# COMPOSITION AND STRUCTURE OF RECENT MARINE SEDIMENTS IN THE NETHERLANDS

BY

L. M. J. U. VAN STRAATEN

CONTENTS

## PREFACE

The chief aim of this paper is to give some new data concerning the recent marine deposits in the Netherlands. The data were collected in the course of about six years, and refer mainly to the (present) Dutch Wadden Sea. Many of them are of a scattered nature. Some aspects of the petrology were not touched upon at all. Since the mere enumeration of these additional results would make hardly digestible reading, the author did not hesitate to put in many summarizing reviews of the work of others. This should not lead, however, to the conclusion that any attempts have been made in the direction of an exhaustive treatise. Nor does this paper claim to be a well balanced account of the subjects under consideration. While some topics, e.g. that of the sediment structures, have received a great deal of attention, others have been dealt with only superficially.

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# I. INTRODUCTION. ENVIRONMENTS AND SEDIMENTATION

## A. General character of environments

1. *The Wadden Sea.* — This environment, the tidal sea in the North of the Netherlands, consists of three subzones: the salt marshes, above the level of mean high tides, the tidal flats proper, between the lines of mean high and mean low tides, and the subzone of the channel floors (*sensu lato*), below the low tide level (Fig. 1 and 2).

The marshes are restricted, in the present Wadden Sea, to the mainland shores and to those of the barrier islands which separate the Wadden Sea from the North Sea. Only one exception is found, viz. the small marsh islet of Griend, situated halfway between the town of Harlingen in Friesland and the islands Vlieland and Terschelling. Nowadays it measures not more than a few hundreds meters across, but formerly it has been much larger.

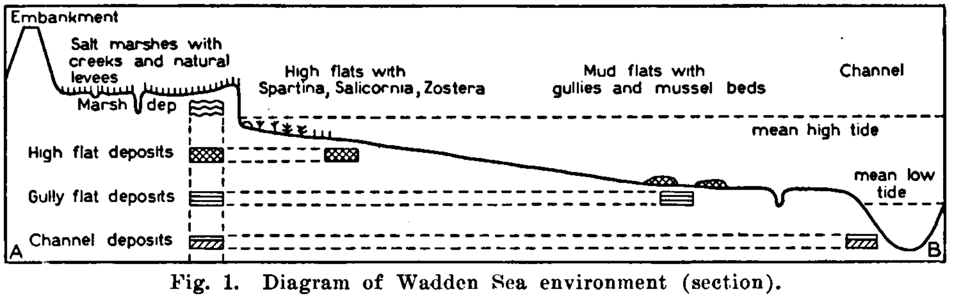


Fig. 1. Diagram of Wadden Sea environment (section).

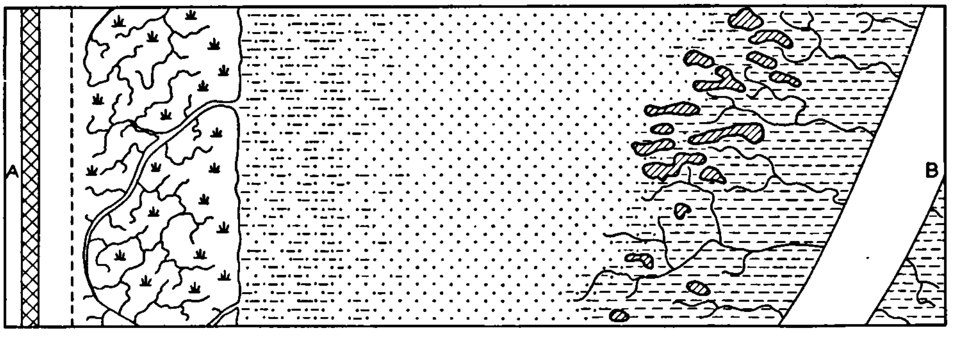


Fig. 2. Diagram of Wadden Sea environment.

The Wadden Sea in its more restricted sense, i.e. the part below the high tide level, can be divided into a number of basins, each of which is drained at ebb tide and inundated by the flood via its own tidal inlet. These Wadden basins are separated from each other by "watersheds", called "wantij-en" which run from the barrier islands to the mainland shore [1].

[1] In the Southwestern part of the Wadden Sea the wantij-en at the back of the islands Texel and Vlieland join each other and do not reach to the main coast.

The middle parts of the wantijen may be comparatively low and are often cut through by shallow channels (Pl. 12). The latter can be considered as short cuts, due to the circumstance that the boundaries between the current systems of adjoining Wadden basins never retain a constant position, but shift to and fro. Moreover, strong westerly winds may produce continuous currents over the wantijen from West to East.

The channel systems of the Wadden basins show many similarities to ordinary drainage patterns on land. Anastomosing of the larger channels, resulting in the formation of isolated tidal flats, completely surrounded by deep water, is relatively rare. It is chiefly found in the lower parts of the Wadden Sea, in the vicinity of the tidal inlets and in the Western area between Friesland and the islands Texel and Vlieland.

On the North Sea side of the inlets large tidal deltas are formed, mainly by deposition from the ebb currents flowing out into the sea. Their surface lies mostly below low tide level. The dimensions of the deltas vary with the discharge, that is the masses of water ("tidal volumes") which flow through the inlets with each successive tide.

2. *The estuaries* in the southwestern part of the Netherlands differ from the Wadden Sea in their shape and orientation and in the importance of the supply of fresh water. In opposition to the Wadden Sea, which forms a more or less narrow zone parallel to the coast, the estuaries have their axis transversely to this direction, each estuary corresponding to a single Wadden basin. Whereas the ebb currents in the Wadden Sea converge into the narrow tidal inlets, the greatest widths of the estuaries are often found at their mouths.

In the upstream parts of most estuaries transition zones are present between the marine and the fluvial environments, in which the movement of the tides is still of great importance, the water being, however, nearly or completely fresh. Apart from these transition zones the estuary environment is very similar to that of the Wadden Sea. The same zonation in salt marshes, tidal flats and channels is found and the sediments show the same petrological and structural properties.

3. *The Zuiderzee.* A much gretaer difference exists between the Wadden Sea and the former Zuiderzee (Redeke, 1922). This latter belonged to the lagoon type of environment. Nearly the whole area remained covered by water even at the lowest tides, the depths lying mostly between 2 and 5 meters. The relief of the bottom was very weak. In the wide basin, South of the narrow entrance between the projecting parts of the provinces North Holland and Friesland, the average range of the tides varied between about 20 and 40 cm. The composition of the water was brackish, with average salinities of 5 to 15 $^{0}/_{00}$. With the exception of a few bottom samples from the present Noordoostpolder, the author did not extend his investigations to this area.

### B. Sedimentation processes

The main types of sedimentation processes, which are responsible for the structures and fabrics, found in the Wadden Sea deposits and in those of the estuaries, are the following:

1. *Filling up of channels, gullies and creeks.* — Owing to the cutting

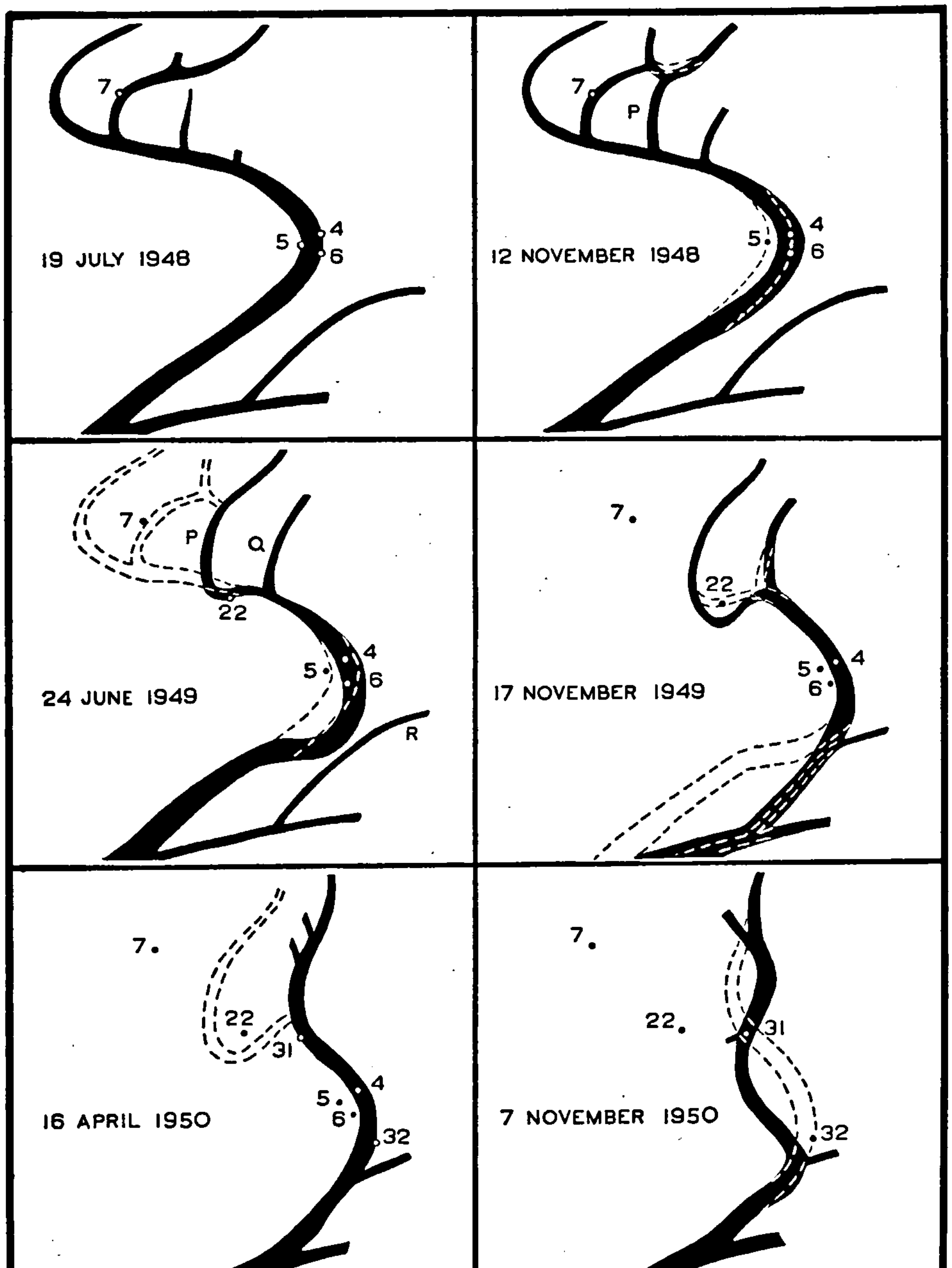


Fig. 3. Sketch-map of changes in ebb gully system South of Nes (Ameland) approx. 1: 1600. The general trend of decreasing erosional activity, deducible from this figure, has not continued up to the present day. A revival of the erosion has taken place in the last years.

off of meanders, to stream captures, and to the formation of new incisions in the vicinity, etc., water courses may become abandoned by the currents, or may show at least a decline of the current activity (Fig. 3). The filling sediments are sometimes of sandy character; in many cases they are of pronounced muddy composition. Other examples of silting up of water courses are due to the work of waves. It has been observed that small gullies may disappear during a single storm, as the result of the trapping of great masses of sand which had been churned up by the waves on the adjacent tidal flats.

