Vera Van Lancker
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HOLOCENE SHORELINE AND SEA-LEVEL DATA FROM THE BELGIAN COAST

Cecile Baeteman and Luc Denys 1997

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Global change project?

1. Introduction

The Belgian coastal plain was formed during the Holocene in a wave/tide-dominated environment. At present the plain is a 15 km wide low lying polder area, protected from the sea by dikes and strongly degraded dunes (Fig. 1). The elevation ranges from +2 to +5 m, viz. from about mean sealevel, as the Belgian ordnance datum (T.A.W.) refers to LLWS. In the west, the plain is crossed by a single small river, the IJzer, along which the plain extends up to about 20 km. It appears that this river provided no significant sediment supply to the area throughout the Holocene.

The Holocene deposits reach a thickness of about 30 m in the seaward area and wedge out towards the border of the plain. In the largest part of the plain, the Holocene sequence exhibits the typical cyclic alternation of clastic deposits with peat layers (Fig. 2), found along most North-Sea coasts. Intercalated peat layers are absent in the area adjacent to the present shoreline. In the entire plain however, a basal peat, the fore-runner of the marine infill, occurs at the base of the Holocene sequence. The basal peat is absent only in well delimited areas where sand-filled tidal channels occur, and in areas where the Pleistocene subsoil lies higher than ± +2.5 m (fig. 3).

Although general ideas on Belgian palaeoshorelines and related sea-level changes were already put forward in the first half of this century (e.g. Blanchard, 1906; Briquet, 1930; Tavernier, 1938; De Langhe, 1939; Waterschoot, 1939), the results of the soil survey in the fifties, and the hypotheses developed concomitantly, were to predominate strongly in the later views on the coastal development of the area. As synthesized by Tavernier & Moormann (1954), and again by Tavernier & Ameryckx (1970), sea-level changes were described in a stratigraphical context within the framework of two major transgressions, the *flandrienne* (later *Calais*) and *dunkerquienne* respectively (*cf.* Dubois, 1924). Both these trangressions were considered to have been linked intimately to periods of positive sea-level change and destruction of protective dune barriers, for which a tentative chronology was proposed. The main argument for the differentiation of these separate phases was the presence between the corresponding marine lithosomes of an extensive and well developed peat layer, the so-called surface peat. Although the authors also discussed some obvious evidence for sea-level rise during the formation of the surface peat, it was concluded that it represented a stand-still or fall of the sealevel. Echoing studies in The Netherlands, the second transgression was subdivided into three distinct phases, for which age estimates were proposed in line with the Dutch results, and documented further by regional archaeological features and historical data relating to dike building and habitation (Table 1). Of these phases, the Dunkerque II (D-II) transgression was considered to have been by far the most important for the development of the coastal plain.

This scheme of alternating transgressions and regressions, was rapidly considered an established fact in the Belgian literature, and dominated the history of sea-level research until the eighties. Even in some of the most recent reviews (Marechal, 1992; Houthuys *et al.*, 1993), it reverberates apparently untouched.

STATE THE RULING OPINION !

A revived archaeological and geological interest in the area since the late seventies, and not unimportantly the introduction of radiocarbon dating, undisturbed hand-augered cores, and deep mechanical coring, provided new data, leading to a series of new viewpoints, often conflicting with the ruling opinion (*cf.* Thoen, 1978; Verbruggen, 1979; Baeteman, 1981).

A first tentative palaeogeographic reconstruction, based on lithofacies mapping, with time windows at *c.* 7000, 6500, 5500 and 4500 BP, was drawn up by Baeteman (1981), with Köhn (1989) presenting a more recent update. So far, actual shoreline reconstructions for historical times (e.g. Depuydt, 1972) remained highly speculative - both in space and time - because no former coastal dune barriers can be observed in the present landscape, except for a 3.5 km long stretch of dunes at the French border (the Older Dunes of Adinkerke-Ghyvelde), the "subrecent dunes" of Bredene-Klemskerke-Vlissegem, and some dune patches at Nieuwpoort-Lombardzijde, of which the relation to the present dunes still remains obscure (fig. 1). Even the most recent attempts (Thoen, 1987; Köhn, 1989; De Ceunynck, 1992) suffer from the highly fragmented nature of the remaining evidence.

Sea-level reconstruction itself was given hardly any attention until the most recent decades. Again, it was only in 1981 (Baeteman, 1981) that some basal peat dates were considered in a sea-level perspective, yielding an embryonic sea-level curve. A few years later, Mostaert (1985; see also Mostaert & De Moor, 1989), working in the eastern part mainly, considered sedimentary sequences and their relative elevation in a stratigraphical context, and designed a curve for Holocene sea-level changes on a relative time-scale. Additionally, the indicative meaning of the few ^{14}C-dated sea-level index points available at the time from the entire plain was discussed. An elaborate list of ^{14}C dates on basal and intercalated peats, resulting from the geological mapping of the western part, was published by Baeteman & Van Strydonck (1989). These authors did not consider their data in a sea-level context however, as it was argued that this should be proceeded by a thorough reconstruction of the coastal environments in space and time. Yet, with some of them, Köhn (1989) constructed a time-depth graph. Unfortunately the validity of the data as indicators of water or tidal levels remained undiscussed, and dates from intercalated as well as basal peat were used next to each other, without further notice. More recently, an envelope for the observed variation of local mean high water levels in the coastal area, and hence the general trend of sea-level rise, was derived by Denys (1993), using a calibrated ^{14}C timescale.

In this paper, an overview of the palaeogeographical evidence on coastal plain extension and former shoreline positions is given, incorporating some new stratigraphical and chronological data. The chronology of coastal peat development is discussed. As most of the available data pertain to the western part of the coastal plain, emphasis is placed on this area. Moreover the relative sea-level rise is illustrated. This is done following the approach of Denys & Baeteman (unpublished), in which error envelopes are constructed for the minimal level reached in the coastal area by the highest local mean high water spring tides, as well as for an upper and an extreme lower limit of the mean sea level. The influence of the relative sea-level trend on the Holocene development of the area is discussed.

2. Basal peat growth and palaeogeography of coastal plain extension

For the reconstruction of the sea-level rise, reliable basal peat data are generally considered to be most appropriate. As this peat was formed on top of the Pleistocene deposits, which may be considered not to have undergone compaction and consolidation during the Holocene, it retained its original elevation. Prior to the Subboreal, basal peat formation was determined primarily by the sea-level rise. Generally it was terminated by tidal flat sedimentation already soon after peat inception. As a result, the basal peat beds remained thin. These conditions of transgressive basal peat growth also make it possible to derive former limits of the coastal plain quite accurately from the age/depth occurrence of the basal peat.

Most of the basal peat data available are from the western part of the plain, SW of Oostende, where it was sampled mainly from mechanically cored drillings, allowing undisturbed retrieval (Fig. 1). Up to now, conventional methods were applied mostly in the radiocarbon dating. Full details on the 38 dates from the basal peat (top, base or complete layer) are given by Denys (1993) and Denys & Baeteman (unpublished). The chronology of the basal peat is strongly related to the altitude and morphology of the subsoil, and hence it is essential to delineate the relief of the substrate.

In general, the altitude of the Pleistocene subsoil is much higher in the eastern part of the plain than in the west. Its surface remains fairly flat, dipping seawards more strongly only close to the coastline (Fig. 4). However the surface morphology was mapped in detail only in the surroundings of Brugge (Mostaert & De Moor, 1984; Mostaert, 1985).

In the western part, the morphology of the Pleistocene surface, based on approximately 1100 boreholes, presents a major NW-SE directed depression (Fig. 5). A deep but narrow valley extends far inland, where it turns SSE and branches into three smaller ones. In the remainder of the southernmost area, the surface keeps a rather high elevation between 0 and +5 m, beyond which the Pleistocene deposits are outcropping. In the seaward area, the surface dips to the NW, with two valley-like depressions occurring, respectively in the vicinity of Nieuwpoort and De Panne. The latter one most likely results from Holocene erosion. However, and in contradiction to the description given by Houthuys *et al.* (1993), the relief of the Pleistocene subsoil generally cannot be considered erosional, in view of the presence of basal peat. Only in well delimited zones, Pleistocene deposits were deeply or even completely scoured away by Holocene tidal channels (see Fig. 3).

The basal peat data were plotted on a corrected morphological map of the Pleistocene subsoil on which tidal channel incisions were omitted. The time slices used are determined by the availability of evidence (Fig. 6). The maps delineate the landward extension of tidal environments; related shoreline positions cannot be inferred. They clearly illustrate the transgressive nature of the basal peat, as a rather narrow belt of peat growth rapidly shifted land- and upwards with the sea-level rise. Only one date, the top of a peat situated close to a gully and dated at *c.* 9200 cal BP [1], shows a serious divergence from this pattern (Fig. 6a). Presumably this represents an erroneous date, resulting from contamination with older soil carbon or redeposited material.

