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A preliminary investigation into the possibility of erosion in the area of the Flemish banks.

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1) Introduction

A knowledge of the distribution of sediment in terms of bed and suspended load is essential for a good working description, both qualitative and quantitative, of a coastal sea. A variety of physical, chemical and biological processes in coastal waters are directly connected to, or influenced by, the sediment regime present there. Physical processes may be affected by erosion, transport and sedimentation phenomena, all of which have a direct bearing on beach and harbor stability, the formation of coastal deltas, navigability of shipping lanes, etc. The importance of chemical processes may be inferred from environmental problems arising from the transport and build-up of heavy metal concentrations and their relation to suspended sediment transport. The role of biological processes is typified by the underwater light regime in association with primary production and is eventually coupled to fisheries capacity. These are particularly important considerations in the case of the North Sea. As a result, many investigations of phenomena relating to the distribution of bottom and suspended sediment have been carried out over a long period. An area of major importance for investigators is the southern bight of the North Sea, bounded by the coasts of England, France, Belgium and the Netherlands and separated from the northern North Sea by the Humber Spur and the Texel Spur (fig.1).

The present study is based on a preliminary investigation into the possibility of bottom erosion in a relatively small region of the North Sea along the French-Belgian coast, the northern extremity of the Flemish banks. The possibility of such erosion taking place is a question of especial interest with regard to sediment transport along the Dutch coast. Depending on the results of this study, future investigation on a considerably larger scale will be carried out.

2) Background

A series of investigations were made in 1974-1975, whereby the horizontal distribution of suspended sediment in the Dutch coastal zone was determined under various conditions (fig.2). These measurements form the basis of the hypothesis that a possible source area for longshore sediment transport to and along the western coast of the Netherlands is the shallow banks region off the coasts of northern France and Belgium.

This is, in fact, not a new idea. A number of authors have considered this possibility.

1) According to Wassing (1968), one of the three sources of supply for longshore sediment transport is the shallow sea floor in front of the coast from Belgium to Hook of Holland.

2) In discussing the transport pattern of sediments on the floor of the North Sea, Stride (1965) found, on the basis of correlations between ripple form and the dominating tidal current, a region of bed transport along the Belgian-Dutch coast. This north-going sand stream is, according to the author, notable for its abundance of sand.

3) Houbolt (1968) has noted that a Dutch pilot book from 1632 mentions that the highest parts of the Flemish banks off Dunkerque were exposed at spring tides, but that this is no longer the case. The bank tops are on the order of a few meters under mean sea level at present. According to Edelman (1974), the rise in mean sea level during the last 350 years has been less than 50 cm. This difference may be an indication of erosion, at least in the case of the bank tops.

4) Many investigators believe that the southern North Sea itself was wholly or in great part the source of the Netherlands barrier sand. This would imply a northeasterly transport of bottom sediment, beginning just north of the cretaceous rock bottom of the Straits of Dover. That many authors have shared this opinion is shown in fig.3. Although this build-up of the Netherlands coastal barriers took place during the Holocene and the rate of sand transport reached a maximum during the period of the subboreal transgression (5000-2600 B.P.), it is likely that a certain amount of transport is still taking place.

5) Van Veen (1936) concluded that there is at present practically no erosion from the Straits of Dover (rock and gravel bottom) and that the transport of sand through the Straits of Dover is negligable.

On the other hand, Van Veen found that the configuration of the Flemish banks as shown in charts issued after 1800 differs only slightly from that now prevailing, and that the banks have undergone only minor changes during the last 300 years. This would imply that, if erosion is taking place, it will not be on a very large scale and may be difficult to discern.
Furthermore, Bastin (1971) pointed out that each of the Flemish banks constitutes a dynamic whole, showing little exchange with its environs. He postulated that sediment moving in suspension in the area of the Flemish banks will arrive on the coastal banks in the long run, due to the slight current and wave resultants toward the coast.

3) The Flemish banks

The Flemish banks are a complex series of elongated ridges rising up to 25 m above the surrounding sea bed. This sea bed, often exposed in the intermediate swales, is considered to be of pre-Pliocene origin, and Bastin has shown that the bed is a level transgression plane continuing under the banks and consequently that the Flemish banks are sand accumulations resting on this plane. The banks extend over an area of approximately 1800 km^2, running parallel to the coast between Calais and Zeebrugge, and thus parallel to the direction of the strongest tidal currents.

3.1) Origin and formation

Various dates have been placed on the formation of the North Sea basin, ranging from the late Paleozoicum (ca. 280 million years B.P.) to the late Cenozoicum (ca. 5 million years B.P.). We are here, however, only interested in the most recent changes in, and the uppermost sedimentary levels of, the North Sea, i.e. the Quaternary period.

Part of the southern North Sea has been subjected to heavy glaciation and deglaciation during the Pleistocene epoch (ca. 2,000,000 to 11,000 B.P.), resulting in an irregular relief and causing directly or indirectly an abundance of moveable material. From the end of the last glaciation up until the present time, the older deposits have been intensively reworked and have been transported and deposited elsewhere. Just as the present shape of the sea bed sand ridges is influenced by tidal currents, so also were the bed materials of fluvial and glacial origin reworked by strong tidal currents during and after the Holocene transgression of the North Sea over this area. A contributing factor moreover, according to Van Straaten (1959), was wave action, when the water depth in the North Sea was much lower than at present.

An idea of the development of the North Sea, to almost its present size, during the period from about 9300 to 8300 B.P. (i.e. the early Holocene), can be obtained from the schematization (fig.4) according to Jelgersma (1961).

A few interesting aspects are worth noting.

a) The supposed sea levels are based on pollen-analysis of "moorlogs", related to a time-depth graph of sea level changes. The hypothetical coastlines were arrived at assuming that the present North Sea bottom represents a "submerged landscape".

b) The outlines of the present day Texel Spur and Humber Spur, gentle sea bottom elevations off the Dutch and English coasts, become visible at about 8600 B.P. (cf. sketch 3).

c) Under the influence of the wave action and strong tidal currents of the advancing sea, the Flemish banks, the Hinder banks and the Zeeland ridges were gradually manipulated into being, from about 8600 to 8300 B.P. This phenomenon can perhaps be explained by considering that the change in water depth during a transgression will cause changes in the tidal forces. In some places, due to their shallow depth, the tidal currents may have an influence on bed forms. Another opinion is that oppered by Swift (1974, p.126), who suggests that the Flemish banks and Zeeland ridges were formed in the confined, estuary-like flow regime present in the southern North Sea prior to the cutting of the Straits of Dover.

The advance and retreat of glacial ice and the rise and fall of mean sea level in the North Sea basin during the Quaternary, have also had an effect on the flow patterns of the large rivers emptying into this basin. From a course northwards over the, for the most part dry, North Sea floor at the end of the Pleistocene, the Rhine and Meuse, at the beginning of the Holocene, and with mean sea level at about 40 m beneath its present level, changed course and discharged southwards through the Straits of Dover. These rivers carried large amounts of sediment into the slowly-filling North Sea basin. A large portion of this fluvial material was deposited along with aeolian loam and sands of predominantly marine origin in the region between about 52° N and the Straits of Dover. Well documented descriptions of the bottom sediments of the southern North Sea, detailed with respect to region and type of sediment, have been given by Eisma (1971), Oele (1971) and Wassing (1968).

Typically, the Zeeland ridges were formed by erosion of the sea bed (see, for example, the explanation given by Houbolt, 1968 , p.265), while on the other hand, the region between the Dutch-Belgian coast and the deep water channel became an area of accumulation on an originally flat sea bed. Such accumulations of sand are, according to Zenkovich (1968), formed in regions with a decreasing transportation capacity of the sediment carrying streams, viz. Rhine and Meuse discharge and North Sea tidal flow. Thus it was this fluvial, glacial and marine material which was reworked into the present day banks of the southern North Sea during the early Holocene.

3.2) Sedimentary composition

The Flemish banks are made up of both Tertiary and Quaternary deposits. In general, they are composed of relatively mobile, homogeneous, medium-fine, sea sand with shells, derived from the earlier heterogeneous deposits. Apart from recent mud deposits in the swales, the sea floor beneath and between the banks, the pre-Pliocene transgression plane, is composed of coarser sand mixed with gravel and small pebbles, probably of indirect fluvial origin, indicating that the banks are sedimentary structures.

Several investigators have discussed the lithology and structures of the banks area. The sands which make up the banks belong to the H and NH Provinces according to Baak (1936). Van Veen (1936) also noted that the bed material of the Flemish banks is of two sorts. In the banks region off the French coast and the further seaward lying parts of the banks off the Belgian coast, there is almost no fine material (silt) on the sea bed surface (Van Veen placed the boundary between silt and fine sand at 20 microns). Van Veen was of the opinion that, if silt were ever present there, it had been washed away long ago. On the other hand, he found very much silt in the surface layers of the area along the Belgian coast. The dividing line between the two bed types is between Nieuwpoort and the French-Belgian border according to Van Veen and the same line has been maintained by Bastin (1971) for his measurements. In general, this means no sand on the bottom in the Straits (90% rock), a sandy bottom along the French coast and in the deep water parts (90% sand), and a clayey bottom in the Belgian coastal banks area. Over the entire area a certain amount of shell and broken shell may be found.