Important accretion on tidal flats and on salt marshes in the innermost parts of embayments like the Lauwerszee and the Dollard may lead to decrease of current action on a regional scale, with the concomitant deposition of sediment in entire channel systems.

2. *Lateral deposition.* [1] — Channels and gullies hardly ever occupy a quite fixed position. They shift to and fro with varying velocities. The displacements may be caused by lateral or downstream migration of meanders, by the obstructing influence of growing mussel beds, or by deflection of the water courses as a whole. An important factor determining the intensity of these phenomena is the cohesiveness of the sediment. The creeks of the salt marshes show a much weaker tendency to such lateral movements in correspondence with the greater firmness of the material of the banks.

In these lateral displacements erosion of the receding banks is accompanied by deposition on the prograding banks (lateral sedimentation, see Fig. 4). The newly formed sediments are often of a very muddy composition.

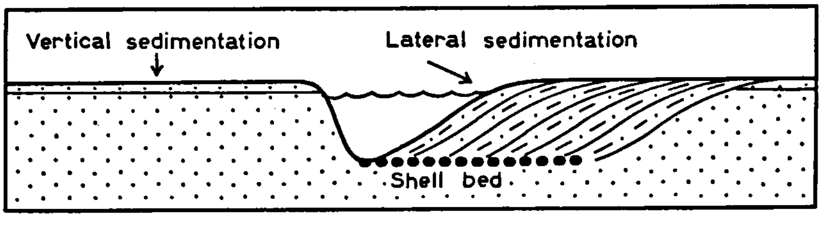


Fig. 4. Diagram of "vertical" and "lateral" sedimentation.

This is for a great part the result of the comparatively rapid deposition. Important quantities of the mud, laid down at the turn of the tides are immediately buried under new sediment, before subsequent currents have the opportunity to remove it again.

The process of lateral sedimentation is not limited to channels and gullies. It is also active on tidal flats, which may sometimes show quite considerable inclinations, e.g. at those places where channels run closely to the shore. Normally, however, the slopes of the flats are only very slight, and the sedimentation is more of the "vertical" type.

3. *Vertical deposition.* [2] — This is the upward growth of horizontal parts of the tidal flats. The material is supplied by channels and gullies. From the banks of these incisions it is spread out gradually over the flats

[1] Cf. HAENTZSCHEL (1936), VAN STRAATEN (1950b, 1951a, 1954), TRUSHEIM (1929).
[2] Cf. VAN BENDEGOM (1950).

in the shape of ripple marks. The rate of accumulation is mostly very low. The velocity is probably of the same order as the relative rise of sea level, periods of excess sedimentation alternating with periods of sediment shortage. At the present day the vertical accretion may amount to 1 or 2 mm per year. Any mud that may be deposited at a given moment, will, under these circumstances, be removed sooner or later, since it is not sufficiently protected from erosion by burial under new material. Hence the sandy character of many of these flats, as opposed to the more muddy composition of the sediments bordering the channels and gullies, which are formed by lateral deposition.

4. *Trapping of sediment by plants.* — This process is of particular importance for the deposition on marshes. When the marshes are flooded, a considerable part of the material, carried on by the currents, is dropped: first the sand, then the finer fractions. In this way a laminated deposit is formed, which is comparatively rich in clay. A characteristic property of this type of sedimentation is the development of natural levees along the creeks [1] (Pl. 1, fig. 1). The plants on the banks are the first to trap the suspended sediment, when, during high floods, the water starts to flow over the sides of the creeks. The same circumstance accounts for the formation of the "marsh ridges" on the seaward edge of the marshes (cf. p. 10). At the latter places, the raising of the surface is hastened, moreover, by the throwing up of material by waves, splashing against the marsh cliffs.

### C. Salt marshes

The term salt marshes is sometimes applied to the whole area which is exposed at low tides. More commonly it is used for those parts which are covered by a close vegetation of halophytes (other than algae). In the Dutch Wadden Sea area [2] and in the marine parts of the estuaries, the lowest zone of this vegetation is usually formed by the *Salicornieto-Spartinetum*, the plants of *Zostera*, which grow at still lower levels, showing as a rule only a very poor development. The lower part of the zone of *Salicornia* and *Spartina* descends below the level of mean high tide and is inhabited by bottom dwelling animals such as molluscs (e.g. *Scrobicularia plana*), worms, crustaceans etc. For botanical reasons it seems logical to include the whole of this zone into the salt marsh environment. The most essential geological difference, however, between the (bulk of the) marsh deposits and the deposits of the tidal flats, lies in the sediment structure and is largely determined by the presence or absence of marine bottom dwelling organisms. Since the upper limit of these animals corresponds more closely to mean high tide level,

[1] Along the gullies, incised in the tidal flats of the Dutch Wadden Sea and of the E. and W. Scheldt, no such levees were encountered by the author, probably owing to the absence of vegetation. In other areas, however, natural levees may apparently be formed without the influence of plants, e. g. in the Bay of l'Aiguillon (France). There, high flat gullies, issuing from the marsh, are bordered by raised banks over which the *Spartina* and *Salicornia* vegetation extends as narrow fingers into the environment of bare mud flats (F. VERGER, 1954, Sur la morphologie et le colmatage de l'anse de l'Aiguillon, C. R. séances Ac. Sci., t. 238, pp. 2248—2250).

[2] Most of the marshes along the Wadden Sea are used as pasture land, or have been formed under the influence of reclamation works. It is obvious that the observations given here have reference only to the natural marshes.

it is, from a geological point of view, preferable to choose this latter level as the limit between salt marshes and tidal flats.

The marshes may pass gradually into the adjacent tidal flats, but more often they are cut off abruptly by small cliffs (Pl. 1, fig. 2). These cliffs are sometimes due to the circumstance that, at a given locality, a period of sedimentation is succeeded by a period of erosion. They may also be the

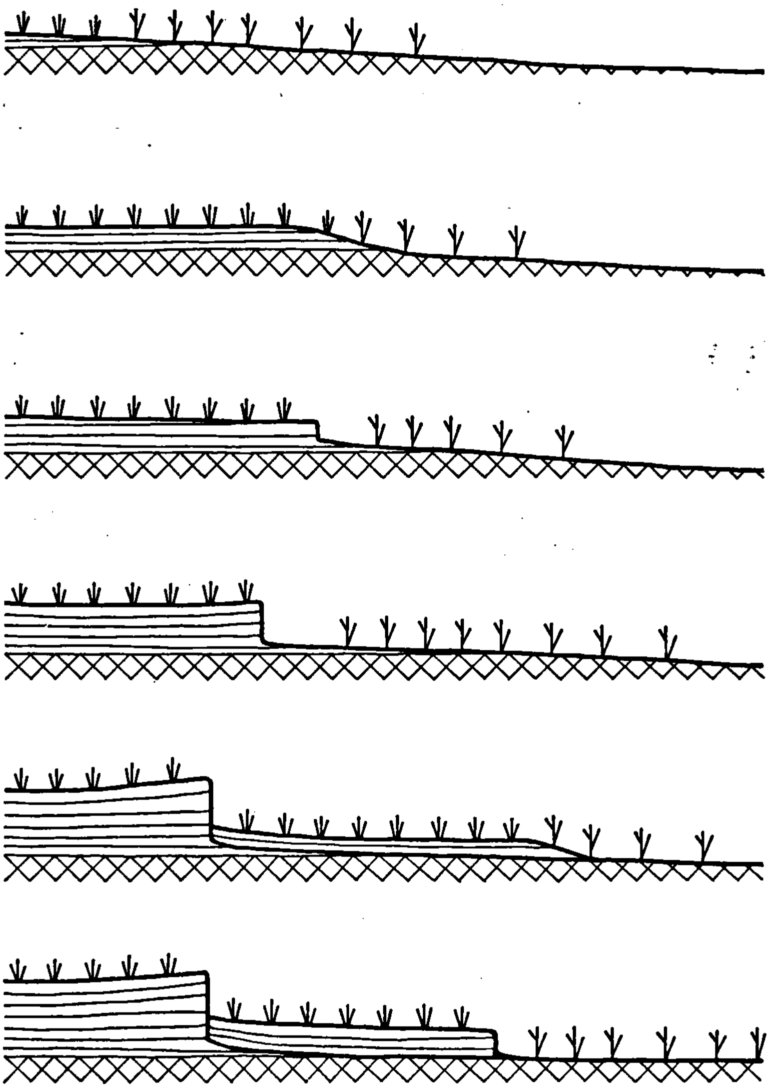

Fig. 5. Diagram of marsh development. Owing to the increased vertical upgrowth due to the trapping of sediment by marsh plants, a rise of the surface is formed, which is sculped out by the waves into a small cliff. Vertical accretion on the marshes may then take place simultaneously with the cutting back of the cliff. The recession of the cliff, however, gradually slows down and a new marsh, with a new cliff may be formed in front of it. The old cliff then disappears sooner or later by weathering and by erosion.

result of the interaction between the accumulative influence of the marsh plants and the erosive effects of the waves (cf. RIVIERE, 1948a, 1948b). When the surface of the flats has been raised to the height where marsh plants start to grow, the rate of vertical accretion can suddenly be increased, owing to the trapping of sediment by these plants (Fig. 5).

The ensuing rise of the surface is then modelled out by the waves during high tides and miniature cliffs are produced. In the following stages of the development the marsh surface may be raised by further deposition, simultaneously with the cutting back of the cliff by wave erosion. This retreat of the cliff, however, soon slows down and a new, lower marsh may be formed at its base.