A particularly rapid displacement is noted during Boreal and early Atlantic times. The oldest and deepest date obtained so far implies that at *c.* 9500 cal BP tidal environments occurred in a rather limited area, whereas by *c.* 8000 cal BP the major part of the western plain was already under tidal influence, with an important extension occurring in the very southern part of the plain. At *c.* 6500-6000 cal BP, tidal environments already stretched out almost as far as the southern- and easternmost parts of the present coastal plain. The displacement of the peat belt slows down considerably by this time, as a wide range of dates, from *c.* 6850 to 5900 cal BP, occurs between -2.5 to -1 m. By *c.* 6000 cal BP, the basal peat covered a much wider surface, resulting in a significantly thicker peat bed occurring throughout the landward part of the entire plain, except for areas with an elevation of the subsoil above +2.5 m.

3. Chronology of intercalated peat formation

In the western part of the plain, intercalated peat layers occur all over the central area, as well as in the former Pleistocene valleys in the S. They are encountered very scarcely between -7.5 to -6

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[1] All dates mentioned are in calibrated years BP, with the highest age probability maxima obtained in calibration of individual data (Stuiver & Reimer, 1993, method A) serving as guide-lines. In the text these dates are given rounded to the nearest fifty. For ease of reading, no reference is made to the related uncertainties. Actual calibration results are not reproduced here, but most of them are listed by Denys (1993).

m, with the deepest one found yet at -7.5 m. Between -6 and -2.5 m, up to three successive peat beds may be present, alternating with tidal flat deposits. However, their altitude is not at all regular and their distribution is very local. These deeper peat layers are generally only a few cm to dm thick, but in the S they may reach 1 m exceptionally. From a depth of -3 m up to - 2 m, a well developed and widely distributed peat, with a thickness from a few dm up to 1 m, is encountered, known as the *second peat layer*. Finally, at a level ranging from -1 to +2 m, another peat bed - often about 2 m thick - is found with a very widespread occurrence, the *surface peat*. In the eastern part only the surface peat is known (except for the much more extensive basal peat; e.g. Allemeersch, 1984). In some restricted and more seaward areas however, such as in the neighbourhood of Bredene (Mostaert, 1985) and the region of Veurne-Wulpen-Booitshoeke (Baeteman & Verbruggen, 1979; De Ceunynck & Termote, 1987; Denys, 1993, 1994; *infra*), the surface peat may be split up by a more or less important clay layer, resulting in the presence of an *uppermost peat*.

From intercalated peat layers, 69 acceptable radiocarbon dates are available from the western, and only 7 from the eastern coastal plain (Fig. 1). These dates, ranging from *c.* 7800 to 1100 cal BP, have been plotted in fig. 7 to show their chronological distribution. Although lithostratigraphically, the different peat layers can be differentiated clearly (*cf.* Baeteman & Van Strydonck, 1989; Baeteman, 1991), their temporal pattern shows that there are no significant time gaps between their formation, except perhaps for the deepest and deeper series.

The ages of the deeper peat beds show a continuing onset of growth between *c.* 7400 and 7150 cal BP, and two further dates at *c.* 7000 cal BP, both from the southern area. These peat layers nevertheless occur at quite different depths (-4.68 and -2.53 m respectively), possibly resulting from differential compaction, and the occurrence of both appears to be very local. As apparent from the 7 available dates, sampled at depths from -2.95 to -2 m, the second peat layer formed between *c.* 6900 and 6300 cal BP. The three oldest dates are from the more seaward area, with age decreasing in a landward direction.

The base of the surface peat ranges between *c.* 6400 and 4750 cal BP. There is no consistent relation between location and age, yet the two oldest dates originate from a more seaward position in the eastern part of the plain. Until *c.* 5700 cal BP peat initiation occurs rather erratically, with more continuity arising from *c.* 5600 to 5400 cal BP, and the frequency declining hereafter. By *c.* 4750 cal BP nearly the entire coastal plain was occupied by coastal fens and peatbogs, except for a narrow belt along the outcropping Pleistocene deposits bordering the plain, and some areas outside the former Pleistocene valleys in the very south. At the landward part of the plain, the surface peat merges with the peat that initiated as basal peat (Fig. 2).

The termination of surface peat formation dates from *c.* 4450 to about 1500 cal BP. An exceptionally young date of *c.* 1100 cal BP needs further control. Although the dates are not concentrated strongly, some more significant periods might be put forward tentatively, and of course approximatively: 3400-3350, 2800-2750, 2200-2150 and 1550-1500 cal BP[2].

In the western coastal plain, the uppermost peat yielded dates between *c.* 4500 and 3800 cal BP for its base, and 3450 to 2050 cal BP for the top. At Bredene a much younger age was obtained, respectively 1900 and 1850 for the base, and 2150 and 1850 cal BP for the top.

The exact processes which halted surface peat formation are not yet fully understood. The first

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[2] In fact, the dates refer to a moment when peat was still being formed and predate the actual terminations.

and very localized termination can be explained by reactivation of one of the major tidal inlets (*cf.* also Baeteman & Verbruggen, 1979; Baeteman, 1981; Denys, 1993, 1994). Close to the channel the peat has been eroded, whereas a gradual evolution to salt-marsh and/or mud flat took place further away from it. In the Wulpen-Nieuwpoort area the expansion of tidal sedimentation occurred at about 3900-3800 cal BP (Baeteman, 1993). Near Booitshoeke an earlier phase is recognized, *viz.* 4850-4450 cal BP, however with low dating precision.

These and similar reactivation phases, possibly corresponding to the above mentioned periods of peat termination, also caused considerable scouring of former tidal channel deposits. Reworked peat often occurs as a lag deposit within the channel sequences (Baeteman, 1985a). Radiocarbon dates on such material (four dates from *c.* 4250 to 2800 cal BP) suggest that it did not originate from the youngest part of the surface peat.

Possible mechanisms for the channel reactivations include climatic phenomena (e.g. drought, storm floods), which might affect the volume of their tidal basin, and - more directly - increased tidal amplitude. As discussed by Dieckmann *et al.* (1987) the latter will cause erosion of the barrier island system and alter the structure of the tidal flats, especially by deepening of tidal channels and gullies by erosion.

The end of surface peat growth indicates a progressive landward shift of the tidal influence. The final and general end of peat growth may also be related to the activity of the tidal channels, inducing erosion and hence dewatering of the peat bog, resulting in a considerable and rapid lowering of its surface. Climatic dryness and human influence, such as salt production or even some agriculture, may have acted similarly. In certain areas dry conditions appear to have existed at the end of peat formation, and some peat wastage may have occurred (Denys, 1993).

The top of the Holocene sequence consists of tidal flat sediments, mostly showing a single and gradual transition from mud flat to salt marsh. The distribution of these deposits, generally some 1.5 m thick, indicates that the tidal flat transgressed over the Pleistocene area, extending further than ever before. Sea-level change probably only played a minor role in the renewal and expansion of tidal sedimentation, as its rise after 2000 cal BP was quite limited. The rather sudden compaction of the thick bed of surface peat however provided a considerable vertical space. Erosion of the coastal barrier chain, tidal ebb delta's (*cf.* Beets *et al.*, 1992) and the seaward part of the flats, caused by increased local tidal amplitudes, supplied the sediment for its infill.

Clearly, the end of surface peat growth cannot be attributed solely to the "D II transgression", which would have taken place between the 3rd and the 8th century AD according to the classic notion. In fact it should be noted that the D II is marked in the Belgian coastal area only by a single well-dated phenomenon: the sudden end of the Roman occupation between 268 and 270 AD (Thoen, 1978).

4. Shoreline evidence

So far, the only evidence relating to shorelines prior to 5000 cal BP are some dates on *Cerastoderma edule* valves from tidal flat deposits at about 0.5 and 1 km offshore. These range from *c.* 7400 to 5200 cal BP and indicate a still more northern shoreline. Also the presence of an Atlantic-Subboreal *Angulus pygmaeus* fauna in a nearshore or beach facies 5 km offshore Nieuwpoort (Wartel, 1989) may be considered.

Additional shoreline indications come from the dune belt in the area of De Panne and the inner dunes of Adinkerke-Ghyvelde, where thourough stratigraphic investigations yielded some relevant data (Lebbe & De Ceunynck, 1980; De Ceunynck & Thoen, 1981; De Ceunynck, 1984, 1985, 1992; De Ceunynck & Denys, 1987).

At the most southern part of the Adinkerke-Ghyvelde dunes (from here on called the *Inner Dunes*), the base of a peat layer, assumed so far to have developed transgressively upon the dune, was dated at *c.* 4800 cal BP (De Ceunynck, 1985). The base of a peat occurring higher-up in the Inner Dunes was dated at about 3300 cal BP (De Ceunynck, 1992). Since beach deposits are present just north of these dunes, this would imply a shoreline by this time at least some 3 km landward of the present one.

New borehole evidence sheds some doubt on part of this hypothesis however (Fig. 8-9). The peatlayer S of the Inner Dunes can be correlated with the surface peat, initiating on mud flat deposits at +0.5 m. The surface peat is only slightly developed just S of the Inner Dunes, but reaches a greater thickness more to the E. In the reclaimed "De Moeren", S of the Inner Dunes, it is lacking, which is however due to the particular development of that area (Baeteman, 1985b).

