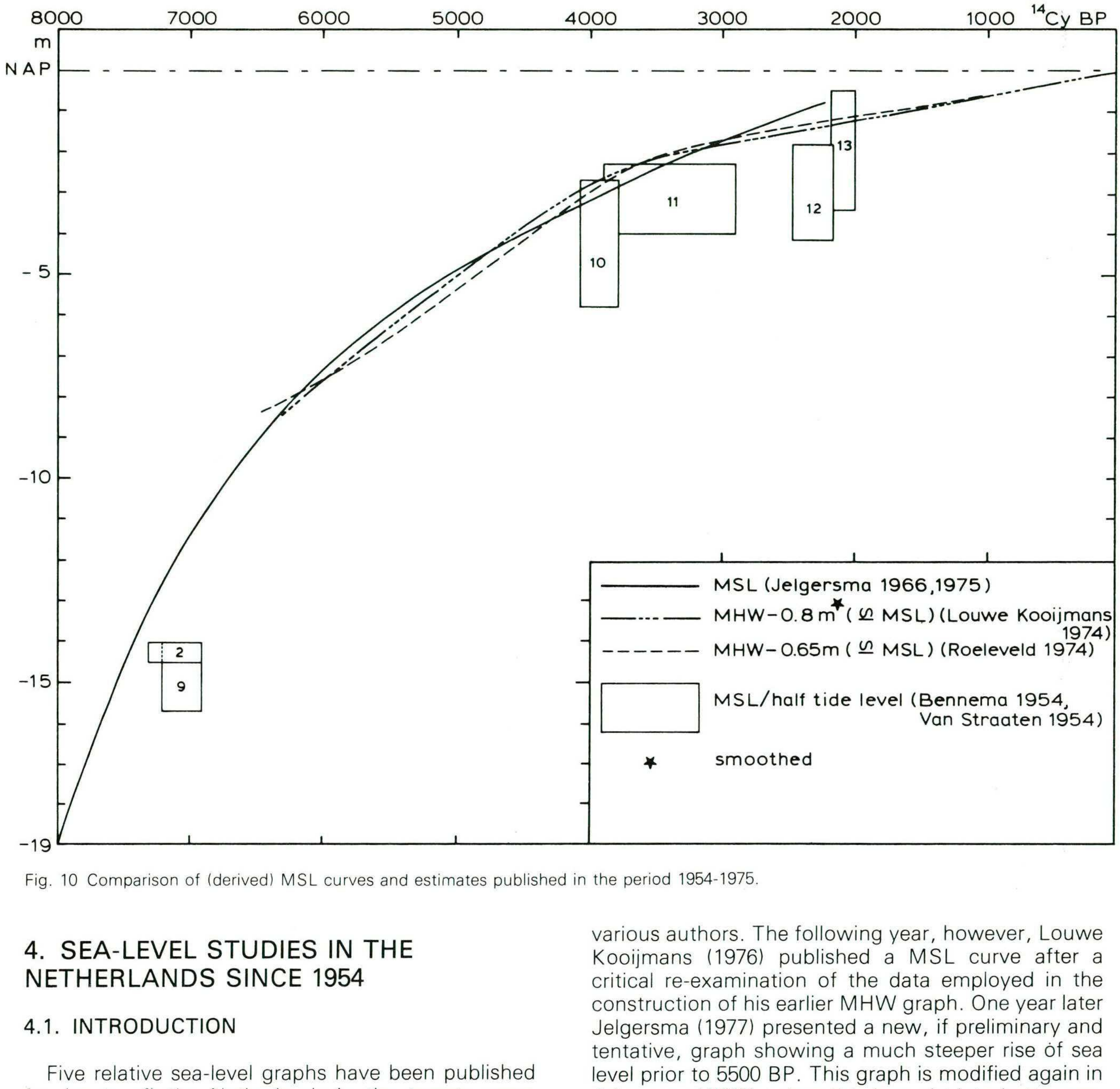


Fig. 10 Comparison of (derived) MSL curves and estimates published in the period 1954-1975.

4. SEA-LEVEL STUDIES IN THE NETHERLANDS SINCE 1954

4.1. INTRODUCTION

Five relative sea-level graphs have been published for (parts of) the Netherlands in the twenty years preceding the start of the Dutch IGCP sea-level project (Bennema, 1954; Van Straaten, 1954; Jelgersma, 1961, 1963; Louwe Kooijmans, 1974 and Roeleveld 1974). The curves given by these authors have been assembled in figure 9. Coincident with the start of the project it was announced that Jelgersma's curve represented the rise of MSL rather than of MHW (Jelgersma et al., 1975). The situation that arose upon this reinterpretation may be read from figure 10. Here the graphs of Bennema and Van Straaten have been substituted by the few radiometrically dated samples then available, and the MHW curves of Louwe Kooijmans and Roeleveld have been lowered uniformly respectively by 0.8 and 0.65 m to approximate MSL (in the latter case a lower figure for half the tidal range is used because Roeleveld did not correct for compaction). It can be concluded that there is considerable agreement between the results of the various authors. The following year, however, Louwe Kooijmans (1976) published a MSL curve after a critical re-examination of the data employed in the construction of his earlier MHW graph. One year later Jelgersma (1977) presented a new, if preliminary and tentative, graph showing a much steeper rise of sea level prior to 5500 BP. This graph is modified again in Jelgersma (1979), when it is brought into better correspondence with data from the North Sea. Finally, Jelgersma (1980) gave a preliminary MHW graph based on data from the coastal barriers obtained by Roep and colleagues (in prep.).

This preliminary graph from the barriers, and the graphs of Roeleveld (1974), Louwe Kooijmans (1976) and Jelgersma (1979) are depicted in figure 11. There is sufficient agreement between the results that, for the purpose of testing model predictions, no further evaluation seems required. However, since the purpose of this chapter is to establish the most probable sea-level curve for (parts of) the Netherlands on the basis of the published data, a careful analysis of the different methods and of the quality and interpretation of the time-depth data employed by the abovementioned authors is required. Sea-level data and graphs will be discussed in order of publication. The analysis is mainly concerned with the evaluation of in-

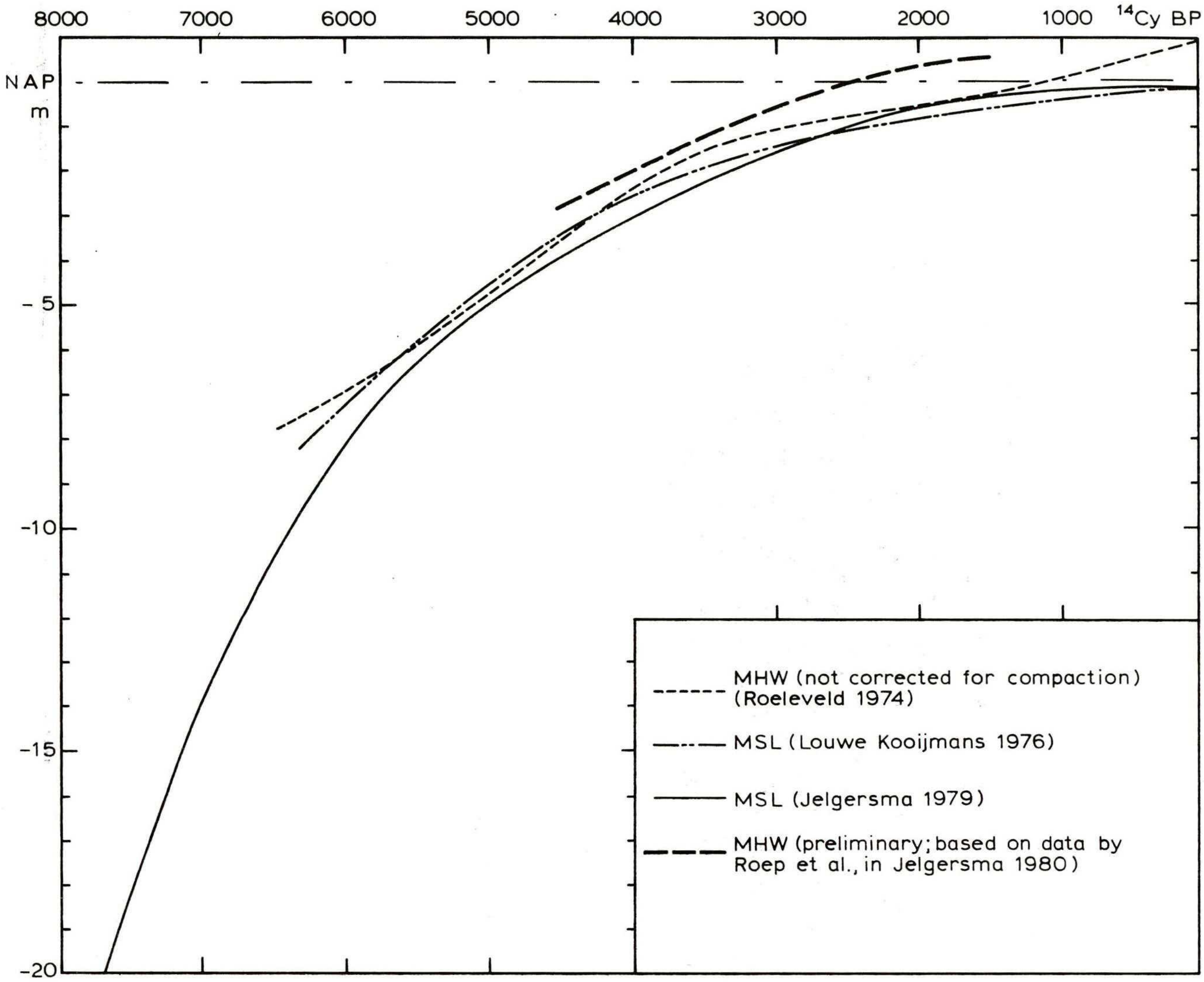


Fig. 11 Relative sea-level curves (MHW and MSL) for the Netherlands published in the period 1974-1980.

dividual time-depth points in terms of former MHW or MSL positions, but attention is also paid to historical and methodological aspects.

Not included in the evaluation are time-depth data older then 8250 BP and younger than 2000 BP.

4.2. EVALUATION OF PUBLISHED TIME-DEPTH DATA AND GRAPHS

4.2.1. Bennema

4.2.1.1. INTRODUCTION

Bennema (1954) made an admirable evaluation of appropriate geological and archaeological data in terms of former half tide level (= about MSL) stands. He was, however, handicapped by the absence of reliable dates. His sea-level curve is depicted in figure 12. The six time-depth points used for the construction of the curve prior to 2000 BP are evaluated below and, where necessary, amended in the light of information that has become available since.

4.2.1.2. EVALUATION OF TIME-DEPTH POINTS

– Index point 1 (Velsen, Rotterdam)

Pollen diagrams of sections from the Lower Peat at Velsen (Florschütz, 1944) and at Rotterdam (Florschütz and Van der Vlerk, 1939) show that the Boreal-Atlantic transition occurs at depths of −16.65 and −15.50 m NAP respectively. Bennema, allowing for compaction of peat and (peaty) fresh-water clay and for a small water depth, estimated the original water level at Velsen at c. −16 m NAP. A comparable depth (c. −16.25 m NAP) can be derived from pollen diagrams published by Doppert (1957). The corresponding water level at Rotterdam was estimated at c. −14.8 m NAP. Bennema, acquainted with the gradient curve of the Late-glacial/early-Holocene floodplain of the rivers Rhine and Meuse (Bennema and Pons, 1952), attributed the higher position of the Boreal-Atlantic boundary in the Rotterdam section to the slope of the groundwater table upstream. Later, Louwe Kooijmans (1974) called this the river-gradient

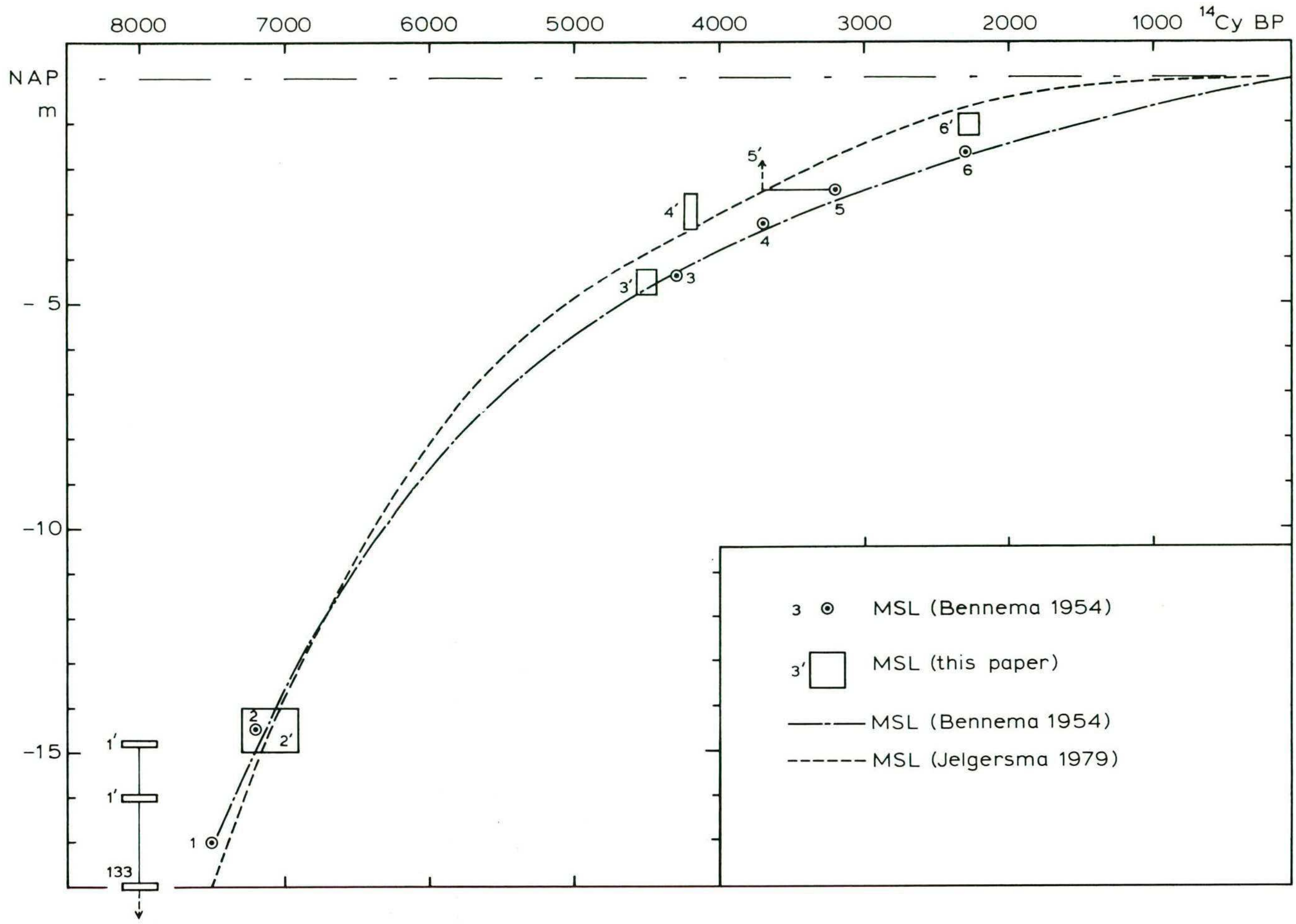


Fig. 12 Time-depth diagram showing MSL estimates and curve by Bennema (1954) and revised MSL estimates (discussion in text). MSL curve by Jelgersma (1979) is given for comparison.

effect. According to Bennema the data from Velsen and Rotterdam point to a MSL stand of −17±1 m NAP.

Bennema accepted an age of c. 5500 BC for the Boreal-Atlantic transition, which is about 500 years too late. The two estimates of former local water level at Velsen and Rotterdam (c. −16 and c. −14.8 m NAP) have been plotted against the correct age (viz. c. 8000 BP) in figure 12.

The height of the local water level c. 8000 years ago at a site about 7 km west of Velsen can be estimated in exactly the same way from a pollen diagram of a Lower Peat section published by Jelgersma (1961, Plate I). The *Pinus-Alnus* crossing in this diagram lies at a depth of c. −20.25 m NAP, c. 0.25 m above the sandy substrate. The composition of the vegetation (mainly ferns and sedges) points to very shallow water conditions. Even with a very high degree of compaction of the peat (89%), the 8000-BP water level at this site cannot have reached much higher than −18 m NAP (see index-point 133 in figure 12). It can be argued that MSL very probably occured still lower (see 4.2.4.).

– Index point 2 (Velsen)

Bennema computed the compaction of the Lower Peat at Velsen according to different methods that gave similar results: at the time of first inundation the surface of the Lower Peat reached a height of −14.25±0.25 m NAP. Breakdown of peat growth must have occurred shortly after 7100±200 BP (GrN-75), indicated by the radiocarbon age of a piece of wood 0.05 m below the slightly eroded top of the peat. Since the drowning of the peat took place at the margin of a lagoon, Bennema assumed that local tidal range was small (0.5 m). Accordingly, he placed MSL at −14.50±0.25 m NAP.

The fact that different methods of computing the amount of compaction of the Lower Peat gave comparable results may be taken to indicate that the figure arrived at for the original altitude of the top of this peat is reasonably reliable. Nevertheless, in figure 12 an extra margin of error of ±0.25 m has been added.

According to Florschütz (1944) and Doppert (1957) the upper part of the Lower Peat at Velsen consists mainly of fen peat. Therefore, it is not certain whether the dated piece of wood occurred in place. It may have drifted in, in which case its age might not be representative for the end of Lower Peat growth there. Because of this uncertainty and the large standard deviation of the dating additional data are required for a more complete evaluation of this index point. In this respect radiocarbon datings on samples of bivalves from the lagoonal clay overlying the Lower

Peat are of some relevance (Van Straaten, 1954). Samples from the top of this clay bed gave the following results: 7070 ± 120 BP (GrN-181), 7155 ± 230 BP (GrN-194), and 7130 ± 240 BP (GrN-200), while a sample from the lower part of this bed was dated at 6880 ± 150 BP (GrN-154). Van Straaten reports that many of the shells were in an inclined or horizontal position, indicating transportation after death. Secondary displacement, however, cannot have been very much, otherwise the valves would have come apart. Hence their age can be considered representative of the age of the sediment that contains them. In view of the shell dates and the large standard deviations the age of the dated piece of wood can be accepted as being fairly representative of the age of the top of the Lower Peat at Velsen.

– Index point 3 (Haarlemmermeer polder)

Haans (1955) recognized three depositional phases in the Haarlemmermeer polder based on soil and sediment characteristics and distribution patterns. The tidal flat and gully sediments of the Hoofddorp deposits belong to the first (oldest) phase. The top of these deposits has been decalcified down to considerable depth, which Haans explained by a high level of sedimentation and subsequent exposure to subaerial conditions due to a (drastic) reduction in local tidal range as a result of changes in volume of the coastal inlets. Due to differential compaction the sandy gully deposits came to lie as low ridges in the landscape. During the second phase of deposition (of the so-called old sea-clay) the relief that had come into existence was reduced, and only the highest parts of the Hoofddorp deposits remained free of younger sediments. In most cases the old sea-clay deposits show a fining upward sequence from (very) sandy clay to heavy clay. According to Haans where the upper part of the old sea-clay deposits is free of lime, as is often the case where they rest on Hoofddorp deposits, sedimentation occured under salt-marsh conditions. Finally, he recognized a third phase of deposition in the SW part of the Haarlemmermeer, where a lime-rich clay – the so-called Beinsdorp deposits – overlie a clayey sediment free of lime, which Haans interpreted as old sea-clay deposits. A thin peat bed often separates both deposits.

The Hoofddorp deposits, of which the sandy gully sediments extend down into the Pleistocene substrate, reach a maximum height of just above −4 m NAP. The minimum depth of the old sea-clay deposits is about −4 m NAP. This value is found where the clay feathers out against compaction-free gully sediments of the Hoofddorp deposits.

With regard to the fact that the old sea-clay deposits do not cover the highest parts of the Hoofddorp deposits, Bennema remarked that this does not necessarily imply a higher sea level during the time that the Hoofddorp deposits originated; it could simply mean that subsequently the tidal range in the area of deposition had become smaller due to narrowing of inlets through the developing coastal barrier system. He assumed that the old sea-clay deposits are indicative of former local MHW. Assuming, furthermore, a former local tidal range of 0.75 ± 0.25 m, he arrived at a figure for MSL of −4.25 ± 0.25 m NAP. Bennema adopted an age of 2300 BC (4250 BP) for these sediments.

Radiocarbon dates from the base of the peat overlying the old sea-clay deposits immediately east and west of the Haarlemmermeer polder (Riezebos and Du Saar, 1969) indicate that there peat growth began at about 4500 BP. It is reasonable to assume that the time of beginning of peat growth east and west of the polder is fairly representative of the end of sedimentation of the old sea-clay deposits in the polder. It is stressed, however, that on this point no certainty can be obtained. Assuming furthermore that the top of the old sea-clay deposits, where they overlie compaction-free Hoofddorp deposits, reached 0.15 ± 0.1 m above local MHW, and that local tidal range was 0.8 ± 0.2 m, MSL at about 4500 BP can be computed at $-(4 \pm 0.1) - (0.15 \pm 0.1) - (0.4 \pm 0.1) = -4.55 \pm 0.3$ m NAP.

– Index point 4 (Hekelingen)

Like Tesch (1922) and Zwart (1951) before him, Bennema employed the mean elevation of the inter-barrier beach-plain floors as a measure of former sea levels. The procedure requires that the figure used is known to relate to the top of a beach deposit with known vertical relationship to MHW. This condition has not been fulfilled, and the figures for MSL that Bennema arrived at for the time of the oldest and second oldest beach-plain formation (4050 BP; −4 m NAP and 3650 BP; −3.4 m NAP) are interesting only from a methodological point of view. The fact that these two pairs of coordinates fit his curve can, apart from the erroneous ages, largely be attributed to Bennema's *a posteriori* assumption that beach plains are formed to a level of 0.3-0.5 m above MHW. With the assumption of Tesch (1922) that beach plains reach to MHW, the two time depth points mentioned above would plot too much above the curve as determined by the other time-depth points.

Index point 4 (3750 BP; −3.25 ± 0.25 m NAP) is primarily based on data obtained from an archaeoligical excavation near Hekelingen (Modderman, 1953; Bennema, 1953). Here an occupation site of the Vlaardingen Culture was found on the northern levee of a fresh-water tidal creek. Radiocarbon dates on bone and charcoal from the occupation layer showed that the levees were formed prior to about 4150 BP (Van Regteren Altena et al., 1962; Louwe Kooijmans, 1974, 1976). An age of 4200 ± 50 BP is accepted here for the top of the levee deposits. According to Bennema (1954, p. 38) these deposits reach an altitude of about −2.2 m NAP. It is difficult to assess how representative this figure is for, from figure 3 of his 1953 publication, a height of −2.4 m NAP can be read for the top of the uninhabited southern creek levee. Moreover, on page 12 of the same paper Bennema mentions an altitude of c. −2.5 m NAP, while figure 1 on page 11 suggests an altitude of c. −2.3 m NAP. Renewed inspection of the creek levee (Louwe Kooijmans and Van de Velde, 1980) has yielded a depth of −2.35 ± 0.05 m NAP for the altitude of the top of levee sediments below a corresponding occupation level. Bennema estimated the maximum amount of subsidence due to compaction as 0.3 m. This estimate seems acceptable in view of the limited occurrence of clay beds in the subsoil. Furthermore, it may be assumed that the levees have been silted up to a level of 0.1 ± 0.1 m above local MHW. To give a well-founded estimate of the local tidal range at that time is much more difficult, since one cannot evaluate the effect of factors leading to either an increase or a decrease of the tidal amplitude. For example, increase in amplitude due to confinement of the tidal wave in a creek may (partly) have been compensated for by a reduction in amplitude due to friction. Comparison with the situation in the former fresh water tidal area of the Biesbos (Zonneveld, 1960) suggests that at Hekelingen local tidal range amounted to about 1.5 m (Pons in Van Regteren Altena et al., 1963). We accept this figure as an approximate upper limit and assuming that local tidal range was 1.4 ± 0.3 m, MSL at 4200 ± 50 BP can now be computed as follows: $-(2.35 \pm 0.05) + (0.2 \pm 0.1) - (0.1 \pm 0.1) - (0.7 \pm 0.15) = -2.95 \pm 0.40$ m NAP. This result differs slightly from that of Louwe Kooijmans (1976) (-2.6 ± 0.45 m NAP) for two reasons: (1) he used for the top of the levee deposits a figure of -2.1 ± 0.1 m NAP which, however, refers to the maximum observed height of the top of the occupation layer studied by Modderman, and (2) he did not apply a correction for sedimentation of the levee to above local MHW.

Further data from the Hekelingen site are discussed in 4.2.5.

Bennema attributed the subsequent occupation of the creek levee to a reduction in local tidal range due to (unspecified) changes in the estuary mouth(s) further west. Later, Louwe Kooijmans (1974) made this sequence of events – sedimentation followed by reduction in local tidal range and occupation of the previously formed sediment surface – the main principle in his analysis of suitable archaeological data in terms of former sea-level stands.

– Index point 5 (West-Friesland)

Bennema concluded from the age of the older barrows in the eastern part of West-Friesland (1400-1000 BC, Van Giffen, 1953), that the sediment surface on which they were built dated from c. 1200 BC. This conclusion has proved to be incorrect; the age of the sediment surface is about 500 years older (Roep et al., 1979). The observed maximum altitude of the base of the barrows is c. -1.6 m NAP. According to Van Giffen this figure should be corrected for compaction of the subsoil. Bennema, however, argued that since the barrows were underlain by slightly clayey, marine sands, compaction can be neglected. But as he lacked information as to the depth to which these sands continued, this was in fact an unfounded assumption which he may have accepted for the reason that it gave him a figure for MSL that was in reasonable agreement with the other time-depth points. Meanwhile, however, it has become clear that the original altitude of the base of the barrows has been affected by compaction of deeper occurring beds of clay and peat (Louwe Kooijmans, 1976; and references therein).

– Index point 6 (Loosduinen)

This time-depth point is mainly based on an observation of the original altitude of an inhabited peat surface in the Escamppolder near Loosduinen (Modderman, 1952). The surface of this peat intersects a low dune resting on coastal barrier deposits at a compaction-free altitude of -0.75 m NAP. The archaeological finds have been correctly dated to the third century BC (Modderman, 1952; Hallewas & Van Regteren Altena, 1981). According to Modderman the peat surface became inhabitable for a short period due to improved drainage in the vicinity of tidal creeks and gullies that penetrated the peat landscape. This explanation is supported by other observations (Mezger, 1969; Hallewas & Van Regteren Altena, 1981).

Bennema assumed that at the time a tidal creek began to drain the site where the Late Iron Age finds were made, the surface of the (eutrophic) peat reached a level of coastal MHW or slightly higher. Having assumed, furthermore, that tidal range at the coast was c. 1.9 m he arrived at a figure for MSL of $-0.75 - 0.95 = -1.7$ m NAP.

According to Louwe Kooijmans (1976) the site was sufficiently far from the estuary mouth for the tidal wave to have been strongly diminished in amplitude there. He assumed that half the local tidal range was no greater than 0.1 ± 0.1 m. Thus, he arrived at a figure for MSL of $-(0.75 \pm 0.1) - (0.1 \pm 0.1) = 0.85 \pm 0.2$ m NAP.

While it can be agreed with Louwe Kooijmans that the tidal range at the Escamppolder site will have been smaller than in the estuary mouth, it can also be argued (see below) that the position of MSL in the third century BC probably occurred closer to -1 m NAP than to -0.7 m NAP. The fact that the surface of the peat became inhabitable for a short period implies that the local groundwater level was lowered. This may be explained by the penetration of the peat by a tidal creek. It must be assumed, however, that as a consequence the peat surface itself was also lowered. Now, if MSL stood at -0.75 m NAP the site would be flooded with every high tide, no matter how small the local tidal range. Therefore, the conclusion must be that at the moment that drainage of the site began (2275 ± 75 BP; Hallewas and Van Regteren Altena, 1981) the peat surface occurred at least several decimetres above MSL, say 0.4 ± 0.1 m. Taking 0.1 ± 0.05 m for compaction one arrives at a figure for MSL of $-(0.75 \pm 0.1) - (0.4 \pm 0.1) + (0.1 \pm 0.05) = 1.05 \pm 0.25$ m NAP.