Gradual transitions of salt marshes into tidal flats are only found where erosion is largely outweighed by sedimentation. Such conditions are encountered in areas which are sheltered from the larger waves. In the Dutch Wadden Sea, where the prevailing and dominating winds come from the West and Southwest, the marshes on the exposed northern and eastern shores (e.g. on the islands Ameland and Schiermonnikoog) are usually cliffed, whereas the best instances of gradual transitions are found on the southern and western shores.

Along the edge of the cliffs the marsh surface is often notably higher than in the area behind[1]. These elevated marsh edges ("marsh ridges") are built up partly by material thrown up by the waves. For another part they are formed as natural levees, due to the trapping of sediment by the plants during high floods.

The marshes are dissected by numerous, strongly meandering creeks. In close proximity to the marsh ridges the minor creeks are frequently directed towards the land. More inland they traverse the marsh surface in more or less random directions, only the major creeks flowing comparatively directly towards the sea.

Whereas a part of the creeks has been formed by later erosion, after a considerable thickness of marsh sediments had already been built up, an important part has been present since the beginning of the marsh formation (cf. STEERS, 1946, 1953), so that their depth is not so much the result of erosion as rather of the vertical growth of the marshes themselves. A photograph of these earliest stages of creek development is given in Pl. 2, fig. 4. Here, the creeks were formed by headward erosion, shortly after the first establishment of marsh vegetation and the resulting formation of a rise of the surface and of a miniature cliff. In other cases these primary creeks are due to the tendency of the marsh plants to grow together in isolated groups, which form small marsh hummocks. In the hollows between them the action of the waves and the currents is concentrated and they are kept open for long periods. In this way they may develop gradually into systems of creeks.

Sometimes the floor of the marsh creeks is raised by sedimentation with about the same velocity as the surface of the surrounding marshes. Cross sections then show a curious, bilaterally bent stratification.

It is not infrequently seen that marsh creeks form anastomosing patterns as a result, either of the original morphology of the area, or of capturing phenomena, short cuts etc. In many cases, especially in the vicinity of the marsh edges, these captured courses are kept open and do not show any

[1] See also JOHNSON (1925, p. 532).

signs of degeneration (Fig. 6). This may be due to the changing water depths. While one system of creeks may be active during lower stages of the tides, another system, lying discordantly across the former, may take over its function during higher water levels.

The creeks are almost universally bordered by raised banks (Pl. 1, fig. 1), closing off large depressions, which are normally covered with marsh plants and can easily be distinguished from another kind of depressions of much smaller dimensions, which are devoid of such plants (Pl. 2, fig. 3). The latter are mostly the remnants of silted up creeks. They have been described by STEERS (1946, 1953) from the English marshes, under the name of salt pans. The water which is left in such pans after the inundations of the marshes

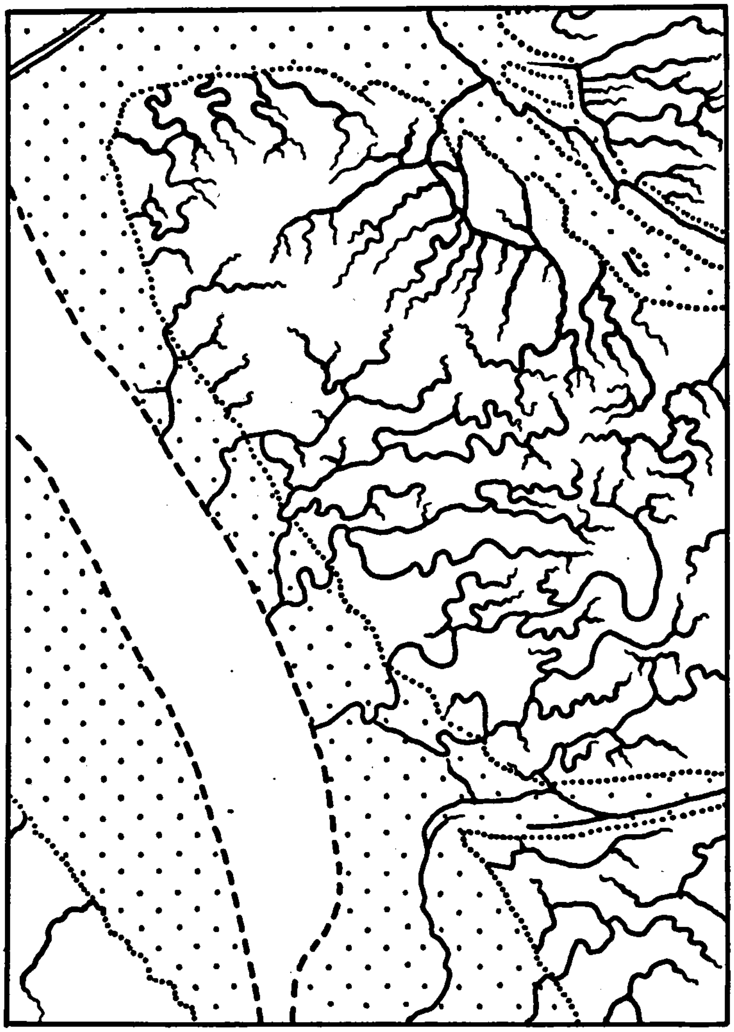

Fig. 6. Creek patterns in salt marshes of Scheldt estuary, drawn after air photograph of Verdronken Land van Saaftinge; dotted areas: tidal flats; blank: flood channel.

may become highly saline by evaporation. These saline stages alternate with fresh water stages owing to the stagnation of rain water, and the large variations in salt content which are produced in this manner may well account for the absence of a higher flora (HEPBURN, 1952).

### D. Tidal flats

The tidal flats of the Netherlands are for the greater part free of halophytes (except algae). Only in narrow zones along the marsh edges *Spartina* and *Salicornia*, and, at somewhat lower levels, *Zostera* (both *Z. nana* and *Z. marina*) are found. The latter are encountered also on the highest parts of tidal flats in the centre of the Wadden Sea.

A conspicuous feature on the tidal flats is formed by the mussel beds, which are generally concentrated in groups, especially on the lower parts, in the vicinity of gullies and channels. The mussels are of geological importance, not only as producers of carbonate of lime, but also because of their influence on the deposition of mud, in the shape of faecal pellets and of pseudo-faeces [1]. The beds often possess elongated shapes. They may then show a preferred orientation with their long axes transverse to the prevailing currents or winds. Their cross section is frequently highly asymmetrical, with a gently sloping "stoss" side, a more or less horizontal top part and a steep lee slope. The stoss sides are exposed to the erosive action of waves and may be transformed into small beachlets, covered with shell debris. The top parts and the lee sides are overgrown with mussels. On the lee slopes considerable sedimentation may take place, owing to the trapping of sand between the mussels and to the deposition of faecal pellets of mud. Through this newly deposited material the mussels work their way upwards, to maintain their position at the surface. The lee sides may, in this way, accrete rapidly. Since the stoss sides are at the same time eroded by the waves, a slow migration of the beds may be observed in the direction of the steeper sides, not unlike the mode of travelling of transverse current ripples (VAN STRAATEN, 1951a). During heavy storms large pieces of approximately rectangular outlines are sometimes lifted out of the top parts. The resulting hollows may then be filled with stagnant water after the surrounding flats have become uncovered (Pl. 3, fig. 6).

The tidal flats are dissected by gullies (Pl. 3, fig. 5). These are of much greater abundance on the low flats than on the higher parts. The scarcity of gullies in the latter areas is partly due to the comparatively small volumes of water which have to be carried off at normal ebb tides, so that the currents do not attain very high velocities. The fact that the salt marshes, which lie at a still higher level, and from which still less water has to be drained, are nevertheless closely intersected by creeks, may be explained as follows. The base level of marsh erosion is situated at the foot of the marsh cliffs and the whole surface at the back of these cliffs lies above the equilibrium profile of the creeks. The surface of the high tidal

[1] A considerable part of the mud, suspended in the sea water, is so finely divided, that it has little chance of being deposited. After passing through the intestinal tracts of the mussels (or other "suspension feeders", e.g. *Cardium edule*), it is compressed, however, into faecal pellets, which are easily sedimented. Some of the suspended mud is not taken up at all in the intestines, but is directly rejected: "pseudofaeces" (cf. VERWEY (1952) SCHWARZ (1932), KAMPS (1950) et al.

flats and the adjoining parts of the low flats is, on the contrary mostly (very slightly) concave (see Fig. 7).

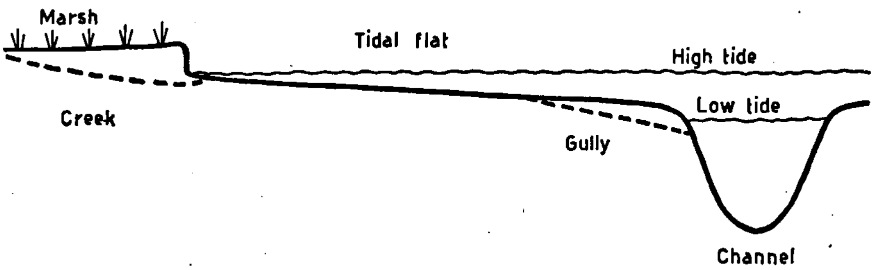


Fig. 7. Position of base level of erosion and the formation of creeks and gullies.

Then also, a considerable difference exists between the effects of wave action in marsh areas on the one hand and on tidal flats on the other. In the tidal flat areas, the waves are of greater sizes, and active during longer periods. The sediment is moreover of notably smaller cohesiveness. The relief features on the tidal flats are therefore much more easily smoothed out. Most of the marsh creeks which debouch on the high tidal flats do not continue, accordingly, over these flats as ebb gullies, but disappear at a short distance beyond the marsh edges. Their waters spread out laterally and the current velocities are greatly diminished. Through-going creek-gully-incisions are found only where the marsh creeks are very large, or where the tidal flats form a narrow fringe with a steeply sloping surface (see Fig. 6).

The lower zones of the tidal flats are much richer in gullies, in correspondence with the higher current velocities prevailing here. Vertical erosion is of greater importance also because most channel banks rise comparatively steeply above ordinary low tide level (Fig. 7).