Ferguson (1943) gave a schematic survey of the depth of the clay layer in the banks region near the mouth of the Western Scheldt. Van Straaten (1959), in classifying a variety of depositional forms, e.g. tidal flat, coastal lagoon, beach, barrier, etc., mentions the "drowned land topografy" of the southern North Sea as an example of normal open shelf deposits. His zonation of bottom deposits follows closely the lithology depicted by Bastin in his study of the banks region along the Belgian coast. He also points to the strong influence of tidal currents on the present shape of the sea bed sand ridges.

Houbolt (1968)gave an extensive lithologic description of a number of sections in the southern bight of the North Sea. In his analysis he considered three banks belonging to the Flemish banks group, Outer Ratel, Outer Ruytingen and West Dike. He found that the banks themselves were predominently made up of cross bedded sand (as opposed to Bastin (1971) who found no cross bedding) with a median diameter of some 200 to 350 microns, with some dispersed shells and pebbles. Unbedded sand and dense clay deposits are irregularly and sporadically present in the banks.

In the intermediate swales he noted the presence of much gravel larger than 3.5 cm. He did not include any of the coastal banks in his survey.

A number of investigations in the neighbourhood of the Belgian coast, including the Hinder, Flemish and "coastal" banks as well as the Zeeland ridges, have been carried out in relation to pollution problems by Bastin (1971). With the help of natural radioactivity and current measurements, bottom samples and boomer profiles, Bastin charted the sediment composition of the sea bed over a large part of the Flemish banks (fig.5). He found that the bottom material changes progressively from mud to clay to sand with silt and finally to sand as one goes from shore seawards. His measurements covered an area of some 880 km^2 of which 50% was overlain with a layer of yellowish-brown to brown sand. The remaining sea bed was covered with silt (comprising about 19% of the total surface area), clay (ca. 15%) and mud (ca. 16%). A comprehensive study of the sedimentology and morphology of the southern North Sea was reported by Bastin in 1974.

Finally, an abridged review of the most salient hypotheses concerning the recent geological history of the southern bight of the North Sea was given by Gullentops et al.(1972). Of interest is their dating of the last "breakthrough" of the Straits of Dover at ca. 150,000 B.P. This seems to have occurred when ice meltwaters and the discharges of the northwest European rivers were forced to flow southwards due to glacial ice to the north.

4) Qualitative analysis of changes

The sedimentary regime in the region to the north of the Flemish banks gives rise to the idea the latter area may be a source of suspended material found in the Dutch coastal zone. A simple model may be postulated, whereby bed material is entrained from the sea bed in the banks region into the water column during rough weather, and later transported as suspended matter with the slightly dominating northerly residual current. Alternative possibilities are that a more or less circular residual current pattern tends to trap a large portion of the entrained sand and silt, allowing only a relatively small net sediment transport to the northeast (Ronday, 1975); or that all material moving in suspension will arrive on the coastal banks in the long run, due to slight current and wave resultants towards the coast (Bastin, 1971).

The two questions to be answered may be formulated as follows:

1) is erosion taking place in the area of the Flemish banks, and
2) if erosion does take place, how much material leaves this area on a regular basis?

If both of these questions can be answered, then it will be of value to know the strength of such a source relative to other sources (e.g. the Rhine river) and its effect on suspended sediment concentrations in the Dutch coastal zone.
Various authors have attempted to analyse morphological changes occurring in rivers and coastal waters on the basis of comparisons made between old and recent maps and charts, e.g. De Wijkerslooth (1939), Nijhof (1932), Kleinjan (1933), Van Veen (1936) and Morra et al. (1961). The last two studies are of some significance and will be considered here briefly.
Van Veen (1936) gave a qualitative review of the changes in the Flemish banks over the last few hundred years. On the basis of six sea charts, dating from 1776 to 1910, he concluded that, on the whole, the banks have changed little during this period. He finished by saying that "details change without a doubt". Morra and Haring, colleagues of Van Veen at Rijkswaterstaat, made volume-change calculations for the entire tidal drainage area of the Dutch Zeeland coast for various years between 1823 and 1958 on the basis of sounding chart comparisons (Morra et al., 1961). Of special interest for the present study are the results for the mouth of the Western Scheldt and the northern part of the Flemish banks.

Changes in the configuration of the sea bed caused by the movement of sediment (erosion and deposition) and investigated by comparing sounding charts, have been measured according to three methods, i.e. by means of surface, line and point comparisons (see fig.6).

a) Surface: the volume of a given region from reference surface to sea bottom is determined on the basis of a summation of volumes derived from horizontal layers, the boundaries of which are given by the (interpolated) depth contours.

$$\Delta V = V' - V'' = \left(d'_n\Omega'_n - d'_a \sum_{i=a}^{n-1} \sum_{j=1}^{m} \Omega'_{ij}\right) - \left(d''_n\Omega''_n - d''_a \sum_{i=a}^{n-1} \sum_{j=1}^{m} \Omega''_{ij}\right)$$

$\Delta V<0 \Longrightarrow$ erosion

$\Delta V>0 \Longrightarrow$ sedimentation

V' = volume of water within a region bounded by a reference surface (e.g.MSL) and the sea bed at time t'
V" = volume of water within the same region, again bounded by reference surface and sea bed, at a later time t"
Ω = surface area measured within a depth contour line
d = average depth within a given contour
a = shallowest depth contour
n = number of horizontal layers (depth contours), chosen at regularly spaced intervals i
m = number of surfaces bounded by a given depth contour

b) Line: the volume change within a region is derived from the differences in a number of vertical profiles, running parallel to one another over the entire region.

$$\Delta V = b \sum_{i=1}^{k} \sum_{j=1}^{m} \Omega_{pos_{ij}} - b \sum_{i=1}^{k} \sum_{j=1}^{n} \Omega_{neg_{ij}}$$

$\Delta V > 0 \Longrightarrow$ erosion

$\Delta V < 0 \Longrightarrow$ sedimentation

Ω = profile area whereby later soundings are deeper (pos), repectively shallower (neg), than earlier soundings

m,n= number of areas contributing positively or negatively respectively to the total amount of erosion or sedimentation along a given profile

k = 1/b = number of profiles used for the determination of the volume change

l = length of the region under consideration

b = segment width or distance between profiles

c) Point: a point-for point determination of the charted depths available throughout a region is made. These depths are then graphed versus one another and the slope and intercept of the resulting regression line are a measure of the erosion and/or sedimentation that has taken place in the time between surveys.

$$\Delta V = \sum_{i}^{n} (y-y')_i \cdot \Omega_i$$

Ω_i = total surface area between two depth contour lines, characterized by the median of these two depths, i

y = depth value at point i along the line y=x

y'= depth value at point i along the line of regression y'=a + bx', based on the charted depth data

n = number of surfaces to be analyzed, i.e. the number of depth contours minus one

There are certain objections to using the first two methods.

1) Old sea charts have relatively few depth ciphers and therefore the construction of isobaths will be with limited accuracy.

2) Approximation of the average depth applicable to a given bed layer on the basis of the available sounding data can lead to rather large discrepancies.

3) For the same reasons, the determination of continuous linear profiles by means of extrapolation from available data can lead to serious errors.

4) Since the distance between profiles is usually rather large (order

of 1 km), the interjacent areas may be misrepresented.

As opposed to the surface and line techniques, the point-for-point method uses only the available data, and interpolations are carried out only over relatively short distances. Many other factors may have an influence on the ultimate accuracy of this sort of calculations.

1) Hydrographic charts give information especially with reference to minimum depths, since these are the most important for shipping.

2) Detailed soundings, which form the basis of hydrographic charts, are generally unavailable for the southern North Sea before 1933.

3) Comparison of two charts, differing in age by a span of many years, leads to problems in reducing the sounding data to an appropriate reference surface, e.g. MSL or NAP (mean sea level, Amsterdam ordnance datum).

4) Errors in the determination of ship's position and water level play a role in the case of old sea charts.

5) Wire or line soundings may deviate from true vertical due to ship drift and subsurface currents, and depth readings may be influenced by a soft sea bottom. A detailed discussion of all of these factors along with estimates of the errors involved is given in the report of the Delta Commision (Morra et al., 1961).

5) Quantitative analysis of changes

In this section the average yearly sea bed change for a test area within the Flemish banks region will be calculated.