With the development of a tidal drainage system in the peat area north of the Rhine-Meuse estuary local tidal ranges can only have increased. Hence peat growth above MSL prior to that development should be attributed to a relatively high groundwater table. This may be explained in terms of poor drainage conditions in the peat-filled beach plains (see 8.3).

The results of the above re-evaluation of Bennema's first six time-depth points are shown in figure 12. The MSL curve by Jelgersma (1979) is given for comparison.

4.2.2. Van Straaten

'Radiocarbon datings and changes of sea level at Velzen' is the title of Van Straaten's (1954) paper on relative sea-level movements based on a sedimentological analysis of tidal deposits exposed in the deep tunnel pit at Velsen. In fact, the presence of peat and (peaty) clay layers in the sequence render the site unsuitable for accurate determination of former sea levels. Van Straaten's impressive attempt to do so nevertheless is readily understood from his considerable knowledge of tidal flat environments, but above all from the fact that for the first time in the Netherlands a series of radiocarbon dates (on shells) from marine (influenced) deposits at one locality had become available. With the estimated margin of error for compaction added to those for former tidal range and for depth of deposition with respect to MHW or MLW, he obtained very large vertical error intervals for a number of paleo half tide levels (fig. 10).

In the method employed by Van Straaten the significance of the tidal sediments in terms of former tidal levels was known, but the price for their use as sea-level indicators was lack of accuracy primarily due to compaction. In the approach taken by Jelgersma (1961) in the years thereafter, the problem of compaction was eliminated, but the price was lack of certainty concerning the meaning of the main indicator used, namely the base of the Lower Peat.

4.2.3. Jelgersma

4.2.3.1. INTRODUCTION

Jelgersma's (1961) time-depth graph has been subject to several modifications in the course of time (fig. 13). The first change concerned a correction of the radiocarbon data for the Suess effect (Vogel and Waterbolk, 1963). The corrected curve was first published in Pons et al. (1963), but is more often referred to in Jelgersma (1966). The second modification concerned a change in meaning of the curve. In 1975, coincident with the start of the Dutch IGCP sea-level project, the first results were announced of a study on paleo tidal levels derived from shell-dated sedimentary structures in the coastal barrier deposits (Roep et al., 1975; Jelgersma et al., 1975). The time-depth position of derived former MHW levels appeared to be about 1 m above Jelgersma's curve. In the light of this new evidence her curve, or at least the part younger than 5000 BP, was reinterpreted to indicate the rise of MSL instead of MHW. Finally, Jelgersma (1977, 1979) steepened the older part of the curve on the basis of new data from the North Sea area (Oele in Jelgersma et al., 1979) and a new basal peat date.

4.2.3.2. DATA (JELGERSMA, 1961, 1966) AND METHOD

Jelgersma (1961) collected samples from the base of peat (1) on the gently seaward sloping surface of the Pleistocene substrate, (2) on the steep slopes of two Late-glacial/early-Holocene river dunes ('donken') in the presentday lower course area of the major rivers, (3) in the beach plains, and (4) from the base of peat overlying sandy tidal flat deposits. In the first two cases the problem of compaction is eliminated. The time-depth results and various curves are given in figure 14a and b.

Basal peat data

Pollen analytical studies (Vermeer-Louman, 1934) had shown that the age of the Lower Peat decreased with decreasing depth of the Pleistocene sub-surface. Once the development of the Lower Peat was explained in terms of a rising groundwater table controlled by the sea-level rise, it remained a matter of assuming or establishing a vertical relationship between the two in order to employ it for sea-level height reconstruction.

Like Bennema (1954), Jelgersma (1961, p. 20) is of the opinion that the groundwater level, at which basal peat growth begins, is not constant but '. . . depends on the distance to the shore-line, the height of the tides, and the permeability of the sandy subsoil'. However, according to her, in a humid climate it will never be below MSL. Although she did not exclude the – in her opinion not very likely – possibility that groundwater may be lower than MHW, Jelgersma assumed in her thesis that the level at which basal peat growth commences coincides with MHW.

For the sake of discussion the suitability of the individual basal peat data for estimating former sea levels is dealt with later on (4.2.4.).

Age-altitude data from the two 'donken'

The slopes of Late-glacial/early-Holocene river dunes that occur (a.o.) in the presentday lower reaches of the rivers Rhine and Meuse are covered with peat (and clay) that originated (was deposited) in a fluviatile/estuarine (perimarine) environment under influence of the postglacial sea-level rise. Because of the isolated position of the dunes, the steepness of the slopes, and the permeability of the sand, the upper limit of peat growth is closely determined by the surrounding (ground)water level. Thus, by dating series of samples from the peat/dune sand interface accurate information about water-level changes is obtained. The main question, however, is how water level was related to sea level.

Jelgersma (1961) investigated and sampled two river dunes: the 'donk' of Barendrecht and the 'donk' of Brandwijk (Fig. 14c). In both cases the material sampled consisted of fen-wood peat which, according to her, is formed at 0.5 m above local groundwater. She accepted that due to the former presence of storage basins in the Rhine-Meuse tidal river area, the tidal wave diminished in amplitude in landward direction (Zonneveld, 1960). Close to sea groundwater will approach MHW, while far inland it will be near MSL. Thus, with the tidal amplitude set at 1 m, the upper limit of fen-wood peat growth in the area concerned can be expected to have occurred between MHW + 0.5 m and MHW – 0.5 m depending on the distance to the coast. Jelgersma (1961, p. 21) accepted '. . . that fen-wood peat in the mentioned estuary is formed at high tide'.

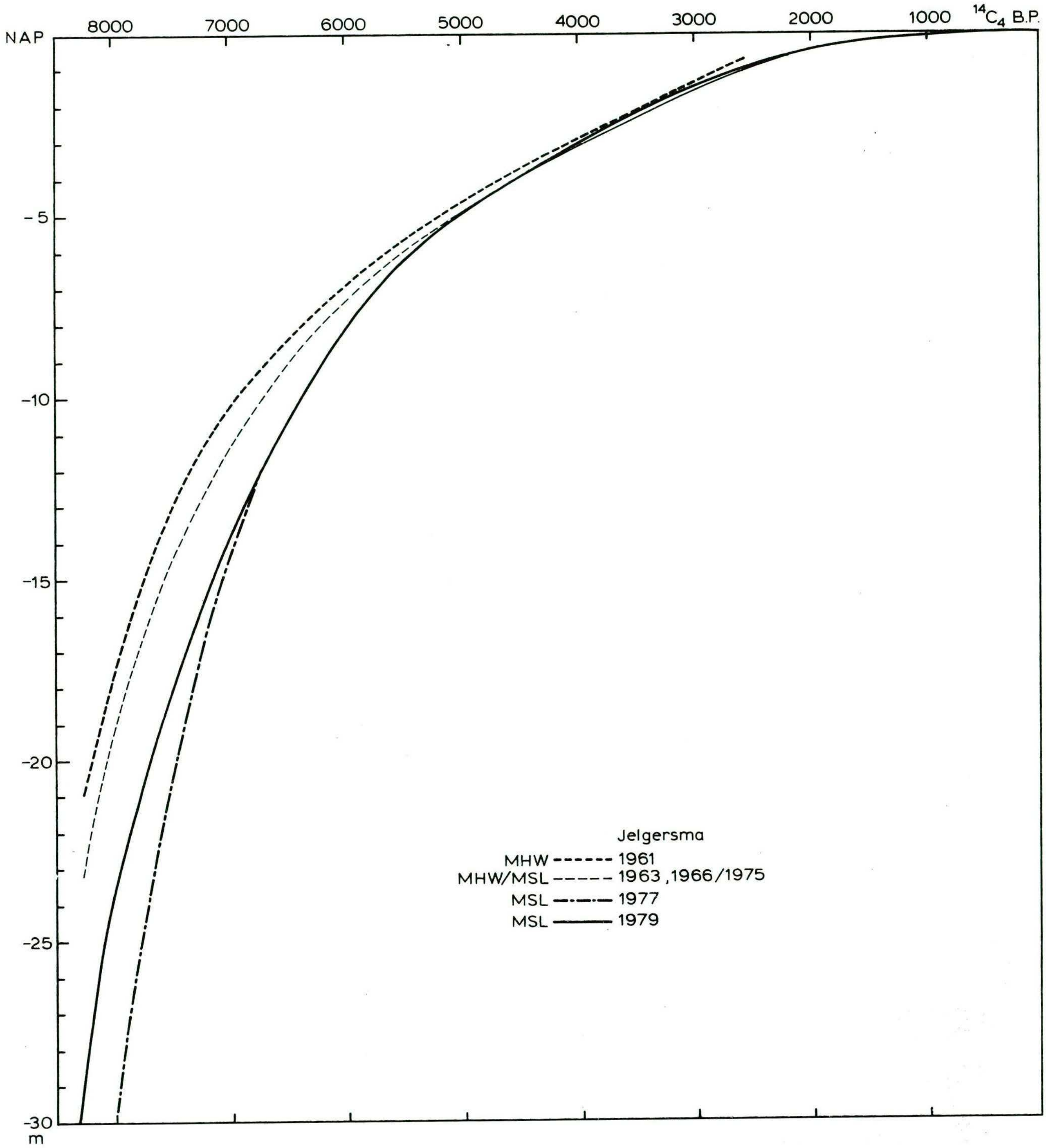


Fig. 13 Relative sea-level curves by Jelgersma.

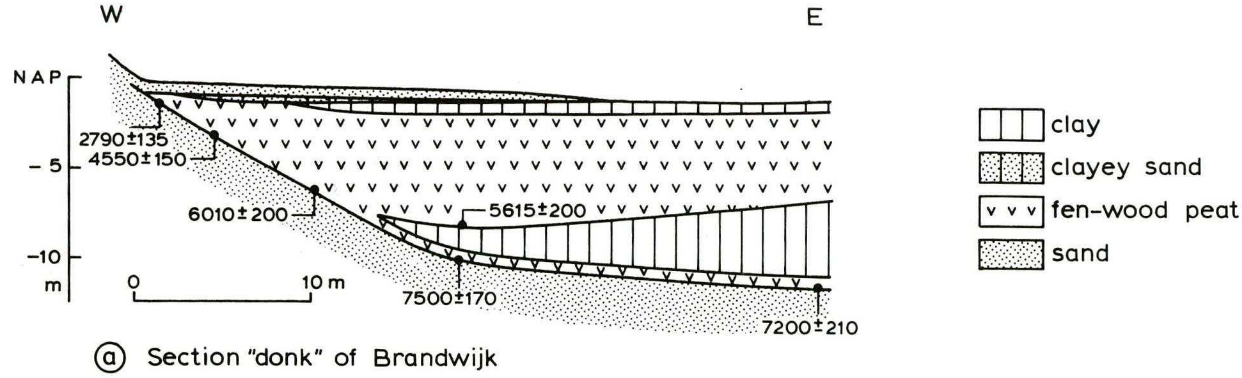
The time-depth data obtained from the Barendrecht and Brandwijk 'donken' are given in figure 14b. Jelgersma considered the oldest and second oldest Brandwijk samples less reliable for the purpose for which they were collected because they come from the very foot of the dune and the former valley floor respectively, where the general slope is small. However, only the oldest Brandwijk date was definitely rejected (Jelgersma, 1961, p. 45) as it appeared that the second oldest date fitted the trend of the groundwater-level rise as indicated by other time-depth data.

Beach-plain and intercalated peat data

With respect to the five beach-plain data and two from the base of intercalated peat beds in the Province of Zeeland it suffices to mention that Jelgersma assumed that the first represent former spring tide levels, while the latter indicate former MHW.

Methods of curve construction

Jelgersma followed two approaches of curve construction to derive the most probable graph of the rise



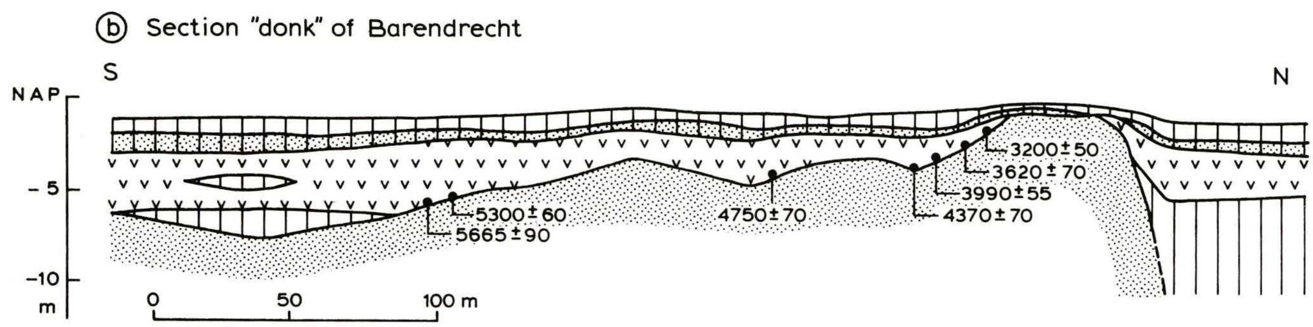


Fig. 14c Sections across the Brandwijk and Barendrecht river dunes. Ages in conventional radiocarbon years BP. (After Jelgersma, 1961.)

of MHW from the individual age-altitude data. The smooth curve I (fig. 14) is based on the supposition that peat growth locally (on the gently sloping Pleistocene surface) may have occurred above MHW. Hence, '. . . only the points located in the lowest places for a given age, or even slightly lower, represent a groundwater table which coincides with high tide level' (Jelgersma, 1961, p. 45). It follows, from this line of reasoning, that '. . . all aberrations are considered as errors and not as fluctuations of sea level'. Curve II, which shows fluctuations, is based on the assumption that the 'donken' data provide '. . . the most reliable indications of sea-level changes.' (p. 45.) Jelgersma concluded that curve I represents the most probable graph of the rise of MHW for the reason that the Zeeland data do not suggest any clear variations in the sea-level rise, and to the extent these might be discerned they are contradictory to those of curve II.

Curve III is the line connecting the younger of the Zeeland data. It gives the change in MHW position in the S.W. Netherlands between 6000 and 4000 BP. According to Jelgersma (1961, p. 46) the distinctively higher position of this curve may be explained by a combination of a higher tidal range (as is the case at present) and a smaller amount of tectonic subsidence. She held the larger tidal range to be the main responsible factor.

To Jelgersma (1961, p. 46) the main conclusion to be drawn from the curves is '. . . the existence of an uninterrupted positive change in level which is gradually slowing down'. A marked drop in sea level in the early Subboreal, as proposed by several authors (e.g. Umbgrove, 1947; Zwart, 1951), was not confirmed by her study. Jelgersma accepted the possibility that minor sea-level fluctuations did occur. However, in view of the possible errors contained in the data, she refrained from drawing final conclusions in this respect.

4.2.3.3. DISCUSSION

The major unknown with which Jelgersma had to cope in her study was the significance of the data. In the absence of modern analogues she had to assume their meaning on the basis of general considerations and available information about the relationship between groundwater and sea level, and relevant sources of error. Given this problem, it is noticeable that in her final considerations of the data (see the above summary) she did not consider her assumptions about the significance of the data against the observational evidence. For by accepting curve I as the most likely MHW curve, a discrepancy arises with the assumption that fen-wood peat growth in the Rhine-Meuse tidal river area occurred between MHW + 0.5 m and MHW − 0.5 m depending on the distance from the coast. In the case of the Brandwijk 'donk' this distance may be considered to have been sufficiently large to expect that the upper limit of fen-wood peat growth on this river dune took place below, or at most at, coastal MHW level. Yet two time-depth points from Brandwijk lie as much as 0.75 m above curve I (fig. 14b). The discrepancy becomes even more pronounced when the possibility is considered that the fen-wood peat was formed at a lower

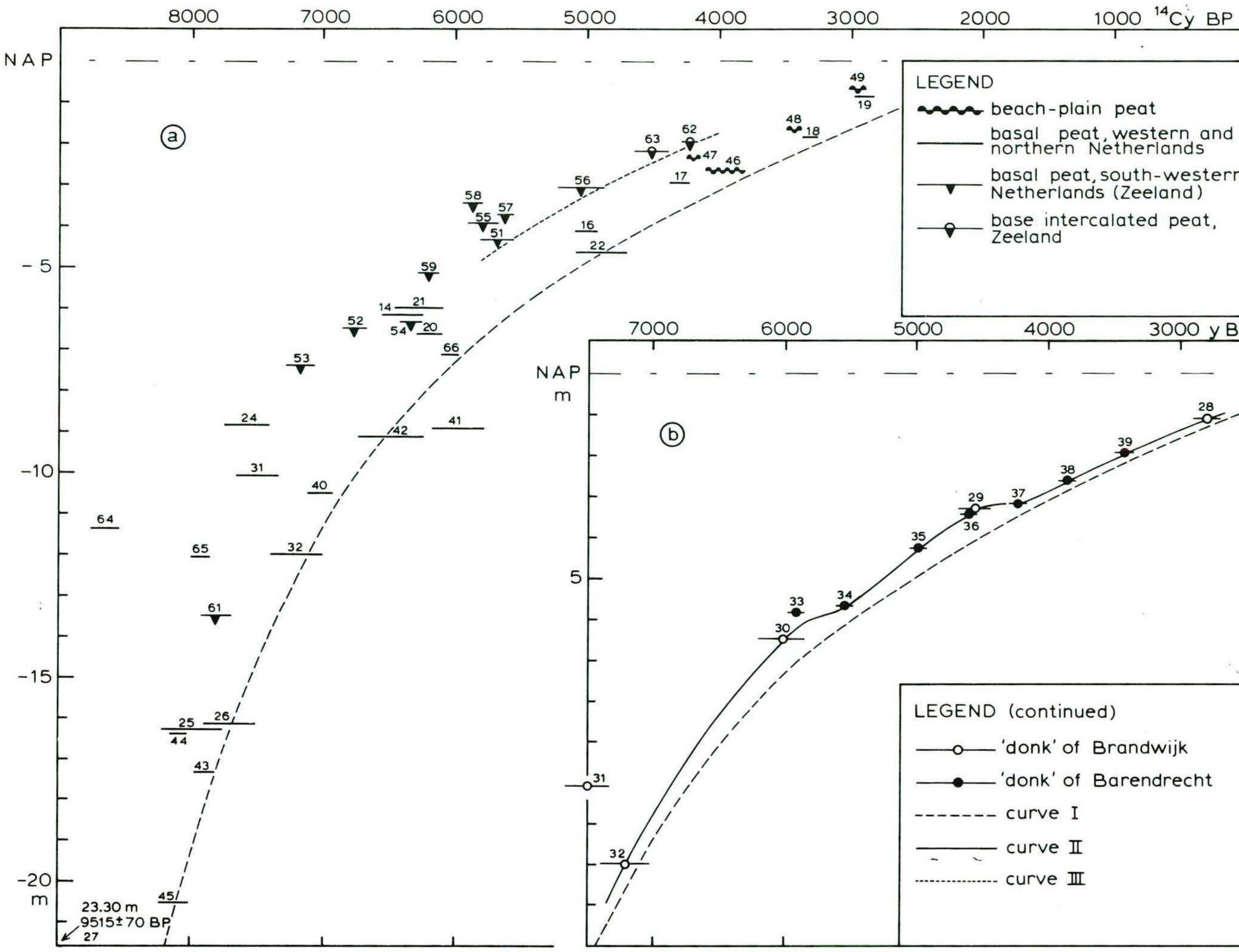


Fig. 14 Time-depth data obtained by Jelgersma (1961).

level than 0.5 m above local groundwater. Thus, either the hydrodynamic concept requires modification or further specification, or curve I, at least parts of it, apparently is an approximation of the rise of MSL or of a level somewhat higher. This alternative interpretation of curve I leads to an equally, if not more acceptable interpretation of the other time depth data:

1. The beach-plain data then indicate former levels between MSL and MHW rather than former MHWS levels. This resolves the problem of explaining the extreme position of two points about 1 m above curve I (MHW).
2. The beginning of basal peat growth at about MSL can be explained in terms of (nearly) complete extinction of the tidal movement in landward direction.
3. The relatively high position of the older Brandwijk data can be accounted for by assuming that reduction of the tidal amplitude inland (flood-depression effect) has been compensated by, as Bennema (1954) pointed out, the slope of the groundwater table in the river area.

A second, more important point of discussion derives from the two assumptions made in constructing curve I:

1. In a humid climate, and providing the Pleistocene surface is sloping and no excessive seepage occurs, the onset of basal peat growth takes place at the level of coastal MHW, and
2. The sampling sites where the youngest c.q. lowest points of the set of basal peat data come from fulfill the conditions for initial basal peat growth at coastal MHW, i.e. for a given depth no younger basal peat sample can be obtained.

Both assumptions require close scrutiny as to whether, on the basis of available geo(morpho)logical, paleogeographical, and other information, (a) the curve should be drawn below a given youngest c.q. lowest time-depth point or, (b) if this is not the case, whether the assumed significance (MHW) is supported by the available (field-)data. These questions can best be treated as part of the more general problem of understanding the (relative) time-depth positions of all basal peat data that are in principal suitable for estimating former sea levels. For organizational reasons this matter is analyzed in a separate paragraph (4.2.4.). It appears from that analysis that sufficient grounds can be established to conclude that the true MHW curve should lie below the basal peat samples from Velsen and IJmuiden-V (index points 26 and 45, fig. 15). With respect to the

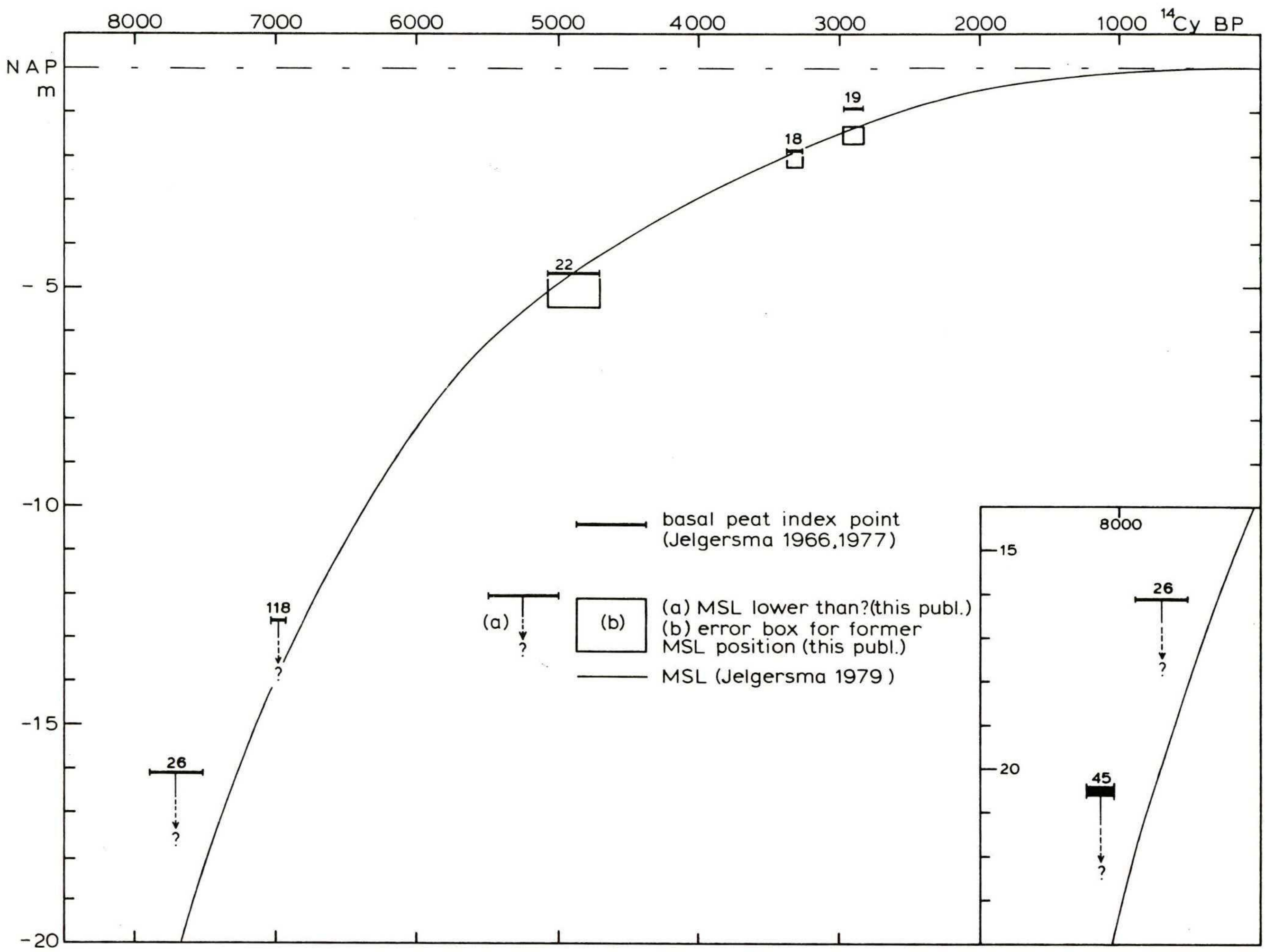


Fig. 15 Estimates and indications of former MSL stands based on reassessment of basal peat data collected by Jelgersma (1961).

significance of other youngest c.q. lowest basal peat data it is concluded that the sample from Koegras (index point 22, fig. 15) represents a former water level anywhere between MHW and slightly above MSL; furthermore, that the most attractive interpretation of the two younger Winschoten samples (index points 18 and 19, fig. 15) is that the older one represents a water level between about MSL and MSL+0.4 m, while the younger one indicates former local MHW. Assuming in the latter case a local tidal range of 0.6 ± 0.2 m, MSL may have occurred between about -1.3 and -1.7 m NAP.

Figure 15 shows that the results of the above evaluation of the basal peat data collected by Jelgersma (1961, 1966) support the change in meaning and trend represented by her 1979 graph. No attempt is made to derive MSL positions from the 'donken' data for the reason that the changing effect of the river gradient through time is unknown. We therefore take the approach of first establishing a MSL curve on the basis of which the gradient effect for different sites and times may be approximated (see chapter 5). With respect to the four youngest time-depth points from the 'donken' it suffices to mention here that these probably indicate former water levels between MSL (or slightly above) and coastal MHW depending on the combined result of the flood-depression and river-gradient effects.

4.2.3.4. THE 1979 GRAPH

The course of this curve between 8000 and 6000 BP is largely determined by a new basal peat date: sample Zwaagdijk-oost (index point 118 in fig. 15). This sample consisted of the lowermost 2 cm of a *Phragmites* peat layer overlying a forest soil. Pollen analysis of the sample has shown a high value for *Sphagnum*. According to De Jong (pers. comm.) the *Sphagnum* indicates the death of the forest, and the sample is interpreted to represent approximately the actual drowning of the site. In view of the paleogeographic situation (fig. IV-38 in Jelgersma et al., 1979) it may be assumed that the sample represents a groundwater table above MSL. How much above it is unknown.

4.2.4. Evaluation of basal peat data[2]

4.2.4.1. INTRODUCTION

In this paragraph an analysis is made of the (relative) time-depth positions of basal peat data published by Jelgersma (1961, 1966). Formal reasons for this analysis have been given in 4.2.3.3. The initial reason, however, has been the close relationship found to exist (Van de Plassche, 1979b) between time-depth position of five basal peat samples, collected at random in N.E. Friesland (Griede, 1978), and their location with respect to substrate morphology (fig. 16). The two Friesland points which coincide with Jelgersma's curve I have been obtained from elevated, well-drained parts in the former landscape, whereas each of the remaining Friesland samples were collected at sites which were favourable for the concentration of surface and/or seepage water. This could explain the early onset of peat growth at these locations. Thus, the question was raised: to what extent can the relative time-depth position of the basal peat samples collected by Jelgersma be explained in similar terms?