By far the greater number of low-flat gullies is found in mud flats. Where gullies have been scoured out accidentally in sand areas, the steep parts of the banks collapse very easily during subsequent inundations, owing to the lack of coherence between the sand grains. Moreover, such gullies tend to be filled up with sand as soon as the changing current pattern of the tidal cycle does not correspond any longer with the direction of their courses. The gullies in mud areas are affected by these influences only in a much smaller degree and are more persistent features of the relief.

The relation between the abundance of gullies and the muddy character of the bottom is reciprocal. Not only is the development of more or less closely spaced ebb gullies favoured by a muddy composition of the bottom, but the deposition of mud is itself favoured by the presence of (shifting) gullies and channels (cf. p. 7).

The gullies of sand flats frequently show typical braided courses, a property which is never found in the case of mud flat gullies. The latter are conspicuous, on the other hand, by their tendency towards the development of meanders. These meanders are enlarged in lateral directions and migrate at the same time slowly towards the channels into which the gullies debouch, completely analogous to the meanders of rivers on the land (Fig. 3) [1].

[1] VAN STRAATEN (1949, 1950b).

This may seem perhaps somewhat surprising, since the gullies on the tidal flats are used by alternating currents of opposite directions. The ebb currents in the gullies are, however, of far greater strength, and of longer duration than those of the flood (Fig. 8), so that the current sequence approaches in character to that of the unidirectional type of rivers. These incisions can, therefore, appropriately be referred to also as "ebb gullies".

A noteworthy property of the drainage patterns on the flats is that the upper courses of the gullies lie frequently in the same line with the upper

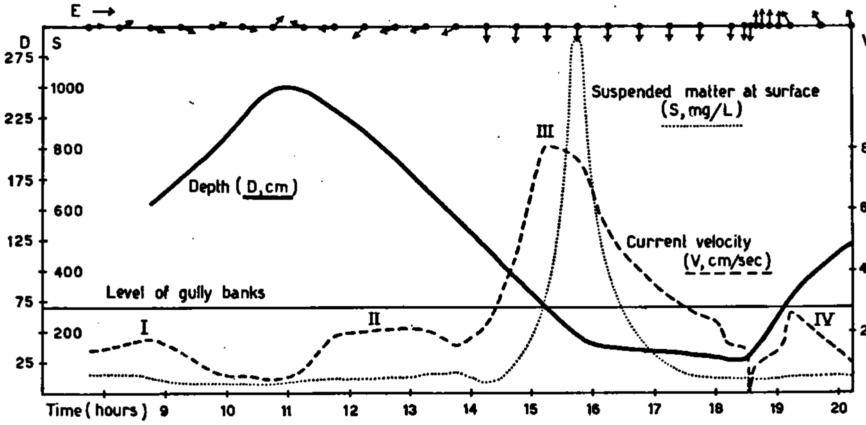


Fig. 8. Current sequence in ebb gully, South of Nes, Ameland, 6-VIII-1948. — E: directions of current relatively to direction of gully. This latter was transverse to the average direction of the coast in the North, as well as to that of the nearest major channel in the South. — I and II: maxima of current velocities during submergence of flats; III and IV: maxima of current velocities in gully during emergence of flats — (see also VAN STRAATEN, 1951b). —
It is seen in this figure that the ebb current attains its highest velocities at the moment that the water sinks below the level of the gully banks, in correspondence with the sudden decrease of the area of cross section of the flowing water. No such high velocities were measured during the first stages of the flood current, owing to the smaller inclination of the water surface in the gully during the rising tide. Since the inflowing water moved against the last quantities of the ebb water, coming down the upper course of the gully, the water level was raised quickly and the banks became submerged in a very short time.

courses of gullies which flow off in the opposite direction. The same thing is found with respect to the channels. The phenomenon is caused by the circumstance that, at certain stages during the submergence of the flats, the currents (both of ebb and of flood tides) may flow upwards in one gully, continue over the divide and flow downwards in the next.

## E. Channels

The term channel is used in this paper for those water courses which, at low tides, have depths of at least one meter. The distinction between channels and gullies is not merely a matter of dimensions. Although, of course, all transitions between the two types are encountered, an essential difference is found to exist between the major channels and the small gullies, both in hydrological and in morphological respects.

An example of the current sequence in a comparatively straight part of a normal channel is given in Fig. 9. It is seen that in this case the ebb and

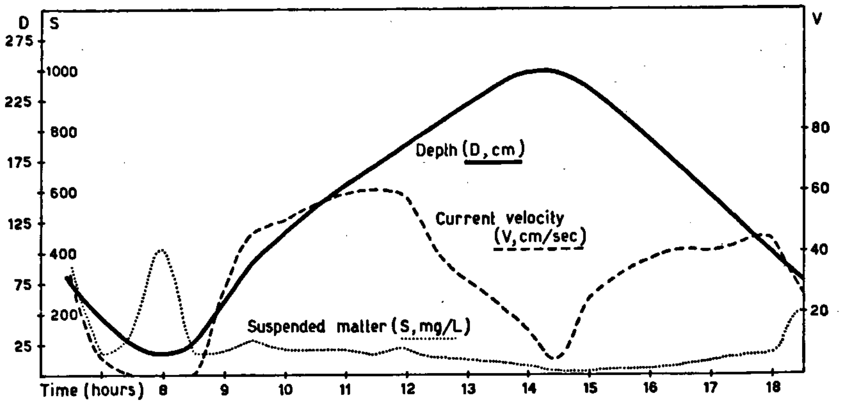


Fig. 9. Current sequence (on side) of tidal channel, South of Nes, Ameland, 9-IX-1948.

flood currents differ only little in strength. The conditions are often complicated, however, by the phenomenon of the "tidal wedges", or separate ebb and flood channels (VAN VEEN, 1950, VAN STRAATEN, 1950a, 1953). The origin of these tidal wedges is due to the principle of inertia, affecting the flowing water masses (Fig. 10). At the higher stages of the tides, the currents are not limited to the channels themselves, and the surface water need not follow any primary bends of the channels that may be present, but may continue straight ahead. It scours out tidal wedges at these localities, at the downstream ends of which the eroded material is accumulated. The longitudinal

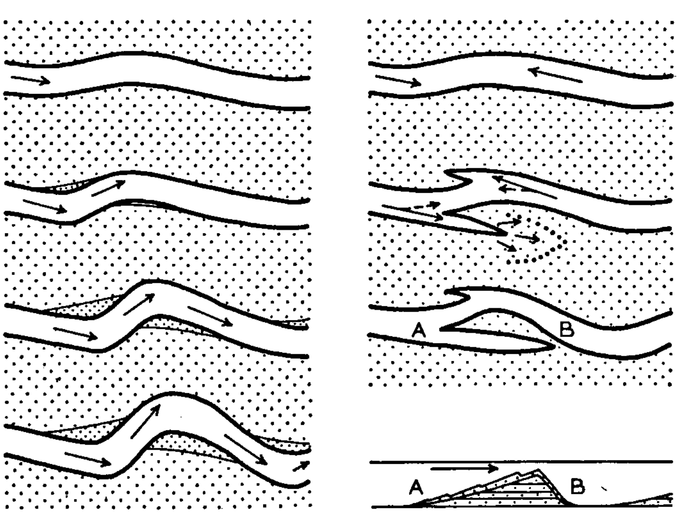


Fig. 10. Successive stages of the development of meanders (left) and of tidal wedges (right). A—B: vertical section through tidal wedge.

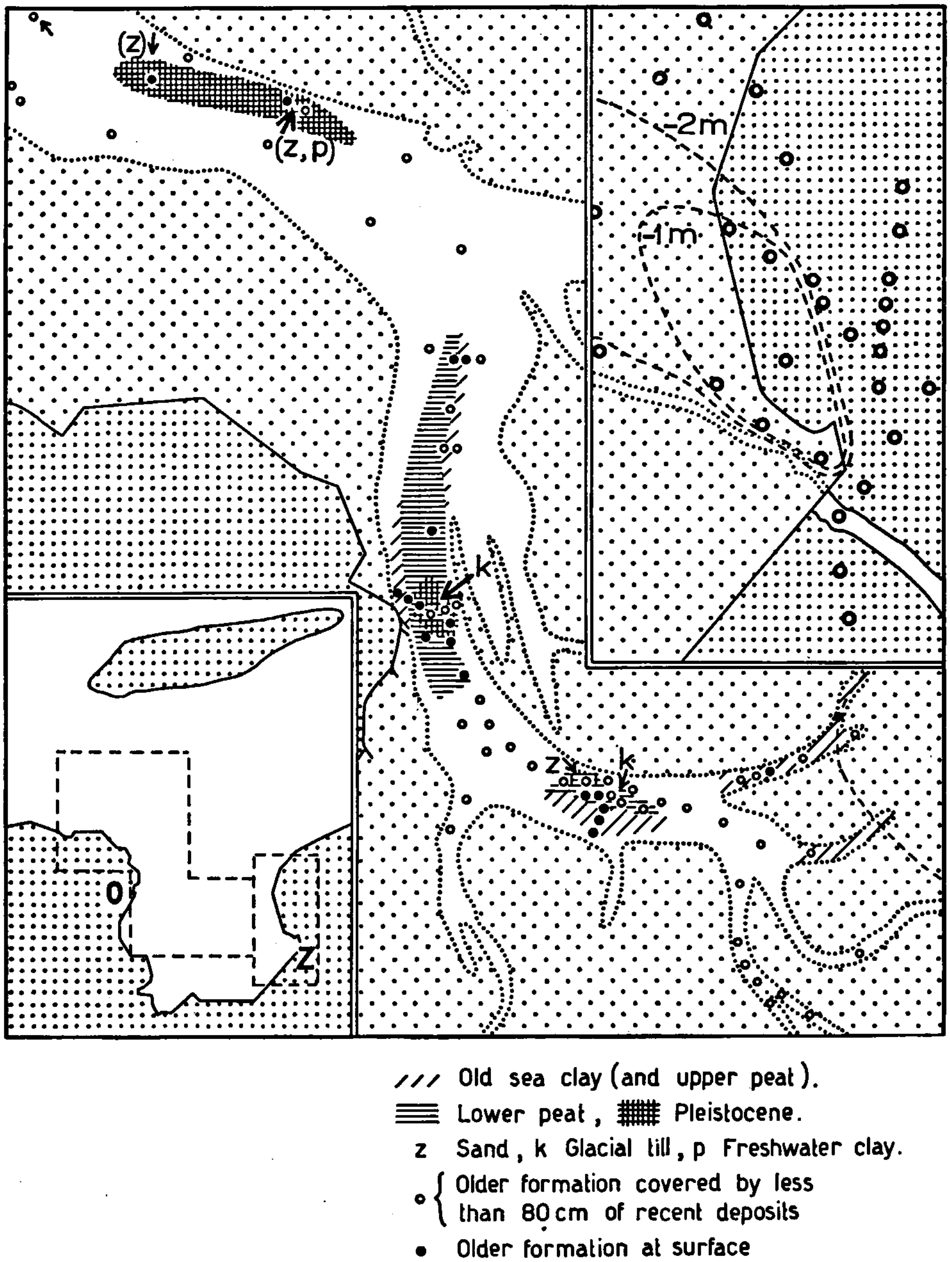


Fig. 11. Outcrops of older deposits in the Lauwerszee area.

section of a tidal wedge may be compared to the cross section of a transverse megaripple (i.e. a transverse current ripple of very large dimensions, see VAN STRAATEN (1953)). In contradistinction to the latter, the tidal wedge structures may be of fairly constant position, since the sand, which is deposited on the lee sides, is removed again by the alternating currents coming from the opposite directions. The curvature of the channel, bending round the tidal wedge, may become augmented in the manner of normal meanders. The majority of the tidal wedges in the Wadden Sea and in the estuaries is formed by the flood currents.