Only at borehole W, the mud flat clay is followed immediately by surface peat. At ANT and AD it is covered, with an abrupt contact, by a brown fine sand with clay ripples and some shell fragments. An erosional lag or high energy facies - a fine to medium sand, containing shell fragments, clay pebbles, flints, sherds and reworked peat - overlies the brown sand or peat, which in its turn is covered by a peaty clay with irregular aeolian sand lenses and containing sherds. Hereafter, each borehole shows a different development. At ANT no further deposition occurred, whereas in W a humic wind-blown sand with humic horizons overlies the peat. In AD, at the extreme edge of the Inner Dunes, a few dm of aeolian sand are followed by intertidal deposits, evolving into salt marsh, a peaty clay with sherds, and finally antropogenically disturbed dune sands.

This stratigraphy rather suggests that the surface peat itself did not transgress over the Inner Dunes, and hence was not related to their formation. Conversely, the much younger peat layer, of which the top was dated at *c.* 2750 cal BP, shows such a development. This would imply that the Inner Dunes were formed after the deposition of the lag, and only some time - a few centuries perhaps - before *c.* 2750 cal BP, considering that the development of peat requires some dune stabilisation. A further dating effort is nevertheless required to refine this hypothesis, as the peat may have developed earlier closer to the Inner Dunes, e.g. as the result of seepage (*cf.* De Ceunynck & Denys, 1987). Moreover, the peat was in such a surface-near position that the dating result may have been affected by contamination.

From the lag deposit S of the Inner Dunes, a date of *c.* 6050 cal BP was obtained in borehole ANT, indicating reworking of older material. Most probably the lag, at least at this site represents a washover or storm deposit, corroborating a rather nearby shoreline when it was formed. The termination of surface peat growth has not been dated in this area, but it may be assumed that it occurred before 3300 cal BP. In this case, it would be quite conceivable to relate it to one of the tidal channel reactivation periods mentioned above, more particularly to the one at *c.* 3800-3900 cal BP. Shell-rich sands in the same stratigraphical position as the lag were found only very close to the Inner Dunes, where they cover sandflat deposits and are overlain by tidal flat clays.

East of the Inner Dunes, no beach deposits were observed, but it should be noted that the presence of a large tidal channel/inlet seriously hampers the interpretation of the sedimentary sequence in this area. Only in the region Koksijde-Oostduinkerke, presently occupied by the coastal dunes, further beach deposits are found, at an elevation between 0 and +2 m. The shoreline must have prograded very rapidly here after *c.* 3500 cal BP, which follows from the observation that the Older Dunes of De Panne go back to before *c.* 2750 cal BP (*c.* 2660 BP; De Ceunynck, 1985).

Palynological and archaeological studies in the broad dune area west of De Panne (Lebbe & De Ceunynck, 1980; De Ceunynck & Thoen, 1981; De Ceunynck, 1985) revealed dune sediments, including a peat layer dating from *c.* 2750 to 1900 cal BP. These *Older Dunes* suggest a shoreline still at least 1 km more north than at present. They probably developed on a barrier island, as to the S - but still north of the Inner Dunes - tidal flat deposits, containing shells dated at *c.* 3100 and 2750 cal BP were encountered.

In the area immediately east of the Older Dunes, a sequence of mainly sand flat deposits is topped by two peat layers, with tidal flat sediments in between (De Ceunynck & Denys, 1987; Denys, 1993). The base of the lower peat was dated at *c.* 2050 cal BP, that of the upper one at about 1550, and at *c.* 1350 cal BP slightly more to the E. The intercalated tidal flat deposits represent a period of increased marine influence, estimated within the interval 2100-1550(1350) cal BP (Denys, 1993). The upper peat is covered directly by sediments from the present "younger" dunes, which did not develop earlier than 1000 AD according to De Ceunynck (1985).

clays
Kleine [illegible]
Ad. 1794-1[illegible]
3943/19~ cal BP

The shoreline configurations at about 3800-3900 and 3500 cal BP must have differed strongly from the present one. There was no continuous coastal barrier, but rather a number of barrier islands existed, perhaps forming a chain, and separated by tidal inlets. Evidence for this is given by the presence of a tidal flat area between the Older and the Inner Dunes. In this area, a facies succession is observed from sand flat (with presumably subtidal deposits below), to a peaty/organic clay with aeolian sand lenses, again sand or mixed flat, salt marsh, peat and finally salt marsh again (Fig. 9 & 10; Denys, 1993). The lower peaty clay can be correlated with the peat associated to the Inner and Older Dunes. Towards the E its clay content increases. Shells of *Cerastoderma edule* at the top of the sandflat, underlying the organic clay, yielded an age of *c.* 3100 cal BP; whereas *Scrobicularia* from a small gully fill incising this clay were dated at *c.* 2700 cal BP (data R. De Ceunynck; *cf.* Denys, 1993). As there was some freshwater influence, a somewhat younger true age may be possible for these shells. By correlation with a similar situation at De Panne, an age approximating 2100 cal BP is expected for the base of the upper peat bed. Although no peat occurs in borehole GR, root traces, reed remains and freshwater gastropods occur abundantly.

An indication for the shoreline position at about 3500 and 2800 cal BP is given by the presence of surface peat, covered by mudflat clay, in front of the present beach at Raversijde, west of Oostende. Both the peat and the clay contain Roman and medieval artefacts, and there is also evidence for peat digging and habitation in the period 170-270 AD (Thoen, 1987). Judging from a date on *Spisula elliptica*, an open marine nearshore mollusc, in sand bank deposits offshore Raversijde, the present-day shoreline position was attained here already by *c.* 1250 cal BP. *Cerastoderma edule* shells from a washover or storm deposit at Middelkerke, some 500 m inland from the present beach were dated at *c.* 750 cal BP.

Ad
[illegible]

In view of the scarcity of preserved shoreline features, it will be clear that the reconstructions shown in Fig. 11 still must be considered speculative to a large extent.

5. Sea-level data

Only relatively few reliable sea-level index points have been collected in the Belgian coastal plain (*cf.* the low number of basal peat dates). This is mainly due to the late arousal of interest in relative sea-level reconstruction among Belgian scientists, and the fact that no large-scale studies were carried out with this specific aim yet. Data collection therefore was mainly occasional and for stratigraphic purposes.

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Using all available relevant data, Denys & Baeteman (un~~pub~~lished) present error envelopes for the minimal level attained by the highest local mean high waters at spring tides (l-MHWS's) within the coastal area during the last 9400 years, a tentative extreme lower limit of the relative mean sea-level (RSL), and an upper RSL limit (also the maximal level of the lowest local mean high waters). These envelopes are shown in Fig. 12, together with the time/depth distribution of all suitable dates from basal and intercalated peats from the entire coastal plain.

missing!

The methods and data on which the error bands are based will only be set out in general here.

The error band for the minimal height of the highest l-MHWS's was derived from different data. Firstly, transgressive overlaps of the basal peat, involving the succession of a subaerial marsh or ? fen to intertidal sedimentation were used, and an average basal peat compaction to 50 % of the original thickness was assumed in constructing an upper limit. Elevations thus obtained can of course only be approximative. Secondly, the envelope was improved by considering the age/depth position of intercalated peat layers, habitation levels within and just outside the coastal plain, and dune soils and peats.

The upper MSL limit is derived from the deepest/youngest dates for the base of the basal peat (Van de Plassche & Roep, 1989), and accounting for the possible vertical (sample depth and indicative meaning, *i.c.* mean local water depth) and dating errors (calibrated 2σ intercepts were used). No such dates are however available for the last 5000 years, and unfortunately, only the position of the top of one intercalated peat within this interval can be considered not to have been affected too seriously by compaction. Nevertheless, there is a good agreement between the lower limit of the error band, and the accurate MSL trend curve for the western Netherlands for the last 4000 years, suggesting only minor deviation of this limit from the actual relative MSL.

An envelope for an extreme lower MSL position was obtained by subtracting the full present-day difference between coastal MHWS and MSL at Nieuwpoort (where it is higher than towards the E) from the limits for the minimal highest l-MHWS's, uncorrected for compaction of the basal peat. In view of the results obtained from tidal modelling yet (Franken, 1987; Austin, 1991), significantly larger tidal ranges in the past than at present are not very likely (see however Roep & Beets, 1988). Moreover smaller local tidal amplitudes are to be expected within the intertidal sedimentation area than at the coast, large rivers being absent in the area, and the effects of compaction on intercalated peat data will introduce a further lowering of the derived limits relative to the contemporaneous MSL.

Clearly, the envelopes for the highest observed l-MHWS's and the upper MSL limit follow the same trend, suggesting that they reflect the real pattern of relative SL rise. Moreover, the lower limit of the envelope for an upper MSL estimate, and the upper limit of the envelope for an extremely low MSL estimate correspond fairly well, at least for the last 7500 years. On theoretical grounds, and assuming that no major changes in tidal amplitudes occurred, it is more likely that the MSL would be situated in the vicinity of these two limits, rather than near the outer limits of the envelopes.