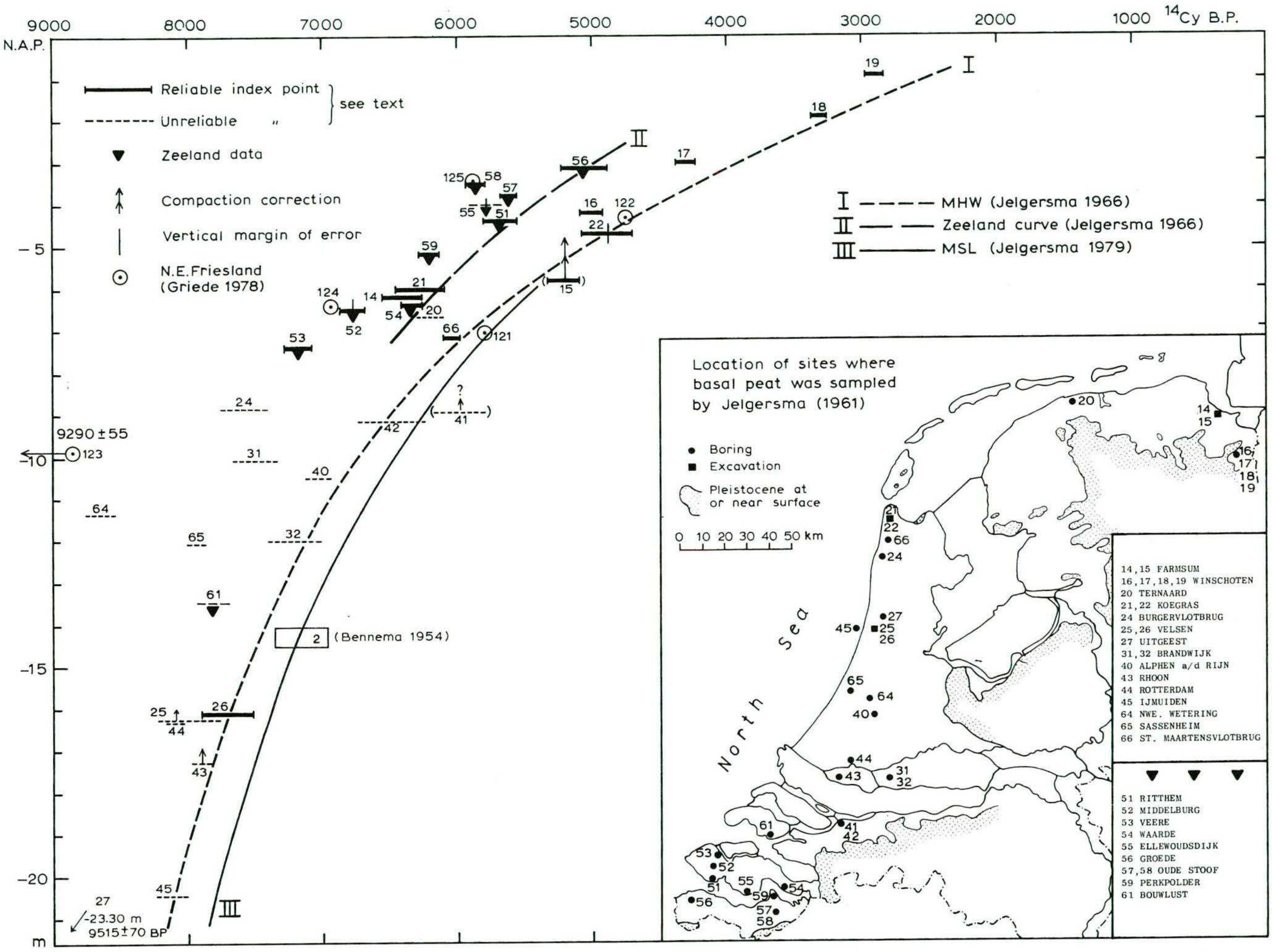


Fig. 16 Time-depth plot of basal peat data published by Jelgersma (1961, 1966) and Griede (1978). Criteria for determining suitability of the index points for estimating former sea-level stands are discussed in the text. Curve III, which merges with the younger part of curve I, is not mentioned, but is included for comparison. (Index points 41 and 42: Willemstad I and II.)

4.2.4.2. COLLECTION OF BASAL PEAT DATA

Jelgersma's principal concern was to avoid sampling peat that might have grown independently of the sea-level-controlled groundwater level. Care was taken to ensure that most samples consisted of eu-/mesotrophic peat (fen or fen-wood), collected at sites where the Pleistocene sub-surface was known to be sloping and underlain by a permeable soil. The slope of the substrate was studied by borings which varied from several hundred metres to occasionally a few kilometres apart. The Pleistocene relief was known in more detail in the Province of Zeeland, where the Geological Survey had carried out extensive mapping. The best insight into local sub-surface features was obtained from excavations at Velsen, Koegras, and Farmsum, (for location see fig. 16). Thirteen, samples were taken from isolated borings.

The 34 basal peat time-depth data obtained by Jelgersma are listed in table I.

4.2.4.3. EVALUATION OF THE BASAL PEAT DATA

Jelgersma considered index points 43, 44, 64, 65, 40, 32, 41, 61, and 55 (see fig. 16) to be less suitable for estimating former sea levels since the samples were obtained from isolated borings. The possibility cannot be excluded, therefore, that the peat was

Table I *Time-depth data plotted in fig. 16/radiocarbon dates used in text*

no.	location/name of sample	GrN-	14C-age 1)	altitude in m below NAP	dated material
14	Farmsum B1	621	6420 ± 145	6.17- 6.20	fen-wood peat
15	Farmsum B2	637	5210 ± 150	± 5.77- 5.80	peaty clay
16	Winschoten 518	1091	5010 ± 80	4.19- 4.23	fen peat
17	Winschoten 515	1088	4310 ± 75	2.98- 3.03	fen peat
18	Winschoten 513b	1090	3310 ± 60	1.87- 1.92	fen peat
19	Winschoten 512	1089	2910 ± 70	0.90- 0.94	fen peat
20	Ternaard 14	606	6255 ± 140	6.62- 6.65	*Sphagnum-Eriophorum* peat
21	Koegras I	455	6280 ± 85	± 6.00- 6.02	fen peat
22	Koegras II	476	4885 ± 190	± 4.70- 4.72	fen peat
24	Burgervlotbrug	1123	7570 ± 65	± 8.88- 8.91	peat (oligotrophic?)
25	Velsen	165	8000 ± 230	16.23-16.24	sandy peat
26	Velsen	161	7705 ± 200	16.10	*Alnus* roots
27	Uitgeest	1054	9515 ± 70	23.25-23.30	gyttja with *Phragmites*
31	Brandwijk 8	186	7200 ± 210	11.96-11.98	fen-wood peat
32	Brandwijk 6	201	7500 ± 170	10.04-10.08	fen-wood peat
40	Alphen	2619	7030 ± 100	10.48-10.51	fen peat
41	Willemstad I	228	6000 ± 130	8.89- 8.92	peat
42	Willemstad II	240	6485 ± 250	9.11- 9.15	detritus
43	Rhoon	2180	7900 ± 75	± 17.22-17.28	fen-wood peat
44	Rotterdam	2177	8090 ± 70	± 16.23-16.26	fen peat
45	IJmuiden	2274	8130 ± 100	20.40-20.50	fen peat
51	Ritthem	405	5680 ± 120	4.40- 4.44	fen peat
52	Middelburg	1626	6760 ± 85	± 6.49- 6.52	fen peat
53	Veere	1580	7170 ± 90	7.43- 7.46	fen peat
54	Waarde	1121	6330 ± 85	6.38- 6.40	fen peat
55	Ellewoudsdijk	1571	5780 ± 70	± 4.05- 4.09	peat
56	Groede	187	5060 ± 180	3.13- 3.15	fen peat
57	Oude Stoof 4	1048	5850 ± 55	3.50- 3.54	fen peat
58	Oude Stoof 3	1042	5615 ± 65	3.77- 3.80	fen peat
59	Perkpolder	1045	6200 ± 70	5.20- 5.25	fen peat
61	Bouwlust	2283	7810 ± 100	13.48-13.55	sandy humif. peat
64	Nwe. Wetering	1618	8660 ± 110	11.34-11.38	fen peat
65	Sassenheim	792	7930 ± 60	12.02-12.07	fen peat
66	St. Maartens-vlotbrug	1633	6040 ± 60	7.17- 7.22	fen peat

Top of Lower Peat

Koegras II	(Jelgersma 1961)	GrN-1060	4920 ± 80	fen peat
Velsen	(Bennema 1954)	GrN- 75	7100 ± 200	wood

1) All ages have been corrected for 13C by substracting 40 years (Mook, pers. comm.)
Offical (previously published) ages are obtained by adding 40 years.

no. = number of index point

formed in a local depression independent of the regional groundwater level. Moreover, she pointed out that in the case of index points 43 and 44 the samples were underlain by clay and sandy clay respectively, which not only may have caused some lowering of the peat due to compaction, but may also be responsible for local peat growth. Furthermore, index points 64, 65, and 40 are located in an area where the Pleistocene surface is sub-horizontal, and drainage conditions were probably very poor. Also, according to Jelgersma (pers. comm.), the samples Willemstad I and II (points 41 and 42) consisted respectively of peat and an admixture of sand, wood, and clay and not of wood and fen-wood peat as stated in her thesis (Jelgersma, 1961, p. 35). Sample Willemstad I was probably disturbed during coring operations due to high groundwater pressure (Zagwijn, pers. comm.).

Index point 27 was considered unreliable for estimating former sea level since the sample came from a broad depression in which peat growth which was unrelated to sea level may have occurred. This, according to Jelgersma, is supported by the absence of diatoms indicative of a brackish environment. For the same reason she discarded sample Burgervlotbrug (no. 24).

Index point 20 was also regarded as unsuitable since the peat consisted of *Eriophorum* and *Sphagnum* sp. remains.

With respect to point 25 she argued that the given date is probably too old due to contamination by material from the top of the underlying soil.

The following time-depth points were thus considered to be sufficiently reliable: 14, 15, 16, 17, 18, 19, 26, 51, 52, 53, 54, 56, 57, 58 and 59. Jelgersma made no special remarks concerning samples 21, 22, 45, and 66.

A few remarks may be made to the above evaluation. Sample IJmuiden (no. 45) was obtained from an isolated boring and therefore should also be considered less reliable for former sea-level stand derivation.

It is invalid to reject index point 24 solely on the ground that brackish diatoms were absent in the sample since the diatom content of other reliable samples has not been investigated. Du Burck (1959, p. 67), however, mentions that the Lower Peat at Burgervlotbrug contains many remains of oligotrophic species.

Index point 15 does not represent a basal peat sample; it is in fact a humic clay sample taken 0.4 m above the base of the Lower Peat (Jelgersma, 1960).

In summary, the following time-depth data can in principle be considered suitable: south-western sector: 51, 52, 53, 54, 56, 57, 58, and 59; western and northern sectors: 14, 16, 17, 18, 19, 21, 22, 26, and 66.

4.2.4.4. METHOD OF CURVE CONSTRUCTION

As stated in 4.2.3.2. curve I (fig. 16) is based on the assumption that peat growth locally (on the gently seaward sloping Pleistocene surface) may have taken place above MHW: hence, '... only the points located in the lowest places for a given age, or even slightly lower, represent a groundwater table which coincides with high tide level' (Jelgersma, 1961, p. 45). From this line of reasoning, which can be exercised without consideration of the earlier evaluation

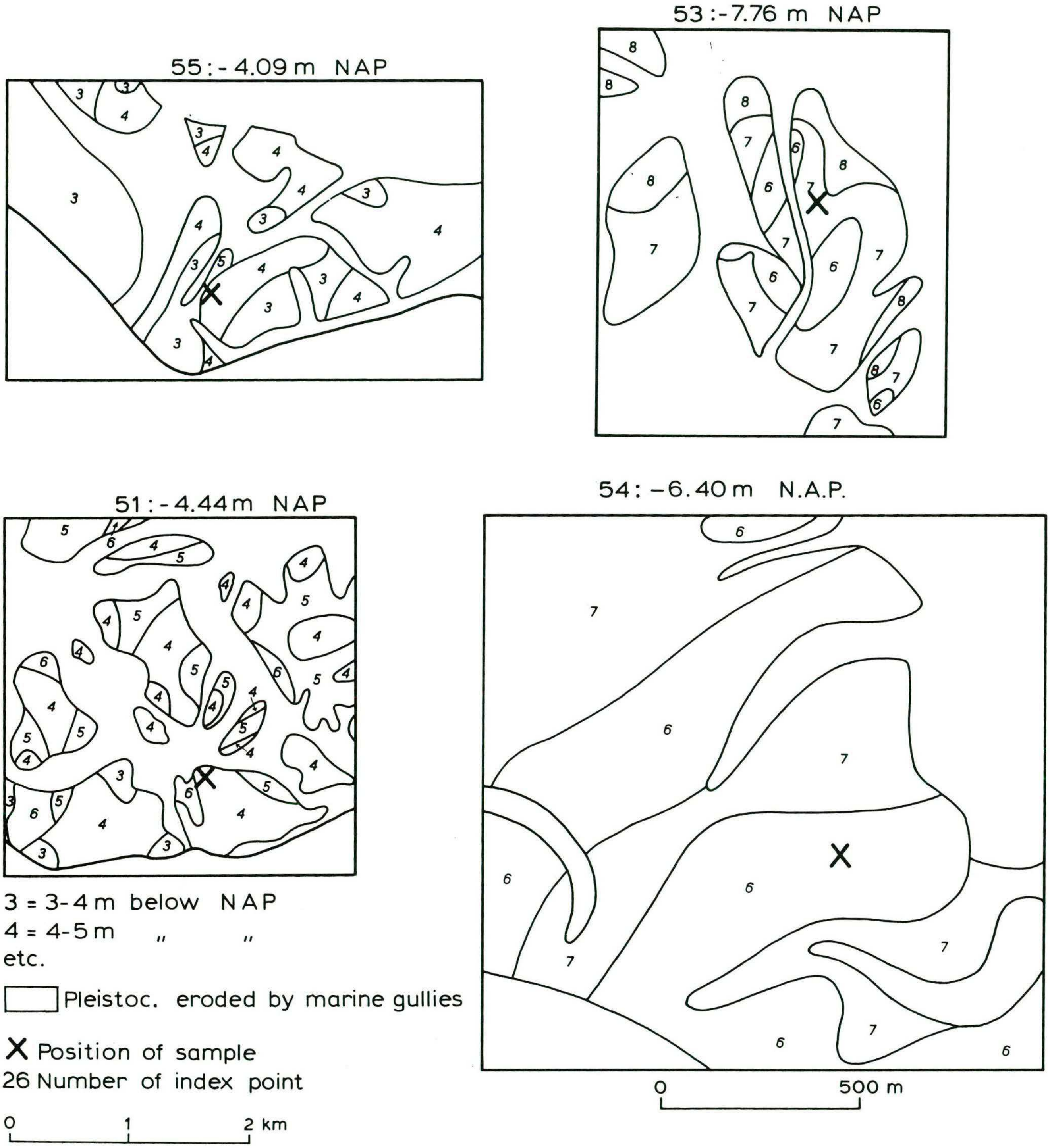


Fig. 17 Maps showing location of some of the basal peat samples from Zeeland with respect to surrounding substrate topography (depth contours from maps produced by the Geological Survey).

of the individual time-depth data, it follows that '... all aberrations are considered as errors and not as fluctuations of sea level'. This statement can also be considered to apply to the position of the Zeeland data relative to curve II. From figure 16 it can be concluded that, in terms of this method of curve construction, index points 16, 17, 19 and 52, 53, 57, 58, and 59, which were all considered as suitable for sea-level height reconstruction in principle (see above), must now be considered in 'error'. As the peat composition of the samples is the same, it seems that the explanation of discrepancies should be sought in the location of samples with respect to (local) topography of the substrate.

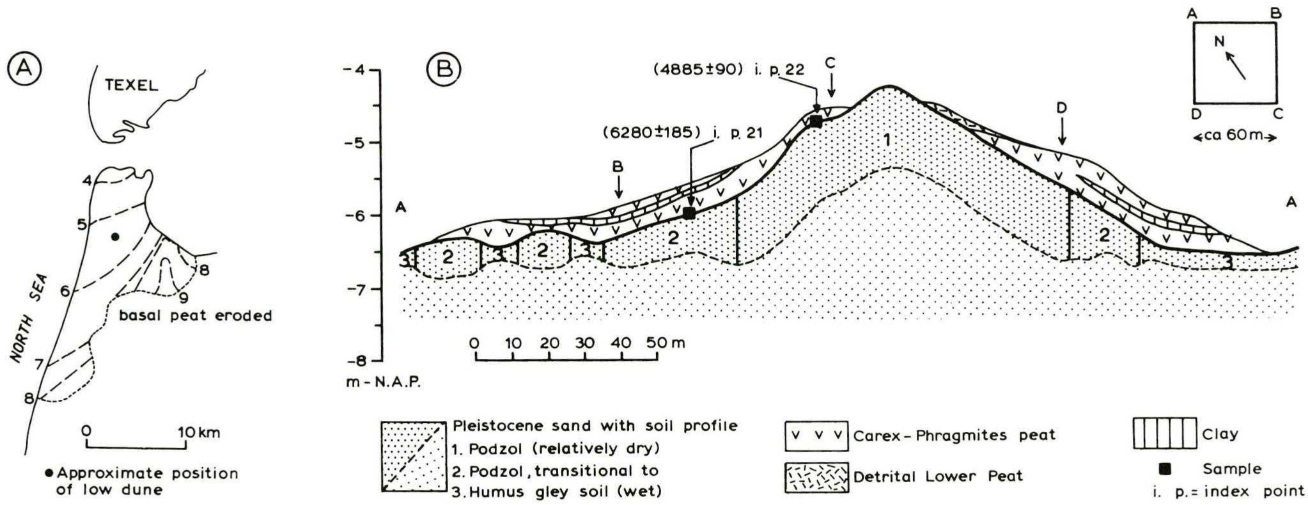


Fig. 18 Schematic corss-section representing in one plane the four faces of a building pit near Julianadorp, North-Holland. The section shows a low dune largely covered by Lower Peat. (After Du Burck, 1959.)

4.2.4.5. FACTORS WHICH DETERMINE THE RELATIVE TIME-DEPTH POSITIONS OF THE BASAL PEAT DATA

South-western sector

Van Rummelen (1965, 1970, 1972, 1978) published 1 m-interval depth-contour maps (scale 1:100.000) of the Pleistocene sub-surface relief in the Province of Zeeland. Locations where basal peat samples were collected by Jelgersma have been plotted on these maps (examples are shown in figure 17). It appears that all index points which do not lie on curve II (52, 53, 55, 57, 58, and 59) are located in topographic positions which are relatively favourable for the concentration of surface and/or seepage water. The opposite holds true for index points 51, 54, and 56. It is concluded, therefore, that there is a remarkably close relationship between relative time-depth position of the index points and the general topographic situation of the sample localities. Even if for one or two index points (e.g. no. 55) this relationship is co-incidental, it suggests again a strong influence of existing (general) relief on the height of the (local) groundwater table, and probably therefore, also on the time of basal peat growth commencement.

Western Netherlands

No evaluation of the St. Maartensvlotbrug sample (no. 66) is attempted because of insufficient detailed data on the surrounding Late-glacial/early-Holocene relief.

Points 21 and 22 have been obtained from a building pit at Koegras, for which detailed information is available on the local cover-sand morphology and former soil-hydrological conditions (Du Burck, 1959). A schematic cross-section of the pit is given in figure 18. The main features shown by the section are a low dune overlain by a peat bed, containing an intercalated clay bed of fresh-water origin, and overlain by marine sediments. The local topography is superimposed on a sloping Pleistocene surface which dips from −4 m NAP (Dutch Ordnance Datum) in the NW to −7 m NAP in the SE over a distance of c. 10 km (Pons and Wiggers, 1958; Ente, Zagwijn, and Mook, 1975; fig. 18). Wet conditions already existed before the onset of peat accumulation at the foot of the dune, as indicated by soil profiles in the sand, and explains the position of index point 21 at about 2.5 m above curve I. However, this sample does not come from the lowest part of the relief but from the sloping foot of the dune 0.35-0.7 m above the base of local depressions. This suggests that the time-depth position of the sample cannot be understood in terms of local peat growth alone (see below). In the case of index point 22, height of the groundwater level was certainly not influenced by existing relief. It must therefore have been a function of the local tidal range and/or (if that tidal range was nil) the slope of the regional groundwater table. At the sites of index points 21 and 22 the *top* of the Lower Peat has been dated as 4830±100 and 4950±50 BP respectively (Jelgersma, 1961, p. 29); the mean of these dates is 4920±80 BP (Grn-1060). Therefore, at the time that the (basal) peat of sample 22 was formed (4885±90 BP), clay deposition took place nearby. It can thus be assumed that peat growth began at a level which was between about MHW and MSL dependent on the amplitude reduction of the tidal wave on its passage from the open coast to the site under discussion. (Paleogeographic evidence for the region (Ente, Zagwijn and Mook, 1975) suggests that an increase in tidal amplitude in a landward direction is not probable.)

A large excavation at Velsen supplied the only reliable index point at a depth greater than −8 m NAP (no. 26). It also provided detailed data on the irregular topography of the Twente Formation and the closely related distribution of dry, wet, and intermediate soil profiles (Pons, 1959; fig. 19). In the north-eastern corner of the pit a sample was collected of *Alnus* roots preserved in the cover sand (Van Straaten, 1954). Since only wet and intermediate soil profiles occur in that part, it is possible that the *Alnus* trees grew above the lowest possible level of peat growth in the

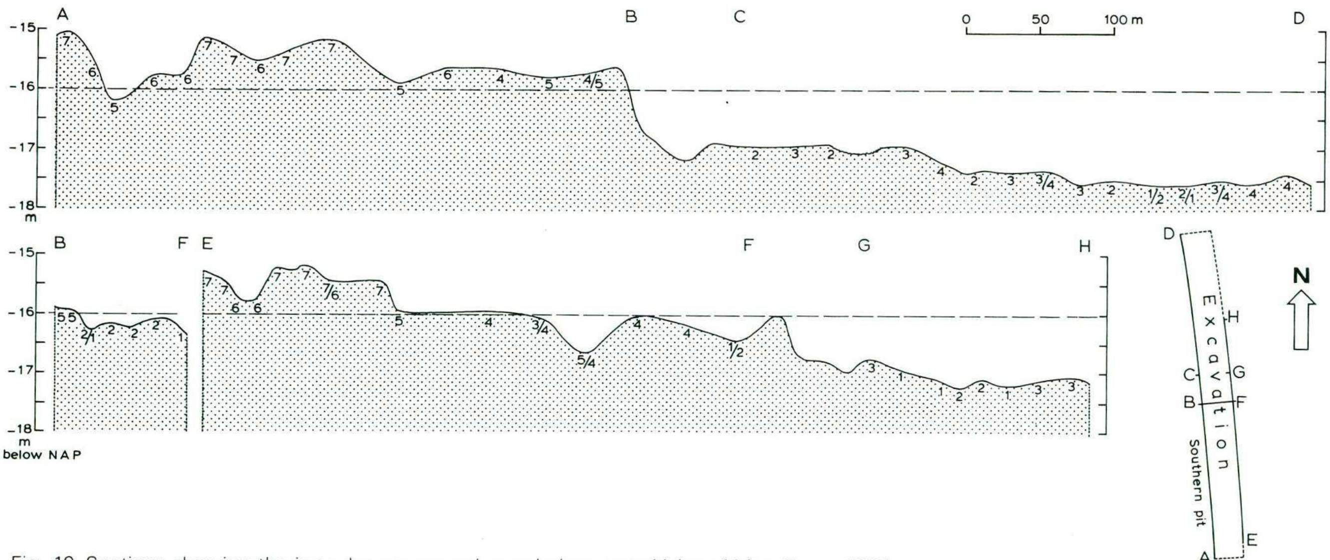


Fig. 19 Sections showing the irregular cover-sand morphology near Velsen (After Pons, 1959).

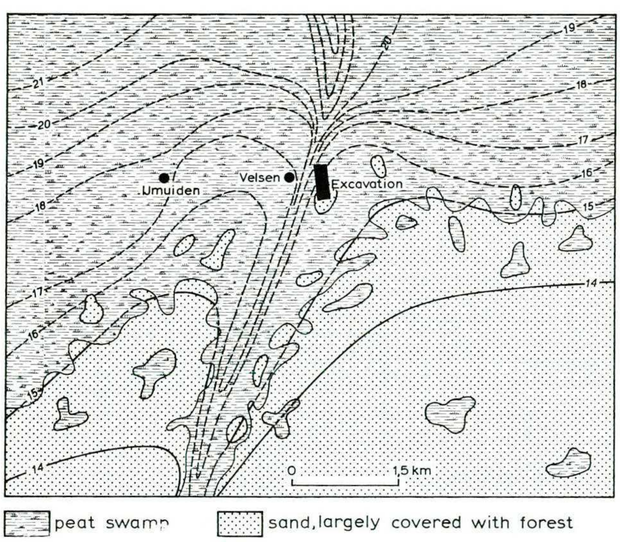


Fig. 20 Tentative paleogeographic reconstruction in the IJmuiden-Velsen area at about 8000 BP. Five km to the west of IJmuiden the top of the peat swamp cannot have reached much higher than c. − 18 m NAP, which is about 1.5 m lower than at Velse.

surrounding area at that time, given also the evidence of index point 21. Pollen diagrams (Doppert, 1957) indicate that the site had a high groundwater table at an early stage and that in local, shallow depressions peat growth had already taken place in the late Boreal.

A pollen section of the Lower Peat sampled 5 km west of IJmuiden harbour (site IJmuiden-V) demonstrates a clear Boreal-Atlantic transition at a depth of c. − 20.25 m NAP, c. 0.25 m above the cover sand (Jelgersma, 1961, Plate I). Assuming 87.5-89% compaction, the altitude of the Lower Peat surface at that time (c. 8000 BP) and location is thus estimated to be at about − 18.25 − 18 m NAP. It is evident from the pollen diagram that the peat at that time was formed in very shallow water. As such, local water level cannot have been much higher than − 18 m NAP.

The − 18 m NAP contour line of the Pleistocene sub-surface approaches the excavation site at Velsen to within 500 m, due to the presence of a former natural drainage channel in the sandy substrate (fig. 20). The proximity of the Velsen site to the drainage channel, in which early peat growth may have taken place, has probably influenced the height of the local groundwater table, thus explaining the late Boreal peat growth in shallow depressions. By about 8000 BP, however, the entire excavation site, except for parts higher than c. − 16.3 m NAP, had turned into a peat swamp (Florschütz, 1944; Doppert, 1957). Yet, at the sampling site 5 km from IJmuiden harbour the surface of the Lower Peat cannot have been much above − 18 m NAP at that time. Since this height difference cannot be explained in terms of water depth, it is concluded that in this region the 8000-BP surface of the Lower Peat was sloping gently upwards in the direction of the land. It is not certain to what extent this slope can be connected with the above mentioned drainage channel. In our opinion this has been of secondary importance, since it can be argued that the origin and maintenance of a sloping peat surface is primarily a function of sufficient supply of fresh (seepage) water. The presence of fresh-water clay in the basal part of the Lower Peat at Velsen suggests that this condition has been amply fulfilled. A tentative paleogeographic reconstruction of the IJmuiden-Velsen area at the beginning of the Atlantic is given in figure 20.