5.1) Method used

A representative area in the northern part of the Flemish banks off the Belgian coast was selected for the study. The bounds of this region were from 51°21' to 51°34' N and from 02°56' to 03°09' E. The hydrographic charts used to make the comparison study were:

1) the mouth of the Western Scheldt by Flushing, surveyed in 1894 and 1895 by Phaff, Planten and Dullemond for the Dutch Hydrographic Service, scale 1:50,000, and
2) the southern North Sea, surveyed in 1970 and 1971 by W. Boer for the Dutch Hydrographic Service, detailed soundings, scale 1:25,000.

With the help of a superimposed grid, the depth ciphers were read off both the old chart (fig.7) and the new sounding sheets at corresponding points. These pairs of points were then graphed and linear and higher order regressions examined. The chosen best fit to the data was a linear regression whereby three possibilities could be considered, a regression of Y on X, one of X on Y, and an orthogonal regression. These three graphs are shown in fig.8. The

95% confidence interval and the line Y=X are shown along with the regression line.

There is, in fact, reason for choosing the regression Y on X, when one realizes that the X values (1970-71 soundings) were much more accurately measured than the values "observed" in 1894-95. (One might think in terms of an experiment wherein known values are plotted along the abscissa and observed values along the ordinate). On the other hand, if the depths are completely independent of one another, the orthogonal regression would be more correct. The calculations, however, have been carried out for all three possibilities.

If the regression line were to coincide with the line Y=X, this would mean that neither sedimentation nor erosion has taken place, i.e. that the depths found in this area in 1970 are, on the average, the same as those found 76 years previously. There are, however, two deviations which may be noted. That the regression line does not pass through the origin is partly due to the different reference surfaces used in reducing the sounding data. And the fact that the regression lines are not parallel to the line Y=X is assumed to be related to sedimentation and erosion phenomena.

5.1.1) Regression line does not pass through the origin

The Netherlands Topographical Service has used the (vertical) position of a marker in Amsterdam as the basis for Dutch surveys, in their present form, since 1875. This reference level is called the Normaal Amsterdams Peil (NAP) i.e. Amsterdam ordnance datum. On the other hand, hydrographic surveys have been related to various reference levels. The hydrographic chart of the mouth of the Western Scheldt, surveyed in 1894-1895, gives depths with reference to average low water (GLW). And the soundings carried out in the southern North Sea in 1970-71 by the Dutch Hydrographic Service are referenced to the average of the lowest monthly spring tide low water levels taken over a 5 year period (LLWS). To relate the charted depths to one another one need simply relate the reference surfaces to NAP.

The ten year's Review of Water Heights and Discharges (Anonymous, 1964) gives the difference between the year-averaged GLW and NAP for Flushing for the years 1891-1900 as -196 cm. The difference between LLWS and NAP at Flushing in 1970-1971 was -250 cm. The difference between the two reference surfaces used is therefore 54 cm. In the same period of time, the mean water level in the vicinity of Flushing rose about 13,5 cm, from NAP -19 cm to NAP -5,5 cm. Since both levels are negative with respect to NAP, no correction need be made for changes in mean water level between 1894 and 1970.

The only correction which need be made, therefore, is for the 54 cm difference in reference surfaces. This may be accounted for by simply "dropping" the regression line of the uncorrected data 54 cm over its entire length.

5.1.2) Regression line is rotated with respect to line Y = X

As shown in fig.8, regression lines for the sounding data are given along with a line at an angle of 45°, shifted to account for the reference surface difference, and the 95% confidence interval for the regression line. If the regression line had coincided with the line Y = X, i.e. if the 95% confidence interval fell with equal spacing on both sides of this line, this would imply that, on the average, neither erosion nor sedimentation had taken place. The fact that these lines are rotated with respect to one another is assumed to be due to erosion or sedimentation where the regression line falls respectively below or above the line Y = X. The distance between these lines is then a measure of the amount of erosion or sedimentation that has taken place.

5.2) Calculation of the amounts of erosion and deposition

The total amount of bottom material eroded or deposited over a period of 76 years may now be determined on the basis of the three different regressions. To do this, the graphs were segmented into intervals of 5 m actual depth, from 0 to 35 m depth. At the center of each interval the average amount of erosion or sedimentation for that interval was determined as being the difference between the shifted base line Y = X and the upper and lower bounds of the 95% confidence interval. These average bottom changes were then multiplied by the surface areas within the respective depth contours. The surface areas were determined with the help of a HP 9810 digitizer. In this way, the volume changes could be calculated over the entire area of interest by means of a summation of the results per interval. The results for the three possible regressions are shown in table 1.

REGRESSION	DEPOSITION (x $10^6 m^3$)	EROSION (x $10^6 m^3$)
Y on X		27.0028 0.9850
X on Y	10.7302	19.3092
Orthogonal		19.2821 0.7242

Table 1. Total sea bed volume change in 76 years as a result of deposition/ erosion according to three possible linear regressions.

Maximum and minimum values of deposition/erosion relate to the upper and lower bounds of the 95% confidence interval for the regression line.

5.3) Water content of the bottom material

A comparison of the Flemish banks as a possible source of suspended sediment with other sources in the coastal North Sea may be of interest. However, in order to find out how much material may eventually be eroded in a given period of time from the Flemish banks, the composition and density of the material must first be determined.

As a result of measurements carried out by TNO and Rijkswaterstaat in 1973 on a large number of coastal sediment samples, it was found that the density of dried sediment containing approximately 15% organic material was 2.26 gm/cm^3. This value may vary somewhat, depending on the type of sediment and the percentage of organic material, but for an order of magnitude estimation it may be considered representative.

A second factor which must be taken into account in determining the density of the bed material is the amount of interstitial water (not to be confused with bound water) present. Several estimates of the ratio of interstitial water to sediment have been made (table 2). The density was calculated using a specific gravity of 1.021 for the interstitial (sea) water.

WATER TO SEDIMENT RATIO	DENSITY
30 % water 70 % sediment	1.89 gm/cm^3
40 % water 60 % sediment	1.76 gm/cm^3
50 % water 50 % sediment	1.64 gm/cm^3

Tabel 2. Density of bottom material for various water to sediment ratios (by volume).

5.4) Calculation of the average yearly change

Taking the above into account, it is now possible to determine the total amount of sea bed material deposited or eroded from the area under consideration. This can be determined as being the yearly averages of the maximum and minimum values, resulting from the confidence limits on the regressions. For the sake of simplicity, the amounts are given per km^2, the total area studied being 22.7 by 15.6 km (≈ 354 km^2).

REGRESSION	WATER TO SEDIMENT RATIO	DEPOSITION	EROSION	
Y on X	30 - 70		1587.8	57.9
	40 - 60		1361.0	49.6
	50 - 50		1134.1	41.4
X on Y	30 - 70	631.0	1135.4	
	40 - 60	540.8	973.2	
	50 - 50	450.7	811.0	
Orthogonal	30 - 70		1133.8	42.6
	40 - 60		971.8	36.5
	50 - 50		809.9	30.4

Tabel 3. Average amount of material deposited/eroded per year and per km^2 (expressed in tons of dry material).

It is evident from tabel 3 that changes in the water content of the bottom material play a less significant role than the type of regression used and the maximum and minimum bounds derived from the 95% confidence interval. An accurate average water to sediment ratio for the uppermost layer of the sea bed at the sediment-water interface, and over a large coastal area is, moreover, diffucult to define. We therefore assume, for the remaining calculations, a ratio of 40 parts water to 60 parts sediment as an overall average for the area.

6) Extrapolation of test area results to the entire banks region

As mentioned in section 2, cruise data for the Dutch coastal zone suggest that the Flemish banks may be an important source of suspended sediment over a relatively large portion of the Zeeland delta area. If, then, the present study is to be of value for a coastal sediment transport model, it is important to know the possible contribution (positive in the case of erosion, negative in the case of deposition, and nil in the case of long-term equilibrium) of the entire banks region to the sediment balance in the North Sea. A prerequisite in making the extrapolation from the test area to the entire banks region is that the area studied be representative for the remaining area. The situation of the test area in the lithographic charts of Bastin (1974) and Van Mierlo (1899) lends support to this supposition, and in fact, suggests that the results will be on the low side. From charts produced by the Netherlands Hydrographic Service, an estimate can be made of the total area of the Flemish banks as being approximately 1800 km^2. The composition of the sea bed over a large part of the Flemish banks was studied by Bastin (1971) and his results are briefly recapitulated in section 3.2.

Roughly the same bed composition may be expected in the area selected for the present study, although a part of the area falls under the classification "coastal banks" according to Bastin (1971). It is then possible to calculate the expected source strength of the entire banks region, assuming a 40 to 60 water to sediment ratio. The values found are given in table 4 and shown graphically in fig. 9.

REGRESSION	RATE OF DEPOSITION	RATE OF EROSION
Y on X		78 3
X on Y	31	56
Orthogonal		56 2

Table 4. Extrapolated rates of deposition and erosion in kg/sec.
Maximum (erosion) and minimum (deposition) values shown.