The depth of the channels is dependent on several factors: volumes of water flowing through, width, scour along the concave sides of bends, confluences with other channels, composition of the floor etc. (VAN STRAATEN, 1952).

The floor of the channels is mostly composed of recent sediments, formed in the channel environment itself. In a few places, however, erosion by the tidal currents has uncovered older deposits. Fig. 11 gives the distribution of these places in the Lauwerszee and the adjacent area.

The cross sections of the channels are normally well rounded or slightly V-shaped. Such is the case when the channels are cut into loose sands and muds which have recently been deposited. When the vertical erosion in the channels reaches the surface of a bed which is more resistant to erosion, e.g. old clays, peat or glacial till, further downcutting takes place very slowly. The main effect of the erosion then becomes directed sideways and the less coherent covering sediments are removed until the resistant substratum is laid bare over large surfaces. In these cases the channel floors are often remarkably flat.

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## II. GENERAL LITHOLOGY AND GRAIN SIZE ANALYSES

### A. Gravels

1. *Hard rock gravels.* — "True" gravels, with pebbles of hard rocks, are extremely rare in the Holocene marine deposits of the Netherlands. They are found on the floor of tidal channels, where glacial till has been eroded by the currents and they must be considered as outwash residues. The finer elements of the till have been removed, and the pebbles are embedded in a matrix of newly deposited sand, with occasional shells, spines of echinids etc. The pebbles are usually very poorly rounded and may be incrusted by Bryozoans. Examples of such deposits were encountered in the Lauwerszee, E. of Oostmahorn (O. on map Fig. 11).

Hard rock gravels may also form a constituent of marsh deposits, e.g. in the innermost part of the deep indentation of the former Lauwerszee at Zuidhorn (Prov. of Groningen). At this place the marshes border an upland shore composed of till.

2. *Gravels of mud and clay.* [1] — "Gravels" composed of mud- or clay pebbles are of great abundance. The mud pebbles are, as a rule, of distinctly flattened shapes in consequence of the original deposition of mud in thin laminae, alternating with sand. The gravels, formed out of homogeneous clays, like the brackish water clays of the Atlantic stage (the so-called Old Sea Clay, s.s.) may show more rounded, sub-globular elements. The cobbles and boulders of recent marsh clays, which are often seen at the base of marsh cliffs, are also little flattened, although these deposits may be finely laminated. The are held together by the roots of marsh plants.

Two main processes are responsible for the production of mud and clay pebbles: undercutting or underwashing and cracking. Where channels cut through the strata, pieces of mud and clay may be worked loose by the washing out of the subjacent sand. Cracking of mud is observed in marsh environments and on the adjacent high parts of tidal flats, as well as on the banks of gullies and channels. Whereas the fissuring on marshes is evidently due to the drying out of the sediment in the atmosphere, this is not always certain in the case of the cracks which are formed near the low tide level. Similar fissures are namely found in recently deposited mud on the floors of channels, which are permanently covered by water.

The beds, composed of mud or clay gravels are usually only of slight thickness, not more than a few centimeters, at the most a few decimeters.

3. *Isolated cobbles and boulders of peat* are not at all rare in the marine deposits. They may attain dimensions of several meters. Small pebbles and granules are also found. The author does not know, however, of cases

[1] HAENTZSCHEL (1936), RICHTER (1926).

where these elements are concentrated in such a degree as to form gravels. Finely divided peat detritus, on the other hand, is often washed together in separate laminae.

4. *Gravels of iron hydroxides.* [1] — In a few localities one may encounter gravels which are composed chiefly of small concretions of iron hydroxides. They form a thin cover on small wave smoothed beachlets at the foot of marsh cliffs. Examples were found N.W. of Zoutkamp (Lauwerszee) and, also, N.W. of Le Teich in the Basin of Arcachon (France). The iron hydroxide elements are only a few millimeters in diameter. They have been formed in the marsh deposits, mainly around plant roots, and are concentrated on the beaches after erosion of the marshes. During strong gales this material may be swept up by the waves, to be spread out over the front parts of the marshes. New marsh deposits may be formed in this way, in which laminae of sand and clay alternate with laminae of rolled and recemented iron concretions.

5. *Shell beds* (Krause, 1950; Richter, 1922 *et al.*) can be considered as a last type of gravels. Their malacological composition may show considerable variations. It is often observed, in the shell beds on the floor of minor gullies dissecting the tidal flats, that the bulk of the material consists of valves of only one species, e.g. *Mytilus edulis, Mya arenaria,* or *Scrobicularia plana,* in correspondance with the mollusc composition of the traversed area. Shell beds at the base of marsh cliffs or those incorporated in the front parts of the marsh deposits themselves, are frequently composed exclusively of a single species, e.g. *Littorina littorea* or *Hydrobia ulvae.* In these cases the concentration is chiefly due to the sorting effect of waves.

The shell deposits on the floor of large channels show mostly a much more diversified character and give a better picture of the average composition of the mollusc fauna of the whole Wadden Sea or estuarine areas.

The largest concentrations of mollusc shells are found on the floors of the tidal inlets and of the neighbouring channels. Important accumulations may occur also on the banks of these waters, where the shells have been thrown up by the waves (e.g. on the Vrijheidsplaat, South of the western end of the island Ameland) (cf. Juengst, 1942).

The shell beds, formed on the bottom of gullies and channels, may attain considerable lateral dimensions, owing to the migration of these water courses.

Not all shell beds are the product of sorting and concentration in water. The so-called *Hydrobia*-beds seem to be formed in the mass of the sediment itself, under the influence of the burrowing action of bottom dwelling animals (mainly *Arenicola marina* L) (see p. 73).

### B. Sands

By far the most important constituent of the Wadden Sea deposits as well as of the estuarine sediments is sand. It is the main sediment in the channels and on the tidal flats. Comparatively fine sands, moreover, make up most of the marsh deposits. The concentration of sand in the channels is due to the currents. On the flats it is the result both of currents and of wave action.

[1] Rousseau (1934), Schaefer (1948).

All transitions occur between sands and muds. In the channels and on the lower parts of the tidal flats the mixtures are mostly composed of fine laminae of rather pure sands and of muds. On the higher parts of the flats the two materials are usually more homogeneously intermixed, owing to the work of burrowing organisms.

### C. Muds and clays

The term mud is used in this paper to denote the soft, lutite-rich deposits, with comparatively high contents of water. Firm sediment, poorer in water, is called clay. Mud may pass over into clay by compaction due to draining (e.g. in marshes), or as the result of loading with new sediments. No sharp limit between the two terms can be given. The fine material of marshes is referred to as clay. Fresh deposits in salt pans and in marsh creeks, which are still soft, are called muds. On the tidal flats most of the (recent) fine sediments are in the state of "mud".

Although in wet, or even in half dried sections of muds and clays few or no sand grains are visible, it may be that granulometrical analyses or thin sections reveal contents of more than 50 % of material with grain sizes larger than 16 $\mu$.

Muddy sediments are encountered mainly on the floors and banks of gullies and channels and along the marsh edges. Channel bottom sediments, rich in mud, are formed especially in those areas where the tidal flats themselves are also of pronounced muddy composition, e.g. in the inner parts of the Lauwerszee- and Dollard embayments. Minor accumulations of mud are generally present around mussel beds. They are chiefly deposited in the shape of faecal pellets and pseudofaeces, produced by the mussels. Since these pellets are very soft, it is only in the uppermost few millimeters of the muds that they are still recognizable. Immediately below they are already compressed to a homogeneous mass. In this respect they differ considerably from the pellets of *Cardium edule,* which may still be recognised in sands and muds at many meters below the surface.

### D. Grain size analyses

Much work has been done on the grain size distribution of the Dutch marine sediments, by Doeglas, Koning, Maschhaupt, de Vries, Wensink and Bakker, Zuur, and many others. Numerous data, which are not yet published, have been collected by the Waterstaat, the Institute of the Zuiderzee Works at Kampen, the Institute of Land Reclamation at Baflo, the Agricultural Institute at Groningen, te Geological Survey at Haarlem, the Soil Survey Institute at Wageningen, the Marine Zoological Station at Den Helder etc. In this paper only the main conclusions, applying especially to the Wadden Sea, will be mentioned. For more details the reader is referred to the original publications.

1. *The typical Wadden sands are of relatively fine grain sizes.* The grains larger than 500 $\mu$ constitute mostly less than 1 % of the material (Fig. 12). Exceptions are found on the floor of large channels, where strong tidal currents sweep to and fro, washing the finer elements away. In other cases such coarse sands are obviously the product of reworking of older, pleistocene sands (Dokkumer Diep, Vaarwater van Oostmahorn, etc.).

2. *The Wadden sands contain usually a certain amount of material finer than 16 μ.* It is impossible to get a good understanding of the grain size distribution of the Wadden deposits without considering their structures. On the floors and the banks of channels and over great surfaces of the tidal flats fine laminations are present, of mud and sand. The laminae may vary in thickness, the mud laminae ranging from 1 mm (or less) to a few centimeters (usually not more than a few millimeters); the sand having thicknesses from 1 millimeter (or less) up to many meters. The mud has been laid down at the turn of the tides, or during other stages of quiet water conditions. The sands are the product of currents, and, on the flats, of waves.