The consequence of a sloping Lower Peat surface at about 8000 BP on the interpretation of index point 26 is difficult to determine; firstly, because of the large standard deviation of the date (± 200 years), and secondly, because it is not known how the configuration of the surface slope changed with the continuing sea-level rise and the accompanying landward migration of the belt of peat formation. However, the hypothesis of a sloping peat surface maintained by seepage is adequate reason to seriously consider the possibility that the *Alnus* tree grew above contemporaneous MHW level. It is equally clear that the altitude of index point 45 (base of Lower Peat at

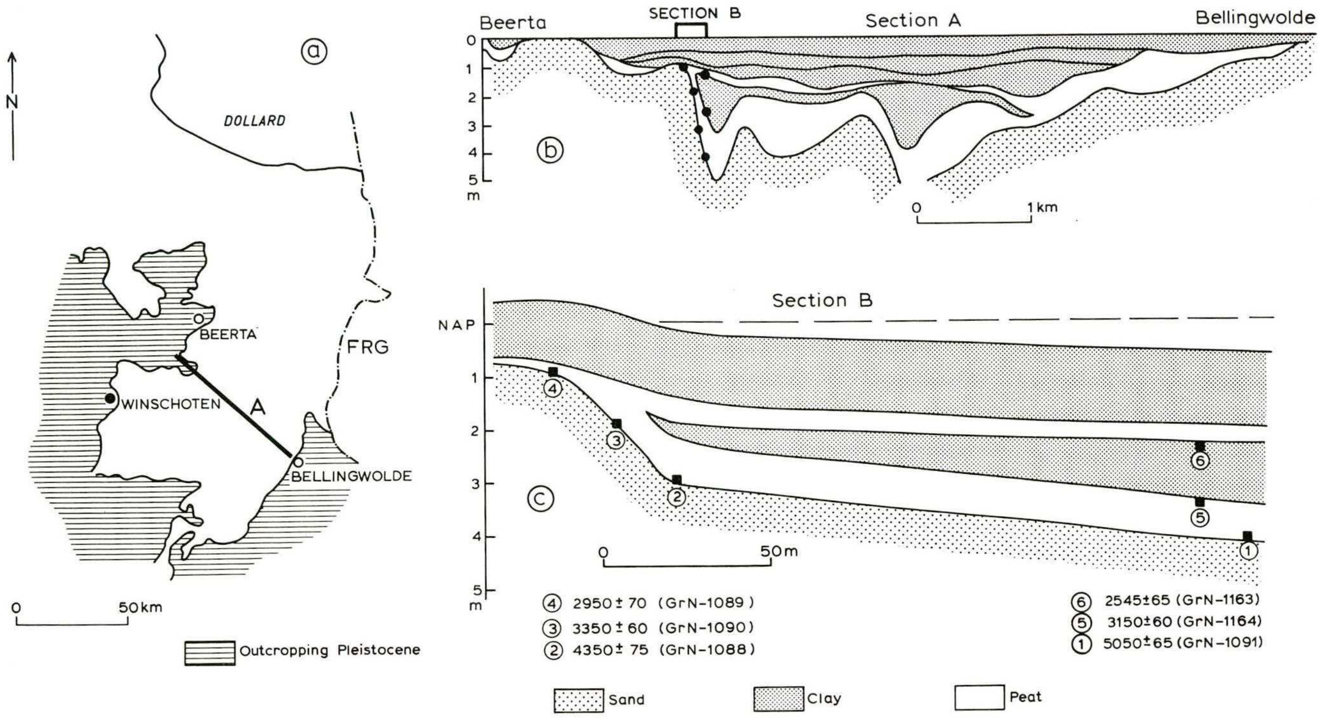


Fig. 21 (a) Location map of cross-section A; (b) lithostratigraphy of Holocene deposits and position of radiocarbon dated samples (after De Smet, 1962); (c) detail of section A (after Jelgersma, 1961); note that at the time of peat growth at the spot of sample 3 (index point 18 in fig. 16) the embayment constituted an extensive peat marsh, whereas during the onset of peat growth at the site of sample 4 (index point 19 in fig. 16) open water conditions occurred nearby.

IJmuiden-V) may also demonstrate a sloping-peat-surface effect.

The time-depth position of index point 21 could not be satisfactorily explained in terms of sample location alone (see above) and may perhaps also be attributed to a previously sloping (basal) peat surface.

Northern coastal sector

The sample of index point 14 has been taken from a broad drainage depression, judging from the Pleistocene depth map for the north-eastern Netherlands (Roeleveld, 1974), and this may account for the early peat growth there.

The question may now be raised with regard to the four Winschoten samples (16-19) as to why three of the four plot above curve I. All four samples have been taken from the flank of a north-east dipping depression in the Pleistocene subsoil which was moderately deep and several kilometres wide (fig. 21a and b). Within this embayment there are two smaller valleys and the two deepest Winschoten samples were collected at the foot of the northern slope of the northernmost valley (fig. 21b). This, combined with the limited width of the valley and the receipt of run-off and seepage from several directions, may explain peat growth at a relatively high elevation.

By the time peat formation had commenced at the level of index point 18 most of the embayment had become an extensive reed swamp or fen marsh in which the Pleistocene morphology exerted little influence on the height of the groundwater table. The same situation also applies to index point 19, but in the meantime several gullies, from which a calcareous clay was deposited, had penetrated the embayment to beyond the sampling site (De Smet, 1962, fig. 21c). It is attractive to explain the time-depth position of the two younger Winschoten samples on the basis of this difference in paleogeography, which can also be expected to have influenced the local tidal range. In the case of no. 18 it is assumed that local tidal range was small because of the presence of a fen marsh in front of the sampling site, which must have had a strong frictional effect on the progression of the tidal wave. Local tidal amplitude will have increased when the influence of the sea extended into the peat area and open water conditions occurred very near the spot concerned. Thus, in the absence of other disturbing factors, one may interpret the two younger Winschoten samples as: index point 18 representing commencement of peat growth at or slightly above MSL and index point 19 indicating a former (local) MHW level. This interpretation assumes a gradual (smooth) sea-level rise over the period concerned.

4.2.4.6. CONCLUSIONS

The introduction to this sub-chapter reflects our preoccupation with pre-existing sub-surface topography as the principal explanatory factor in understanding the time-depth position of basal peat data. This emphasis originated when it appeared that the time-depth position of five basal peat samples randomly collected in north-eastern Friesland (Griede, 1978) could be satisfactorily explained in terms of sample location with respect to substrate morphology. It was further strengthened when, in the case of data from Zeeland, it was found that samples collected from relatively low-lying parts in the pre-existing relief occur higher in the time-depth diagram than samples collected from sites much less likely to receive surface and/or seepage water.

However, examination of available information from the Velsen-IJmuiden area now suggests that the influence of sub-surface topography may explain only part of the relationships. It is clear that, in this area at least, the prime condition for development of a coastal peat formation zone was the supply of fresh (seepage) water (cf. De Vries, 1974), such that the peat crept up the sandy subsoil resulting in development of a sloping peat surface. This surface may intersect both convex and concave parts of the drowning relief at the same time. If, therefore, the basal peat in Zeeland also possessed a sloping surface, the close relationship between sample location with respect to sub-surface topography and time-depth position may be largely accidental (see also 8.1.7.).

It is concluded from the discussion of index points 18, 19 and 22 that if topography plays a subordinate or negligible role and supply of fresh-water is moderate or small, the main factor which determines the level of initial peat growth is the local tidal range.

Basal peat may develop a local or regional slope, implying that peat growth may commence well above coastal MHW without being entirely independent of sea level. In the case of index point 40, 64, and 65, and probably of no. 24, basal peat growth occurred unrelated to sea level.

4.2.5. Louwe Kooijmans

4.2.5.1. INTRODUCTION

It was not until Louwe Kooijmans (1974) published a new, and rather provocative, MHW curve (fig. 22), based entirely on estimates of former water levels at archaeological sites, that an element of competition entered into the scene of sea-level studies in the Netherlands, which until then had been 'monopolized' by Jelgersma's graph. And when in the same year Roeleveld (1974) produced, according to a completely different method, a MHW curve that showed great similarity to Louwe Kooijmans' curve, it seemed certain that Jelgersma's graph would have to be put to discussion. Although one year later Jelgersma et al. (1975) would state that her curve represented the rise of MSL rather than of MHW, it was Louwe Kooijmans' idealized, interpretative, stepped curve that evoked more discussion. He responded to this with a paper (Louwe Kooijmans, 1976) in which he stated that the steps in his 1974 graph were not essential, and gave a new, smooth curve for the rise of MSL based on a selection of the most suitable data (see below). The difference in interpretation of mostly the same data can be attributed mainly to his modified conception of the behaviour of the tidal wave as it moved into the estuarine and lagoonal areas. Whereas in his thesis Louwe Kooijmans (1974) 'curtailed' himself by accepting for the floodbasin effect under natural conditions a maximum value of c. 0.3 m, in his later paper this figure may be as large as half the tidal range at the coast (complete extinction of the tidal wave inland).

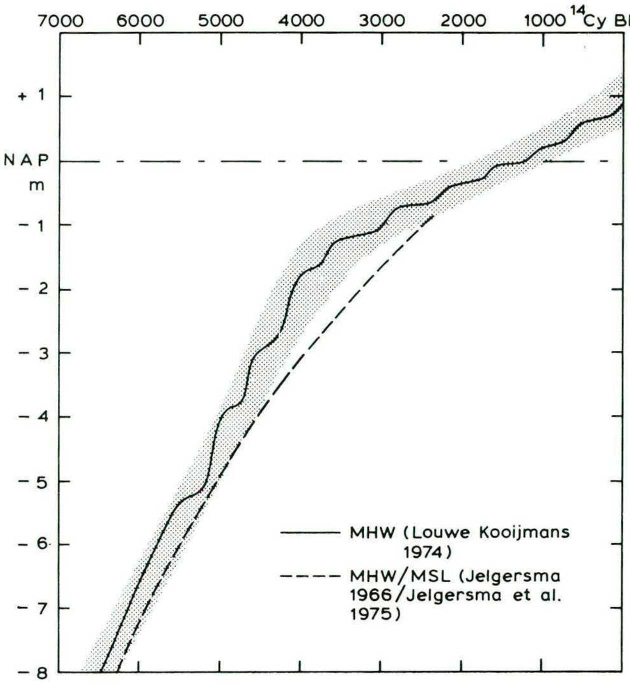


Fig. 22 Time-depth diagram with interpretative, stepped, coastal MHW curve for the western Netherlands by Louwe Kooijmans (1974). Stippled zone contains dated local MHW levels.

4.2.5.2. THE 1974 GRAPH

For Louwe Kooijmans (1974) the theme of sea-level changes was a subsidiary subject in his extensive study on the prehistoric occupation and Holocene geology of the Rhine-Meuse delta. Having noted that at archaeological excavations it is often possible to dertermine good approximations of former local water levels just before and/or during the period of habitation, he analyzed suitable data in terms of (changes in) former local MHW. In brief, his method has been to plot (a) age-altitude data of the habitation deposits, in most cases a sediment from a transgressive phase, and (b) habitation data, nearly always belonging to a regressive phase, and then derive for each site a curve indicating the former fluctuation(s) in local MHW (curves 1-9 in fig. 23a). These local curves show that each period of sedimentation was followed by a lowering of the local MHW level. On the basis of these separate curves he graphically constructed his stepped MHW curve for the western coastal area. (For details of the procedure, see Louwe Kooijmans, 1974, p. 55-62).

In order to explain Louwe Kooijmans' step from the local MHW curves to the general MHW curve, the position of the local curves 1-6 has been plotted relative to his, smoothed, MHW curve (fig. 23b). In explaining the sharp changes in local MHW level Louwe Kooijmans has been influenced by measurement data of local MHW levels in the area between the coast and the former fresh-water tidal area of the Biesbos (Zonneveld, 1960, fig. 20). The measurements show that local MHW may reach to 0.4-0.5 m above coastal MHW (due to confinement of the tidal wave), while the flood-depression effect amounts to c. 0.3 m. Louwe Kooijmans accepted that under

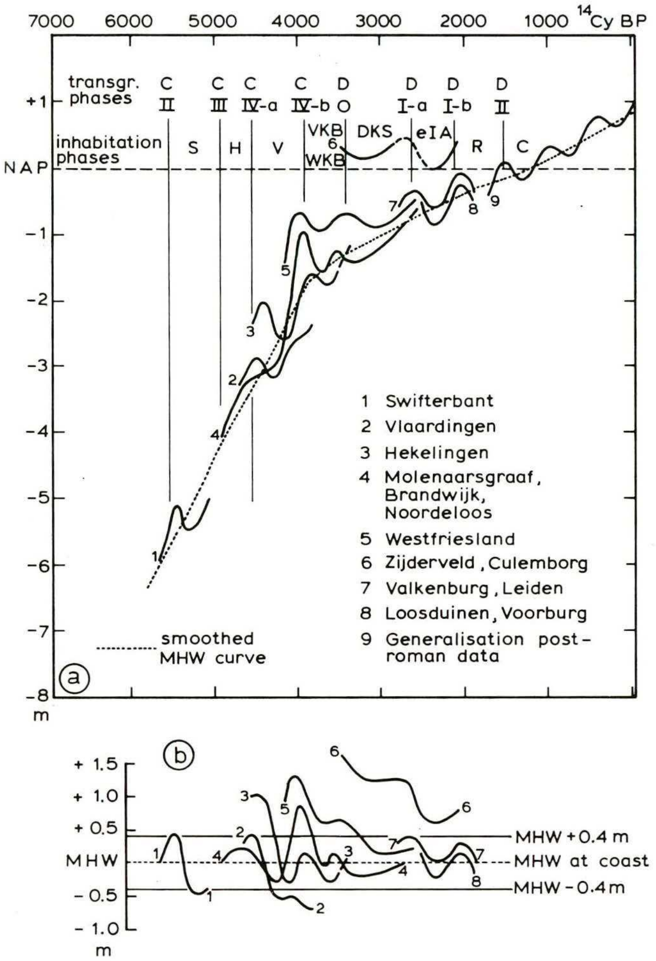


Fig. 23 (a) Time-depth diagram with local MHW curves as determined by Louwe Kooijmans (1974) for some selected archaeological sites or areas of restricted dimensions. His stepped curve has been smoothed. Abbreviations: C = Calais, D = Duinkerke, S = Swifterbant, H = Hazendonk, V = Vlaardingen, VKB = Veluwe Bell Beaker, WKD = Barbed Wire, DKS = Drakenstein, eIA = early Iron Age, R = Roman, and C = Carolingian (from Louwe Kooijmans, 1974).
(b) Plot of local MHW curves depicted sub (a) relative to the smoothed MHW curve. Explanation in text.

natural conditions the intracoastal MHW level could be raised respectively lowered to a maximum of 0.3 m above and below coastal MHW. For the sake of discussion this figure may be extended to 0.4 m. In figure 23b two lines have been drawn representing levels 0.4 m above and below coastal MHW. The figure clearly shows that the local curves do indeed permit an interpretation in terms of an average coastal MHW level around which local MHW levels have fluctuated in the order of magnitude suggested by measurements from a sub-recent environment. Before commenting on this interpretation, it should be mentioned that Louwe Kooijmans attributed, in a qualitative way, the extreme position of curve 6 and the peak in curve 4 at about 4000 BP to the river-gradient effect. An increase in the tidal amplitude behind the coastal inlet near Bergen (North-Holland) is held responsible for the high position of curve 5. The relatively high elevation of the natural levee at Hekelingen (curve 3, c. 4300 BP) remains unaccounted for.

The difficulty in Louwe Kooijmans' interpretation of the local curves lies not in the flood-depression effect during periods of regression, but in how one should conceive a generally raised intracoastal MHW level during periods of transgression. Since a general increase of the tidal amplitude inland is not very likely to occur, it would seem that huge quantities of freshwater are required to obtain this effect. Although the exact influence of variations in river discharge still needs to be evaluated, a much more elegant explanation could be offered when it became apparent that the reduction in tidal amplitude inland may (have) reach(ed) a value as great as half the coastal tidal range (Jelgersma et al., 1975; Ente, 1976). Thus, Louwe Kooijmans realized that, with the exclusion of extremes, the fluctuations shown by the local curves could be explained as having occurred between coastal MHW and about MSL. Or, in terms of figure 23b, the MHW-0.4 m line can be interpreted to approximately indicate the MSL-line (curve), and the MHW+0.4 m line the coastal MHW line (curve). With this in mind, and with a more quantitative conception of the river-gradient effect, Louwe Kooijmans (1976) analyzed the best available archaeological data and arrived at a smooth MSL curve.

4.2.5.3. THE 1976 GRAPH

Louwe Kooijmans' (1976) MSL graph is given in figure 24a. Altitude and vertical margin of error of the time-depth boxes on which the curve is based have been obtained by summing

1. the measured altitude of the sample or indicator,
2. the estimated amount of compaction,
3. the elevation of the sample or feature above local MHW,
4. half the estimated local tidal range, and
5. the river-gradient effect.

The limited number of data and the associated error intervals allow only a smooth curve to be drawn. If the MSL rise has been accompanied by fluctuations, these will have occurred within the stippled zone (fig. 24). Figure 24b compares the graphs of Louwe Kooijmans (1974, 1976) and Jelgersma (1966, 1975).

The MSL curve by Jelgersma (1966, 1975) plots below the lower margin of error between c. 5500 and 2750 BP (fig. 24a). Since Jelgersma's curve is based on basal peat data, and Louwe Kooijmans (1976, p. 140) accepted that these represent points at or above MSL, figure 24a holds a contradiction that invites a re-examination of the time-depth data which Louwe Kooijmans used for the construction of his MSL curve. For the following discussion of index points reference is made to figure 25.

– Index point 76 (Willemstad)

In an excavation near Willemstad a wooden statue was found (Van Es and Casparie, 1968) at a depth of −8 m NAP on a low cover-sand dune, embedded in a thin layer of Lower Peat and in between the roots of a treetrunk. The wood (of the statue) has been dated as 6400 ± 85 BP (GrN − 4922). The preservation of the artifact (and of the treetrunk) indicates that soon after its emplacement at the foot of the tree, the site was rapidly sealed by peat. How long after the wood for the statue was cut this process occurred, however, remains unkown and the time-depth point can only be used to indicate that MSL crossed the −8 m level at a later moment.

– Index point 77 (Swifterbant)

The time-depth position (5610 ± 60 BP, GrN-5067; −6.15 m NAP) of a sample from the base of fen peat on an early-Holocene river dune near Swifterbant (Ente, 1976) coincides with the 1966/1975 MSL curve of Jelgersma. From the paleogeographical situation it can be deduced that a river-gradient effect can only have been very small, and Ente, followed therein by Louwe Kooijmans, accepted that the dated fen peat was formed at MSL. Louwe Kooijmans, (1976), aware of the problem that the significance of the fen-peat sample had been derived indirectly (from Jelgersma's curve), justified the use of this time-depth point by arguing that the close agreement with the trend of the MSL rise as indicated by other data from the Swifterbant site (see index point 78) is an

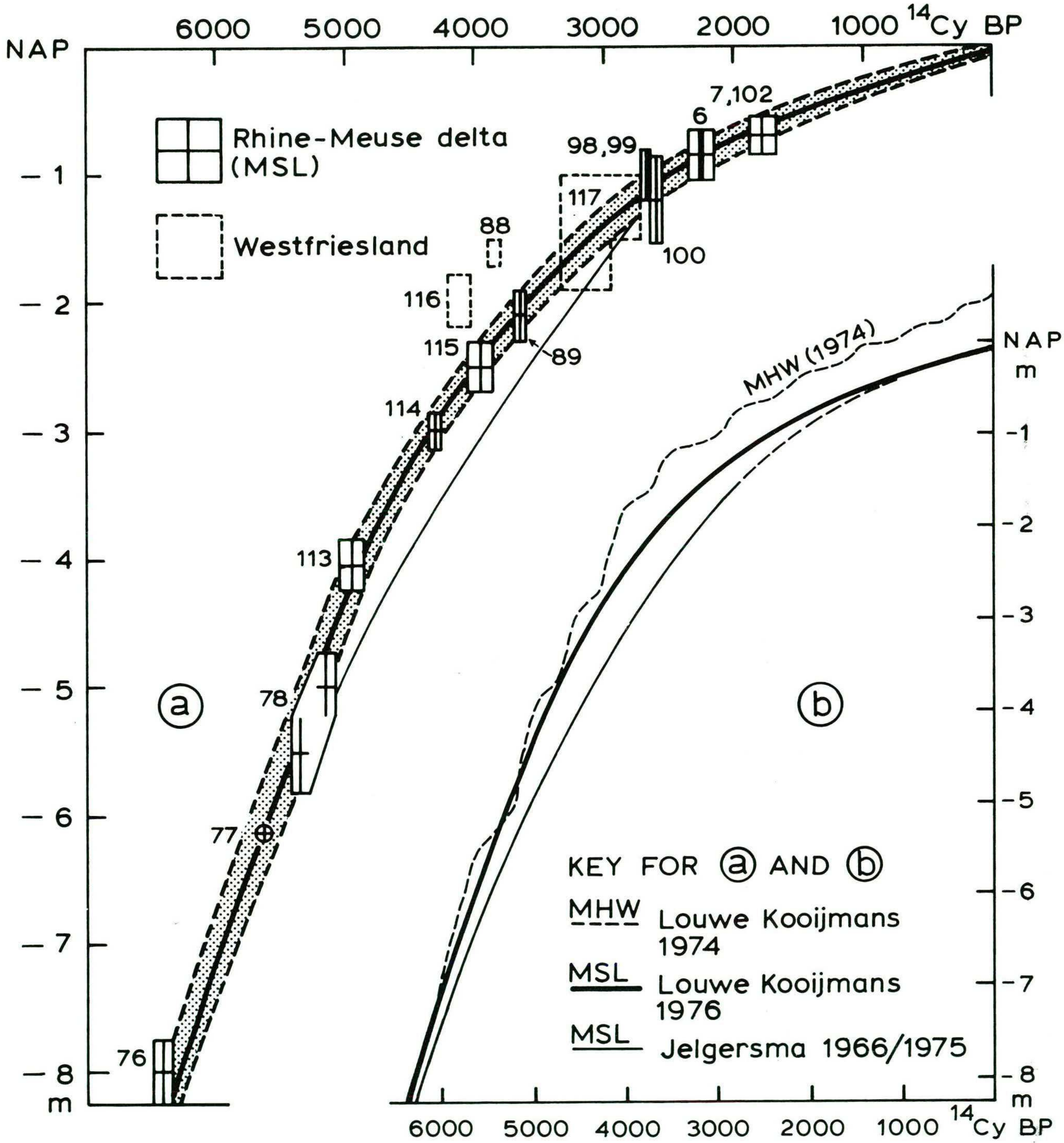


Fig. 24 (a) Time-depth diagram with MSL estimates and MSL curve for the western Netherlands by Louwe Kooijmans (1976).
(b) Louwe Kooijmans' (1976) MSL curve compared to his (1974) MHW curve and Jelgersma's MSL curve.

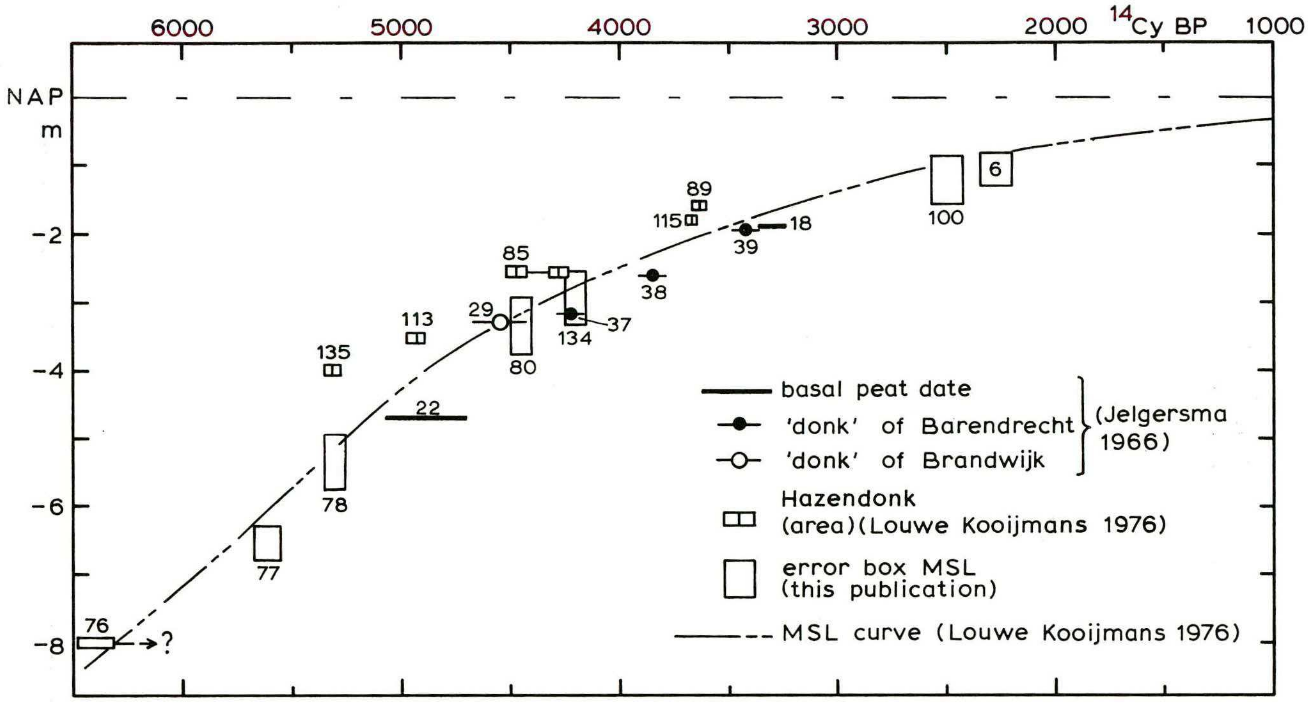


Fig. 25 Diagram with several MSL estimates based on the same data as used by Louwe Kooijmans (1976), and time-depth data relevant to the discussion of Louwe Kooijmans' (1976) MSL curve.

argument in favour of its correctness. It seems possible, however, to evaluate the significance of the fen-peat sample more independently.

The slope of the river dune is covered with a continuous layer of fen peat, indicating that peat growth kept pace with the sea-level rise. At about 5600 BP the landscape in the surrounding area of the dune consisted of a well-developed system of tidal creek levees and backswamp basins (Hacquebord, 1976; Ente, 1976). It may thus be assumed that the area experienced tidal influence. If the upper limit of fen-peat growth is taken at MSL it implies that in the zone between MSL and local MHW no peat-forming vegetation occurred. In our opinion this is not very likely and it is assumed here that fen-peat growth took place at or close to the local MHW level. The local tidal range at that time is not known, but can safely be assumed to have been smaller than at the coast, say 0.7 ± 0.3 m. Thus, allowing for a very small gradient effect (0–0.1 m), MSL at about 5600 BP may have occurred at $-(6.15 \pm 0.05) - (0.05 \pm 0.05) - (0.35 \pm 0.15) = -6.55 \pm 0.25$ m NAP.

– Index point 78a (Swifterbant)

The maximum observed altitude of the top of a major tidal creek levee near Swifterbant amounts -5.15 m NAP (Ente, 1976). The clayey levee deposits are half ripened and have a thickness of over 3 m, indicating gradual silting up in pace with the sea-level rise during a considerable period of time. The deposit overlies much softer, probably sub-aquatic, sediments. A certain amount of subsidence due to compaction must therefore be taken into account. Louwe Kooijmans accepted a figure of 0.1 ± 0.1 m. In view of the uncertainty involved a somewhat larger range is preferred here. 0.2 ± 0.15 m. The levee probably reached its maximum elevation between 5375 ± 40 BP (GrN – 7043), the oldest available date from the occupation layer on top of the levee, and 5250 ± 50 BP (GrN – 7504), the beginning of peat growth on correlative backswamp deposits (Van der Waals, 1977; Ente, 1976). With Ente and Louwe Kooijmans we accept an age of 5300 ± 50 BP for the uppermost sediments. The levees of the larger tidal creeks may be assumed to have reached 0.20 ± 0.1 m above local MHW (Ente, 1976). Local tidal amplitude (= half the range) is assumed to have become somewhat smaller still: 0.2 ± 0.1 m (Louwe Kooijmans assumed a value of 0.1 ± 0.1 m), and the gradient effect is assumed negligible. Thus, MSL at about 5300 BP may have been at $-(5.15 \pm 0.05) - (0.20 \pm 0.1) - (0.2 \pm 0.1) + (0.2 \pm 0.15) = -5.35 \pm 0.4$ m NAP, which is practically the same result as obtained by Louwe Kooijmans (-5.55 ± 0.3 m NAP)

– Index point 78b

This time-depth point concerns the highest observed elevation of the top of the occupation layer mentioned above. The added uncertainty of the amount of compaction of this layer prevents us from employing it for an estimate of former MSL.

– Index points 135, 113, 85, 115, and 89 (Hazendonk, Molenaarsgraaf)

The time-depth boxes 135, 113, 85, and 89 (the first is not considered by Louwe Kooijmans) represent former average groundwater levels in the vicinity of the Hazendonk, a small, Late-glacial/early-Holocene river dune 4 km SSE of the 'donk' of Brandwijk (Louwe Kooijmans, 1974, 1976; see also chapter 5). Index point 115, for which Louwe Kooijmans accepted an age c. 200 years too old (chapter 5), indicates a level (of deposition) slightly below mean groundwater.