7) Comparison of results

Relatively few studies of this sort have been carried out in the past. This is in part due to the time-consuming nature of the work but especially due to the absence of accurate soundings in sedimentologically interesting areas over a long period of time. The fact that soundings are usually made for navigation purposes and that regions such as the Flemish banks are obviously to be avoided by shipping has probably played a secondary role in this respect. As mentioned in section 4, however, a comprehensive study of volume changes using the line or profile method was carried out by Morra and Haring for the report of the Delta Commission (Morra et al., 1961). It is of interest to compare their results with those of the present study where applicable.

a) Morra and Haring found large regions of erosion near the coast while, further seawards, regions of sedimentation occurred. In the present study, however, regions of erosion and sedimentation are intermingled. There is, nevertheless, a general tendency towards more pronounced sea bed change as one proceeds outward from the coast. An idea of the situation of these regions can be obtained from fig.11. The amounts of deposition and erosion, given in terms of change-of-depth, pertain to the total amounts found over the period of study (1894-1970).

b) If we assume that deposition (fig.10, tract A) and erosion (tract B) have taken place uniformly over the entire area of the tracts, we can calculate approximately the volume change in those regions which coincide with the region examined in the present study. According to the investigations reported by the Delta Commission, approximately 7.7 x 10^6 cubic meters of bed material were eroded from the study area from 1894 to 1921. To extend this comparison to the present study, it is necessary to extrapolate the amounts found from those for 27 years (Delta Commission) to those over 76 years (present study).

This gives a value of about 21.7 x 10^6 m^3 erosion, which agrees in order of magnitude with the amounts found in the present study. When compared with the volume changes given in table 1, good agreement is found for the maximum amounts of erosion for each of the three regressions.

The results of the present study may also be compared with sediment load statistics given in recent estimates for various Dutch waters (e.g. Ferguson, Terwindt, et al., 1976 and Terwindt, 1967). A few figures will serve to indicate the relative size of a possible sediment load as determined for the Flemish banks, in comparison with other sedimentary sources.

1) The combined suspended load of the rivers Lek, North, and (old) Meuse is ± 1.5 x 10^6 tons/year. Only a small fraction of this total reaches the North Sea.
2) The suspended load of the Waal brings about 2.5 x 10^6 tons of silt per year to the New Merwede, Amer and Hollands Deep.
3) About 1.5 to 2.5 x 10^6 tons of sediment enter the New Waterway yearly from the North Sea.
4) From the Europoort region and the harbors along the Caland and Beer channels about 5 x 10^6 tons of sediment (mostly silt and very fine sand) are dredged and dumped at sea yearly.
5) The input of the Dutch rivers to the North Sea is about 4.6 x 10^6 tons/year.
6) The amount of mud carried annually in a northerly direction along the French channel coast has been estimated at 2 x 10^6 tons of dry matter.

These values are comparable in order of magnitude to the erosion totals given in fig.9.

8) Conclusion

Using the technique of point-for-point correlation of sounding data, hydrographic charts from 1894-1895 and 1970-1971 were compared for the northern extremity of the Flemish banks. The study was intended as a preliminary investigation of bottom changes in a relatively small area and over a relatively short period of time. Neither absolute accuracy nor completeness are pretended in this first study, the point behind the study being to arrive at order-of-magnitude figures for the bed sediment balance and to test the usefulness of the method used in arriving at these results.

In the light of this, there can be no definite conclusions made concerning the present results except to note that they indicate that future study of a large part of the banks region, using the technique developed here, is warranted. A tentative conclusion might be drawn from the good agreement found between the data of Morra and Haring (see Morra et al, 1961) and the present results. This agreement seems to imply that an extrapolation from 27 to 76 years is reliable and, therefore, that a stable erosion process has been taking place for at least this period of time. The total amount of erosion is relatively small however and consequently difficult to determine accurately.

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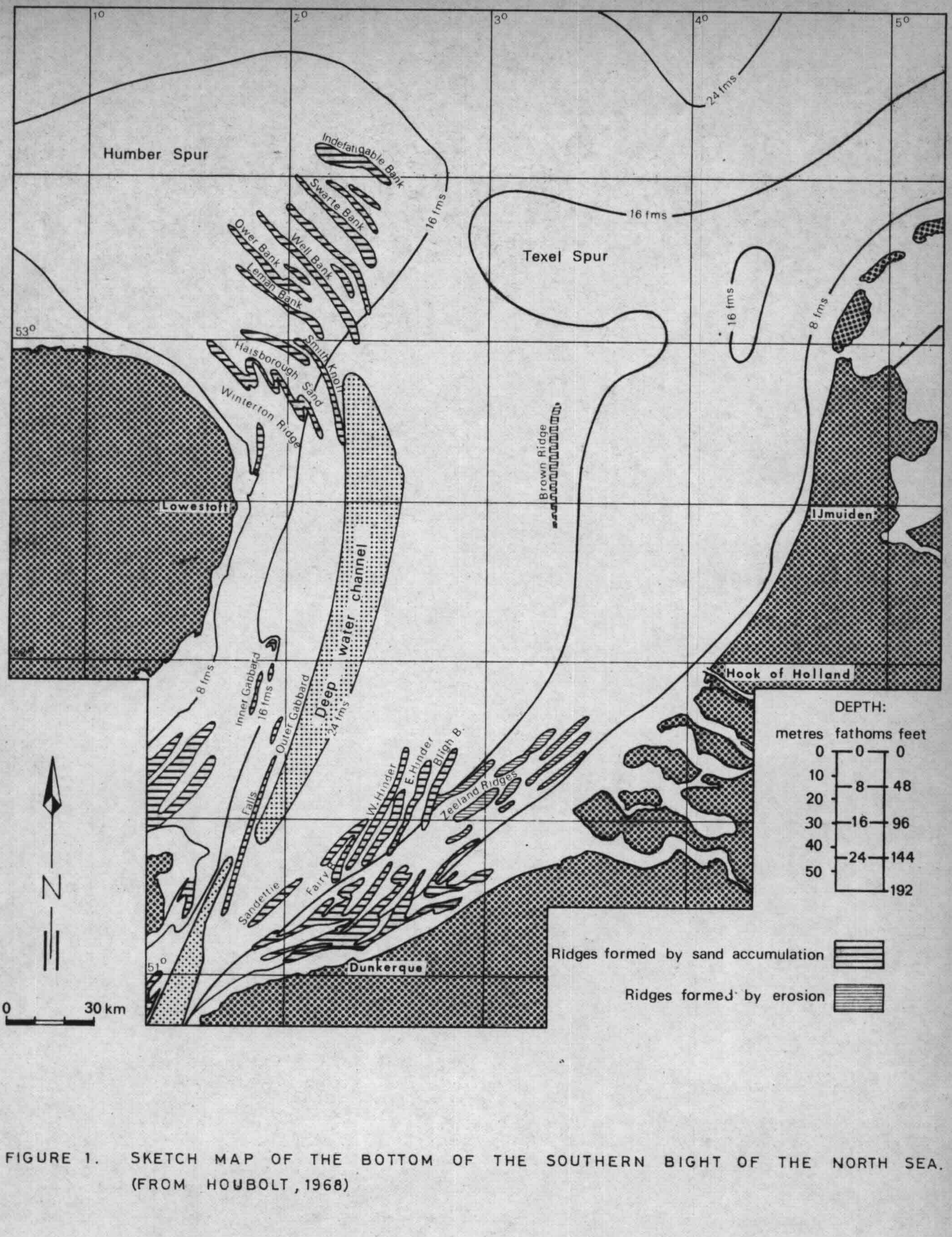


FIGURE 1. SKETCH MAP OF THE BOTTOM OF THE SOUTHERN BIGHT OF THE NORTH SEA. (FROM HOUBOLT, 1968)