When the sand laminae are considered separately, they show often good sorting (cf. Plates 10 and 11), although greatly differing among each other in average grain size.

Apart from the alternation with mud laminae, the sand laminae themselves may also contain a certain amount of clayey material. This is the result of the admixture of faecal pellets, composed of mud, but behaving granulometrically as sand grains. They are found especially in the deposits of the tidal flats proper, which are inhabited by enormous numbers of bottom dwelling animals. Among these organisms *Cardium edule* should be mentioned in the first place, both on account of its abundance and of the compactness and the durability of its pellets.

3. *The sands of the Wadden Sea show a decrease in coarseness from the tidal inlets inwards* (Fig. 12). This is notably so in the case of the channel deposits, but applies also to those of the flats and the salt marshes. A difference exists, moreover, between the sediments of the marshes and the adjacent tidal flats along the barrier islands on the one hand and those along the mainland shores on the other, the latter being, in the average, distinctly finer. Another trend of decreasing coarseness is observed along the axis of the Wadden Sea, from the wide, western part towards the narrow part South of the island Ameland and Schiermonnikoog (cf. KONING).

The decrease in grain size from the tidal inlets shoreward is caused by the diminishing of the current velocities in this direction. The Wadden sands can be regarded as being derived from the sands along the neighbouring North Sea coasts. This conclusion is corroborated by the mineralogical analyses (p. 27).

4. *The sands of the outer deltas are finer than those in the inlets,* but show close analogies to the sands elsewhere along the North Sea shore. It is, however, very unlikely that these materials have been transported only in a lateral sense, along the coasts. For the German Wadden Sea, North of the river Elbe, DECHEND showed that the composition of the sands on the outer deltas pointed to an ultimate deposition by ebb currents, coming out of the tidal inlets. The bulk of the material of the Dutch outer deltas may have been derived originally from the shore and offshore of the North Sea, but it is probably laid down on these deltas only after a more or less prolonged transport to and fro in the inlets and in the adjoining parts of the Wadden Sea.

5. *The Wadden Sea sands show, in general, a decrease in coarseness from below upwards.* The channel sands tend to be coarser than those on the flats, and the latter are normally coarser than the sands of the marsh

deposits. A diminishing in grain size from below upwards is noted also in the channel sediments themselves (cf. e.g. WENSINK and BAKKER, 1951). The distribution of the grain sizes in the different parts of the tidal flats is usually more complicated. On the low lying sand flats and on the high tidal flats, where the sedimentation is more or less of the slow, vertical kind, the sediment may be comparatively coarse. In the muddy areas, characterized by important reworking of the deposits by shifting gullies and channels, the

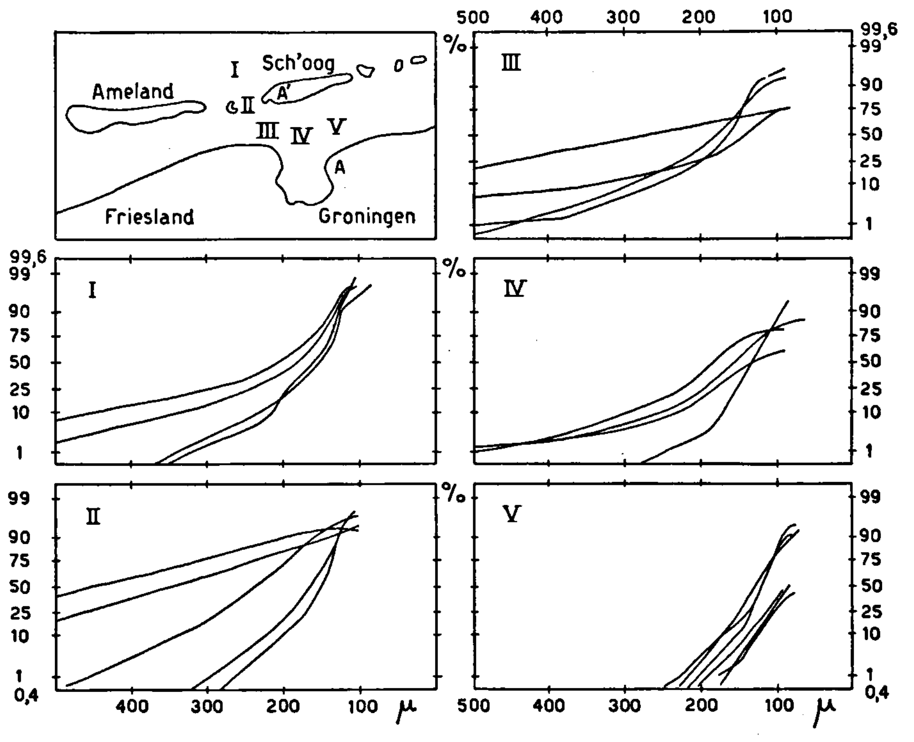


Fig. 12. Cumulative curves of grain size distribution of channel floor sediments (after DOEGLAS). The division of the ordinate, giving the percentages, is based on the Gauss integral. Typical Gauss curves of grain size distributions are therefore presented as straight lines. — I. Outer delta; II: Tidal inlet; III—V: Channel floors between tidal inlet and "wantij".

sand layers are mostly distinctly finer. The sands on the western and southern banks of large channels, exposed to the waves of the prevailing and dominating winds, may again be very coarse. The same is found for beach sands, at the foot of exposed marsh cliffs.

The sand laminae of the marsh deposits show as a rule a decrease in grain size from the marsh ridges and from the creek-built levees inward, and, in each separate section, from below upwards.

6. *The material which has mainly been transported in suspension shows a remarkably uniform grain size distribution along the whole length of the Dutch coast* (DOEGLAS, FAVEJEE, HISSINK, ZUUR) (Table 1). These fractions are mostly found on marshes, but make up also a part of the mud of the

TABLE 1. Ratios of subfractions < 25 μ, with regard to the fraction < 0,5 μ (after FAVEJEE, 1951).

| < 0,5 μ | 0,5—2 μ | 2—5 μ | 5—10 μ | 10—25 μ |
|---|---|---|---|---|
| 1 | 0,3—0,4 | 0,2—0,3 | 0,2— 0,3 | 0,2— 0,5 |

tidal flats and the channel floors (mixed with smaller or larger quantities of sand of bed load origin). According to DOEGLAS this suspension material, brought to the Wadden Sea area via the North Sea, is originally supplied by rivers.

7. *The deposits of the tidal flats,* at least those in front of the marshes, *may show a variation in lutite content in relation to the season* (KAMPS, 1950). The smallest amounts of clay material are observed just after periods of rough weather.

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## III. MINERALOGICAL ANALYSES

### A. Sand fractions

The sands of the Wadden Sea are chiefly composed of well rounded quartz grains. The remaining consists of grains of calcium carbonate and of small amounts of other minerals: micas, felspars and glauconite, the heavy minerals, etc. The micas, felspars and glauconite are in all probability exclusively of detrital origin. The calcium carbonate is mainly derived from skeletons of marine calcareous organisms. No analyses have been made of the samples in their original state, i.e. without preliminary treatments which acids, nor have countings been executed of the light mineral fractions.

The heavy mineral residues have been investigated by BAAK (1936) and CROMMELIN (1940). They consist of opaque minerals, garnet, epidote, hornblende, zircon and of minor quantities of saussurite, staurolite, tourmaline, and other minerals [1]. CROMMELIN comments on the relation which is found between the mineral composition and the grain size distribution of the sediment in the area South of the islands Schiermonnikoog and Rottum. The fine sands along the mainland coast are comparatively rich in opaque minerals, epidote and zircon. The coarser sands in the North contain more grains of garnet (and a little more of hornblende) (Fig. 13).

The same changes of composition dependent on the grain sizes was observed by this author in the estuary of the Scheldt, where the fine marsh sediments are much richer in zircon than the coarse grained channel floor deposits, but poorer in garnet. [2]

The character of these relations is nevertheless only of local significance. DECHEND (1950) states that in the Wadden Sea North of the mouth of the river Elbe, an enrichment of garnet and *zircon* is found in the coarse sands and of epidote and *hornblende* in the finer deposits.

The composition of the Wadden sands, investigated by CROMMELIN shows a close analogy to that of the adjacent parts of the North Sea floor. The sands of the rivers Eems, Weser and Elbe, on the other hand, have a markedly different composition, so that it is obvious that these streams contribute little or nothing to the supply of sand for the (eastern regions of the) Dutch Wadden Sea (CROMMELIN und MAASKANT, 1940). The material has apparently been brought in from the North Sea, via the tidal inlets, by the currents of the flood. The same conclusion was reached with regard to the sands in the estuaries of the provinces Holland and Zealand (BAAK, 1936, CROMMELIN, 1951, VAN VEEN, 1936).

[1] The Wadden sands belong to the A-province of EDELMAN, with slight admixtures from BAAK's H-province.

[2] See also the relation between mineral composition and grain size found in beach placers (p. 70) (CROMMELIN en SLOTBOOM, DE VRIES et al.).

### B. Silt fractions

The silt fractions (grain limits 10 or 16 and 50 $\mu$) of the Wadden deposits consist of the following elements: quartz, felspars (orthoclase, microcline and plagioclase, the latter generally rich in soda), micas (muscovite, biotite, and chlorites), calcium carbonate, dolomite, siderite, glauconite, opal, glass fragments, rock fragments (CROMMELIN, 1943, 1947), iron sulphides or iron hydroxides (depending on the state of aeration of the sediment) and organic material.

The quartz percentages decrease, within the boundaries of the silt fractions, with decrease of the considered grain size. The fine grains are nearly always angular, as opposed to the better rounded character of the grains in the coarser silt fractions. The quantities of the micas augment rapidly in the direction of the finer fractions (Fig. 14). Dolomite is present in tiny, separate rhombohedra, or in small aggregates. According to CROMMELIN it may be largely of authigenic formation. Opal is found in the shape of skeleton remains of silica organisms (mainly diatoms, spicules of sponges and radiolarians) and as silica-elements of primary or replacement origin from higher plants (notable reeds). Among the rock fragments small splitters of flint abound.