Although the accuracy of this model is still quite low, a most likely mean rate of MSL rise approximating 7 m/ka is suggested prior to 7500-7000 cal BP. At about this time an abrupt decrease to an average of *c.* 25 m/ka is indicated for the following 2000 years. A second

7000 mm / 1000 yr

mm/yr

retardation to about 0.07 m/ka occurs at 5500-5000 cal BP. The latter rate is consistent with a present-day rate of MSL rise of 0.01 m/decade, based on tide gauge measurements at Oostende from 1835 to 1852 and 1927 to 1988 (Baeteman *et al.*, 1992).

6. Discussion and conclusions

The evaluation of all radiocarbon dates from basal and intercalated peat, supported by a detailed lithostratigraphic mapping, led to an improved insight into the Holocene development of the Belgian coastal plain. Rapid infilling, in line with the rate of sea-level rise and the morphology of the Pleistocene subsoil, characterized the history of this area.

The complete absence of intercalated peat layers older than *c.* 7800 cal BP results from the very high rate of sea-level rise in the early Holocene. A mean rate of sea-level rise of about 7 m/ka provided a high sediment supply and resulted in relatively energetic sedimentation conditions throughout. As this situation changed, peat could start growing locally - but for almost 200 years - on tidal flat sediments in the most silted-up parts of the former Pleistocene valleys. At the same time, these valleys still served as tidal inlets/channels, implying that the tidal ranges within the channels could not have been very large.

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The relative sea-level rise shows a first distinct retardation at *c.* 7500-7000 cal BP (Fig. 12). It is also obvious that from about 7300 cal BP onwards, tidal sedimentation within the plain decreased progressively in favour of peat development. In view of the rather continuous chronology of the different peat layers, it is likely that their spatial and temporal distribution was determined to a substantial extent by the configuration of the tidal flat and the lateral development of its subenvironments, rather than by (supra)regional changes. Therefore it is not tenable any longer to stick tenaciously to the traditional lithostratigraphic subdivision of the Holocene sequence into 6 Dunkerque and 5 Calais deposits (*cf.* Houthuys *et al*, 1993).

According to the basal peat based palaeogeography (fig. 6), the extension of the coastal plain was close to its present limits by 6500 cal BP. This indicates that the influence of the sea-level rise was very much reduced hereafter. It no longer resulted in a further lateral expansion of the coastal area, but the rise in water levels merely supported some further sediment and especially peat accumulation. However, some pulses appear to have occurred, resulting in transgressive overlaps, related to the vicinity of tidal channels especially.

A second decrease in the trend of relative sea-level rise at 5500-5000 cal BP corresponds rather well with the extensive development of the surface peat, although dates for its initiation appear to be centred somewhat earlier (5600-5450 cal BP). The end of surface peat formation, taking place between *c.* 4450 and 1500 cal BP, cannot be attributed solely to the D II transgression. Most probably it resulted from repeated tidal channel reactivations, causing dewatering of the peatbog, lowering of its surface, and consequently a progressive landward shift of the tidal influence.

From the fragmented record of coastline features, only some general ideas on palaeoshoreline positions can be derived. The shoreline transgressed very fast during the early Holocene. At about 6000 cal BP it was located some 5 km from the present coastline, whereas the *c.* 3900 cal BP shoreline is found inland, at least in the very west. From then on rapid progradation occurred. The shoreline consisted of a barrier island chain with tidal inlets. This setting changed again to a transgressive coast, probably as from *c.* 1200 cal BP, resulting in the present-day closed coastal barrier. The processes causing this retreat still require investigation.

Although the present data already allow an assessment of the general trend in the relative SL rise, actual MSL positions can only be estimated with a precision of at most ± 1 m. This is not surprising, considering that sea-level reconstruction as such hardly ever was the prime reason for the collection of relevant data in the area. Further data are imperative to allow refinement of the present SL reconstruction. Increased dating precision and reliability, which may be attained by using AMS techniques, multiple dating, and consideration of the stratigraphical ordering of results (Biasi & Weldon, 1994), will especially affect the resolution of the oldest part of the sea-level record. In exploring the less strongly sloping part of the relative MSL-curve, additional index points, with both a high altitudinal and temporal accuracy, are badly needed. In this, collection of basal peat dates should be given priority. Equally required is improved knowledge on former tidal ranges throughout the Holocene. Sedimentological investigations regarding this topic are in progress.

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Address of the authors:
Prof. Dr. C. Baeteman, Belgische Geologische Dienst, Jennerstraat 13, B-1040 Brussel, Belgium.
Dr. L. Denys, Departement Biologie, Universitair Centrum Antwerpen (R.U.C.A.),
Groenenborgerlaan 171, B-2020 Antwerpen, Belgium.

CAPTIONS

Fig. 1: Map of the Belgian coastal plain with location of ^{14}C sites (solid circles: intercalated and/or basal peat data; open circles: intercalated peat data only).

Fig. 2: Schematic cross-section of the Holocene sequence.

Fig. 3: Occurrence of basal peat in the western part of the coastal plain.

Fig. 4: Morphology of the Pleistocene surface in the eastern part of the coastal plain. Contours in meters (after Houthuys *et al.*, 1992). Solid circles: sites with intercalated and/or basal peat data; open circles: intercalated peat data only.

Fig. 5: Morphology of the Pleistocene surface in the western part of the coastal plain. Contours in meters. Solid circles: sites with intercalated and/or basal peat data; ~~open circles: intercalated peat data only~~.

Fig. 6a-f: Palaeogeographical maps showing the landward extension of the tidal area.

Fig. 7: Temporal distribution of dated samples from the intercalated peat layers (highest probablility maximum of calibrated age indicated).

Fig. 8: W-E Cross-section south of the Inner Dunes (see Fig. 11 for location of boreholes).

Fig. 9: Section across the Inner Dunes (see Fig. 11 for location of boreholes).

Fig. 10: W-E Cross-section north of the Inner Dunes (see Fig. 11 for location of boreholes).

Fig. 11: Shoreline positions for the western coast since *c.* 3900 cal BP, with detail of the De Panne area showing the different dune systems. Location of boreholes indicated by open circles; numbering of solid circles refers to location of ^{14}C sites. 1. top: 1890 cal BP, base: 2760 cal BP; 2. 1530 cal BP; 3. 1530 cal BP; 4. 2050 cal BP; 5. 1340 cal BP; 6. 3090 cal BP; 7. 2740 cal BP; 8. 2770 cal BP; 9. 4800 cal BP (approximative ages).

Fig. 12: Envelopes for the minimal level attained by the highest l-MHWS's, the upper MSL limit, and a tentative extreme lower MSL limit. Age/depth distribution of radiocarbon dates on basal and intercalated peat shown as rectangles.

Table 1: Chronology of the main subphases of the Dunkerque transgression, according to the soil survey (*cf.* Tavernier & Ameryckx, 1970).

TABLE 1

PHASE	PERIOD
D III	10th and 11th century A.D.
(formation of recent dunes)	
D II	(3rd)4th to 8th century A.D.
(formation of subrecent dunes)	
D I	2nd and 1st century A.D.