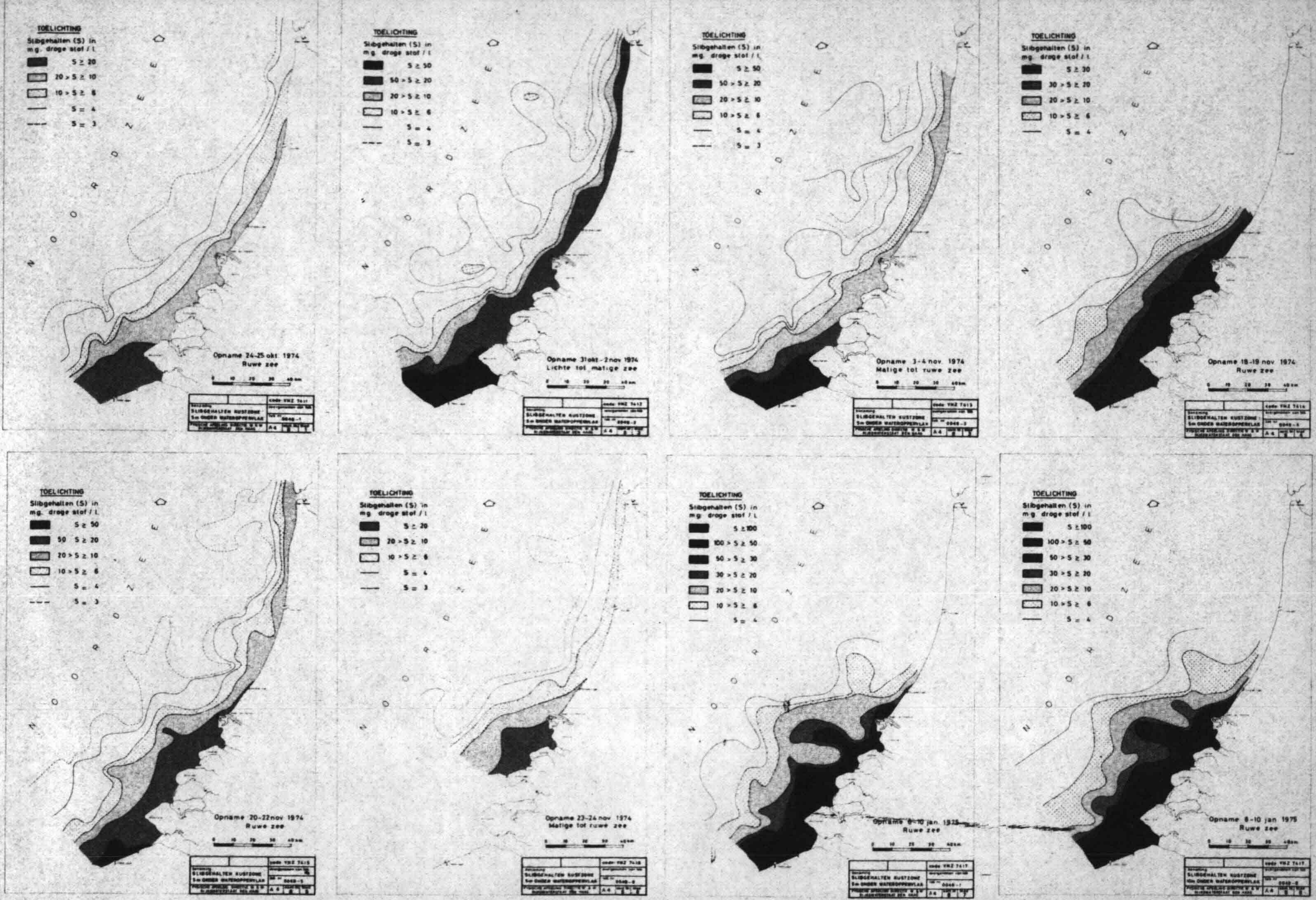


FIGURE 2. HORIZONTAL DISTRIBUTION OF SUSPENDED SEDIMENT IN THE DUTCH COASTAL SURFACE WATERS DURING THE PERIOD OCTOBER 1974 TO JANUARY 1975. CONCENTRATION IN MG/L (FROM GOSSE, 1976).

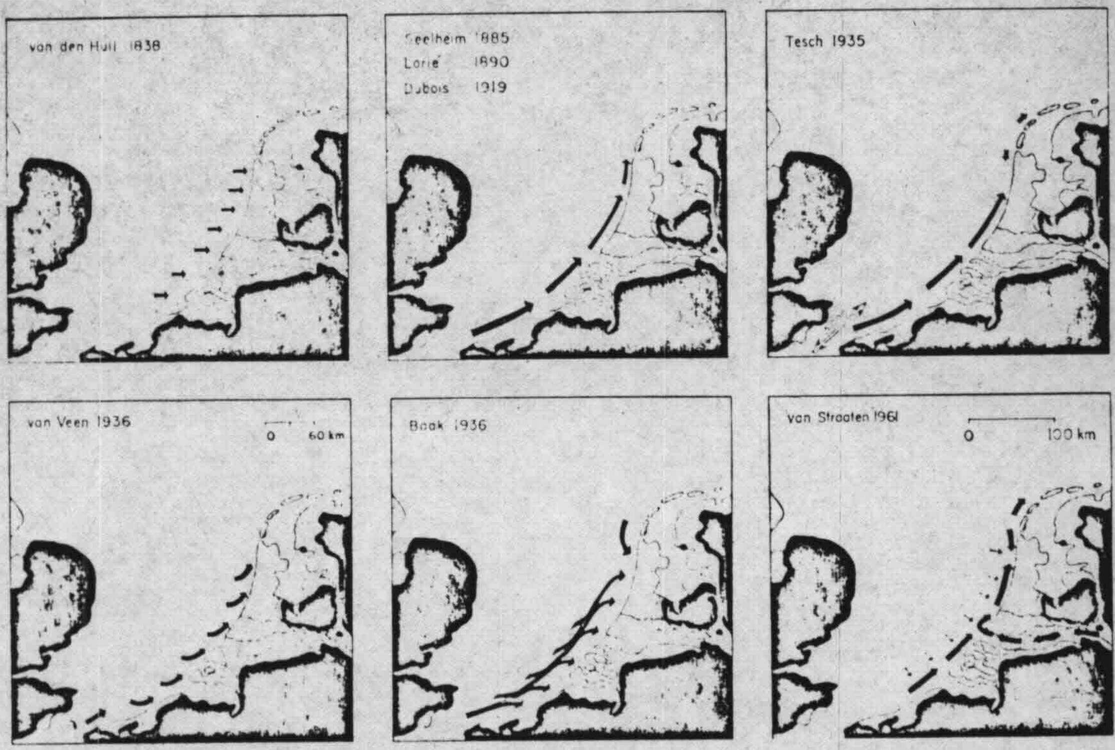


FIGURE 3. SOME OPINIONS CONCERNING SUPPLY ROUTES OF SAND MAKING UP THE NETHERLANDS' COASTAL BARRIERS (FROM KRUIT, 1963)

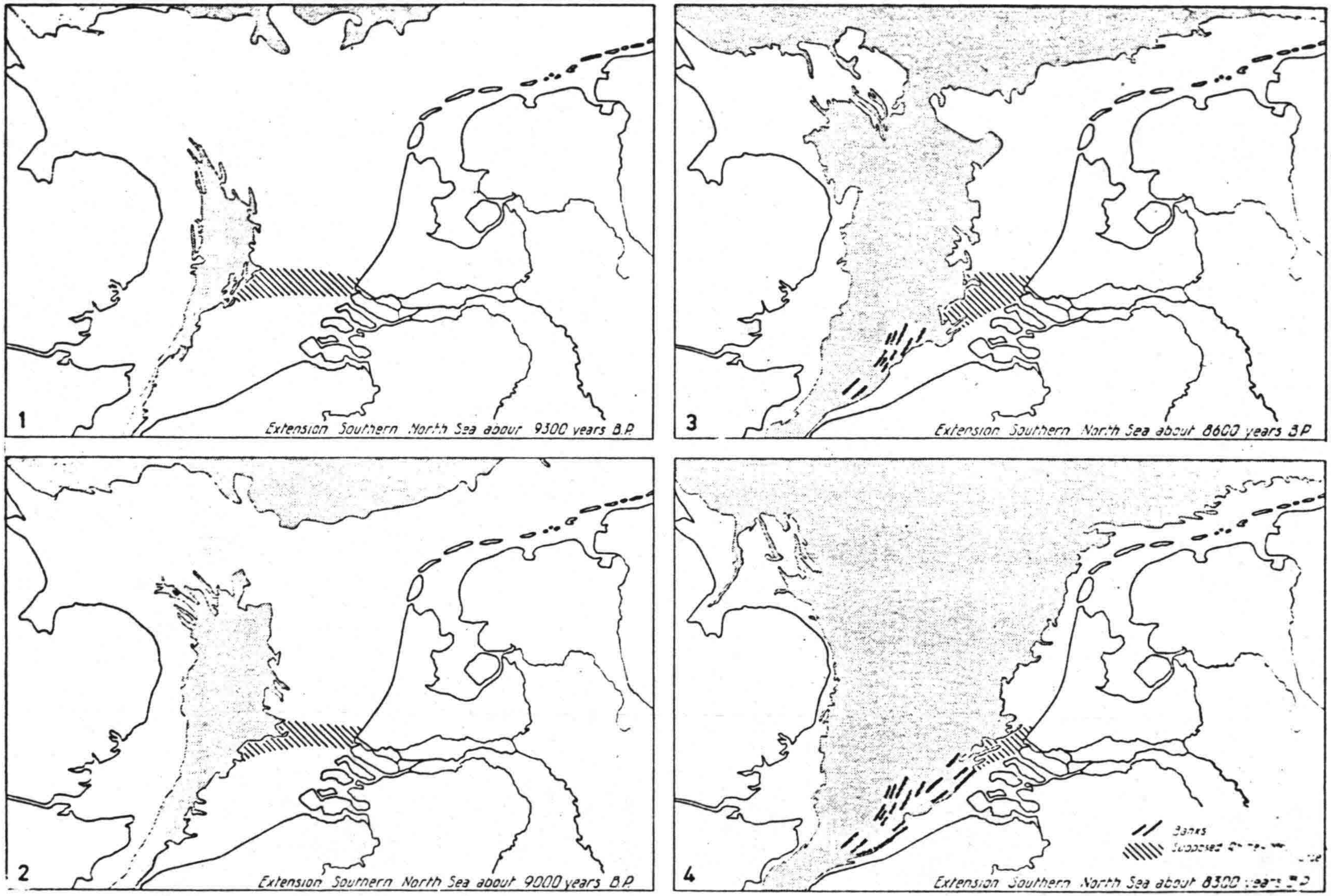


FIGURE 4. HYPOTHETICAL MAPS OF THE EXTENSION OF THE SOUTHERN NORTH SEA DURING THE EARLY HOLOCENE (ACCORDING TO JELGERSMA, 1961)