Iron compounds and organic elements were not studied by CROMMELIN, who treated his samples with $H_2O_2$ and HCl. The most important iron mineral is pyrite. It is authigenic, and is formed under anaerobic conditions in the sediments below the ground water table. More details on the distribution of the iron as well as of the carbonates and the organic constituents, are given in Chapters IV, V and VI.

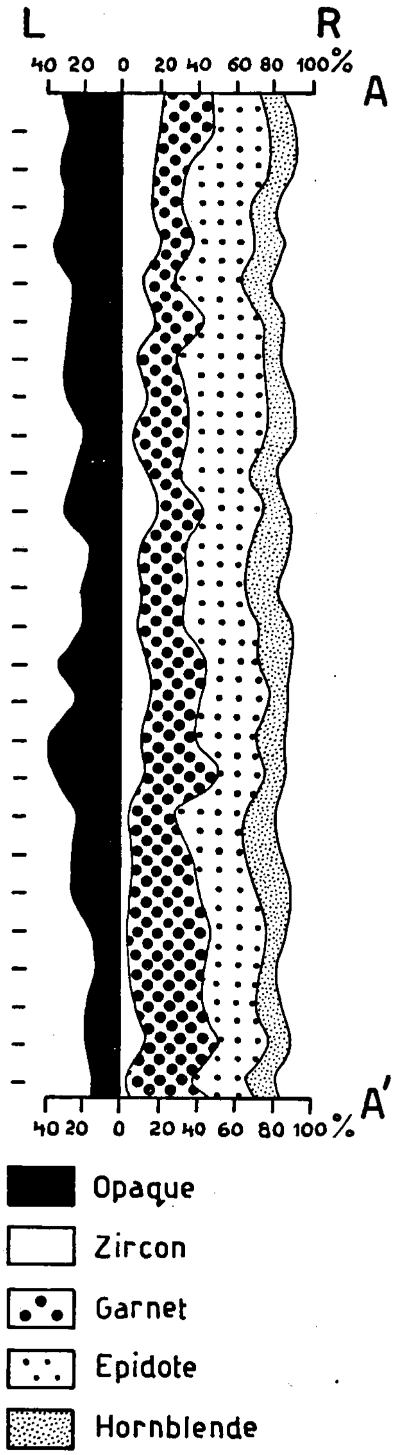


Fig. 13. Heavy mineral composition of Wadden sands. Samples taken along line A—A' of Fig. 11 (coast of Groningen to marsh deposits of Schiermonnikoog), after CROMMELIN, 1940, p. 352. — L: opaque minerals in percentages of the whole residue; R: mutual percentage proportions of transparent minerals.

One of the conclusions, following from the data of CROMMELIN, is that the silt fractions, like the sand fractions, have been supplied, at least for the greater part, out of the North Sea. Direct fluvial supply can have been only of subordinate importance. This applies both to the Wadden Sea silts and to those of the estuary of the Scheldt.

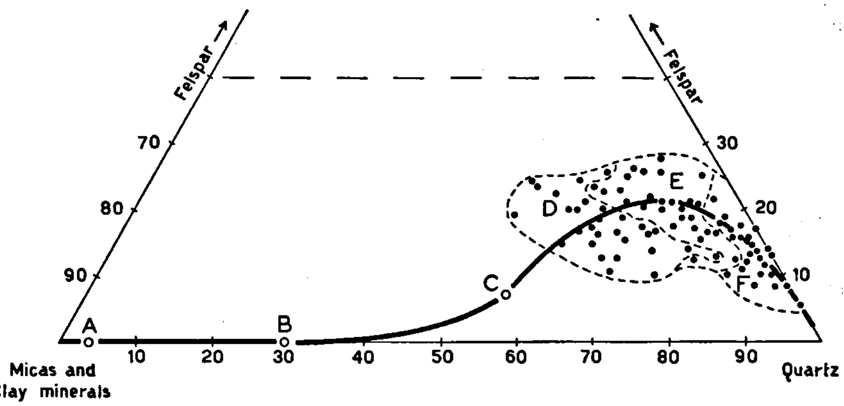


Fig. 14. Relation of percentages of micas and clay minerals, felspar and quartz, in the silts and clays of the Wadden Sea deposits, after CROMMELIN (1943) and FAVEJEE (1951). — A: < 0,5 μ; B: 0,5—2 μ; C: 2—10 μ; D: 10—25 μ; E: 25—50 μ; F: > 50 μ.

## C. Clay fractions

Mineralogical investigations of the clay material (finer than 10 or 16 μ) of Dutch marine sediments have been carried out by FAVEJEE (1951) and by VAN DER MAREL (1950a, b). No data are available, however, concerning the totad composition of the samples. FAVEJEE prepared his samples with HCl and $H_2O_2$; VAN DER MAREL limited his researches to the study of special constituents. Both iron and organic matter are present in considerable quantities in the clay fractions (cf. VAN DER SPEK (1948), VERWEY (1952), and Ch. IV and V).

The bulk of the clay material as analyzed by FAVEJEE is made up of quartz and illite, the first decreasing, the latter increasing in frequency with diminishing of the particle sizes under consideration. The rest is composed of kaolinite, montmorillonite, carbonates, muscovite, felspars, iron compounds and organic material. Quantitative data are given in Fig. 14 and in Table 2.

No significant distinction in mineral composition can be made between the muds from the Wadden Sea, from the Eastern and Western Scheldt estuaries, the North Sea floor and the suspended material in the tidal inlets. It seems to be highly uniform along the whole Dutch coast. The same result was obtained by the grain size analyses (cf. p. 24). A notable difference exists, on the other hand, between the marine muds and those from river water. The latter are poorer in montmorillonite and show strongly varying percentages of kaolinite and quartz.

TABLE 2. Mineralogical composition of the subfractions $< 10\,\mu$ of different kinds of mud (from FAVEJEE, 1951, p. 140). — I: New Wadden mud from land reclamation works on coast of Groningen; II: Mud from sea water in tidal inlets of Wadden Sea; III: Samples from North Sea floor, S. and S.E. of Doggersbank and in Deutsche Bucht; IV: Mud from river water, a) Eems, b) Weser, c) Elbe, d) Rhine; V: Old clay banks in Wadden Sea; VI: Mud from Wadden Sea, a) Mussel beds, b) Shelly clay, c) Mussel pellets; VII: Mud from Wantij South of Schiermonnikoog; VIII: Mud from salt marshes in estuaries of Zealand.

| | Fraction $< 0,5\,\mu$ | | | | Fraction $0,5$—$2\,\mu$ | | | | Fraction $2$—$10\,\mu$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | illite | kaol. | montm. | quartz | illite + musc. | kaol. | montm. | quartz | illite + musc. | kaol. | montm. | quartz | felspar |
| I | ± 80 | 5—10 | ± 10 | ± 4 | 50—60 | 5—10 | 5—10 | ± 30 | | | | | |
| VIa | 80—90 | 5—10 | ± 5 | ± 4 | | | | | | | | | |
| VIb | 80—90 | ± 5 | 5—10 | 2—4 | 50—60 | ± 10 | 5—10 | 25—30 | ± 30 | ± 5 | ± 5 | 50—60 | ±5 |
| VIc | 80—90 | ± 5 | 3—5 | ± 6 | ± 60 | ± 5 | ± 5 | ± 30 | | | | | |
| VII | ± 80 | 5—10 | 5—10 | ± 6 | ± 60 | 5—10 | ± 5 | ± 30 | | | | | |
| V | ± 80 | 5—10 | 5—10 | ± 4 | ± 60 | 5—10 | ± 5 | ± 25 | ± 30 | 5—10 | ± 5 | ± 50 | 5—10 |
| II | 80—90 | 5—10 | ± 5 | 4—6 | ± 60 | 5—10 | ± 5 | ± 30 | 20—30 | ± 5 | ± 3 | ± 60 | 5—10 |
| III | 80—90 | 5—10 | 3—5 | ± 2 | ± 50 | ± 15 | 5—10 | ± 30 | ± 20 | ± 10 | ± 5 | ± 50 | ± 10 |
| VIII | 80—90 | ± 5 | 5—10 | 2—4 | ± 60 | ± 10 | 5—10 | ± 25 | | | | | |
| | | | | | | | | | Fraction $2$—$5\,\mu$ | | | | |
| IVa | very much | — | < 3 | very little | much | very little | < 3 | rather much | rather much | very little | < 3 | much | very little |
| IVb | ± 90 | 3—5 | < 3 | ± 5 | ± 50 | ± 5 | ± 5 | 30—40 | ± 30 | 3—5 | < 3 | ± 60 | ± 5 |
| IVc | 70—80 | 5—10 | < 3 | ± 15 | | | | | | | | | |
| IVd | 80—90 | ± 10 | < 3 | ± 5 | 40—50 | ± 10 | ± 5 | ± 40 | | | | | |

## D. Comparison of the fractions

When the mineral compositions of the sand-, the silt- and the clay fractions are compared with each other, it is seen that, with diminishing of the grain size, the quartz shows a continuous decrease in percentages, that the sum of the micas and the clay minerals increase in the same sense, and that the carbonates (cf. Chapter VI) and the felspars have a maximum distribution in the finest silt- and in the coarsest clay fractions. It is thought that the general trend of these percentage variations may be of universal significance. They can easily be explained as the result of the original grain sizes of the minerals and of the difference in resistance to wear and chemical decomposition. Quartz is mainly derived from crystalline rocks (or their weathering products), in which it is predominantly of sand grain sizes. Owing to its great hardness and extremely poor cleavage, as well as to its chemical stability, these grains are very little influenced by wear and solution, so that only negligible amounts of finer material are produced. Felspars and lime, although formed primarily in crystals of about the same dimensions as quartz, or even larger (carbonates), possess much more pronounced cleavage and are less hard. Their maximum distribution lies, accordingly, in the finer fractions. Micas and clays minerals, which are still softer and show extreme cleavage, form the chief constituents of the very finest material. The clay minerals are, moreover, originally formed in flakes of the most minute dimensions.

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## IV. ORGANIC CONTENT

### A. The origin of the organic material

1. *Older deposits as a source of organic material.* The tidal channels of the Wadden Sea and of the estuaries are incised, at many places, into older deposits of the subsoil, such as pleistocene sands, till and peat beds (see Fig. 11). These latter have mostly been formed under subaerial or lacustrine conditions. A considerable part, often even the major part of the organic matter which is found in the Wadden deposits. has been derived by erosion from such old peat beds and its origin has nothing to do with environmental conditions of the Wadden Sea or the estuaries themselves.