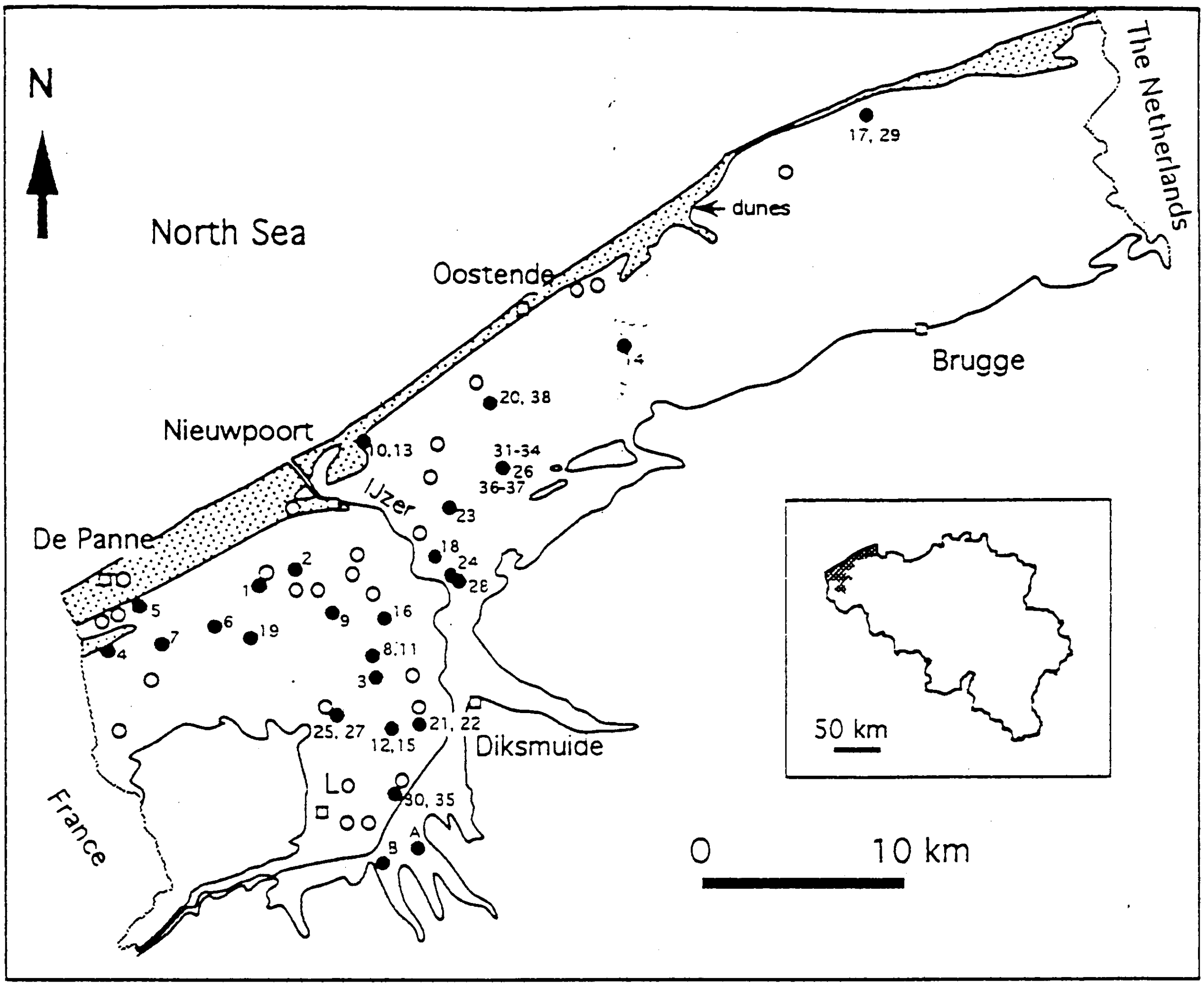

N
North Sea
Oostende
dunes
The Netherlands
Brugge
Nieuwpoort
De Panne
IJzer
France
Diksmuide
Lo
17, 29
14
20, 38
10,13
31-34
26
36-37
23
18
24
28
2
1
5
6
7
19
9
16
4
8,11
3
25, 27
12,15
21, 22
30, 35
A
B
0
10 km
50 km

fig 1

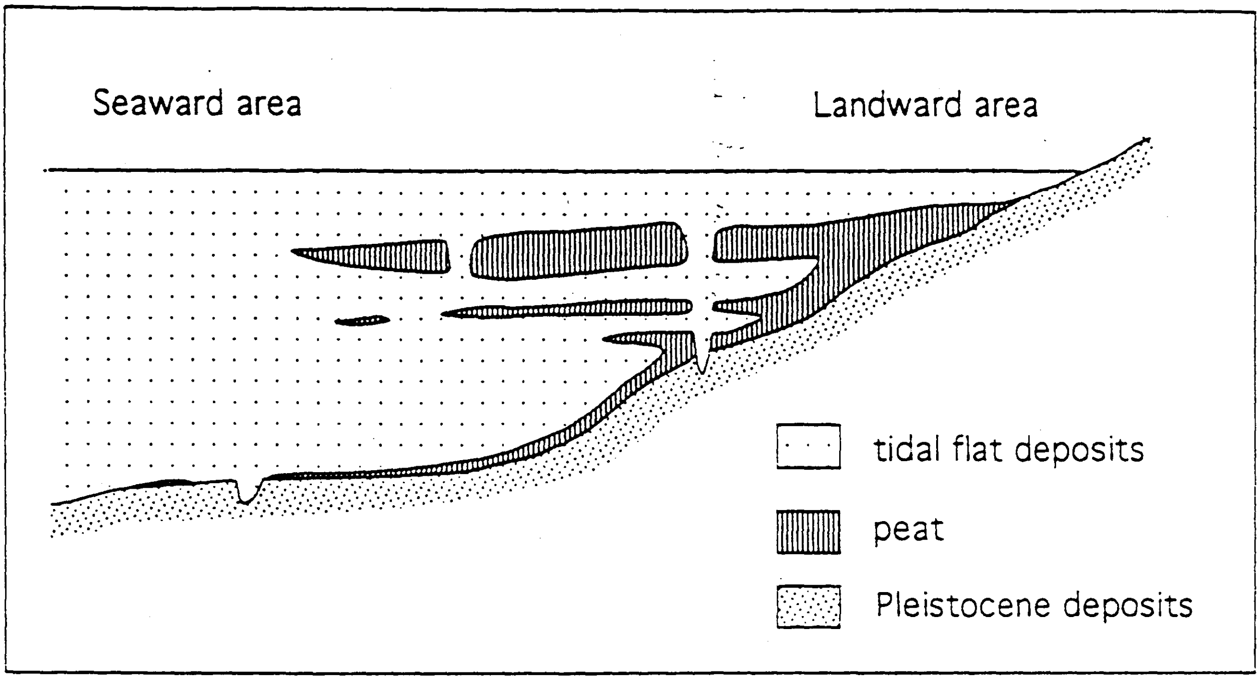
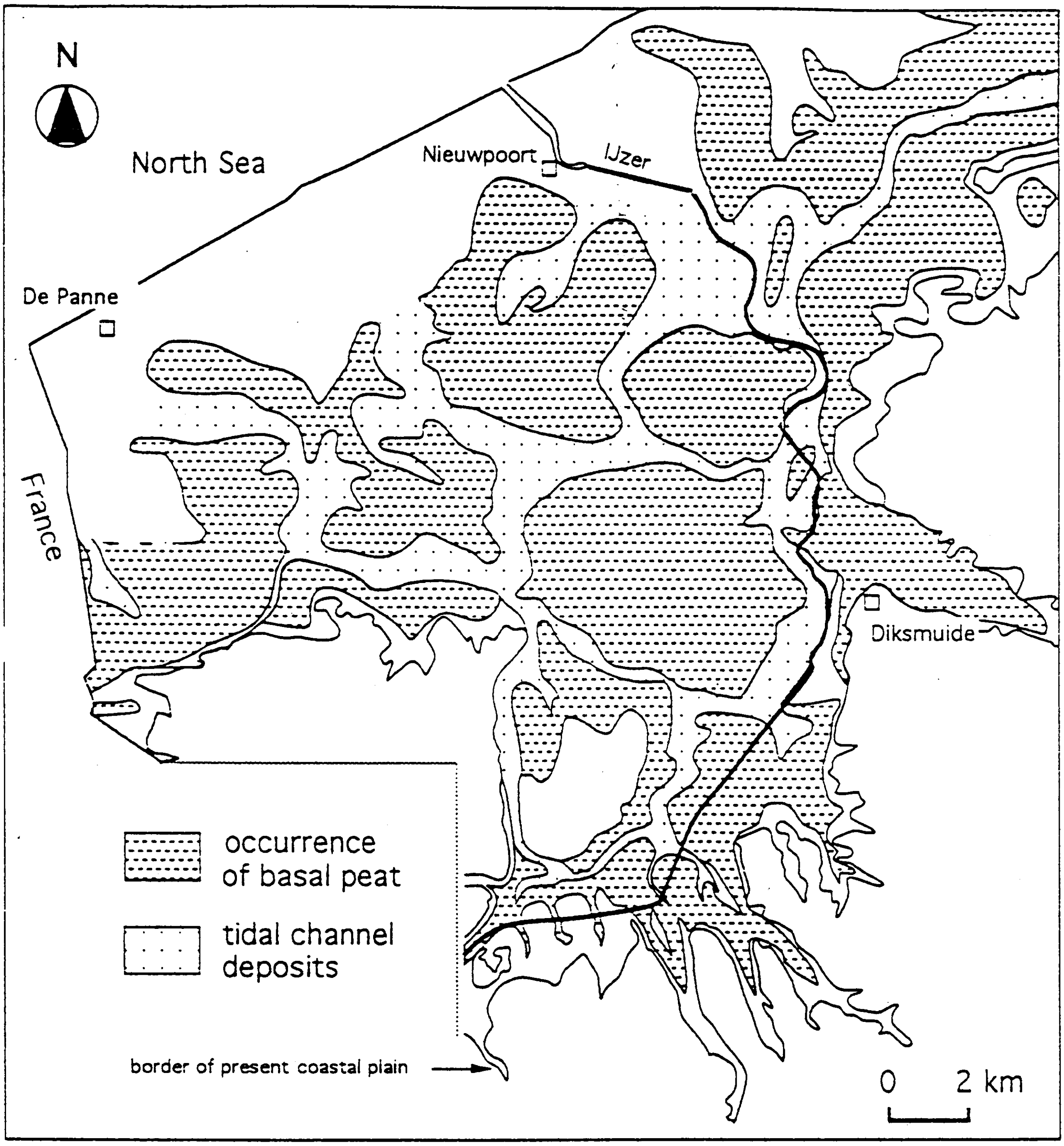

Seaward area
Landward area
tidal flat deposits
peat
Pleistocene deposits

fig 2


N
North Sea
Nieuwpoort
IJzer
De Panne
France
Diksmuide
occurrence of basal peat
tidal channel deposits
border of present coastal plain
0 2 km