According to Louwe Kooijmans tne distance of the Hazendonk to the coast was at all times sufficiently great to assume that, due to the floodbasin effect, local tidal range was zero. Thus, the only effect to be taken into account in deriving a figure for MSL from the observational data is that of the river gradient. Louwe Kooijmans applied for this effect a uniform correction of 0.5 ± 0.1 m. Evidently, if it can be shown that this figure is not an underestimate of the gradient effect, this will be a strong point in favour of his MSL curve.

Louwe Kooijmans based his estimate of the gradient-effect correction on present-day heights of local half tide levels near Schoonhoven and Sliedrecht (resp. +0.65 and +0.75 m NAP). He assumed that under natural conditions the gradient effect on the average groundwater level (zero tidal range) would be somewhat smaller, hence 0.5 ± 0.1 m. A first remark concerns the uniformity of the applied correction. This denies that due to the ongoing sea-level rise the gradient effect must have gradually diminished with time, and index point 113 and 89 differ about 1250 radiocarbon years in age. Since the index point 89 occurs about 0.6 m above the line connecting the two youngest time-depth points (38, 39) from Barendrecht (fig. 25), which cannot indicate a level lower than MSL, it is very probable that Louwe Kooijmans underestimated the gradient effect for index point 113. Two facts seem to support this conclusion. In the first place, the position of index point 135, which has not been considered by Louwe Kooijmans, suggests a gradient effect of at least 1 m. Secondly, time-depth point 29, from the 'donk' of Brandwijk (4550 ± 150, GrN-191), coincides with Louwe Kooijmans MSL curve, despite the fact that it has not been corrected for any gradient effect. Given the proximity of the Brandwijk 'donk' and the Hazendonk, it can be assumed that the gradient effect has been comparable a both river dunes. Provided that the Brandwijk sample has been dated correctly, it can be maintained, however, that even if the gradient effect at the 'donk' of Brandwijk has been smaller than at the Hazendonk at that time, it cannot have been zero. Hence, MSL at about 4500 BP must still have been below −3.3 m NAP. This implies that the gradient effect for the older date of index point 85 was 0.8 m or larger.

In conclusion, it is very probable that the main reason for the higher position of Louwe Kooijmans' MSL curve is that he underestimated the river-gradient effect for the older time-depth data from the Hazendonk. Contrary to Louwe Kooijmans, who was obliged to estimate the gradient effect due to the limited number of (archaeologial) data he considered, no attempt is made here to do so for the reason that the changing gradient effect cannot be quantified in an independent way. However, the subject is discussed at length in chapter 5.

– Index point 80 (Hekelingen)

Time-depth box 114 (71, 80, 81, 85) is, apart from

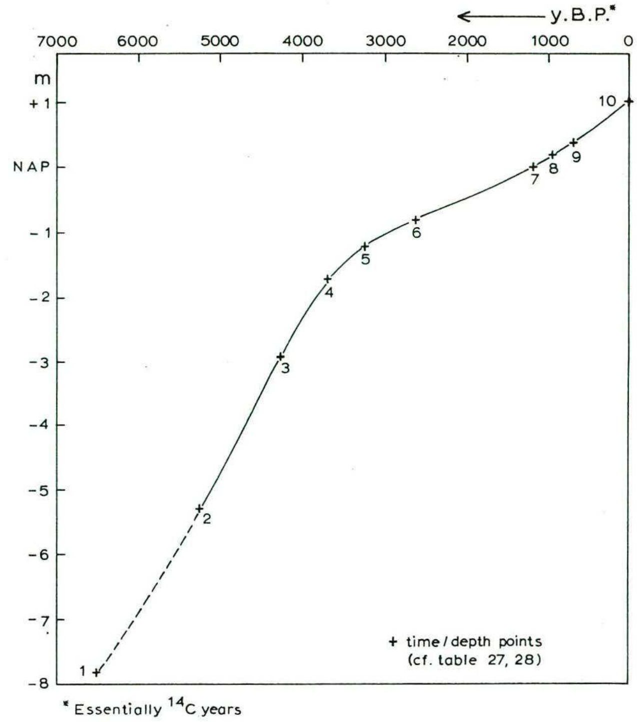


Fig. 26 Relative sea-level curve (MHW) for the Groningen coastal area by Roeleveld (1974). (Time-depth points not corrected for compaction.)

observations made at the Hazendonk, also based on data from occupation sites of the Vlaardingen Culture at the type locality Vlaardingen and at Hekelingen. Louwe Kooijmans' estimate of MSL (index point 79) from the data at the Vlaardingen site (4250 ± 100 BP) was: altitude of the top of the tidal creek fill – half local tidal range + compaction = $-(3.3 \pm 0.1) - (0.3 \pm 0.1) + (0.4 \pm 0.2) = -3.2 \pm 0.4$ m NAP. As discussed in 4.2.2. (index point 80) data from the Hekelingen site allow MSL at 4200 ± 50 BP to be estimated at -2.95 ± 0.4 m NAP.

Recently, Louwe Kooijmans and Van de Velde (1980) published new geological and archaeological data from the Hekelingen site. It appears that the creek levee was formed in two phases. The abovementioned estimate of MSL (-2.95 ± 0.4 m NAP) is based on the altitude of the top of the levee reached at the end of the second phase of construction. The observed altitude of the top of the levee reached at the end of the first phase of deposition, archaeologically dated at 4450 ± 50 BP, is −2.65 m NAP. Assuming a compaction effect of 0.3 ± 0.1 m, a former local tidal amplitude of 0.8 ± 0.2 m, and that the levee was built up to 0.1 ± 0.1 m above local MHW, MSL at that time may thus have occurred at -3.25 ± 0.45 m NAP.

– Time-depth boxes (98, 99), 116, 88, and 117 (West-Friesland)

Age-altitude data from West-Friesland are not very suitable for deriving former MSL stands due to the absence of compaction-free sites, and above all, due to the difficulty of estimating former local tidal range,

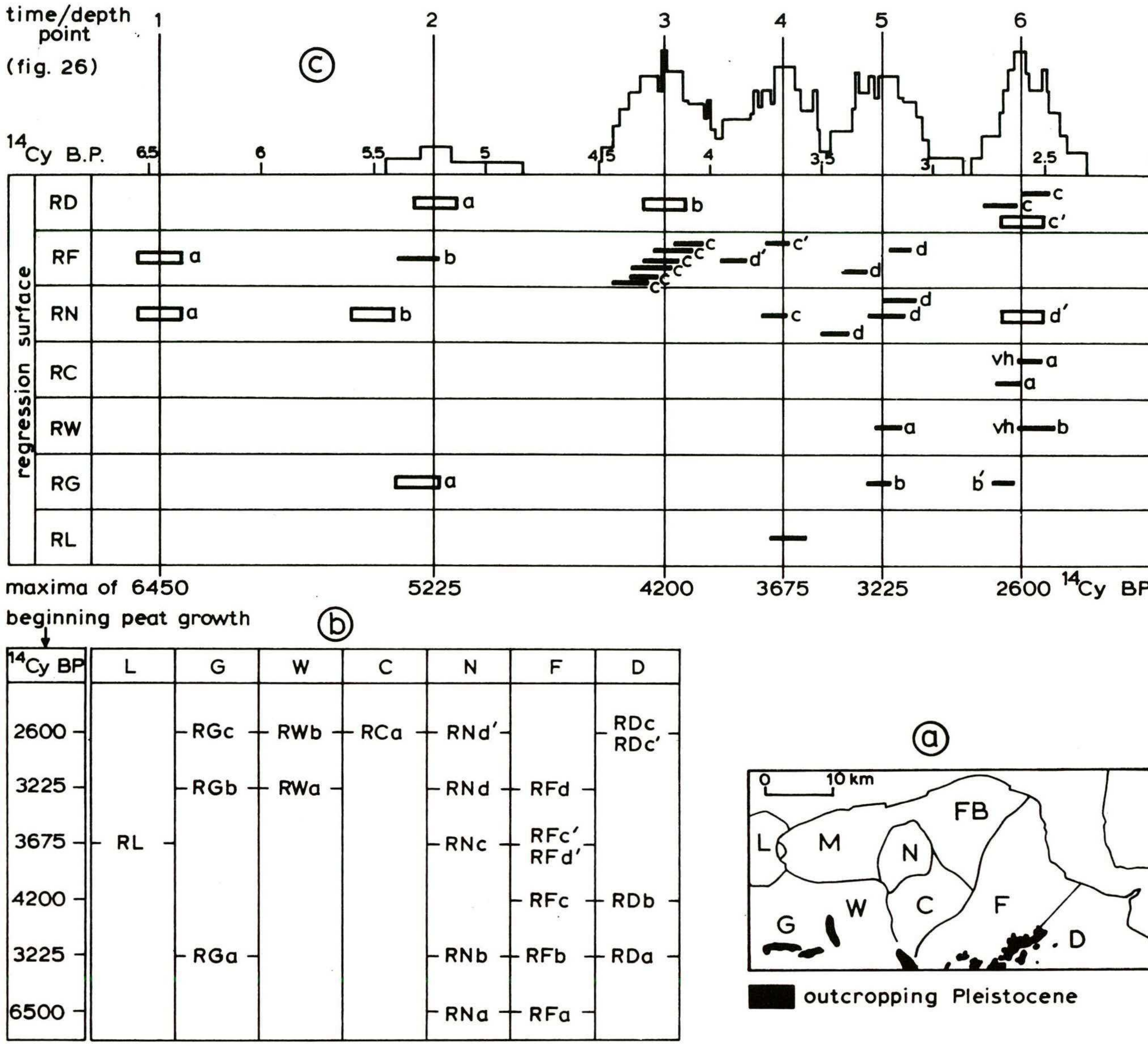


Fig. 27 (a) Map of the Groningen coastal area, showing distinct sections (regions) with more or less homogenous lithostratigraphy. (Regions: L = former Lauwerszee, M = Marne, N = northern centrai, FB = former Fivel bay, G = Grijpskerk, W = Westerkwartier, C = inner central, F = Fivelingo, and D = Dollard; from Roeleveld, 1974).
(b) Chronological correlation scheme of the regression surfaces recognized in the sections sub (a) (after Roeleveld, 1974).
(c) Diagram showing, in upper part, frequency histograms of 14C dates at the base of peat layers in the coastal sequence of the northern Netherlands (from Roeleveld, 1974); lower part of diagram depicts radiocarbon dates (from Groningen only) available for each regression surface (box = estimated/assumed age).

which between c. 4000 and 3300 BP, must have been considerably larger than at the coast (Ente, 1963; Roep et al., 1979). Therefore, the West-Friesland data will not be considered here.

- Index point 100 (Ezinge)

This point concerns the age and depth of the top of the oldest inhabited salt- marsh surface as determined at Ezinge (Groningen). Here the marsh surface occurs at a depth of -0.2 m NAP (Van Giffen, 1936). It is generally accepted that the 'Flachsiedlung' Ezinge originated at about 2500 ± 75 BP (Roeleveld, 1974). Louwe Kooijmans assumed that the marsh surface reached to 0.4 m above coastal MHW, and estimated the overall amount of subsidence due to compaction at 0.4 ± 0.1 m. With tidal range set at 2 m, he arrived at the following figure for MSL: $-(0.2 \pm 0.05) - (1.4 \pm 0.2) + (0.4 \pm 0.1) = -1.2 \pm 0.35$ m NAP.

A single remark that may be made about this estimate is that the relationship of local MHW to coastal MHW is unknown. The possibility cannot be excluded that due to the geometry of the Hunze estuary at that time (see fig. 63 in Roeleveld, 1974) the tidal range increased in a landward direction. On the other hand, the height of the marsh surface above local MHW may have been smaller than assumed.

- Index point 6 (Loosduinen)

This time-depth point has been discussed in 4.2.1.2.

4.2.6. Roeleveld

4.2.6.1. METHOD

The time-depth graph published by Roeleveld (1974) (fig. 26) is a by-product of his stratigraphical approach to the sedimentary sequences encountered in the Groningen coastal area.

Faced with a great regional diversity of sedimentary successions, he divided the study area into nine sub-areas of more or less homogenous lithostratigraphical composition (fig. 27a). Within each, the sedimentary record is described in terms of informal litho-stratigraphical units recognized by the presence of peat(y) intercalations or non-depositional unconformities within the minerogenic deposits. The surface of a clastic lithostratigraphical unit (bed, member) thus defined is called regression surface. The right hand part of figure 27b lists the relevant regression surfaces identified in the sub-areas D, F, C, N, W, G, and L.

The ages indicated on the left of figure 27b represent moments of maximum beginning peat growth/ regression in the northern Netherlands. These ages, except for the oldest one, have been derived from cumulative frequency histograms of available radiocarbon datings from the base of intercalated peat beds in the Provinces of Groningen and Friesland. A few samples of which the regressive nature was doubted have not been included in the diagram. This frequency analysis was done to provide a more quantitative basis for a transgression-regression chronology in the northern Nederlands. The regressive maxima may be looked upon as the moments at which at most places the corresponding regression surfaces have been formed. Thus, by linking these 'calculated' points in time to the 'mean' highest observed (extremes are ignored) altitudes of chronologically correlative regression surfaces, Roeleveld obtained, after correction for an assumed vertical relationship between the sediment surface and coastal MHW, the first 6 time-depth points (104-109) signifying former HMW positions. The altitudes of index-points 110, 111, and 112 were obtained in more or less the same way; the ages have mainly been deduced on the basis of archaeological and historical evidence.

With respect to the effects of compaction Roeleveld stated that these: '. . . were largely eliminated by taking into consideration only the highest observed positions of the respective regression surfaces.'

4.2.6.2. DISCUSSION BY ROELEVELD

Roeleveld did not make an exhaustive evaluation of his curve. He indicated that his method also implies many uncertainties, and that he tried '. . . to reduce the margin of error by avoiding the application of evidence deriving from single profiles.' (p. 115). The actual discussion of his curve is restricted to the following three steps.

1. Comparison with the curve for the western Netherlands just published by Louwe Kooijmans (1974). Both curves appear to match remarkably well.
2. The line connecting the youngest c.q. lowest basal peat data from the northern Netherlands diverges back in time from a similar line (the Jelgersma (1966) curve) for data from the western Netherlands (fig. 28; fig. 8 in Roeleveld, 1974). This suggests that the northern Netherlands were less strongly affected by subsidence than the western part of the country. If this interpretation of the data is correct then the good agreement between the two curves (step 1) is merely coincidental and the older part of the Groningen curve should lie slightly above Louwe Kooijmans' curve. In Roeleveld's opinion this conclusion seems reasonable, since he did not apply a compaction correction to his time-depth points.
3. Even if the curve should have to be raised slightly (to account for compaction), the agreement between both curves is still very good. The fact that the curves have been established on the basis of completely different sets of data is considered a '. . . strong point in favour of their validity.'

4.2.6.3. EVALUATION

With regard to the three steps mentioned above the following can be said. First it is important to note that Roeleveld accepted that the altitudes of his index points contain an uncertain amount of subsidence due to compaction. Formally speaking, therefore, comparison with other curves is an uncertain basis for drawing conclusions about the validity of his curve or that of others. The fact that Roeleveld did so notwithstanding, implies the assumption that compaction effects are only small (not larger than 0.5-0.6 m). Even if this assumption is correct it has a bearing on step 2 in that the good agreement between the curves of Roeleveld and Louwe Kooijmans is not coincidental if it is true that the northern Netherlands have subsided less than the western coastal area, but is accidental because the altitude of the index points has not been corrected for the effect of compaction. One of the possible explanations for a position of Roeleveld's curve (slightly) above the curve of Louwe Kooijmans is differential tectonic and/or isostatic subsidence.

With respect to the suggestion of differential subsidence referred to in step 2, the following points can be made. The interpretation of the two converging curves for the onset of basal peat growth (fig. 28) as possibly indicating differential subsidence between the northern and western part of the country, is based on the implicit assumption that each basal peat datum represents the same vertical relationship between former groundwater level and the contemporaneous sea level. It can be argued that this is not the case by considering the time-depth position of the basal peat data from the northern Netherlands relative to Roeleveld's curve (fig. 28) (see also 4.2.4.). Clearly, index point 18 represents a former groundwater level many decimetres below the contemporaneous MHW level, whereas index points 16 and 17 indicate levels of beginning peat growth at or above coastal MHW. Hence, the implicit assumption mentioned above is false, and curve NN', and therefore the suggestion of differential subsidence cannot be maintained.

The fact that two basal peat dates from north-eastern Friesland (Griede, 1978) coincide with Jelgersma's basal peat curve (fig. 28) suggests that differential tectonic and/or isostatic movements between the northern and western Netherlands have been negligible, at least during the last 6000 radiocarbon years.

In addition to the above remarks concerning Roeleveld's brief discussion of his curve, an attempt is made in the following to evaluate the individual index points 104-109.

– Index point 104

In the absence of radiocarbon dates from the base of overlying peat beds, Roeleveld derived an approximate age for the RFa/RNa regression surfaces with the help of curve NN' (fig. 28), the line connecting the youngest-lowest basal peat data from the northern Netherlands (Jelgersma, 1961). Given an estimated original depth of -7.25 ± 0.25 m NAP he obtained an age of c. 6500 BP. However, curve NN' is unsuitable for this procedure for two reasons. Firstly, for the critical part of the curve (6500-5500 BP) use was made of an assay (index point 20) on remains of *Sphagnum* and *Eriophorum*. Since these oligotrophic species are not groundwater-dependent for their existence, the possibility must be considered that the sample indicates beginning peat growth above the sea-level-controlled groundwater table of that time. The palynological dating of a clay layer rich in plant remains near Uithuizen (Vermeer-Louman, 1934; Roeleveld, 1974, p. 29), taken by Roeleveld to corroborate the trend of the radiocarbon-dated part of curve NN' (see fig. 8 in Roeleveld, 1974), cannot be considered very reliable. The clay might have been formed independent of sea level. The second reason why curve NN' is unsuitable for deriving any age for a given depth has been indicated in the previous paragraph: the curve is invalid because it connects basal peat data having different vertical relationships to coastal MHW.

In conclusion, since a reliable estimate of the age of the RFa/RNa regression surfaces cannot be made, index point 104 must be rejected.

– Index-points 105-109

(a) Relation to coastal MHW

In the absence of reliable sedimentological data Roeleveld assumed that the (highest parts of the) regression surfaces represent levels of deposition up to coastal MHW (index point 105) or MHW + 0.2 m (index points 106-109). He did not make the steps from indicator to local MHW to coastal MHW; i.e. it was implicitly assumed that local MHW equalled coastal MHW.

All that is known (with a fair amount of certainty) is that index point 105 does not, whereas index point

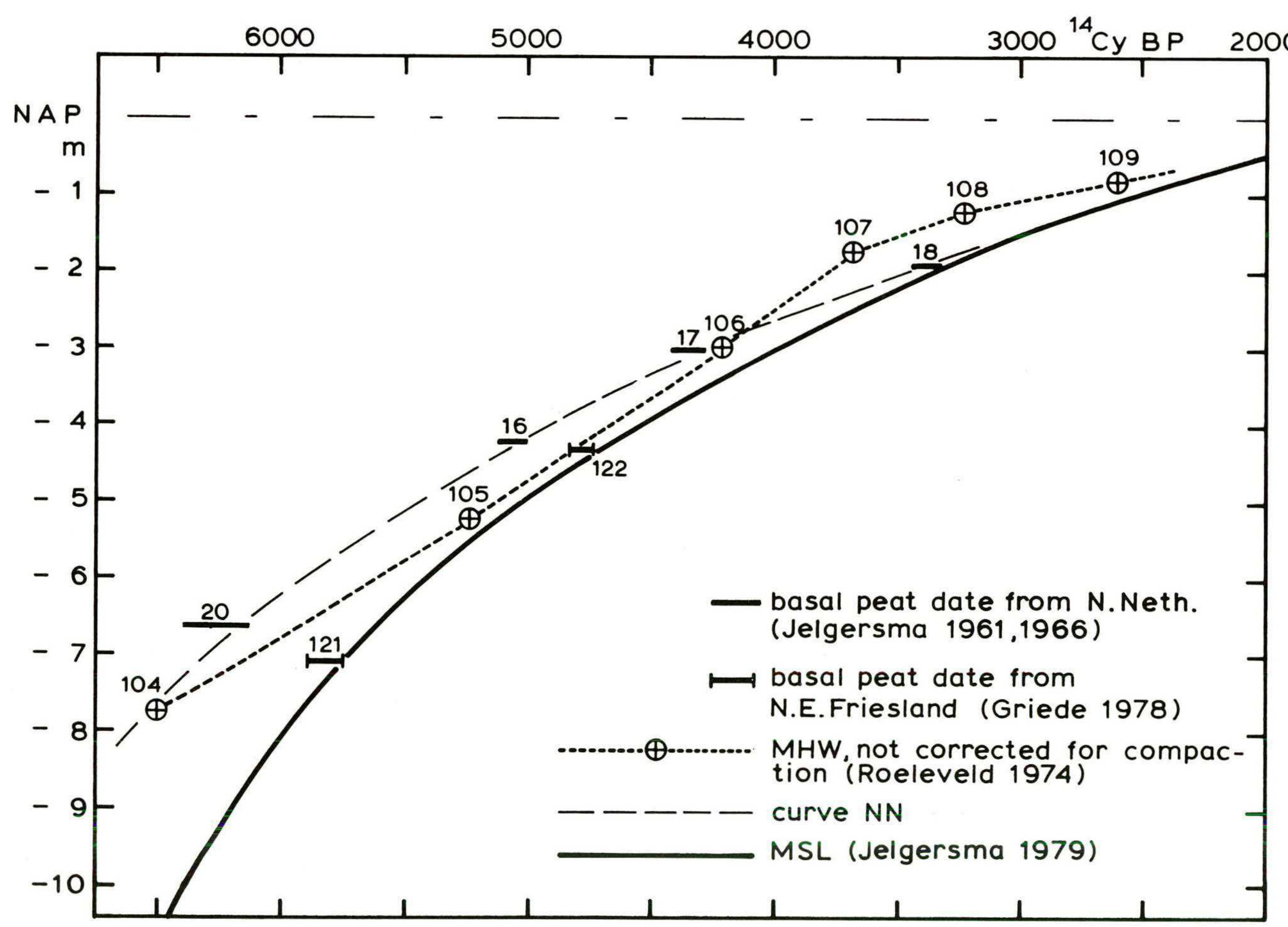


Fig. 28 Time-depth diagram with data and curves relevant to the discussion of sea-level changes in the northern Netherlands.

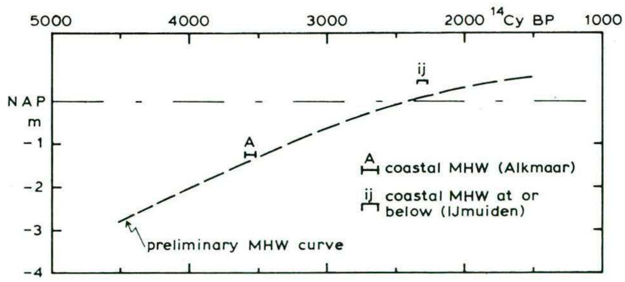


Fig. 29 Preliminary MHW curve (Jelgersma, 1980), based on study of sedimentary structures in coastal barrier deposits by Roep and colleagues (in prep.). Estimate ans indication of former MHW at respectively Alkmaar and IJmuiden (Roep et al., 1980).

109 does represent a salt-marsh stage. Index point 105 may at most indicate former local MHW, but this can also be a level a few or several decimetres below local MHW. Index point 109 may represent a level of deposition of 0.25 ± 0.1 m above local MHW. All one can do in the case of index points 106, 107 and 108 is to assume that these represent former levels of deposition close (± 0.2 m) to local MHW.

Nothing definite can be said about the vertical relationship of local MHW to coastal MHW, except that, in the case of index points 108 and 109 the paleogeography of the area (figs. 62 and 63 in Roeleveld, 1974) raises the consideration of the possibility of an increase in tidal range in a landward direction. Proper evaluation of this aspect can only be done when more and sufficently accurate data, and a reliable MSL curve, are available.

(b) Altitude

Two aspects need to be considered: the effects of compaction and the choice of the 'mean' highest altitude for a given (set of chronologically correlatable) regression surface(s). Roeleveld assumed that 'The effects of compaction were largely eliminated by taking into consideration only the highest observed positions of the respective regression surfaces'. (Roeleveld, 1974, p. 115). Exceptionally high positions are ignored for the reason that the relationship to MHW is uncertain.

The truth of the above quotation concerning compaction is evident from a study of the cross sections published by Roeleveld. The statement becomes an assumption when the phrase 'largely eliminated' is given a semi-quantitative interpretation, as Roeleveld does when he speaks of the possibility of a 'slight correction' of his curve. Although he does (and can) not specify the term 'slight' a reader is given the impression that Roeleveld considers the effects of compaction small, say 0.5-0.6 m. Possibilities for verifying this quantitative interpretation of Roeleveld's term 'slight' are unavailable. Only in one 'point case' is it possible to make a reasonably accurate estimate of the subsidence involved. Sample Emmerwolde (5300 ± 90 BP, GrN-4766; − 5.3 m NAP) is underlain by 0.28 m of clay and 0.12 m of peat (Roeleveld, pers. comm.) and is overlain by about 5 m of sediment. A minimum and maximum estimate of the compaction effect gives respectively c. 0.3 and c. 0.9 m. Because the situation at Emmerwolde is not very representative of the RFb regression surface (index point 105) as a whole, it does not seem appropriate to use this compaction estimate for this surface. However, if one examines the situation at more representative sites (cross sections BB', CC', and DD' in Roeleveld, 1974), where loading is more or less comparable to that at Emmerwolde but the compaction-susceptible deposits (especially the peat) are thicker, it is, in our opinion, beyond reasonable doubt that the RFb surface originally reached to at least c. − 4.8 m NAP. This figure, which cannot be substantiated nor can be denied a certain probability, would confirm the order of magnitude of maximum compaction mentioned above (0.5-0.6 m). If one considers the possibility that the peat overlying the RFb surface began to accumulate in a few decimetres of water, former (local) MHW level may have been at about − 4.6 m NAP.

The problem with the 'mean' highest observed altitudes taken by Roeleveld is that objective criteria to determine the lower limit of what is still an extreme altitude are lacking. However, the following may be said. It can be argued for index points 108 and 109 (mean highest positions accepted by Roeleveld respectively − 1 and − 0.6 m NAP) that because of the possibility of an increase in tidal range in a landward direction, where the highest observed altitudes occur (− 0.6 resp. − 0.35/0.1 m NAP), it is justified to omit these extreme values. Conversely, since it is highly unlikely that in the case of index point 105 deposition occurred above coastal MHW, there is little objection against using the observed minimum depth of − 5 m NAP instead of − 5.25 m NAP. In the case of index point 107 the mean highest position accepted by Roeleveld (− 1.5 m NAP) differs very little from the observed extreme (− 1.4 m NAP). For index point 106 on the other hand there is a difference of 0.4 m. Roeleveld accepted for the RFc surface (index point 106) a mean altitude of − 2.75 m NAP. From cross-section EE', however, it can be read that the RFc surface also occurs between − 2.5 and − 2.4 m NAP over considerable stretches, with an observed minimum depth of − 2.35 m NAP (checked with original bore log). In this case one is faced with the choice between ignoring the relatively low frequency with which these more extreme heights have been observed, and the argument that if Roeleveld's assumption is correct that the − 2.75 m NAP level of the RFc surface represents former coastal MHW + 0.2 m, then it is difficult to see which factor or process has been responsible for the fact that in certain parts of the Fivelingo region sedimentation took place 0.3-0.4 m higher.

Although the above discussion is not exhaustive, the examples go to show that some of the figures accepted by Roeleveld for the mean highest positions of the regression surfaces are open to small but important changes.

(c) Age

One of the conditions for applying the moments of maximum beginning peat growth is that all samples signify regression, i.e. represent peat growth immediately or soon after the end of minerogenic deposition at the sampling site. Roeleveld excluded from the frequency analysis a few dates that did not seem reliable in this respect. For the dates that were considered the question remains how much time in fact elapsed between the end of sedimentation and the onset of peat growth. In view of the fact that fen-peat growth is mainly a function of water depth and salinity, and that the first may be strongly influenced by changes in local tidal range and variation in depositional sub-environment, it is probable that rather large differences in time lapse may occur from locality to locality.