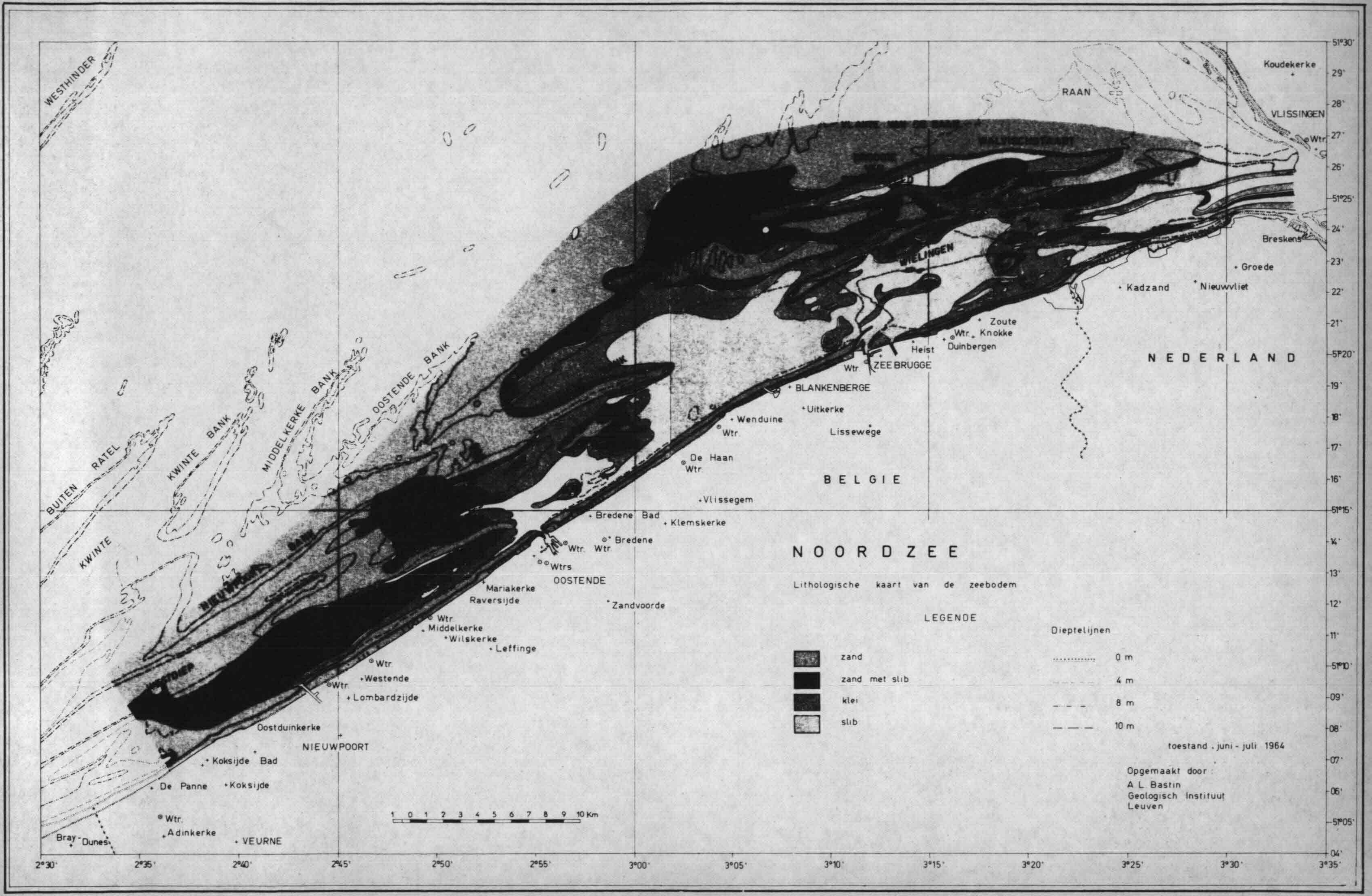


FIGURE 5. SEDIMENT COMPOSITION OF THE SEA BED ALONG THE BELGIAN COAST (ACCORDING TO BASTIN, 1974)

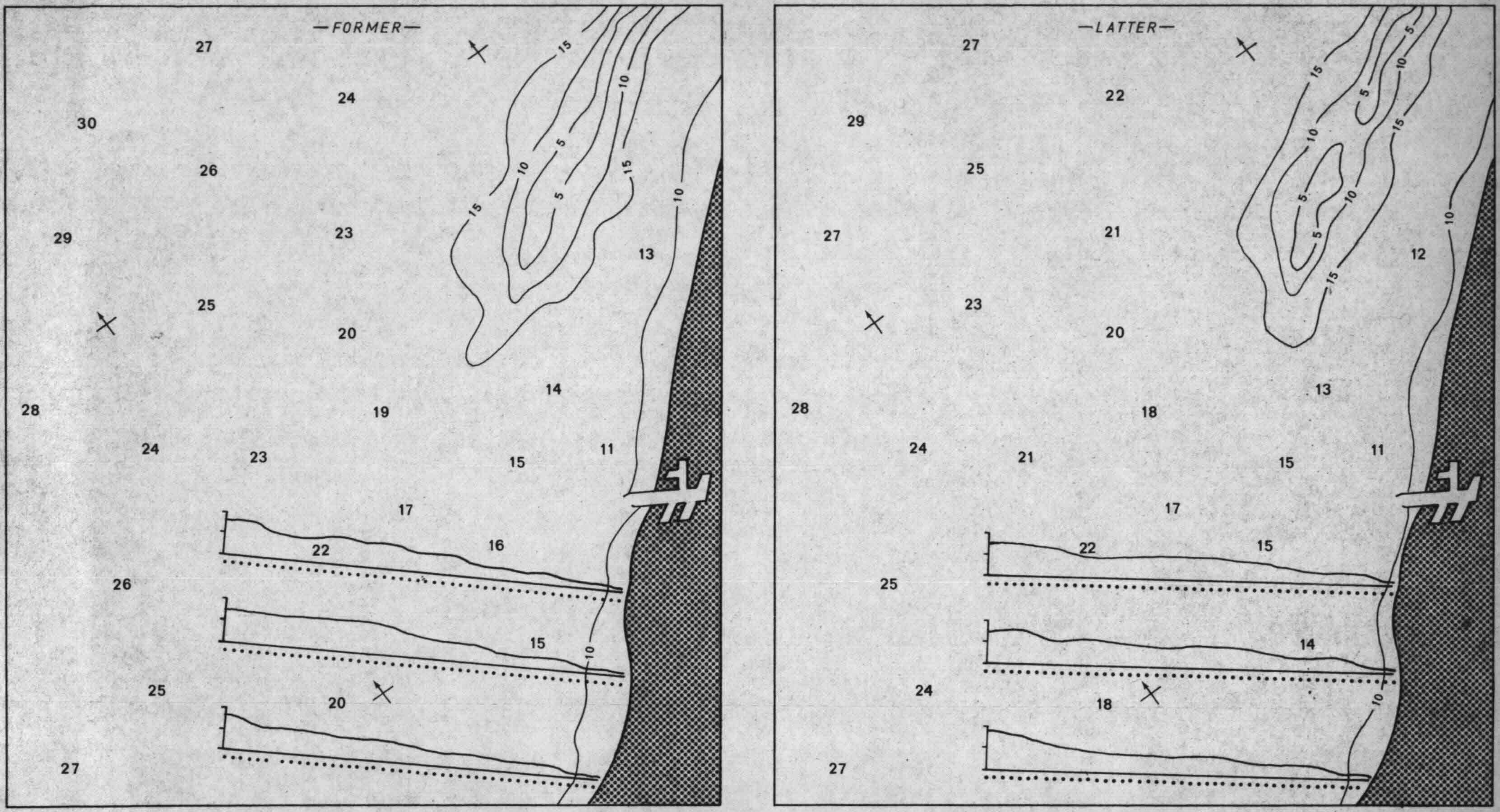
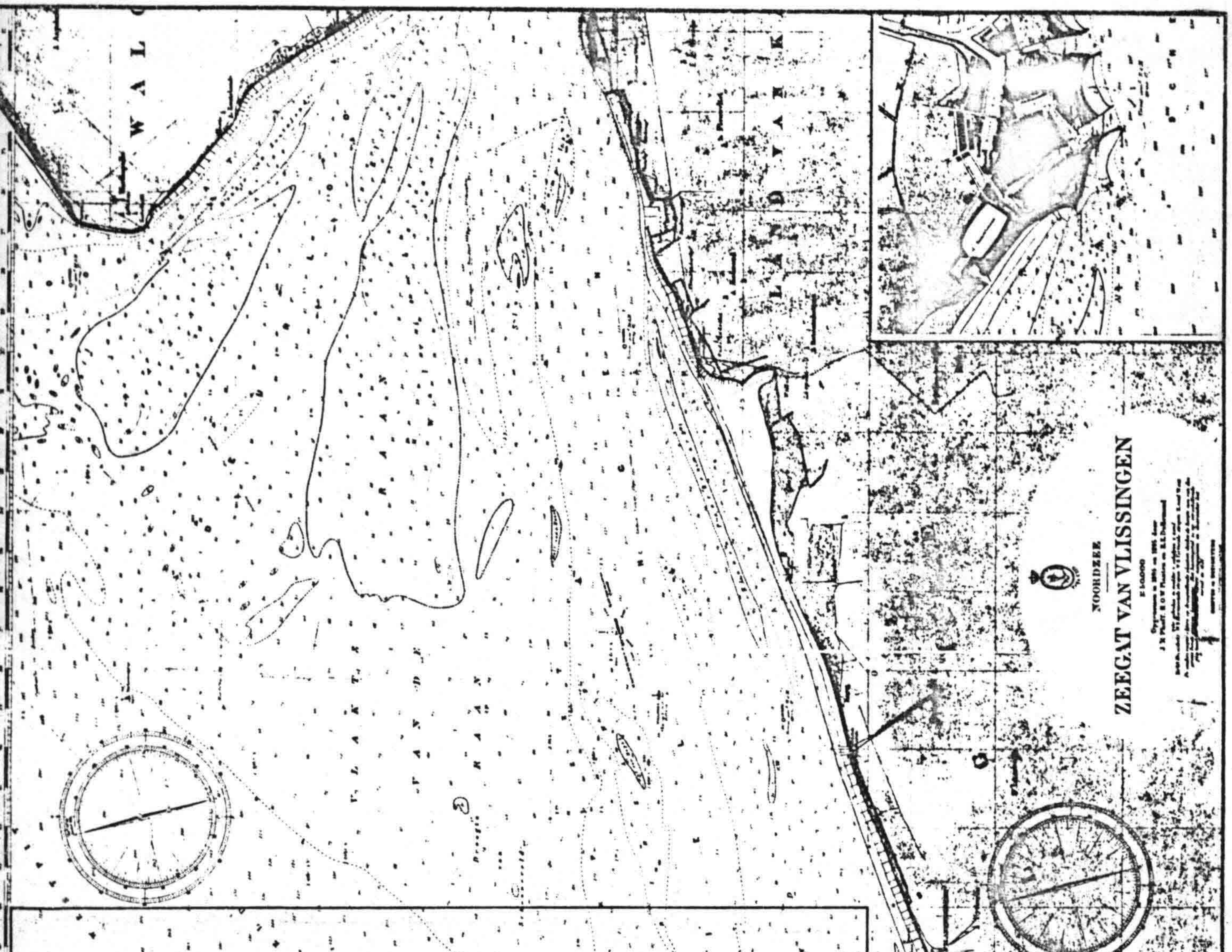