(3)

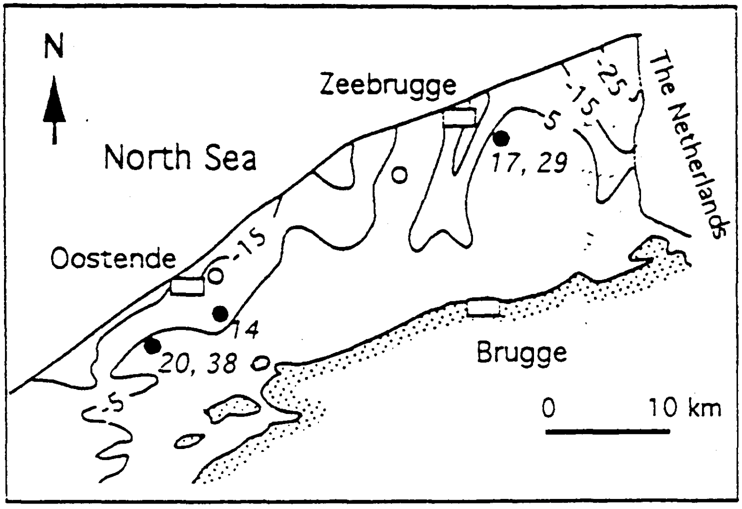

N
North Sea
Zeebrugge
Oostende
Brugge
The Netherlands
-25
-15
-15
-5
-5
17, 29
14
20, 38
0
10 km

fig 4

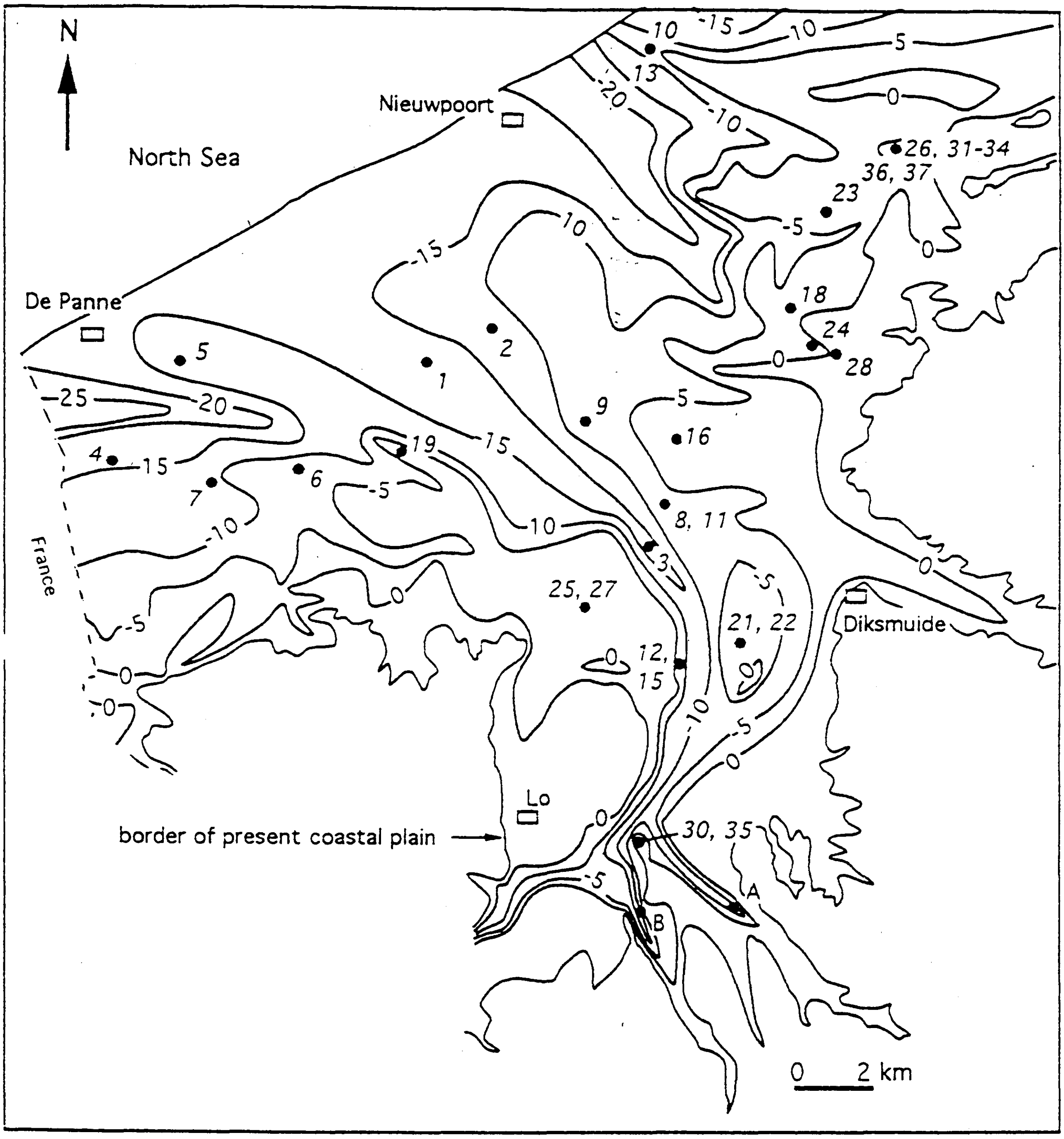

N
North Sea
Nieuwpoort
De Panne
France
Diksmuide
Lo
border of present coastal plain
0 2 km
-25
-20
-15
-10
-5
0
1
2
4
5
6
7
8, 11
9
10
12, 15
13
16
18
19
21, 22
23
24
25, 27
26, 31-34
28
30, 35
36, 37
A
B