The results of a frequency analysis may depend on the population of dates that happens to be available at the time. Table II compares the regression maxima obtained by Roeleveld with figures that would have been found if dates had been used from Groningen and NE Friesland (Griede, 1978) and from Groningen only.

Table II

dates from	Conv. radiocarbon years BP						
G + S.W.F. + N.E.F. (2)	5225	4200	3675		3225		2600
G + N.E.F.	5250	4150	3700	3425	3200	3000	2675
G	5300	4275	3700		3200		2675

The Friesland dates tend to draw the regressive maxima based on dates from Groningen somewhat to the young side.

A second point of consideration, that is only mentioned here, concerns the effect of medium-term variations in 14C concentration on the frequency distribution of the radiocarbon dates (Roeleveld, 1974, p. 22). For a discussion of this matter reference is made to De Jong and Mook (1981).

Of importance in the method adopted by Roeleveld is the question of the representativity of the moments of maximum beginning peat growth (as established on the basis of dates from Groningen and Friesland) for the moments that in certain parts of Groningen the respective regression surfaces reached their 'mean' highest position. In this respect it is important to remember that Roeleveld made the frequency analysis solely for the purpose of establishing a transgression/regression chronology. The aspect of height was not introduced until much later. As a consequence he did not consider the lithostratigraphic position of regression surfaces to which the dates from Friesland are related; and even though the frequency histogram suggests a supra-local synchroneity of events, the possibility cannot be excluded that (some of) the dates from Friesland pertain to regression surfaces that have not been detected or recorded in the Groningen coastal area. Since these regression surfaces may possess different 'mean' highest positions, it would have been more correct if the dates from Friesland had been excluded from the analysis. However, as shown in table II, the effect of the Friesland dates on the regressive maxima for dates from Groningen only, is small.

The 'mean' highest position of the regression surfaces have been determined on the basis of the assumption of regional synchroneity of regressions and transgressions. This synchroneity is suggested, or at least not contradicted, by the frequency histogram. Since, however, age and altitude of the index points have not necessarily been obtained from the same sites, and the possibility of local diachronous development or an erroneous lithostratigraphic correlation (due to, for example, insufficient borings) cannot be excluded beforehand, it is necessary to examine if age and altitude have been obtained from entirely different areas. This does not appear to be the case. Hence the regressive maxima may be considered to apply to the 'mean' highest elevations of the regression surfaces. The question of what must be understood by 'mean' highest position has been discussed above.

Finally, one more remark may be made about the problem of the regressive significance of samples from the base of peat beds. Griede (1978) distinguished in north-eastern Friesland two (local) regression surfaces that have not been detected or recorded in Groningen. In both cases Griede did not exclude the possibility that the dates involved represent transgressive and not regressive peat growth. The point is, however, that this possibility was only recognized after comparison with other data, and not on the basis of sediment or boundary characteristics. The conclusion can be drawn that one should be critical in accepting the regressive nature of samples from the base of peat beds. The possibility cannot be excluded that amongst the dates used by Roeleveld in his frequency analysis one or two represent the moment of increased wet conditions at the beginning of a transgression.

4.2.6.4. FINAL REMARKS

Roeleveld's method of sea-level height reconstruction is useful by making the most of radiocarbon datings that originally have been made for stratigraphical purposes only. However, the approach presupposes:

1. a sound lithostratigraphic analysis,
2. the effect of compaction for the highest observed parts of regression surfaces is 'acceptable',
3. the radiocarbon samples used in the frequency analysis come from known lithostratigraphical positions, and
4. the samples from the base of peat beds signify regression.

The most problematic aspect remains that of compaction. Roeleveld's time-depth graph is a lower limit above which the true MHW curve for the Groningen coastal area should lie, provided, of course, that none of the index points contains a compensating effect of a formerly large local tidal range.

Further evaluation of the method and of individual time-depth points requires a reliable MSL curve for the northern Netherlands.

4.2.7. Roep

Roep et al. (1975) were able to derive fossil tidal levels from sedimentary structures in the coastal barrier deposits (see 3.2.1.). A preliminary MHW curve based on (unpublished) data obtained according to this method was given by Jelgersma (1980). It is reproduced in figure 29, together with the few individual paleo MHW levels published so far (Roep et al., 1975, 1979; a more extensive paper is forthcoming, Beets et al., 1981). The importance of the fossil coastal MHW data has been indicated in 3.1. (see also 4.2.3.1.).

4.3. CONCLUSIONS

All estimates and indications of former MSL stands as derived in the foregoing sections, as well as the youngest or lowest basal peat data and the five youngest time-depth points from the Barendrecht and Brandwijk 'donken' have been assembled in figure 30. Table III summarizes the various errors included in the vertical margins of the error boxes.

Any curve drawn through this data set should fulfill the requirements of passing through or (just) below the basal peat and 'donken' data and satisfy as many estimates of MSL as possible. A spectrum of curves, with or without slight changes of slope, fulfill these conditions. This in itself is sufficient justification for drawing a smooth (trend-)curve and that given in figure 30 is one of several possibilities within a margin of ± 0.2 m.

It is apparent from figure 30a that the revised curve generally confirms that derived by Jelgersma (1979). The position of her graph below the older segment of that now proposed is attributed to the incorrect plotting of index point 118. This does not mean that the position of the older part of the revised curve is more correct, since the paucity of data for the period prior the 6000 BP and the uncertain relationship of index point 118 to MSL, renders the older section of the curve less reliable than the younger part.

As stated in 4.2.5. the slightly higher position of Louwe Kooijmans' (1976) curve can be mainly attributed to an underestimation of the river-gradient effect contained in data from the Hazendonk (area).

Both Louwe Kooijmans' curve and the present revision suggest that MSL after c. 3000 BP was somewhat lower than indicated by Jelgersma's graph. However, the differences lie within the margins of error involved. Moreover, the curves only give a trend; the possibility of past variations in the rate of MSL rise cannot be excluded.

The curve in figure 30 satisfies all but the MSL estimate derived from the top of the old sea-clay

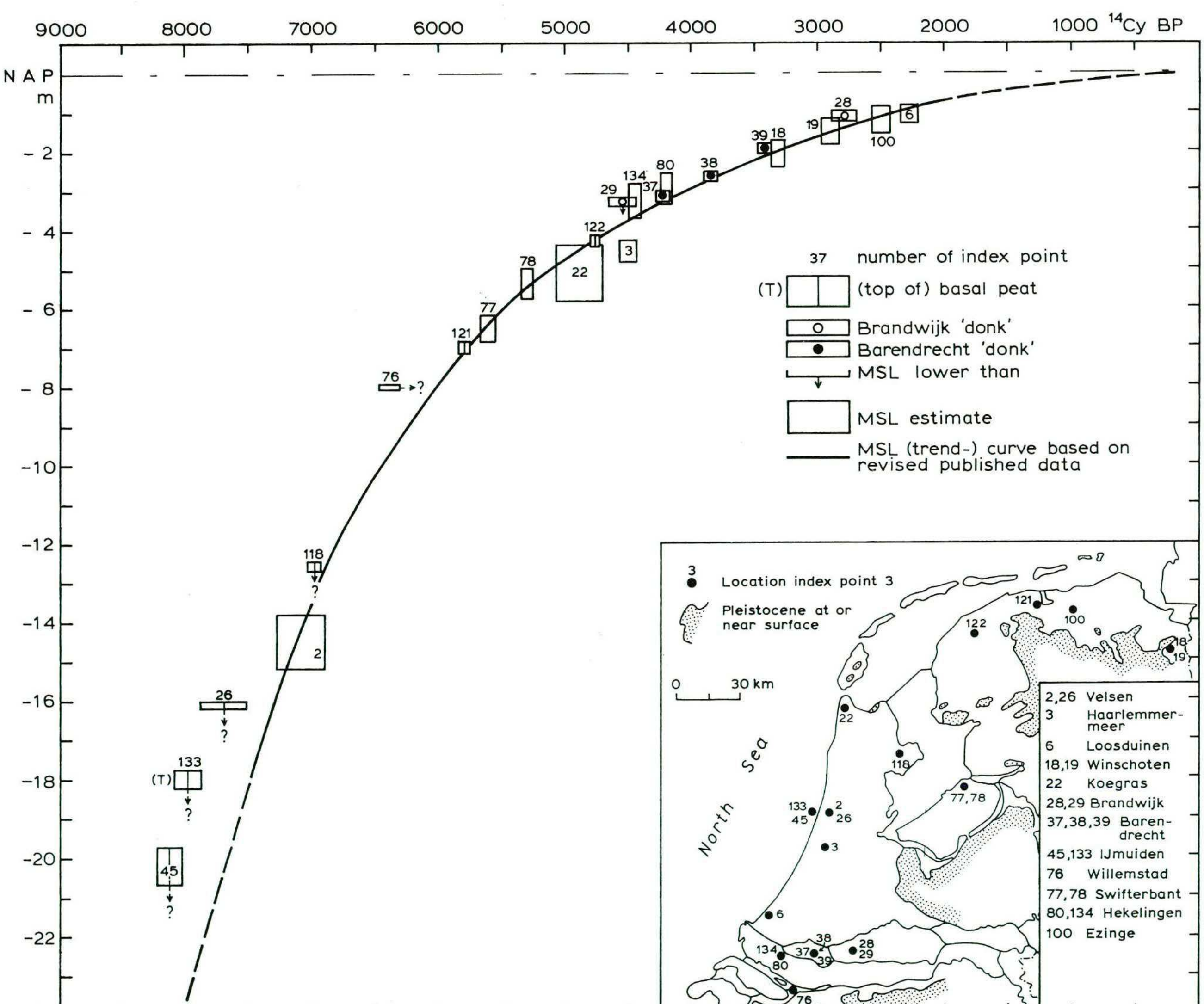


Fig. 30 Summary time-depth diagram with MSL (trend-) curve based on analysis of published data.

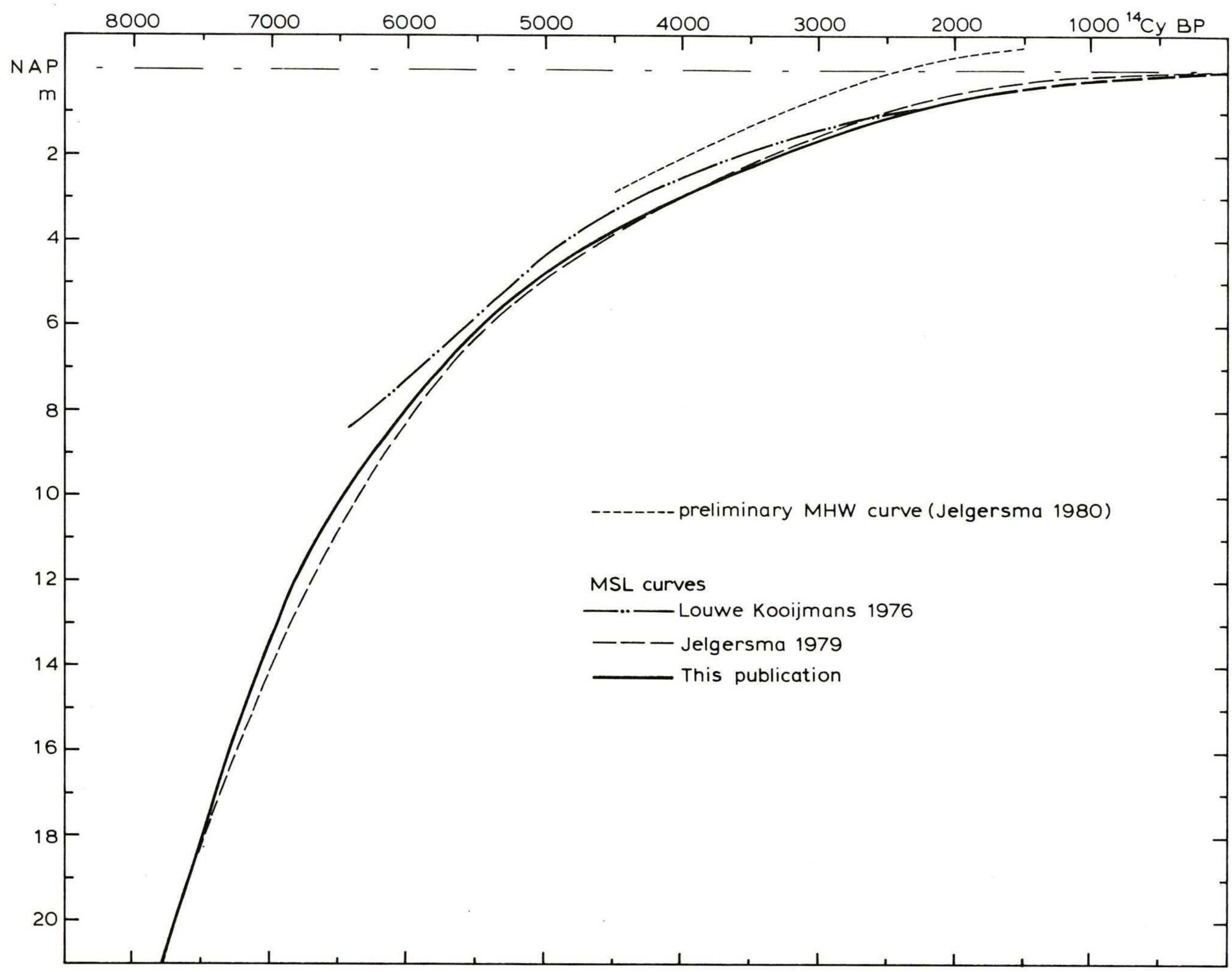


Fig. 30a Revised MSL curve compared with MSL curves by Louwe Kooijmans (1976) and Jelgersma (1979).

deposits in the Haarlemmermeer polder (index point 3). The discrepancy is most easily resolved if it is assumed that the age accepted for the top of these deposits (4500 ± 75 BP) is at least 250 years too young. This would imply that the old sea-clay deposits belong to the Calais III and not, as concluded by Riezebos and Du Saar (1969), to the Calais IV transgressive period. Consequently, the Hoofddorp deposits must have originated during the Calais II and not during the Calais III phase. This conclusion, which needs to be corroborated, is in agreement with the stratigraphic interpretation given by De Jong (1965). In this respect reference should also be made to Van Straaten (1965, p. 45) who, on the basis of paleogeograhic considerations, concluded that '... the main activity of the inlets, through which the material of the Hoofddorp and Omval deposits was brought in, had terminated before the first advance of the coast in the beginning of the Subboreal'.

Now that a most probable MSL curve has been established, attention may be directed towards time-depth data from the 'donken', which, due to difficulties of estimating the gradient effect, thus far have been largely omitted from consideration.

As such, the consequences of using the revised curve for interpretation of time-depth data from the Barendrecht, Brandwijk and Hazendonk river dunes are addressed in the next chapter.

Another set of data that has not yet been considered, that from Zeeland, is discussed in chapter 8.

5. HOLOCENE WATER-LEVEL CHANGES IN THE RHINE-MEUSE DELTA AS A FUNCTION OF CHANGES IN RELATIVE SEA LEVEL, LOCAL TIDAL RANGE, AND RIVER GRADIENT[3]

5.1. INTRODUCTION

With the aim of reconstructing the Holocene relative sea-level rise in the Netherlands, Jelgersma (1961) collected compaction-free samples from (1) the base of the so-called Lower Peat, the peat that occurs at the base of the Holocene coastal sequence and directly overlies the seaward sloping surface of the Pleistocene subsoil, and (2) the base of organogenic deposits on the slopes of two high river dunes – known as 'donken' – that rise from the former Late-glacial/early-Holocene floodplain of the rivers Rhine and Meuse. In figure 31a curve I and curve II indicate respectively the groundwater-level

Table III *Errors contained in the vertical margin of error of index points plotted in figure 30*

(a) index point	(b) measured altitude in m below NAP	(c) error (assum.)	(d) original sample thickness (assum.)	subsidence due to compaction	height above local MHW	local tidal amplitude	gradient effect	estimate of MSL in m below NAP
2	16.05	±0.1	-	1.8±0.5	-	0.25±0.1	-	14.50±0.70
3	4.0	±0.1	-	-	0.15±0.1	0.4±0.1	-	4.55±0.30
6	0.75	±0.1	-	0.1±0.05	0.4±0.1	-	-	1.05±0.25
18	1.87-1.92	±0.1	0.10	-	-	0.2±0.2	-	2.07±0.35
19	0.90-0.94	±0.1	0.08	-	-	0.6±0.2	-	1.50±0.34
22	4.70-4.72	±0.3	0.04	-	-	0.4±0.4	-	5.10±0.72
77	6.11-6.15	±0.1	0.08	-	-	0.35±0.15	0.05±0.05	6.51±0.34
78	5.15	±0.05	-	0.2±0.15	0.2±0.1	0.2±0.1	-	5.10±0.40
80	2.35	±0.05	-	0.2±0.1	0.1±0.1	0.7±0.15	-	2.95±0.40
100	0.20	±0.05	-	0.4±0.1	0.4±0.1	1±0.1	-	1.20±0.35
134	2.65	±0.05	-	0.3±0.1	0.1±0.1	0.8±0.2	-	3.25±0.45

(a)	(b)	(c)	(d)		m below NAP
26	16.10	±0.1	-	=	16.10±0.10
28	1.11-1.15	±0.1	0.08	=	1.11±0.14
29	3.29-3.31	±0.1	0.04	=	3.29±0.12
37	3.19-3.24	±0.1	0.10	=	3.19±0.15
38	2.63-2.67	±0.1	0.08	=	2.63±0.14
39	1.92-1.97	±0.1	0.10	=	1.92±0.15

(a)	(b)	(c)	(d)		m below NAP
45	20.40-20.50	±0.2	0.60	=	20.20±0.50
76	8	±0.1	-	=	8.00±0.10
118	12.58-12.60	±0.1	0.06	=	12.57±0.13
121	7.01-7.05	±0.1	0.12	=	6.99±0.16
122	4.26-4.31	±0.1	0.10	=	4.26±0.15
133	18.0	±0.25	-	=	18.00±0.25

rise based on the base-of-Lower Peat data and on the data from the base of the peat on the river dunes (hereafter referred to as 'donken' data). According to Jelgersma (1961, 1966) curve I represents the rise of coastal mean high water (MHW). However, she deduced that the peat sampled on the 'donken' also formed at the level of coastal MHW (Jelgersma, 1961, p. 21). Until now the discrepancy between theory and observation that is apparent from the position of curve II above curve I (fig. 31a) has not been resolved. On the contrary, with the modification by Jelgersma (1979) of curve I to curve III (fig. 31a) this contradiction has even been enlarged, in particular for the older part of the curves. Compared to her former curve (I) the new one (III) represents the rise of mean sea level (MSL) instead of MHW and, still more important, has a steeper trend for the period before 5000 BP. Figure 31a shows that, whereas curve II and curve I are more or less parallel, the vertical distance between curve II and the new MSL curve (III) markedly diverges with increasing age. This latter point is clearly brought out in figure 31b where the height of curve II has been plotted relative to curve IV, which is a slightly corrected version of curve III (in her 1979 publication Jelgersma slightly misplotted the new Lower Peat time-depth point (GrN-8098: 6980 ± 40 BP − 12.58-12.60 m NAP) that obliged her to revise the original curve. As a result the older part of curve III was drawn somewhat too low. In figure 31a the 1979 curve has been redrawn according to the correct position of the time-depth point concerned: curve IV).[4]

Accepting curve IV as a fair approximation of the MSL rise and assuming a constant tidal range during the last 7200 years (see below), this paper attempts to explain the consequence of Jelgersma's revision of meaning and gradient of curve for the significance of the 'donken' data. As can be read from figure 31b the consequence is that in the Rine-Meuse delta[5] at about 7000 BP peat growth apparently occurred almost 2 m above the contemporaneous MHW level, while by about 4000 BP it took place 0.8 m below that level.

The position of the two river dunes investigated by Jelgersma (1961), the 'donk' of Brandwijk and the 'donk' of Barendrecht, is indicated in figure 32. Four kilometres SSE of the Brandwijk 'donk' lies a small river dune called Hazendonk, from (the vicinity of) which Louwe Kooijmans (1974, 1976) collected fossil groundwater-level data. These time-depth data have also been plotted in figures 31a and 31b. One notes that the vertical distance between the Hazendonk data and curve IV decreases with time too.

5.2. AIM

The area in which the 'donken' under consideration are located was transitional to the fluvial area in the east and the lagoonal-estuarine area in the west during most of the middle- and upper- Holocene (Hageman, 1969). The two main factors which can be expected to have determined the water level in this region are therefore (1) the effect of the river gradient, and (2) the local tidal range.

The aim of this paper is to explore the extent to which the irregular convergence of the 'donken' data on the MSL curve (IV) (fig. 31b) can be explained in terms of these two factors, and to estimate the change in magnitude of their effect in the course of the middle- and late-Holocene development of the region.

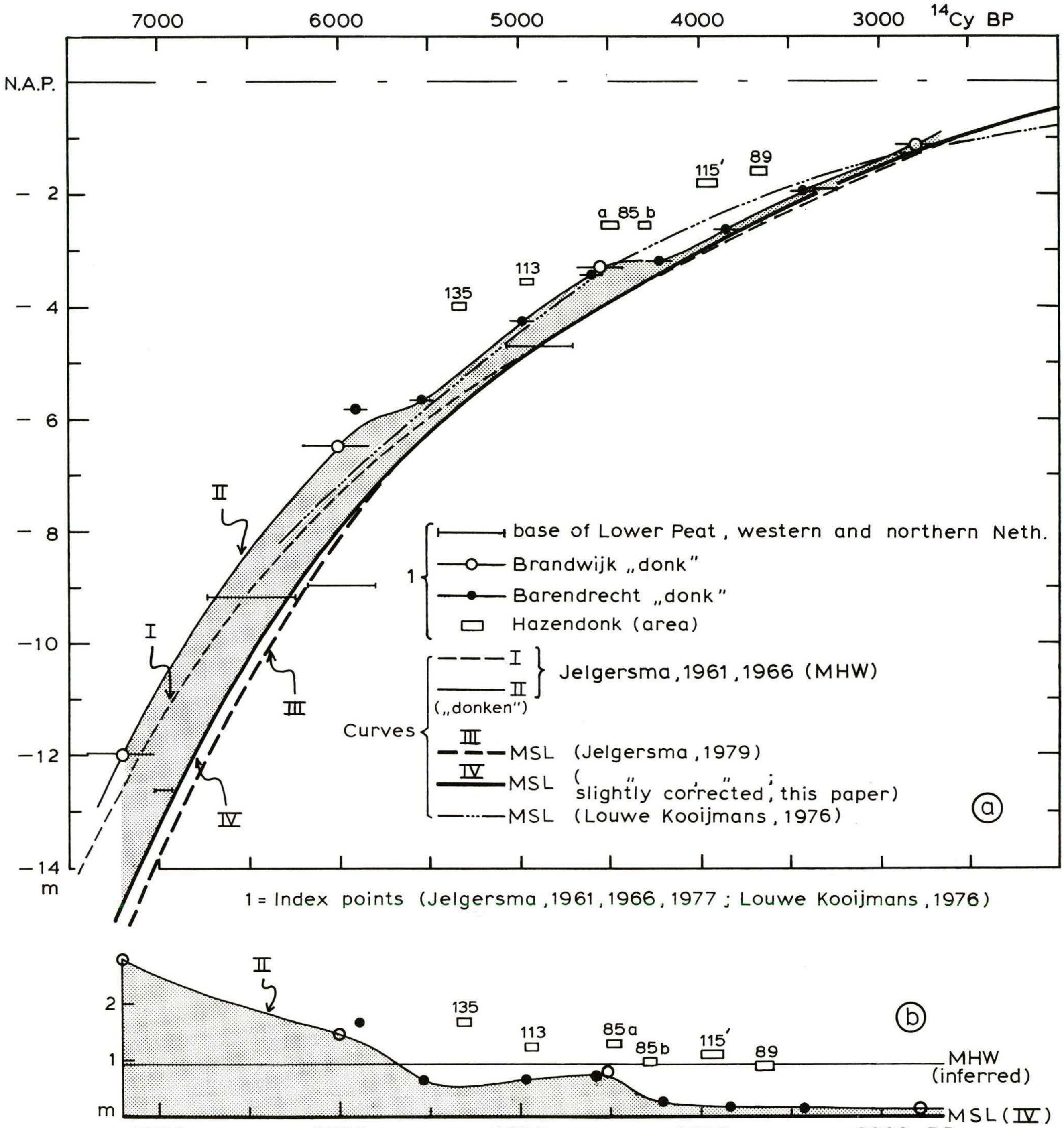


Fig. 31 (a) Time-depth diagram showing several published sea-level graphs for the Netherlands: I Jelgersma's former (base-of-Lower-Peat) graph (MHW, 1961, 1966); III Jelgersma's modified graph (MSL, 1979); IV graph III, but slightly corrected for the older part (this publ.); and II line connecting time-depth data obtained from the base of peat deposits on the slopes of Late-glacial/early-Holocene river dunes near Barendrecht and Brandwijk (see 1 and 2 in fig. 32). The time-depth boxes represent former water levels near another river dune, the Hazendonk (Louwe Kooijmans, 1974, 1976; see 3 in fig. 32). The MSL curve that Louwe Kooijmans (1976) largely derived from these data is also depicted. (b) Plot of the vertical distance above curve IV of (1) the Brandwijk and Barendrecht data, together with curve II (see stippled areas); and (2) the Hazendonk data. The time-depth data clearly converge upon the MSL curve (line) with time. Based partly on field evidence (Roep et al., 1975; Jelgersma, 1980), partly on the assumption of constancy of tidal range, a line representing MHW has been inserted at 0.9 ± 0.1 m above the MSL line.

5.3. BRIEF DISCUSSION OF THE 'DONKEN' DATA

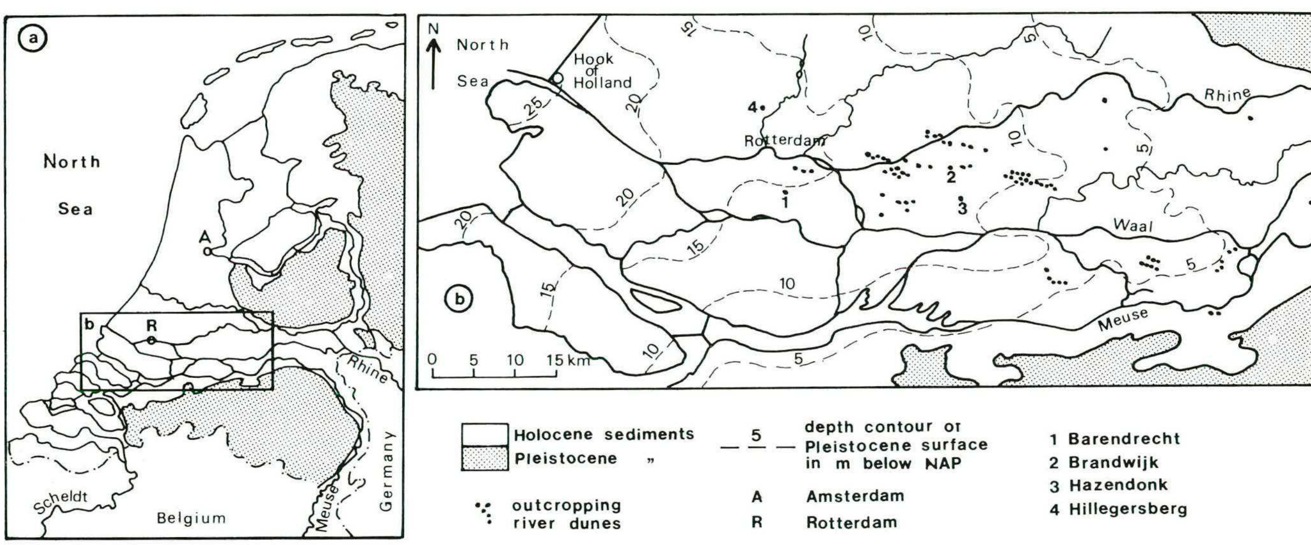
The time-depth data on which Jelgersma (1961) based curve II (fig. 31a) all derive from samples taken at the base of fen-wood peat that began to grow on the Brandwijk and Barendrecht 'donken'. It may be assumed that in the tide-influenced part of the Rhine-Meuse delta the upper limit of fen-wood peat growth about coincided with local MHW; in the non-tidal part this limit will have been set by an average groundwater level. The assumption is made that all samples represent fen-wood peat accumulation at this upper limit and not at various depths below it.