FIGURE 6. EXAMPLES OF THREE METHODS OF INVESTIGATING SEA BED CHANGES: "SURFACE"- BY MEANS OF DEPTH CONTOURS, "LINE"- VERTICAL PROFILING, AND "POINT"- DIRECT USE OF SOUNDING DATA.



IGURE 7. FRAGMENT OF THE HYDOGRAPHIC CHART OF THE NORTH SEA BY THE MOUTH OF THE WESTERN SCHELDT FROM 1894 - 1895, USED IN MAKING THE STUDY.

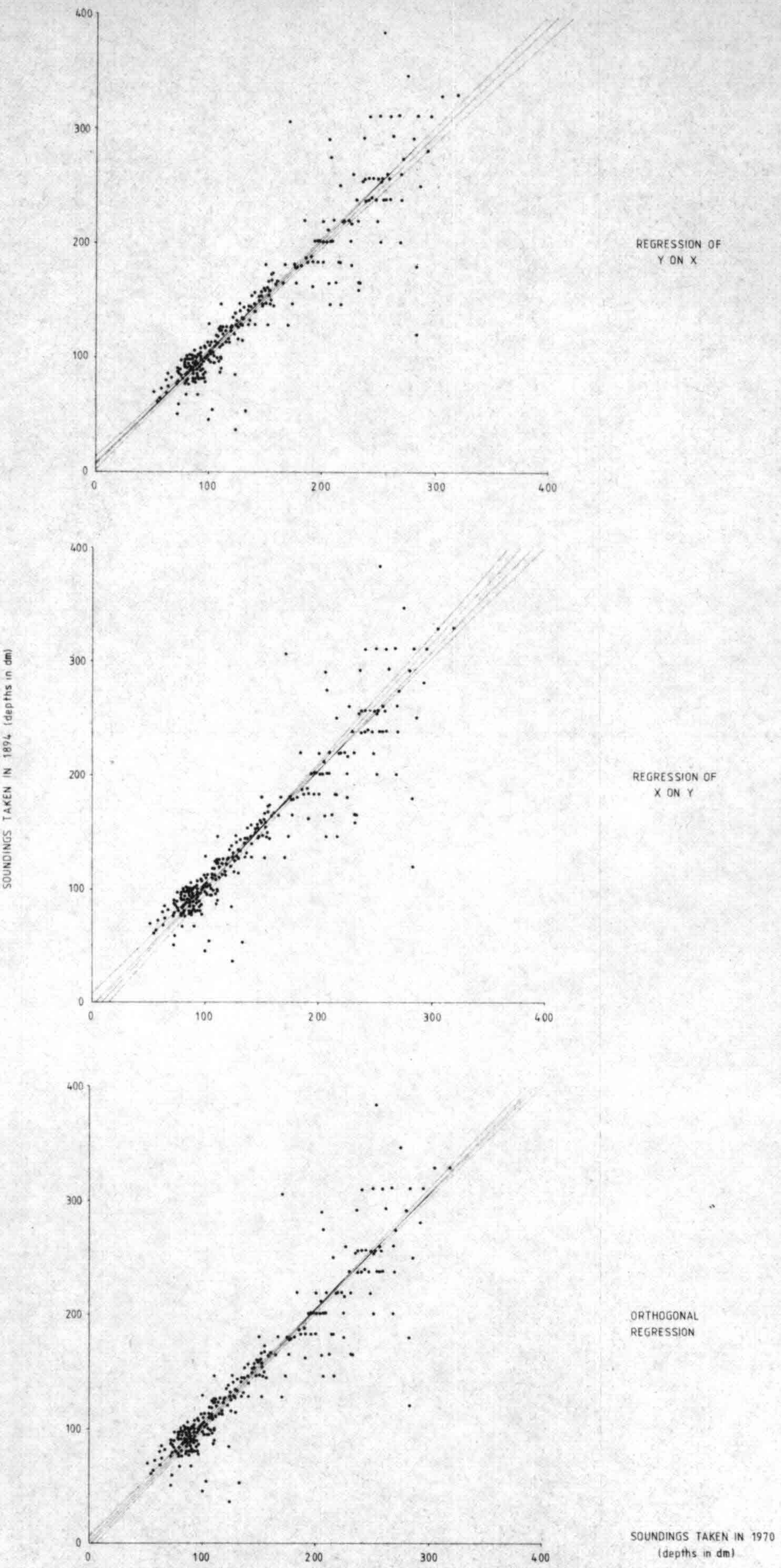


FIGURE 8. SOUNDINGS IN THE STUDY AREA TAKEN IN 1894 AS OPPOSED TO THOSE OF 1970. THE REGRESSION LINE IS SHOWN BOUNDED BY THE 95 % CONFIDENCE INTERVAL. THE LINE Y = X, SHIFTED WITH RESPECT TO THE ORIGIN, IS INCLUDED.