fig 5

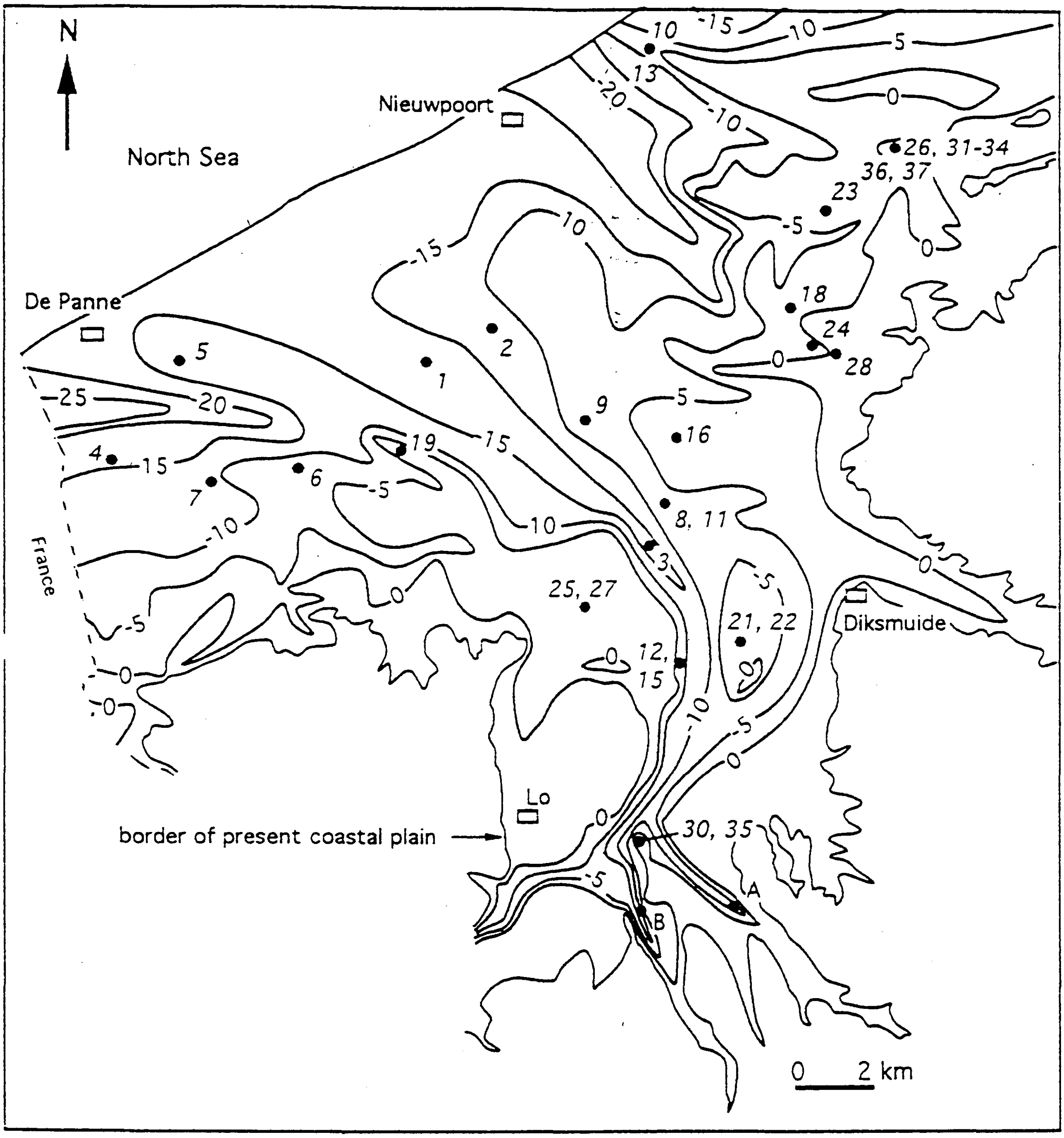
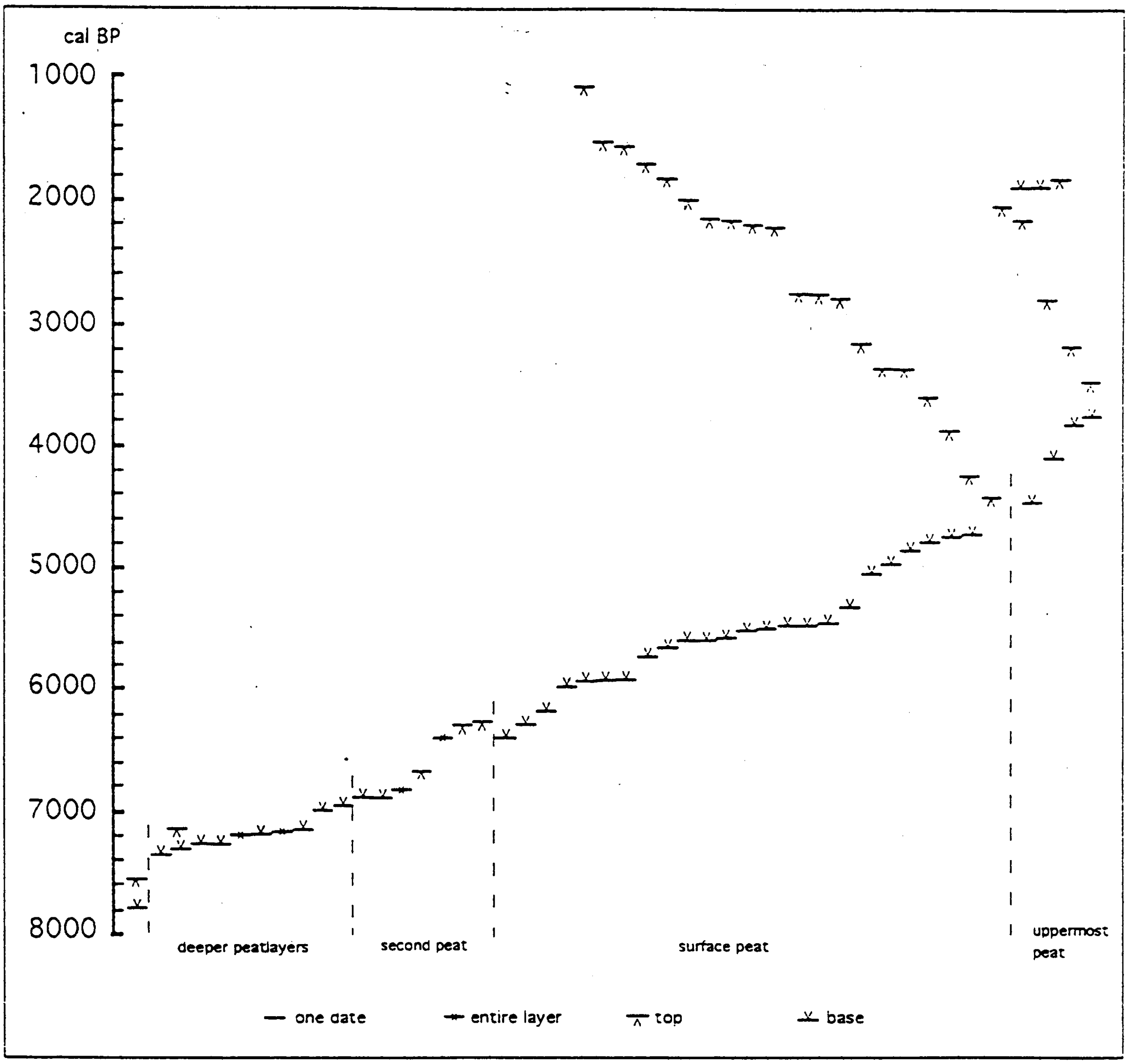
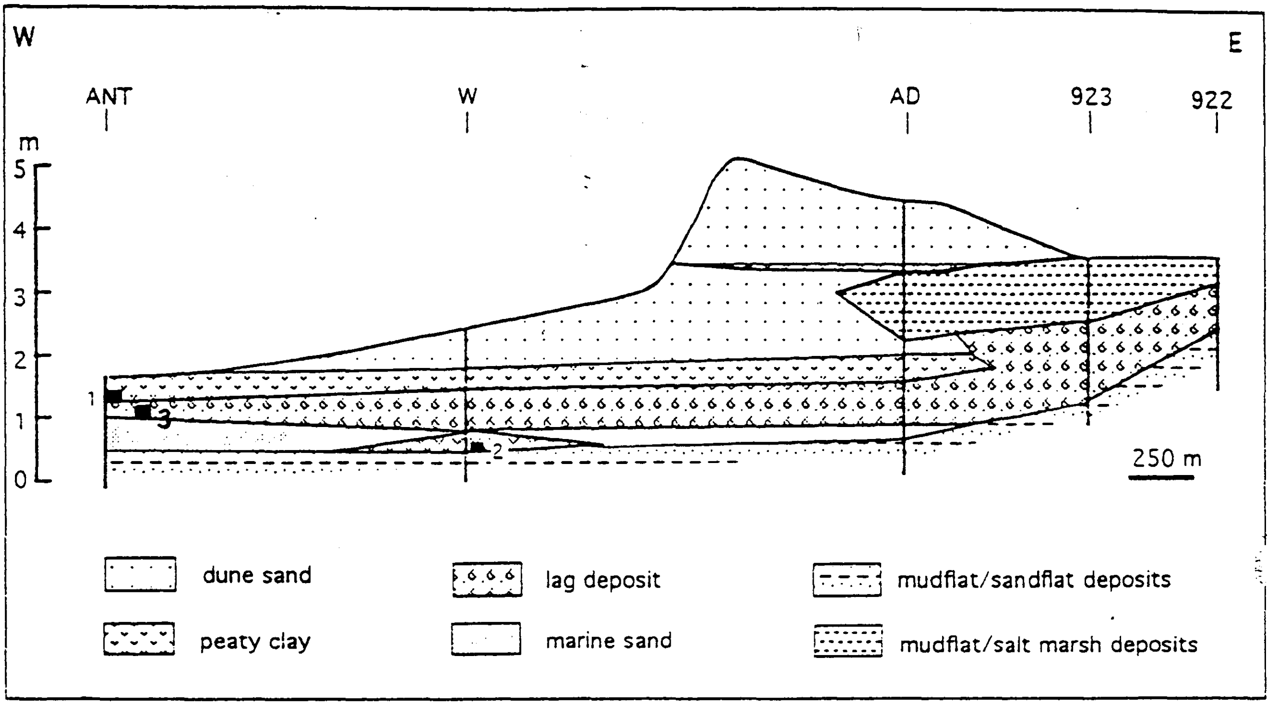

N
North Sea
Nieuwpoort
De Panne
France
Diksmuide
Lo
border of present coastal plain
0 2 km
-25
-20
-15
-10
-5
0
-5
-10
-15
-20
10
13
1
2
4
5
6
7
9
16
19
8, 11
3
25, 27
12, 15
21, 22
18
24
28
23
26, 31-34
36, 37
30, 35
A
B

fig 5



cal BP
1000
2000
3000
4000
5000
6000
7000
8000
deeper peatlayers
second peat
surface peat
uppermost peat
one date
entire layer
top
base