The Hazendonk time-depth boxes 135, 113, 85a and b (fig. 31a) all pertain to moments of inhabitation on or near that river dune (Louwe Kooijmans, 1974, 1976). The altitude of each box relates to the juncture on the dune slope of occupation layers present in the fen-wood peat that surrounds the dune. For the boxes 135, 113, and 85a the time of inhabitation was established by dating a sample from those intervals of a pollen analytically investigated core taken near the 'donk', that exhibited the presence of human influence on the local vegetation and correspond with the respective occupation layers. The sample that gave the age for Hazendonk point 85b consisted of mixed material from the occupation layer concerned. According to Louwe Kooijmans (1976) the occupation layers were situated just above the local groundwater level. As such they can also be interpreted to indicate former upper limits of fen-wood peat growth.

The altitude of time-depth box 115' concerns the top of a backswamp clay deposited by the Schoonrewoerd stream, the sandy filling of which occurs 1 km north of the Hazendonk. The top of this clay reaches a height of −1.8 m NAP on the Hazendonk. From radiocarbon dated samples of charcoal and bone (GrN-6216; 3795 ± 55 BP, GrN-6384: 3820 ± 45 BP; Table IV) collected on the Schoonrewoerd stream ridge, Louwe Kooijmans (1974, 1976) concluded that the clay must have been deposited before 3800 BP. It is assumed here that the clay attained its highest level on the Hazendonk between 4000 and 3875 BP. Louwe Kooijmans stressed the point that the clay shows little or no signs of physical ripening. Consequently, it may indicate a level somewhat below the average groundwater table.

Finally, box 89 gives height and age of the approximate groundwater level or local MHW in a gully transversing the Schoonrewoerd stream ridge (Louwe Kooijmans, 1974, p. 179 and further).

Table IV lists the 'donken' data plotted in figure 31a.



5.4. RIVER-GRADIENT EFFECT

Due to the river gradient, MHW and other tidal levels tend to be raised in an upstream direction. Louwe Kooijmans (1974) called this the river-gradient effect.

The fact that peat growth on the three 'donken' under consideration has occurred under strong influence of river water is indicated by the peat composition: fen-wood. This is only formed in an eutrophic fresh-water environment. The rivers in the early-Holocene must have had a distinct seaward slope which, for a given stretch, decreased in time as a result of the Holocene sea-level rise and simultaneous landward displacement of the coastline until about 5000 BP. Because at the same time the rivers were forced to deposit much of their load upstream (Hageman, 1969), there was a tendency for the gradient to maintain itself. It is expected, therefore, that the raising effect of the river gradient will have decreased more gradually than would have been the case otherwise. Figure 33 schematically illustrates the basic effect of a decreasing river gradient on the upper limit of fen-wood peat growth on three 'donken' located at increasing distance from the coast: the time-depth graph for each dune converges upon the coastal MHW curve with time, and the greater the distance from the coast, the higher is the position of the graph in the time-depth diagram. By plotting the time-depth graphs for the three dunes relative to the coastal MHW curve (fig. 33c) one obtains for each of the three localities a gradient-effect reduction curve.

5.5. LOCAL MEAN HIGH WATER

It has been established from the study of sedimentary structures in coastal barrier deposits (Roep et al., 1975, pers. comm.; Jelgersma, 1980) that during the last 4800 years mean tidal range along the mid-

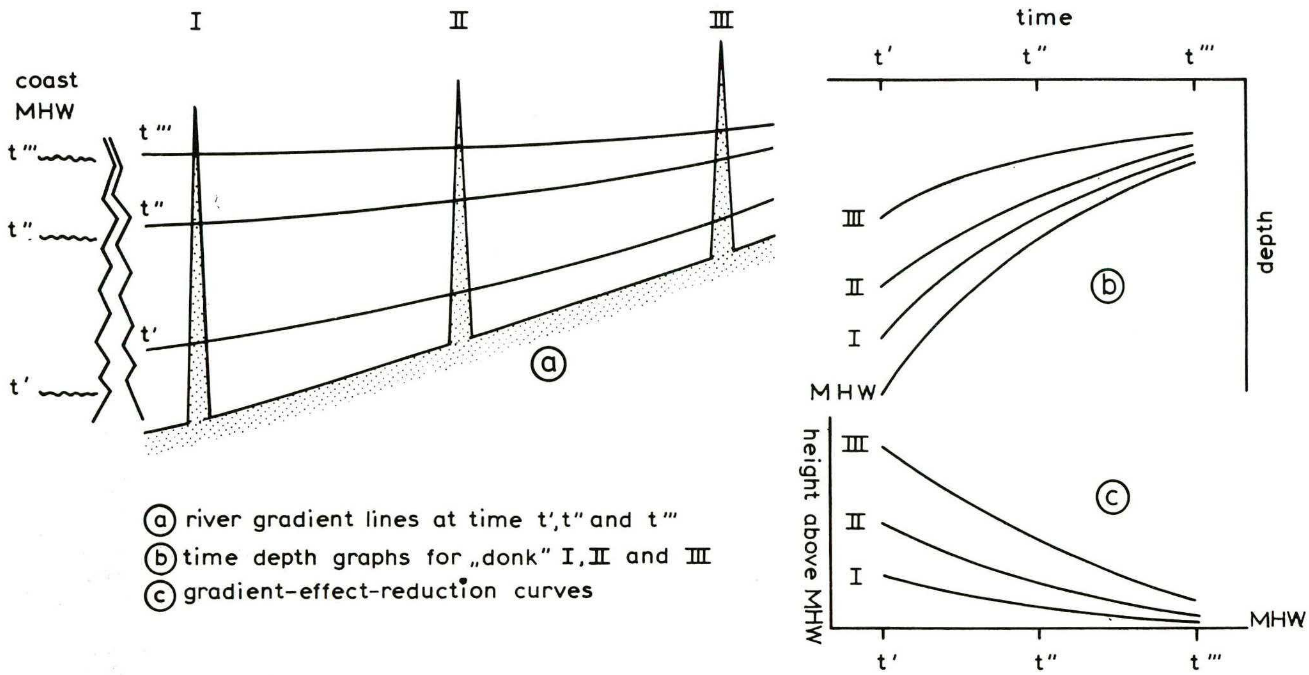


Figure 33 (a) Diagram illustrating the decrease in river gradient near three river dunes as a result of the rising sea level and simultaneous raising of the river bed due to fluvial deposition; (b) time-depth graphs for the rise of coastal MHW and the water-level rise at each of the three river dunes; (c) curves showing the decrease in river-gradient effect with time for each of the three localities.

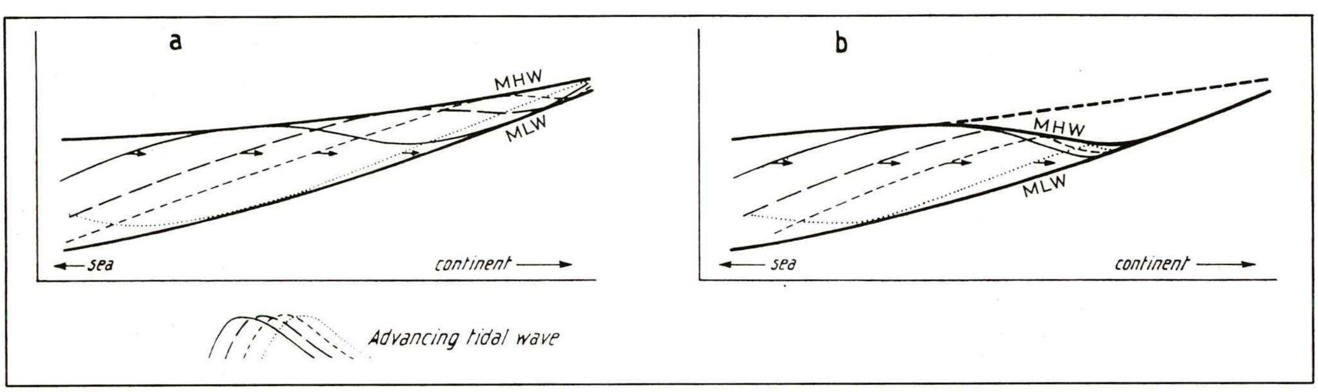


Fig. 34 Schematic illustration of the tidal wave progressing in a river-gradient-influenced water body (after Zonneveld, 1960).
(a) Without floodbasin effect; (b) with floodbasin effect.

western Netherlands coast has not differed significantly from that at present. A value of 1.8 ± 0.2 m is accepted here for the mean tidal range in the mouths of the rivers Rhine and Meuse, and this value is also assumed to have been constant throughout the period 7200-4800 BP. In figure 31b coastal MHW is indicated by a line 0.9 ± 0.1 m above the MSL line.

The fact that sample Barendrecht VII (4230 ± 55 BP, −3.20 m NAP) plots well below the contemporaneous coastal MHW level (fig. 31b), can only be attributed to a reduction of the tidal amplitude behind the coastline. This, in turn, can be explained by frictional dissipation of energy as the tidal wave moved into the lagoons, estuaries and/or tidal gullies and creeks, and by the so-called floodbasin (or flood-depression) effect (Van Veen, 1950; Zonneveld 1960). The lastmentioned effect refers to the lowering of MHW within a smaller or larger area due to an increase in storage capacity within the tidal basin. Apparently, any increase in coastal tidal amplitude due to, for example, the geometry of inlets or basins, has been overruled by the friction and/or floodbasin effect(s).

Summarizing the above it can be said that in the Rhine-Meuse delta the altitude (with respect to coastal MHW) of the upper limit of fen-wood peat growth at a given 'donk' has been the sum of the gradient effect (+), and the friction and floodbasin effects (−, −). In the non-tidal area the latter two are nil and the height of the forementioned limit above coastal MHW represents the full local gradient effect. In the tide-influenced area the floodbasin effect may be absent (fig. 34a) or present (fig. 34b), but a smaller or greater friction effect is always involved. This implies that in the tidal part of the delta the potential value of the river-gradient effect is nowhere reflected in the altitude of former upper limits of fen-wood peat growth (this would be the case if the landward reduc-

Table IV
Age, altitude, and meaning[1] of the 'donken' data used in figure 31a

index-point no.	name of sample	dated material	GrN-	conv. radiocarbon age 3)	compaction-free altitude (m below NAP)	altitude is related to:
	Brandwijk 8	fen-wood peat	186	7200±210	11.96-11.98	base of peat on river-dune slope
	Brandwijk 5	fen-wood peat	203	6010±200	6.45-6.47	
	Brandwijk 4	fen-wood peat	191	4550±150	3.29-3.31	"
	Brandwijk 2	fen-wood peat	192	2790±135	1.11-1.15	"
	Barendrecht I	fen-wood peat	1160	5920±60	5.80-5.85	"
	Barendrecht V	fen-wood peat	1151	5540±60	5.65-5.72	"
	Barendrecht VI	fen-wood peat	1140	4990±70	4.28-4.30	"
	Barendrecht VIII	fen-wood peat	1144	4600±70	3.40-3.46	"
	Barendrecht VII	fen-wood peat	1146	4230±55	3.19-3.24	"
	Barendrecht X	fen-wood peat	1147	3860±70	2.63-2.67	"
	Barendrecht XII	fen-wood peat	1148	3440±50	1.92-1.97	"
135	Molenaarsgraaf-Hazendonk	fen-wood peat	6215	5320±40	4.00±0.08	juncture occ. layer to river-dune slope
113	"	fen-wood peat	6214	4935±40	3.55±0.08	"
85a	"	fen-wood peat	6213	4480±40	2.55±0.08	"
85b	"	mixed material peaty occ. layer	5175	4290±40	2.55±0.08	"
115'	Ottoland-Kromme Elleboog I & II	charcoal bone 2)	6216 6384	3795±55 3820±45	1.80±0.08	highest level of back-swamp clay on dune slope
89	Molenaarsgraaf no. 58	charcoal	5176	3640±30	1.60±0.08	boundary between gully filling and occ. layer on Schoonrewoerd stream ridge

1) Meaning: with the exception of index point 115' all time-depth data are assumed or interpreted to indicate former local MHW or local groundwater level. Index point 115' may indicate a level somewhat below groundwater level.

2) Assumed by Louwe Kooijmans to post-date final phase of activity of Schoonrewoerd stream.

3) Ages for the Brandwijk and Barendrecht samples have been corrected for 13C by subtracting 40 years (Mook- pers. comm.). Previously published ages are obtained by adding 40 years.

Sources: Archive Groningen radiocarbon laboratory, Jelgersma 1961, and Louwe Kooijmans 1974, 1976.

tion in tidal amplitude was solely due to transformation of kinetic into potential energy). Thus, although the MHW line in figure 34a clearly reflects a river-gradient effect, it is impossible to tell how much higher it would have been with a different pattern of energy loss due to friction.

Figure 34b illustrates how a floodbasin effect may cause a seaward extension of the non-tidal zone. It is clear, however, that there too no data representative of the full gradient effect can be obtained.

With the available time-depth data from the Rhine-Meuse delta it is not possible to separate floodbasin from friction effects. The former term will therefore be used synonymous with or to include the friction effect.

5.6. INTERPRETATION OF THE 'DONKEN' DATA

As the 'donk' of Brandwijk is situated about 20 km to the east of the Barendrecht 'donk' (fig. 32), curve II, the line connecting the 'donken' data collected by Jelgersma (fig. 31a), has to be separated – because of the upstream increase in gradient effect – into two curves, one for each 'donk' (fig. 35a). Figure 35b shows the height of these two curves and of the Hazendonk time-depth boxes above curve IV, the slightly corrected MSL curve by Jelgersma (1979) (fig. 31a). The general convergence in time of the time-depth graphs for the Brandwijk and Barendrecht 'donken' and of the Hazendonk data on the MSL and MHW lines respectively (fig. 35b), can be interpreted to reflect a gradual decrease in river-gradient effect.

Since the 'donk' of Brandwijk and the Hazendonk are located at comparable distances from the coast, it can be concluded from figure 35b that if the Hazendonk time-depth data contain a floodbasin effect, it is clearly less than in the case of the Brandwijk data. This conclusion implies that the convergence of the time-depth boxes from the Hazendonk area on the inferred coastal MHW line (fig. 35b) may rather closely approach the decrease in local river-gradient effect with time. It is possible to elaborate this point by further examining the available data.

7200 BP

In view of the relatively low sea-level stand at that time and consequently a more westerly position of the coastline and stronger river gradient, it can safely be assumed that the altitude of the oldest Brandwijk time-depth point does not contain even a small floodbasin effect (i.e. represents the full local gradient effect).

4500 BP

The occurrence of a floodbasin effect can be deduced from the position below the MHW line of

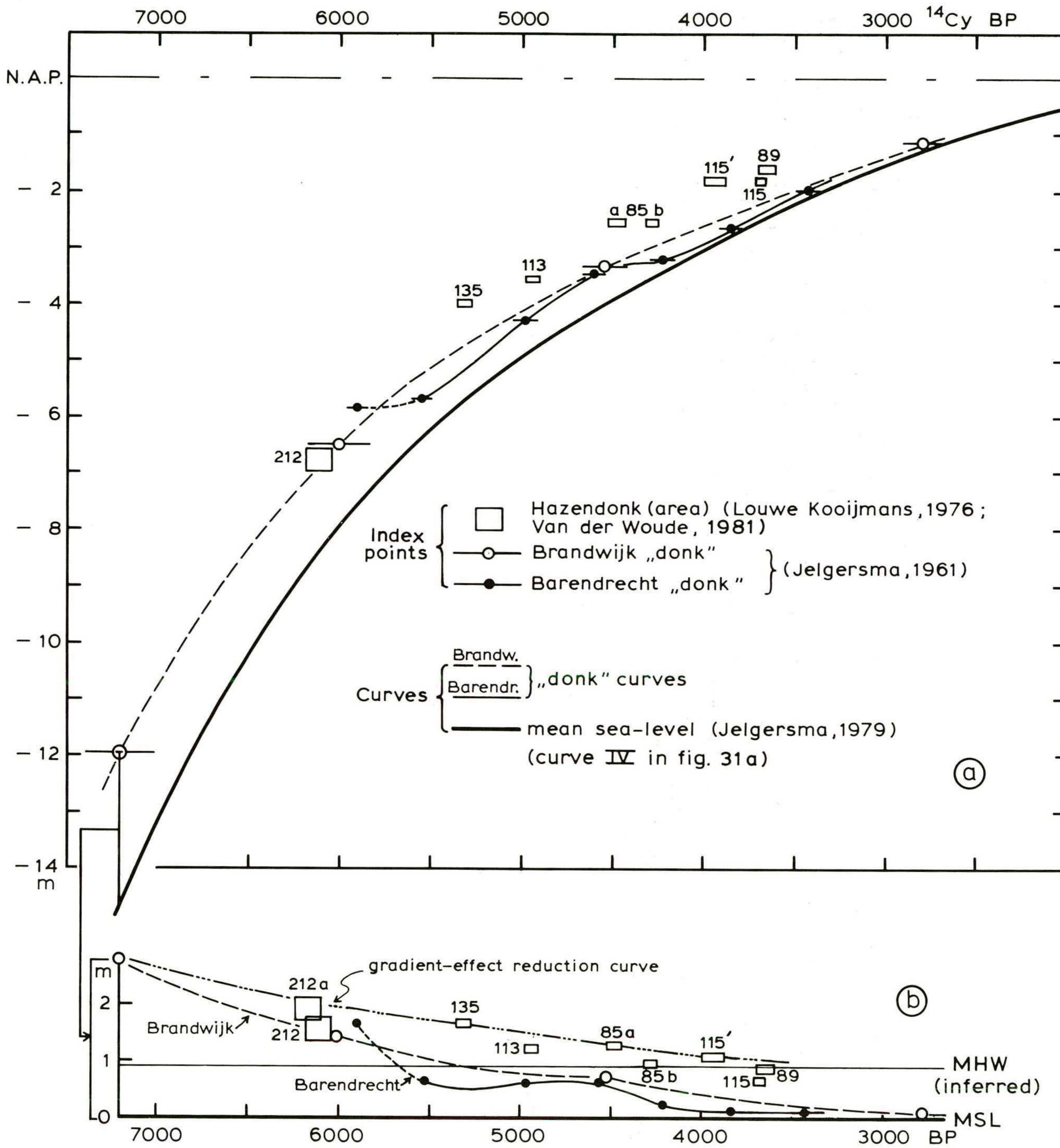


Fig. 35 (a) Time-depth diagram showing the slightly corrected (1979) MSL curve by Jelgersma, the curves based on data from the 'donken' of Brandwijk and Barendrecht, and the Hazendonk data (boxes).
(b) Plot of the vertical distance above the MSL curve of the graphs and time-depth data mentioned sub (a). Convergence of the Brandwijk and Barendrecht curves upon MSL, and of the Hazendonk data upon coastal MHW reflects the decrease in river-gradient effect. It is argued in the text that a line connecting the oldest Brandwijk datum and Hazendonk datum 85a in a slightly concave fashion yields a gradient-effect reduction curve for the Brandwijk-Hazendonk area. With the help of this curve it is possible to estimate the local floodbasin effect(s).

both the Brandwijk and Barendrecht time-depth points (fig. 35b). As suggested by the markedly higher position of Hazendonk time-depth box 85a, the water level surrounding this dune was not, or was much less affected by a reduction of the tidal amplitude. It is tentatively concluded that the altitude of this Hazendonk datum closely approximates the full local gradient effect of that time. According to Louwe Kooijmans (1976), whose sea-level graph is also given in figure 31a, the water level near the Hazendonk was affected by a full floodbasin effect. In correcting the measured altitude of time-depth box 85a for the remaining gradient effect in order to arrive at a figure for MSL, he applied, in our interpretation, too low a value (0.5 ± 0.2 m) (see also 4.2.5.).

5.6.1. Gradient-effect reduction curve for the Brandwijk-Hazendonk area

Assuming the difference in gradient effect between the Brandwijk 'donk' and the Hazendonk to have been negligible (comparable distances to the coast), one obtains, by connecting the two previously discussed time-depth data in a slightly concave fashion, a curve that approximately indicates the reduction in river-gradient effect in the Brandwijk-Hazendonk area (fig. 35b). With this curve it is now possible to specify for each of the Brandwijk or Hazendonk time-depth data the extent to which the floodbasin effect has (over)compensated the gradient effect. The height above coastal MHW of the second oldest Brandwijk point, for example, is the sum of the gradient effect and the floodbasin effect: 0.56 m $= 1.08 - 0.52$ m. In view of the approximate nature of the gradient-effect reduction curve, the fact that Jelgersma's MSL curve is assumed to provide a reliable line of reference, and that constancy of tidal range before 5000 BP remains to be proved, the given example illustrates the principle rather than the quantitative truth.

5.7. THE GRADIENT-EFFECT REDUCTION CURVE AND THE FURTHER INTERPRETATION OF FIGURE 35

From the position of the second oldest Brandwijk time-depth point below the gradient-effect reduction curve it is concluded that at about 6000 BP a floodbasin effect was present there. As the area bounded by the 'donken' of Barendrecht and Hillegersberg (fig. 32) in the west and by the Brandwijk 'donk' and Hazendonk in the east at or just before 6000 BP apparently constituted a wide body of more or less open water (Jelgersma, 1961; Van de Plassche, 1979b, Van der Woude, 1979), it would be rather surprising if the forementioned floodbasin effect would not also have affected the water level at the Hazendonk. Unfortunately, time-depth data from the peat/dune sand interface of the Hazendonk to test this hypothesis are not available. There is, however, a date of 6060 ± 80 BP (GrN-7864, Van der Woude, 1979) for the base of a peat bed sampled at 1 km distance from the Hazendonk. This peat bed, the base of which consists of *Phragmites* remains, overlies a fluvial clay. The top of this minerogenic bed attains a compaction-free altitude of -6.8 ± 0.2 m NAP on the Hazendonk (Van der Woude, pers. comm.). This value must have been reached before the onset of peat growth 1000 m from the dune. The question is: how much before? If the age of the top of the clay is assumed to be 100 years older than the base of the peat, then the upper half of a hypothetical time-depth box (6160 ± 80 BP -6.8 ± 0.2 m NAP) would coincide with the gradient-effect reduction curve (box 212a in fig. 35b), suggesting (near) absence of a floodbasin effect at that time. However, in that case one is obliged to account for the rather large time gap between the end of sedimentation and the beginning of peat growth, which is difficult without invoking a considerable drop in water level causing conditions to become too dry for peat formation. We therefore prefer to accept the more simple possibility that within a time span of less than 40 years after the end of sedimentation the clay surface was colonized by *Phragmites* and peat formation had begun. The corresponding time-depth box (no. 212 in figs. 35a and 35b) plots below the gradient-effect reduction curve and confirms that the expected floodbasin effect at the Hazendonk is indeed present.

It is noted above that around 4500 BP MHW in the Hazendonk area was lowered much less than in the Brandwijk area. This can be accounted for in two ways: either the tidal wave reached the Hazendonk without much dampening of amplitude additional to that caused by frictional dissipation of energy; or, the Hazendonk had come to lie beyond reach of the floodbasin effect due to a more or less local, seaward shift of the tideless fluvial zone. The latter possibility is favoured here since the occurrence of a floodbasin effect in both the Barendrecht and Brandwijk areas suggests it to have been of more than just a local nature and would certainly also have been felt at the Hazendonk.

From the position of time-depth box 135 on the approximate gradient-effect reduction curve it follows that the abovementioned seaward shift of the fluvial zone occurred in the course of the period 6000-5500 BP. A westward extension of the tideless area can result from an increase in river discharge and sediment transport and/or a lowering of either sea level or the intracoastal MHW level. In this connection it is interesting to note that according to Van der Woude (1979) clastic deposition in the Hazendonk area recommenced at about 5600 BP after a period of 400 years of peat growth, and that data collected from the 'donk' of Hillegersberg permit the reconstruction of a period of reduced (local?) water-level rise between 5650-5500 BP (Van de Plassche, 1980).

With respect to time-depth box 115, the following is remarked. Its position on the gradient-effect reduction curve is somewhat contradictory to the interpretation given above (see brief discussion of the 'donken' data) that it might indicate a level (of deposition) slightly below mean groundwater. This contradiction is resolved if the age of the top of the clay would be younger than 3800 BP and not older as Louwe Kooijmans (1974) argued. That the sedimentation may indeed have ended later is indicated by the age of a sample, taken near the dune, from the base of the peat overlying the backswamp clay: 3650 ± 35 BP. (GrN-6212, Louwe Kooijmans, 1974). Since the very low degree of physical ripening precludes the possibility of a dry period, it can be concluded that sedimentation near the Hazendonk did not end before 3800 BP, but continued to about 3675 ± 25 BP. In figures 35a and 35b box 115' may thus be replaced by box 115. The position of this new time-depth box below the groundwater level indicated by time-depth box 89 corresponds well with the low consistency of the backswamp clay.

In the Barendrecht area the floodbasin effect can be seen to have been quite large, except in the period 5250-4500 BP. The fluctuating Barendrecht curve can be interpreted to reflect changes in the width and/or depth of the former inlets of the rivers Rhine and Meuse, and/or in the degree to which the creeks and water courses connected to the inlets allowed the tidal wave to migrate inland.

5.8. DISCUSSION AND CONCLUSIONS

Although it has been shown in the previous paragraph that the gradient-effect reduction curve for the Brandwijk-Hazendonk area can be successfully confronted with time-depth data and geological information, the curve should be regarded as preliminary. Firstly, because the 'donken' data have been considered relative to Jelgersma's smooth (1979) MSL curve. As her graph is based on only a limited number of widely spaced (basal peat) time-depth points (fig. 31a), additional data may in due course reveal the presence of fluctuations in the sea-level rise. This may alter the relative position of Hazendonk point 85a and other time-depth points and, consequently, oblige a change in the gradient-effect reduction curve. In the second place, because the mean value of the radiocarbon age for the lowest Brandwijk sample and for the Hazendonk-85a sample have been assumed to be correct (i.e. the statistical nature of the dates has not been taken into consideration). A third reason is that either or both of these two time-depth points may not fully represent the upper limit of fen-wood peat growth. Two more arguments for stressing the preliminary character of the curve under discussion can be given. One is that the gradient effect may have temporarily increased, namely during periods of prolonged increase of river discharge and sedimentation. If such events have been recorded in the fen-wood peat growth, the gradient-effect reduction curves will show fluctuations. The second, and final, reason is that all radiocarbon dates will have to be converted into historical years when a definite dendrochronological calibration curve is availabe. (This includes the problem of ambiguity of convertion posed by medium-term fluctuations in the atmospheric 14C concentration).

A check on any gradient-effect reduction curve is that the floodbasin effect cannot become greater than half the tidal range at the coast. In this connection it may be remarked that if it is accepted that the 0.65 m difference in water level between the 'donk' of Brandwijk and the Hazendonk is real, the two time-depth points concerned will always put an important constraint on the ultimate position of the gradient-effect reduction curve for the area.

In conclusion, the irregular convergence of age-altitude data from the Brandwijk and Barendrecht 'donken' and the Hazendonk upon the smooth curve for MSL or MHW can largely be explained in terms of (1) a gradually decreasing river-gradient effect and (2) a floodbasin effect, the magnitude of which varied both in time and space.

The first effect renders 'donken' data in themselves less suitable for sea-level studies than previously held; the second is a disturbing factor in distinguishing true from apparent variations in sea-level rise.

6. THREE PART-PROJECTS FOR COLLECTION OF NEW AGE-ALTITUDE DATA

6.1. INTRODUCTION

Almost all of the new time-depth data collected for the present study have been obtained from the three sources employed by Jelgersma (1961): the Lower Peat, peat on the slopes of river dunes in the Rhine-Meuse delta, and peat in the beach plains. Since Jelgersma's investigation comprised the total Dutch coastal plain, it is understandable that she could not exhaustively explore and exploit the potential for sea-level study of each of the organic deposits involved. As a result, these three peat occurrences still required systematic study.