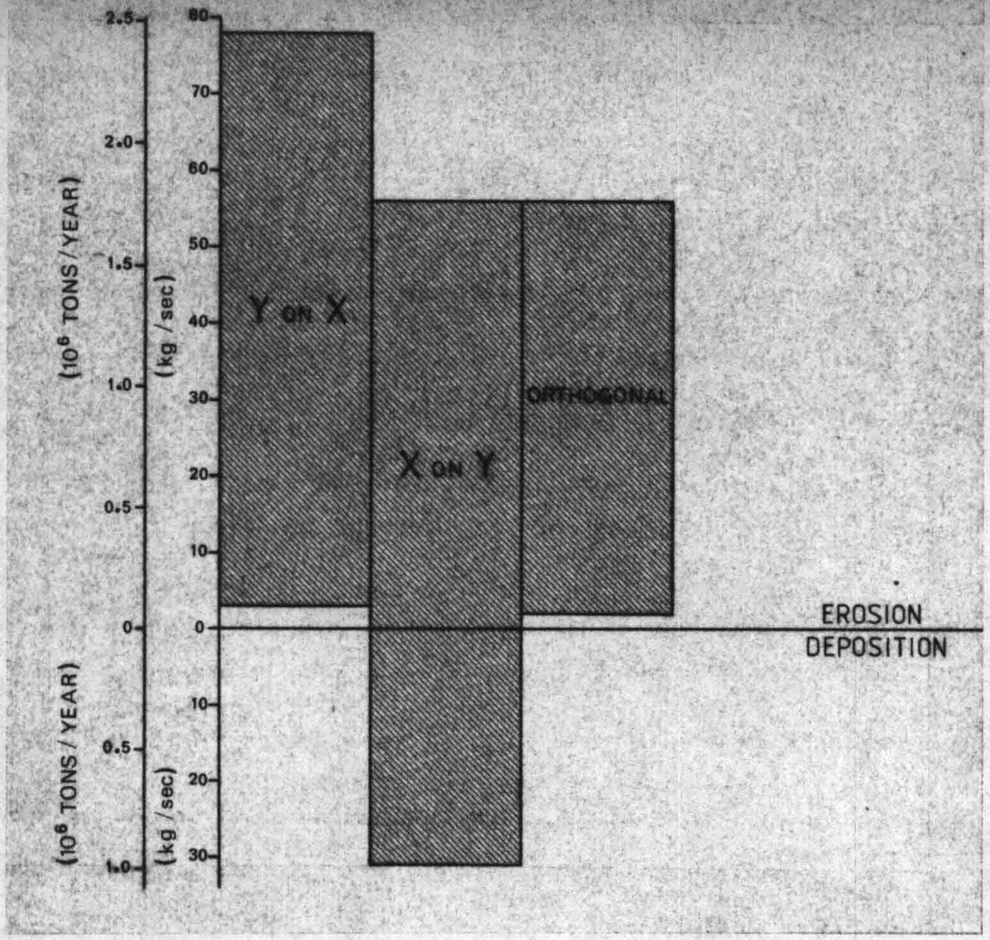


FIGURE 9. BOUNDS OF THE EXPECTED SOURCE / SINK STRENGTH OF THE FLEMISH BANKS REGION.

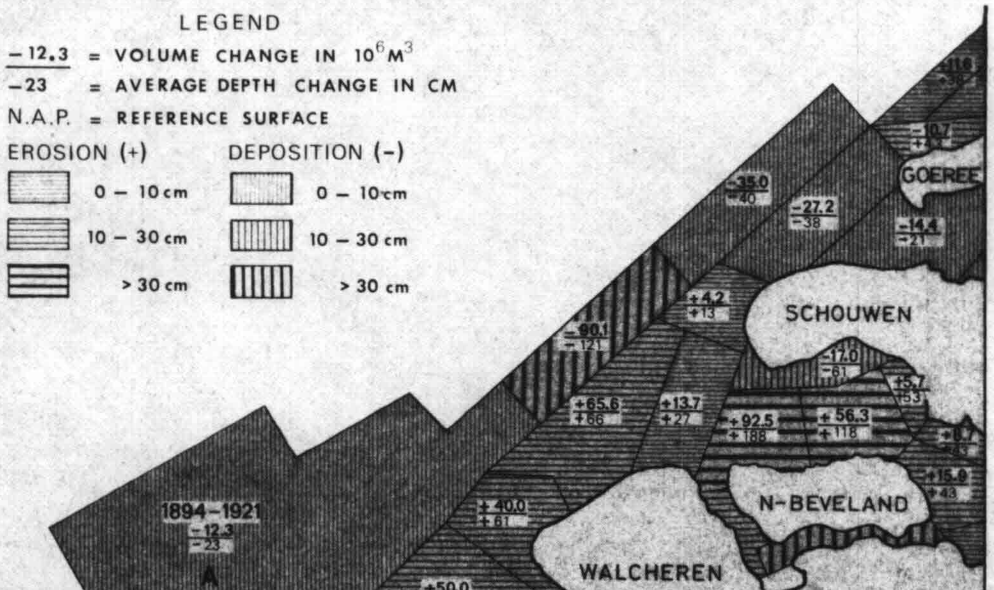


FIGURE 10. AREAS FOR WHICH THE AMOUNTS OF SEDIMENTATION AND EROSION HAVE BEEN DETERMINED OVER THE PERIOD 1872−1933 AND 1894−1921 (AFTER MORRA, HARING ET AL., 1961)

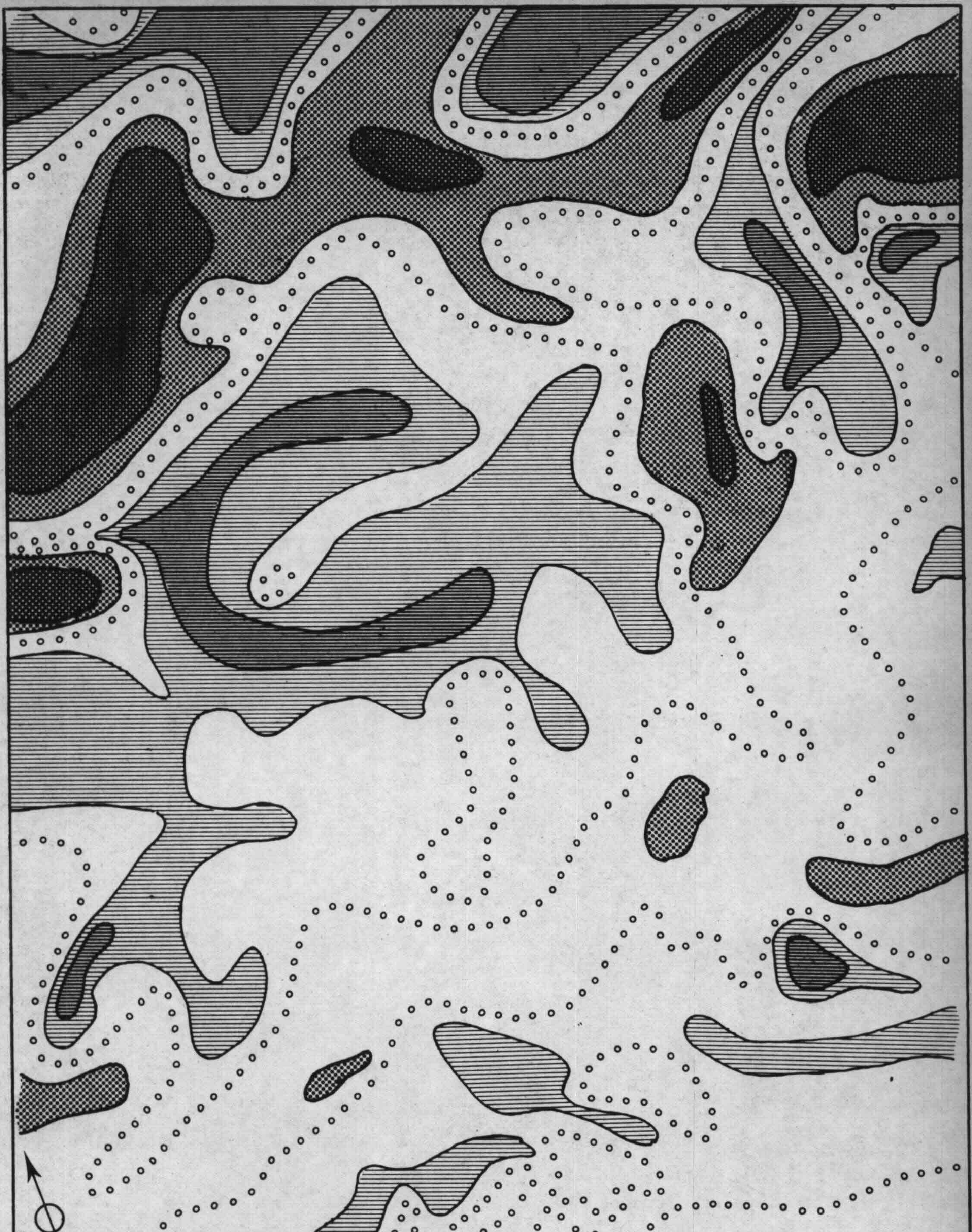


FIGURE 11. REGIONS OF SEDIMENTATION AND EROSION IN THE AREA UNDER STUDY.