fig 7



1. 2690 ± 60 BP
2. 4300 ± 65 BP
3. 5680 ± 75 BP

fig 8

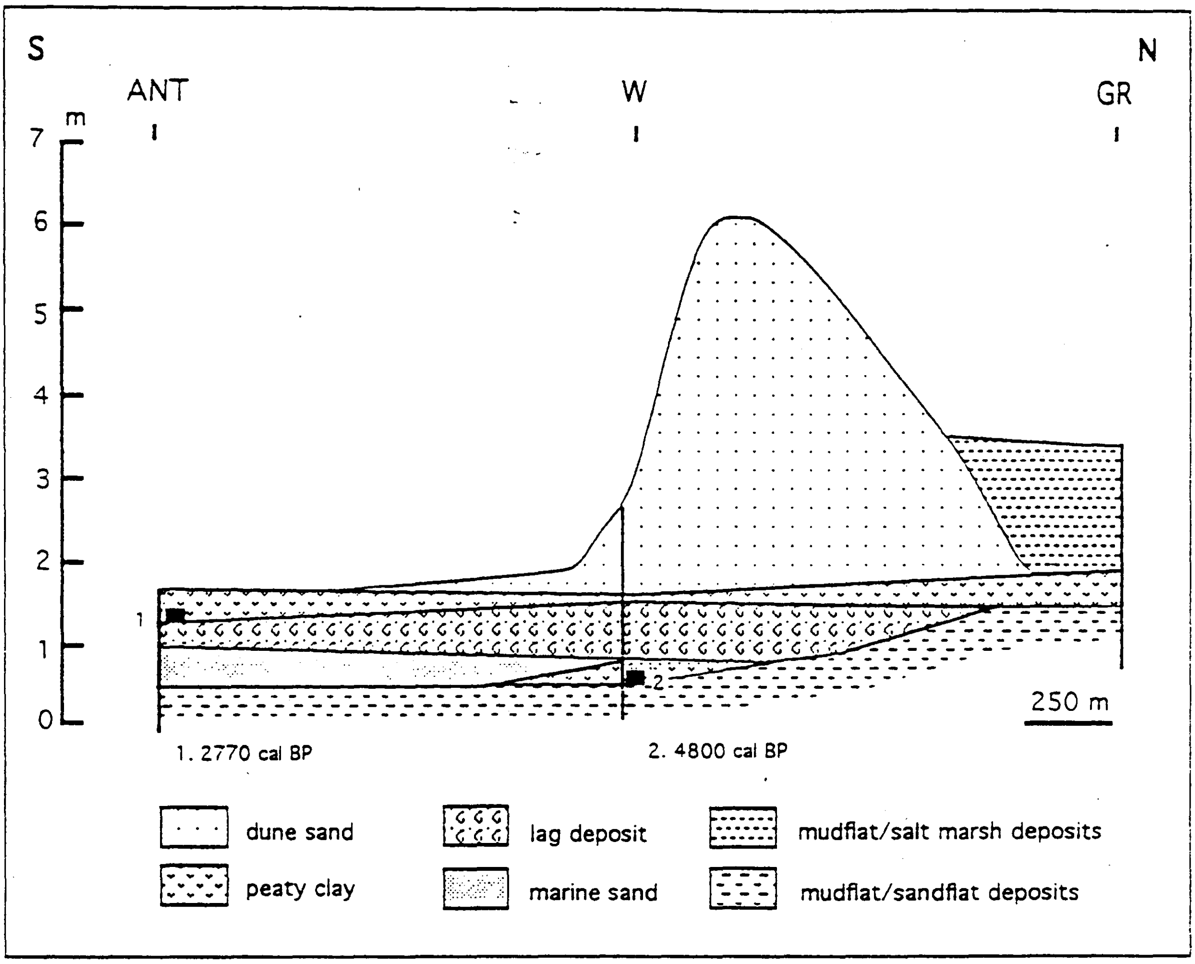

S
N
ANT
W
GR
m
7
6
5
4
3
2
1
0
1
2
250 m
1. 2770 cal BP
2. 4800 cal BP
dune sand
lag deposit
mudflat/salt marsh deposits
peaty clay
marine sand
mudflat/sandflat deposits

fig 9

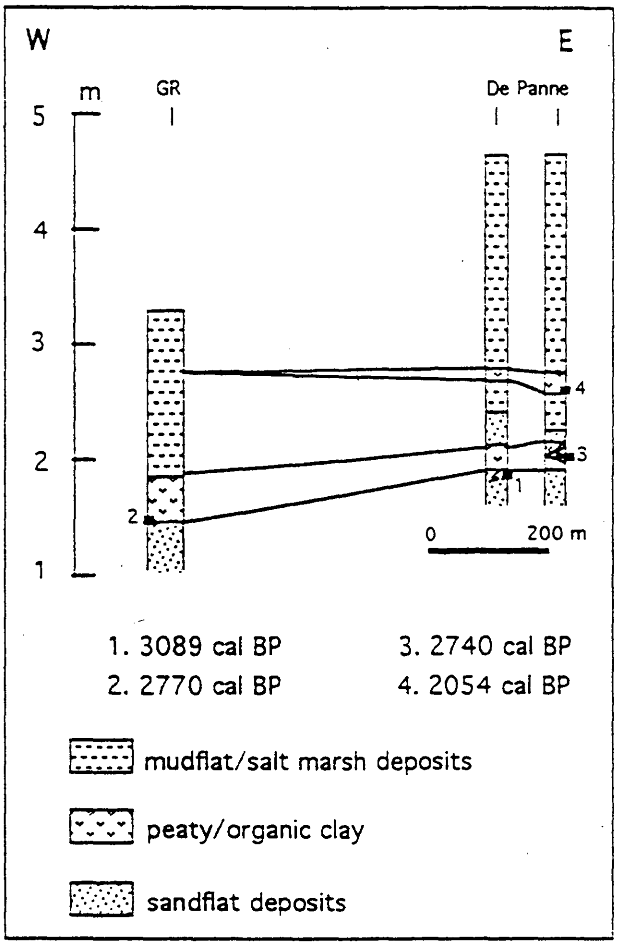
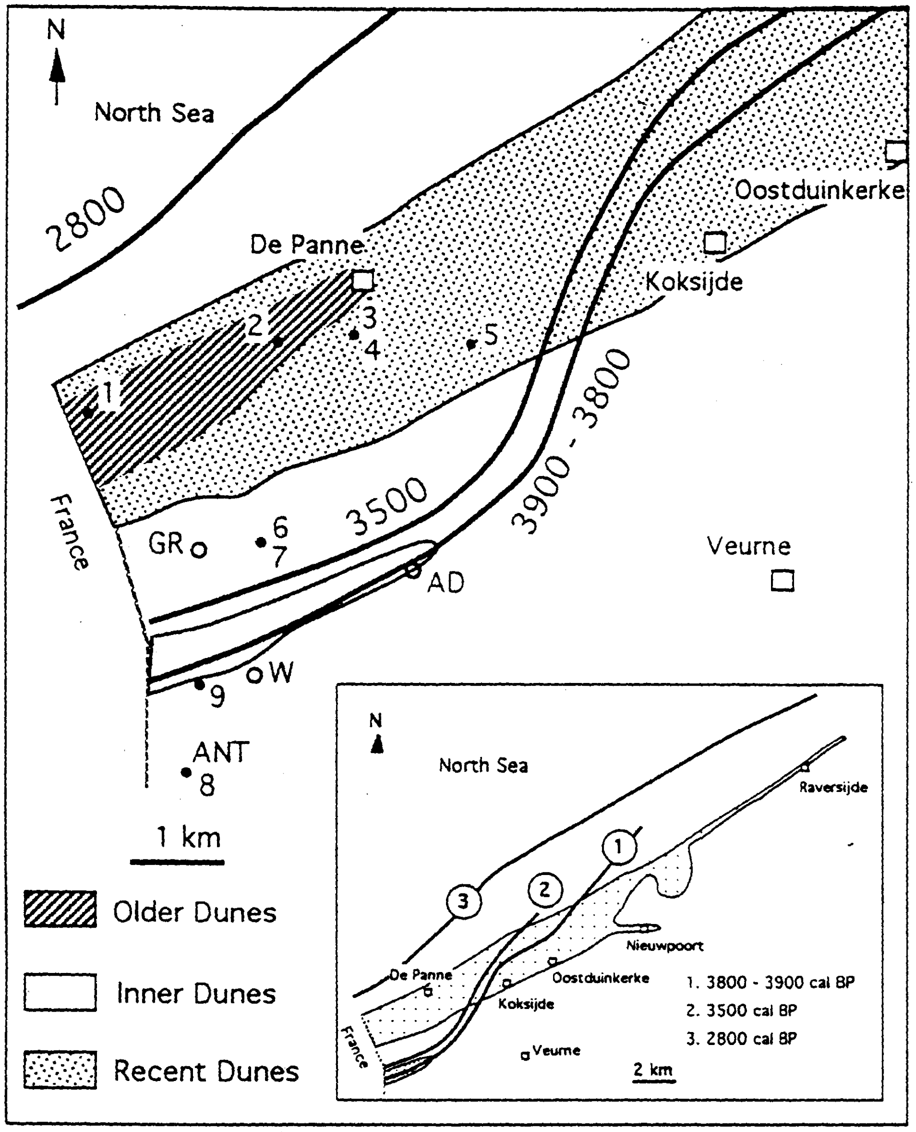

W
E
m
GR
De Panne
5
4
3
2
1
1
2
3
4
0
200 m
1. 3089 cal BP
2. 2770 cal BP
3. 2740 cal BP
4. 2054 cal BP
mudflat/salt marsh deposits
peaty/organic clay
sandflat deposits

fig 10


N
North Sea
2800
De Panne
Oostduinkerke
Koksijde
3900 - 3800
3500
France
GR
AD
W
ANT
Veurne
1
2
3
4
5
6
7
8
9
1 km
Older Dunes
Inner Dunes
Recent Dunes
N
North Sea
Raversijde
Nieuwpoort
De Panne
Oostduinkerke
Koksijde
Veurne
France
2 km
1. 3800 - 3900 cal BP
2. 3500 cal BP
3. 2800 cal BP
①
②
③

1.1