The approach followed by Louwe Kooijmans (1974) and Roeleveld (1974) offered little or no practical opportunities for gathering additional information. The first author exhausted the available archaeological data, and application of Roeleveld's method would require considerable time-consuming mapping and a large number of radiocarbon dates; moreover, compaction would present a difficult problem.

The method of deriving paleo tide levels from the study of sedimentary structures in fossil beach deposits (Roep et al., 1975) has been applied in the few instances where a building pit in the coastal barrier deposits was available for inspection.

6.2. THE THREE PART-PROJECTS

6.2.1. Basal peat

The base of the Hollandpeat Member deserved renewed attention for several reasons. Firstly, as discussed in chapter 4, Jelgersma's method of curve construction implies that with every find of a younger time-depth datum the curve will need to be changed accordingly. A conscious attempt to collect basal peat samples from parts of the underlying surface which have the youngest possible age for a given depth has never been made. A second point is that if basal peat is formed locally at about MSL (Jelgersma et al., 1975), it is most suitable for the study of differential crustal movements within the coastal area, since it would be relatively independent of variations in tidal range. Of all possibilities for sea-level study in the Netherlands this offers the greatest range in depth and the largest geographical application. A third argument in favour of collecting new basal peat data, particularly for the period prior to 5500 BP, derived from the facts that the curves of Louwe Kooijmans and Roeleveld cannot be extended further back in time due to a lack of the kind of data employed in their respective methods, and that the older part of Jelgersma's curve is based on very few time-depth points.

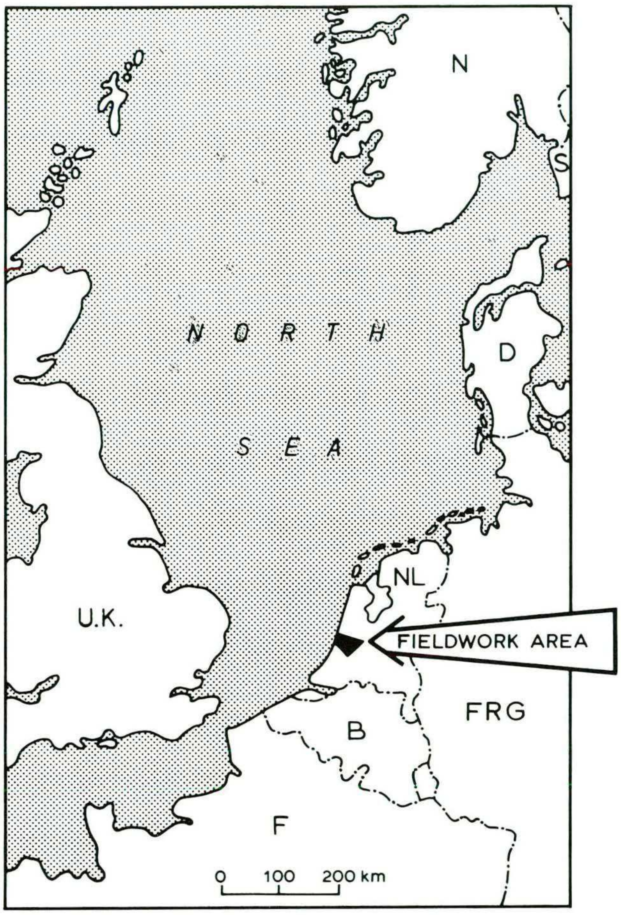


Fig. 36 Map of the North Sea area, showing position of study area.

6.2.2. Peat on river dunes

As stated in chapter 4, the peat-covered slopes of Late-glacial/early-Holocene river dunes in the lower areas of the Rhine and Meuse are an excellent source of information on local water-level changes during the middle- and upper-Holocene. The age-altitude data collected by Jelgersma from the 'donken' of Brandwijk and Barendrecht clearly suggest past variations in the rate of water-level rise in the Rhine-Meuse delta (fig. 14b). The vertical interval of the (14) samples is, however, rather large and/or irregular. Hence it was decided to investigate the deposits on and surrounding another 'donk', and to take samples from the peat/dune sand interface at close and regular intervals in order to determine whether the fluctuations found by Jelgersma are real and whether any more can be detected.

6.2.3. Beach-plain peat

Jelgersma dated one or two samples from the base of the peat in each of the four beach-plain depressions that occur immediately to the north and south of the former Older Rhine estuary. A more intensive use of the beach-plain peat for sea-level study was both desirable and possible. In the oldest beach plain, for example, the fen peat is over 1 m thick. Since the inter-barrier depression stood in more or less open connection with the estuary, peat growth must have followed the relative sea-level rise rather closely. In the process it (partly) covered the low Older Dunes that cap the coastal barrier ridges. By close-interval sampling of the peat base along the slopes of the Older Dunes, part of the history of water-level rise in the Older Rhine estuary could be reconstructed. Furthermore, the study of peat growth in the beach plains would provide valuable complementary information to the work of Roep and colleagues on paleo tide levels determined from sedimentary structures in the coastal barrier deposits.

6.3. GENERAL APPROACH

In the absence of modern analogues of sea-level-controlled peat growth along the southern North Sea coasts, comparison of systematically and carefully collected sets of data representing peat formation in different situations behind the coastline provides an important basis for interpretation of the results (cf. the changed significance of Jelgersma's curve following the work by Roep and others). To ensure optimal comparability, all data have been collected in as small an area as possible in order to minimize possible effects of differential crustal movements between the sampling areas, and with the greatest possible attention to various sources of error.

In general, the procedure has been to investigate the stratigraphy and morphology of each sampling area on a semi-detailed scale, on the basis of which potential sampling localities were selected for more detailed inspection. In addition, a limited number of cores have been investigated paleoecologically.

6.4. LOCATION OF SAMPLING AREAS

The condition of sampling area proximity required that the three part-projects briefly described above be concentrated in the Province of South-Holland (figures 36 and 37).

South-Holland would seem to be least suitable of the coastal provinces for obtaining basal peat data reflecting a sea-level-related groundwater rise. The irregular topography of the Late-glacial/early-Holocene floodplain of the Rhine and Meuse, the occurrence of clay beds, and the influence of river discharge render it completely unsuitable for our purpose. In the area to the north, bordering the floodplain, the situation is hardly any better (Pons and Bennema, 1958). The very gently seaward dipping surface of the Pleistocene substrate, the superimposed irregular eolian topography, the absence of drainage channels, its position 'at the foot' of relatively high push moraines to the east (seepage!), and its proximity to major river systems must also have made this region highly susceptable to peat growth which was unrelated to sea level. However, reconnaissance

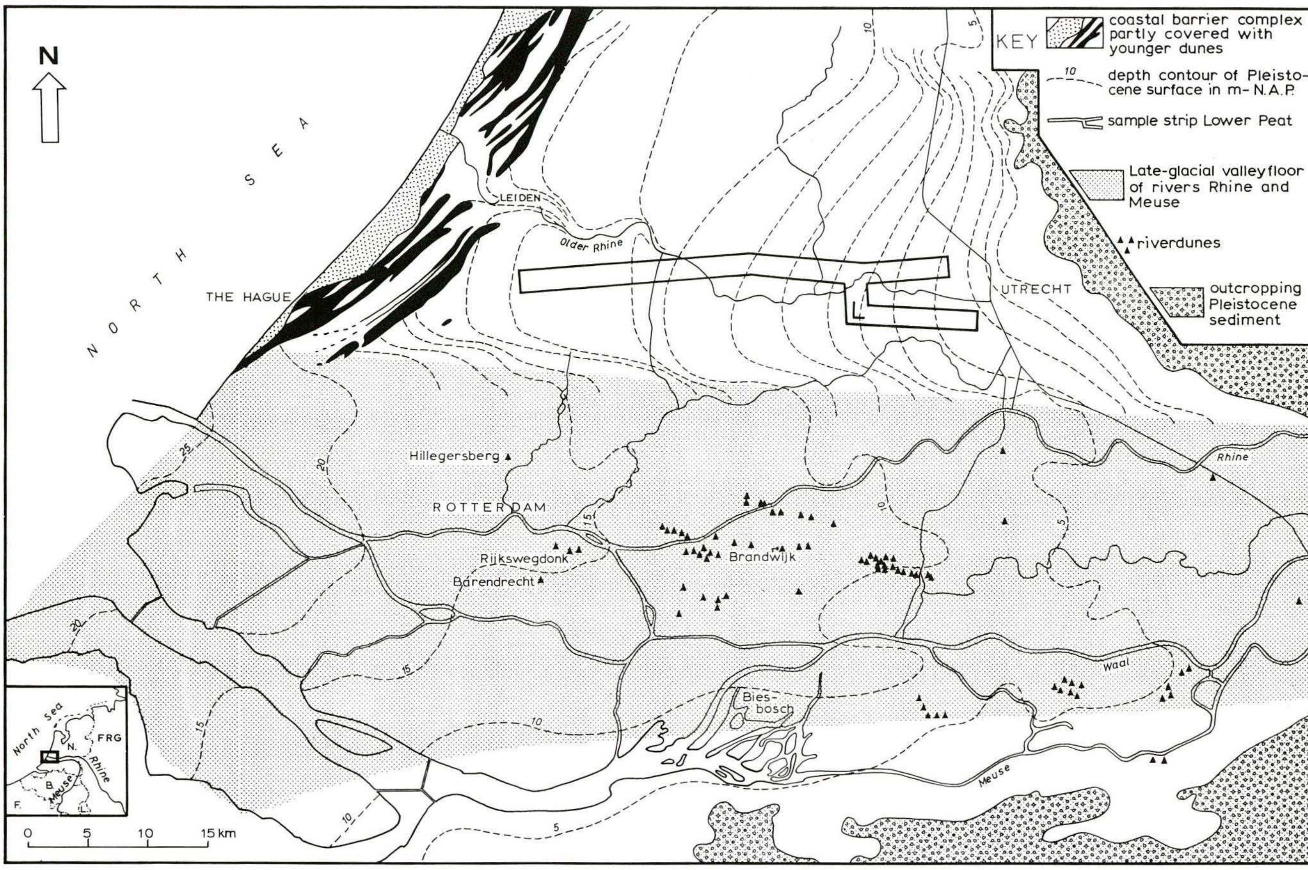


Fig. 37 Map of the mid-western Netherlands, where fieldwork for the national IGCP sea-level project was carried out. Samples (mostly basal peat) were collected from the Hillegersberg and Rijkswegdonk river dunes near Rotterdam, a strip on the so-called Mid-Netherlands Plateau between The Hague and Utrecht, and from the coastal barrier complex between Leiden and The Hague. (Based on maps from Hageman (1969), Jelgersma et al. (1970), Pons and Bennema (1958), Verbraeck (1974), and Oele and Pruissers (1975).)

mapping revealed the sub-surface topography to be sufficiently pronounced to justify the expectation that basal peat samples from the highest parts of the substrate morphology would indicate former supra-local groundwater tables.

The middle of the broad topographic ridge bordering the northern side of the former Rhine-Meuse valley (fig. 37) initially seemed the least unsuitable for planning a sampling strip. However, it appeared that there the base of the peat is often separated from the underlying sand by a greyish-black, greasy, organic substance. Slightly further to the north this material was encountered much less frequently.

Of the many outcropping river dunes in the fluviatile area the one in the most westerly position – the 'donk' of Hillegersberg – was selected for investigation. Here the river-gradient effect will have been smaller and ceased earlier than further upstream. It subsequently proved necessary to collect supplementary samples from a second river dune several kilometres more eastward: the Rijkswegdonk near Bolnes.

The coastal barrier complex south of the former Older Rhine estuary and north-east of the city of The Hague was considered best suited for study because of the clearly defined geological structure and its general accessibility. One drawback of this area is that the most westerly swale and barrier are covered by thick accummulations of Younger Dune sand and had to be left unstudied.

7. RELIABILITY AND ACCURACY OF THE NEW DATA

7.1. INTRODUCTION

In a comparative study like the present one it is of prime importance to avoid unnecessary scatter of time-depth data and too large margins of error. Therefore, much attention was paid to the accuracy and reliability of the data, both by avoiding or reducing as much as possible the effect of several sources of error, and, in a few cases, by codating suspected or contaminated samples to obtain an impression of the order of magnitude of the error involved. The following aspects were considered: altitude – compaction, depth of sample below surface, and levelling; age – *in situ* position of dateable material, contamination, and sample interval in relation to the degree of compaction of the peat.

7.2. ALTITUDE

7.2.1. Subsidence due to compaction of underlying deposits

As far as the basal peat data are concerned the influence of compaction is negligible since the substrate consists of sand and gravel down to considerable depth. Whether the data from the river dunes are entirely free of subsidence due to compaction is not absolutely certain. 'Donken' may be underlain by a layer of sandy clay or loam, as in all probability is the case for the 'donk' of Hillegersberg (Grondmechanische Dienst Rotterdam). (For the Rijkswegdonk no information is available in this respect.) It may be assumed, however, that by the time peat growth commenced on the slope of the dune, consolidation of the sandy clay/loam under the weight of the dune will have proceeded to such extent that the effect of further loading will be negligible.

In contrast, the presence of lagoonal clay and peat below the (two) easternmost barrier(s) and of clay(ey) beds intercalated in the shallow marine sands (Van Straaten, 1965; pers. obs.) require that there the possibility of compaction is taken into account.

Firstly, it is important that the peat on the Older Dune slopes on the eastern flank of the easternmost barrier should not be sampled. This is because the compaction-susceptible deposits have only partly been replaced by littoral sands. The presence of considerable (differential) subsidence due to the weight of younger deposits is well illustrated by the flexure of a very humic, rooted clay bed intercalated in the clay below the barrier sands (fig. 38). Seaward, the barrier deposits increase in thickness and the effect of subsidence due to compaction of lagoonal clay and peat can be expected to decrease accordingly. Still, in the case of samples from the western part of the oldest barrier or from the easternmost beach plain, particularly the eastern part of it, a possible effect of compaction should be kept in mind. Secondly, it is important that potential sampling sites should be checked for the presence of clay(ey) beds within the barrier deposits, and for clay and peat hidden below a firm-looking cover of sand. In this respect a prerequisite for a proper site evaluation is that borings reach to sufficient depth. The following example illustrates the point.

A c. 4 m deep boring through the top of a small, peat-covered dune in the north-centre of the easternmost beach plain, showed that the sediments consisted only of sand. The site was adjudged suitable for sampling, until further, less deep borings nearby revealed the presence of a thin band of clay, the variation in height of which strongly suggested the dune to have been lowered (fig. 39), apparently due to compaction of deeper occurring sediments. A boring down to a depth of 6 m proved that from about 4 m downwards the sediment comprised clayey sand, very sandy clay, and many thin clay beds. The locality was subsequently rejected for taking samples.

At each sampling site one or two borings reaching 6 m below surface were attempted. However, in a number of cases the handboring equipment did not permit penetration any deeper than 4 m into the sand.

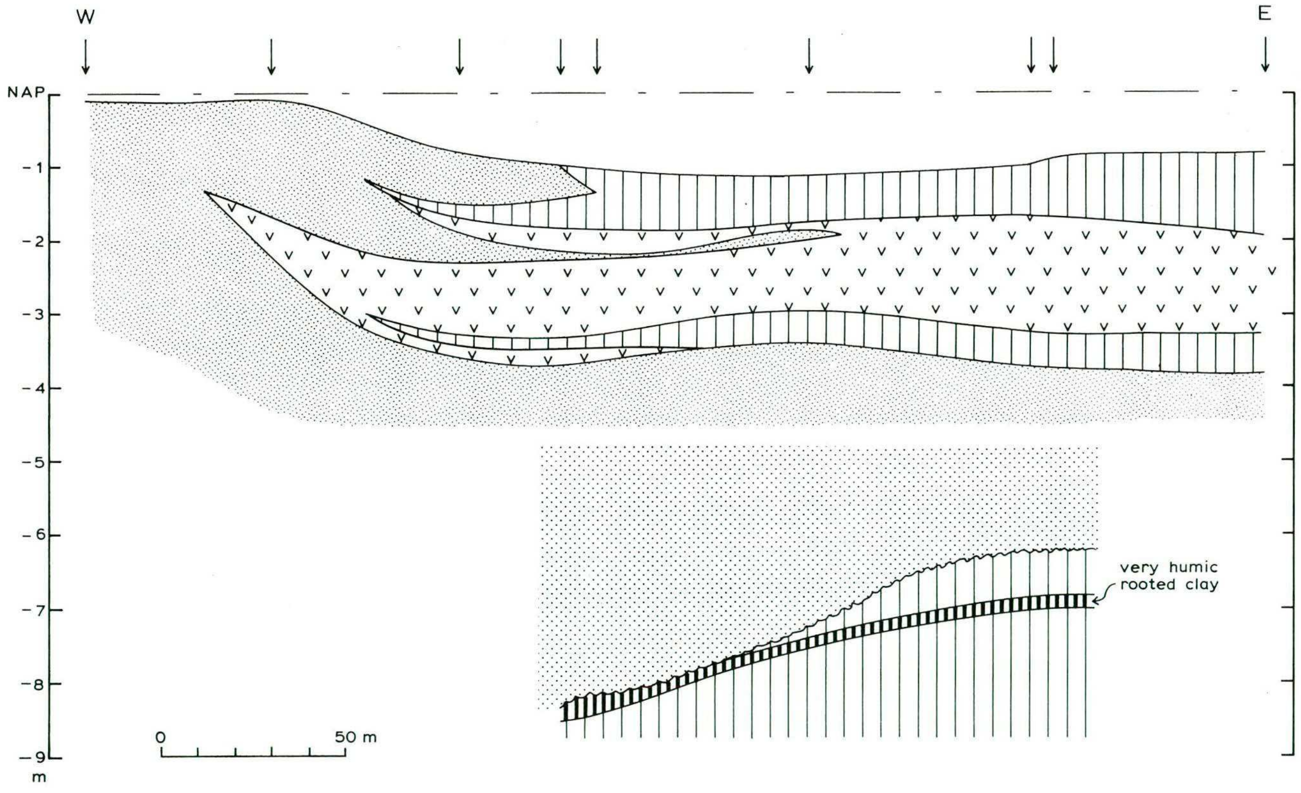


Fig. 38 Section (at Voorschoten) across landward boundery of easternmost barrier ridge. Flexure in very humic, rooted clay bed, intercalated in lagoonal clays below barrier depositst, indicates differential compaction. (Legend: see fig. 39.)

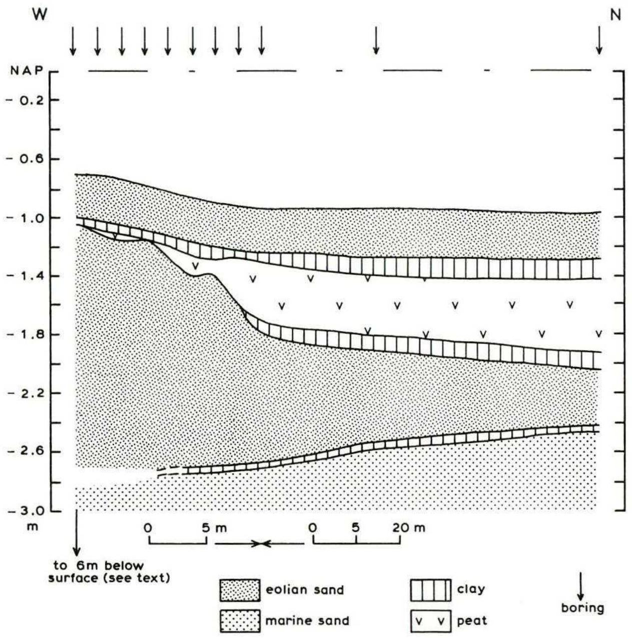


Fig. 39 Section across the northern slope of a small dune in the centre of the (northern part of the) easternmost beach-plain south of the Older Rhine. The dune and its surroundings have been lowered by compaction of deeper lying sediments.

7.2.2. Depth of sample below surface

In almost all cases depth measurements have been made relative to the top of a short wooden pole or a T-shaped metal strip driven into the ground next to the borehole. Where this procedure has not been followed, the surface around the borehole was initially clearly defined and then levelling was carried out immediately after the core was acquired.

The basal peat samples (except for the five most shallow ones) and the samples from the 'donk' of Hillegersberg and from the Rijkswegdonk (except for the six most shallow ones) have been derived from cores taken by fieldstaff of the Geological Survey using hand-operated and power-driven coring devices. The diametre of the cores, 0.065 m and 0.1 m, was large enough to allow sufficient organic material for radiocarbon dating to be obtained from one core and yet keep the sample interval small (0.04 m or less). The beach-plain peat samples and the relatively shallow samples mentioned above were collected by the author by means of a gouge borer with a diametre of 0.045 m. The smaller diametre necessitated taking several cores, three, sometimes four, in order to obtain sufficient organic material for radiocarbon dating. The differences in depth of the peat/sand boundary in a set of cores from one site appeared to be small, 0.03 or 0.04 m at most, and mostly only 0.01 or 0.02 m. In the few cases where this boundary in a core differed by as much as 0.06 to 0.1 m from the others, the information was rejected. The mean of the observed depths was taken to represent the depth of a particular sample. The error introduced thereby amounts to no more than a few centimetres.

Somewhat more serious is the difference in depth of the peat base as determined from the 0.065/0.1 m Ø cores and from handborings which were made to locate the sampling spot and to check the depth to be obtained from the cores. The maximum observed difference was 0.23 m, but generally it was less than 0.1 m, and in 27 cases the difference was less than 0.03 m. For establishing the correct depth below the surface of the peat base it is critical that the boring is made vertically. Since the handborings were made with light, relatively flexible equipment, these are more likely to deviate from the vertical than the steel-cased core-borings, particularly when they go down to greater depth. However, inspection of the data indicates that depth figures from the borings made by hand were not in all cases higher (Table V).

Table V *Number of times that peat/sand boundary in handboring (H) was shallower or deeper than in sample core (C)*
(difference greater than 0.03 m)

	H) C	H (C
Hillegersberg data	2	2
Rijkswegdonk data	3	1
basal peat data	0	5

Since a conscious effort was made to put down the handborings as vertically as possible, and to within 0.01 m of the core hole, it seems justified to assume that the shallower values from the handborings are more correct. In two cases, however, all evidence pointed towards the deeper values being more correct.

7.2.3. Levelling

Boring and sampling sites were levelled with the aid of a JENA instrument. With few exceptions, sampling sites were levelled two or three times. Closing errors or differences between the results of separate levellings varied from less than 0.01 m to 0.06 m. Altitudes have been measured relative to Nieuw Amsterdams Peil (NAP), which is the zero datum for the Netherlands. Mean sea level along the Dutch coast, i.e. the average value of MSL as established at various tide gauge stations, is c. 0.1 m below NAP.

7.3. AGE

7.3.1. In place position of dateable material

Of the 86 samples for radiocarbon assaying collected for the present investigation 81 consisted of peat, 2 of wood from clearly *in situ* tree roots, 1 of the uppermost horizon of a podzol soil, 1 of amorphous, slightly clayey, organic material in a depression of the Pleistocene sub-surface, and 1 of juvenile bivalved shells. Of the 81 peat samples one was rejected due to its detritic appearance and the rather high clay content. For the remaining 80 peat samples there is no reason to doubt that they represent in place accumulations of vegetational remains. The juvenile bivalves were found washed together in coastal barrier sediments. In this case the age of the sample can be considered representative of the age of the sediments, since dead bivalves cannot be transported very far without the two valves coming apart.

7.3.2. Contamination

7.3.2.1. ROOT CONTAMINATION

In order to reduce the rejuvenating effect of roots from plants and/or trees that lived on and contributed to the forming of a peat bed, all peat samples were pretreated manually. All Hillegersberg samples were separated most carefully into a root- and a restfraction according to the method described by Streif (1971). Since it proved to be very time-consuming to remove all recognizable rootlets, it was decided to subject most of the samples from other sites to a slightly less rigorous pretreatment. From these, without using the binocular microscope, loose bits of wood, all or all larger woody roots and rootlets, *Phragmites* rhizomes, and (sub-)vertically positioned roots and stems were removed. Inspection of several tens of peat cores demonstrated that (sub-)vertically positioned roots were often present in non-negligible quantities. Figure 40 shows three cores and one sample in which part of the vertical roots have been laid bare.

For cost reasons quantitative assessment of the effect of this manual pretreatment was made only once. A sample of beach-plain peat, taken from a depth of 0.7 m below the surface of a meadow, appeared to be heavily penetrated by brown to darkbrown roots and rootlets from the overlying 0.35 m of peat. All roots and rootlets, observed under the binocular microscope, were removed from the sample. No living rootlets were encountered. A twin sample taken at the same depth and 0.1 m to the side of the other sample, was submitted for dating without having been pretreated manually. A check on the presence of living rootlets was negative too. The age of this sample turned out to be conclusively younger than that of the pretreated sample: 3470 ± 60 BP (GrN-8866) versus 3860 ± 50 BP (GrN-8865). Since both samples have been subjected to standard chemical pretreatment (diluted acid, diluted sodiumhydroxide, acidification), the age difference cannot be attributed to contamination by infiltrated recent humic acids. However, the possibility cannot be entirely ruled out that the younger sample has been slightly contaminated by (undetected) recent rootlets. In the unlikely case of 5% contamination by recent carbon, due to which the sample (GrN-8866) would have been dated 230 years too young, the difference between the mean values of the dates is 170 years, which is significant at the 66.7% confidence level. This result shows that if it is suspected (as was the case here) that the peat above the sample has accumulated slowly, removal of all (sub-)vertical roots and rootlets is a necessary operation.

Obvious contamination by recent, living rootlets was noticed in two beach-plain peat samples collected only a few decimetres below the grass-covered surface. Despite extremely careful extraction of all rootlets visible under the binocular microscope, the assays gave an age (far) younger than was to be expected on stratigraphical grounds (Van de Plassche, in prep.).

7.3.2.2. CONTAMINATION BY OLDER MATERIAL

In quite a number of borings the base of the Hollandpeat Member appeared to be separated from the Pleistocene sand below by a thin layer (0.01-0.04 m) of black, greasy, organic material. Because it occurs mainly in connection with a podzol profile in the cover sand and follows the topography (fig. 41), the black layer is interpreted to be the uppermost soil horizon (AO, AOO). As it predates the onset of continuous peat accumulation it would be interesting to know the age difference between a sample of this horizon and a sample from the base of the overlying peat. Figure 41 shows the position of such a sample pair in a section near Linschoten. The sample from the uppermost soil horizon was carefully cleared of the many roots and rootlets that descended from the peat above. However, a complete elimination of the smallest rootlets could not be achieved. From the significant age difference between the two samples (fig. 41), which would even have been larger if all rootlets could have been removed, it is apparent that in collecting basal peat samples care should be taken not to include (part of) the top of the underlying soil. This may prove very difficult if the base of the peat is itself black and amorphous.

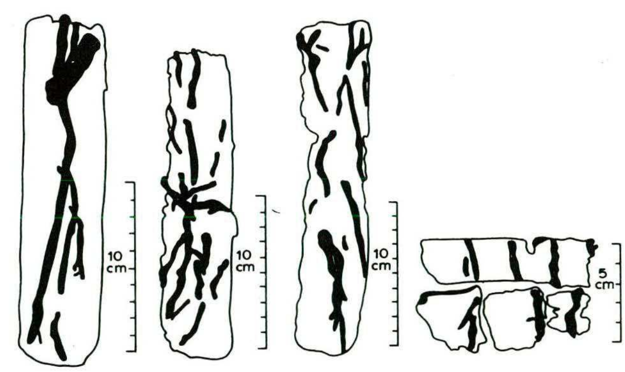


Fig. 40 Part of (sub)vertically positioned roots (in black) laid bare in three peat cores and one sample.

7.3.3. Sample interval and degree of compaction

The peat on the 'donk' of Hillegersberg, and on the Rijkswegdonk at a depth greater than c. 8 m below surface, has been subject to considerable compaction due to the weight of the overlying deposits and artificial drainage of the surroundings. This is apparent from the dry and compact nature of the peat and the difficulty of penetrating it with a pointed gouge borer.

In order to determine the rejuvenating effect of compaction on the age of a sample in relation to its thickness, a sample pair from the base of the peat (core 1 in fig. 42) was dated. The very insignificant age difference between the two samples demonstrates in this case that the age-reducing effect of the considerable compaction on the radiocarbon age of a sample 1.1 + 1.2 would have been entirely negligible.

Core 1 was selected for its rather sharp transition between peat and dune sand. In three other cores