The particles composing this washed peat detritus, are mostly rather coarse, much coarser than the grains of normal Wadden sands. This circumstance, together with the small specific weight leads often to their concentration in separate laminae. It is not unusual to find finely stratified deposits, in which each lamina consists of sand at the base, mud (or clay) in the middle and a thin covering of peat detritus at the top. In ripple marked sediments peat particles may be washed together in the ripple troughs. In the case of current ripples their concentration takes place mainly on the lower sides of the lee slopes of the ripples. The organic particles are often associated with other coarse elements of low settling velocity, like the tests of foraminifera, spines of echinids (*Echinocardium cordatum*), valves of ostracods etc.

2. *Newly provided material.* This comes from three main sources: the land, the North Sea and the Wadden Sea (or estuarine) environments themselves. The material which is derived from the land is partly washed in, by rivers and brooks, partly blown in by the winds. It consists of leaves, branches of trees, seeds, pollen grains etc. The quantities supplied in this way are however very small.

A much greater part of this organic matter is originally brought in from the North Sea, via the tidal inlets. It forms, according to VERWEY (1952) the bulk of the food for the mussels and cockles (and other animals) in the Wadden Sea. This conclusion was reached after a study of the biological relations and corresponds completely to the results of the granulometioal, mineralogical and micropaleontological investigations of the Wadden sediments. The environment of the Wadden Sea and of the estuaries can truly be considered as the dump of all the finer materials which are transported in the coastal zones of the North Sea.

A last part of the basic organic materials is formed by photosynthesis of plants and microflora in the Wadden Sea environment itself. Producers are: the phytoplankton, the flora of the tidal flats (plants of *Zostera*, algae such as *Ulva, Enteromorpha, Chaetomorpha,* benthonic diatoms etc.) and the halophytic vegetation on the salt marshes. The quantities generated by the latter are quite considerable, but their influence remains chiefly restricted to the marsh deposits. They do not seem to play an important part in the general cycle of biochemical processes in the Wadden Sea area as a whole. The amount of organic matter, formed by *Zostera* is, nowadays, practically negligible. Before these plants were attacked by the *Zostera* disease, shortly after 1930, it must have been much greater. Apart from their role in the supply of food for animals, they contributed directly to the formation of sediment. Great masses of dead *Zostera* plants were washed shoreward and were accumulated at the foot of marsh cliffs or on the marsh surface (cf. e.g. FEEKES, 1950). Yet, on the Dutch tidal flats *Zostera* probably never flourished as it does at the present day in the basin of Arcachon (France), where all mud flats, with the exception of those in the innermost parts of the bay, have the aspect of veritable meadows (Pl. 4, fig. 8). Their quantities are so great that locally (e.g. near Le Teich) thick layers of marine peat have been formed by the accumulation of the dead leaves.

Although the suspended material in the water, flowing in from the North Sea, and the vegetation of the Wadden Sea area itself, thus constitute the primary sources of much the organic matter, these substances are used and re-used by all kinds of Wadden Sea organisms, their chemical composition accordingly changing all the time. The main part of the organic matter, which is finally embedded in the Wadden sediments, can therefore probably best be divided, with regard to its immediate origin, into the following groups: (a) reworked material from old peat beds; (b) material supplied by the Wadden Sea animals and (c) material from diatoms and other organisms.

### B. The decomposition of the organic material

It is a striking fact that, notwithstanding the profusion of fishes, birds, crabs, etc. in the waters of the Wadden Sea, these animals become, to say the least, extremely rarely fossilized as a whole. The writer does not know of a single example. What is left of the higher animals amounts only to occasional vertebrae or teeth of fishes. Of crabs only the end parts of the claws are sometimes found. The disintegration of the remains of these larger animals is to a very small extent the result of purely inorganic effects of mechanical (waves and currents) and chemical character. The main destruction is due to the work of organisms, in first instance that of scavengers of all kinds (crabs, small crustaceans, worms, protozoans etc.), Decomposition of organic material takes place furthermore by bacterial activity. The processes are most rapid in the upper, aerobic layers of the sediment (mostly not more than a few centimeters thick) and on the sediment surface.

Apart from the purely chemical reactions, oxidation of organic substance takes place in general (according to ZOBELL) by direct bacterial activity and by enzymes which are produced by bacteria and which may continue their work long after the death of the bacteria themselves. These processes cause the liberation of $CO_2$ and $H_2O$. In the underlying anaerobic zone of the sediments decomposition is still continued, although at a lower rate, by sulphate reducers and other bacteria and their enzymes, whereby $CH_4$, $H_2$, $H_2S$ and a small amount of $CO_2$ are produced. The remaining parts of the organic matter become more and more resistant to further decomposition and the numbers of living bacteria, found in these sediments, strongly decrease with increase of depth. The result is that the organic content of the deposits normally diminishes downward. This relation is also seen in the Wadden sediments (see Fig. 15). The decrease is not very gradual, in connection with differences in granular composition of the various layers (see next paragraph) and as a result of the rather accidental supply of reworked peat detritus. In

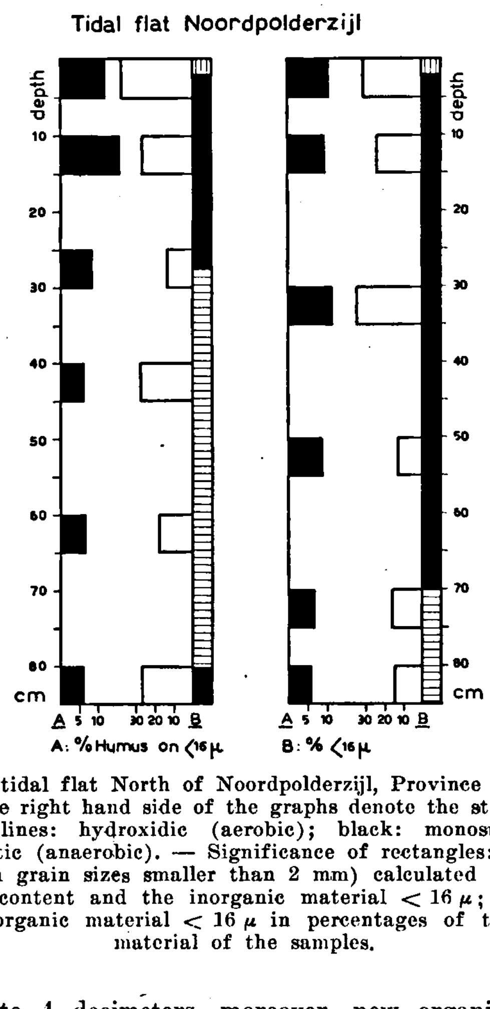


Fig. 15. Cores from tidal flat North of Noordpolderzijl, Province of Groningen. — The narrow columns at the right hand side of the graphs denote the state of the iron in the sediments: vertical lines: hydroxidic (aerobic); black: monosulphuric (anaerobic); horizontal lines: pyritic (anaerobic). — Significance of rectangles: A, black rectangles: organic content (with grain sizes smaller than 2 mm) calculated as percentages of the sum of the organic content and the inorganic material $< 16\,\mu$; B, white rectangles: quantities of the inorganic material $< 16\,\mu$ in percentages of the whole (inorganic) material of the samples.

the uppermost 2 to 4 decimeters, moreover, new organic material is constantly added to the sediment by the work of burrowing animals, and by the remains of these animals themselves after their death.

Somewhat different circumstances are found in the marsh deposits, which are formed above the high water level and which are for the greater part in aerobic state. When such sediments attain a certain thickness, the inundations during the highest tides become less and less frequent and eventually they may come to lie altogether outside the marine influence. In the first stages of the ensuing continental conditions, the organic content may decdease rapidly, but the diminishing soon becomes progressively retarded owing to the new supply of organic substance by the roots of plants. Sometimes the organic content shows even a small rise (e.g. in the dyked lands of the Dollard area, see MASCHHAUPT, 1948).

### C. Relation between grain size and organic content

It was shown above that the peat detritus is often concentrated in separate laminae, chiefly owing to its small specific weight. In most cases the sedimentation of the fine materials even takes place after a great part or all of the mud (or clay) material has been deposited. This circumstance and the fact that the newly supplied organic substance, when not directly in a very finely divided state, is soon disintegrated into such fine elements, accounts for the strong increase in organic content with decreasing grain size of the sediments (see e.g. Fig. 16). Similar conditions were found in

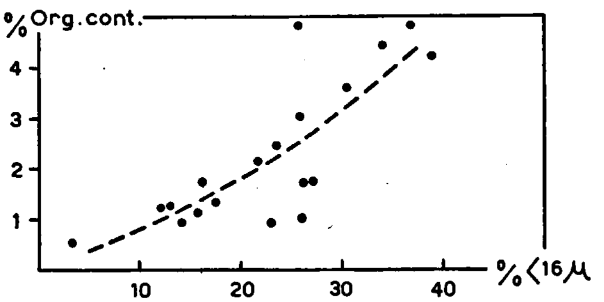


Fig. 16. Relation between grain size and organic content in samples from Wadden Sea area.

tidal flat sediments of other areas (FRANCIS-BOEUF, 1947, FRANCIS-BOEUF and ROMANOVSKY, 1950; HERRMANN, 1943, LINKE, 1939 et al.).

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# V. IRON COMPOUNDS

## A. Origin of iron compounds

Since sea water is extremely poor in dissolved iron, containing less than $10^{-9}$ grammes per ton (Rankama and Sahama), most of the iron in the Wadden sediments must have been transported in colloidal state or as detrital particles, either of pure iron-compounds or of more complicated, iron-containing substances. Deposition takes place by mechanical processes or by flocculation and adsorption. The iron minerals may be divided into those which are very stable and do not take part in chemical processes in the sediment, e.g. augite, epidote, hornblende, garnet, and those which are easily weathered or are readily involved in chemical reactions. The latter may give rise to the formation of new minerals in the Wadden deposits.

The authigenic iron compounds, formed in this way, are mainly hydroxides and sulphides. In some tidal flat sediments, notably those, deposited in comparatively brackish water surroundings, phosphates (vivianite) are also found. Siderite has been mentioned by Crommelin (see Ch. III) as a constituent of the Wadden silts, but it is not stated whether it is of authigenic or of detrital origin. The grains of glauconite are in all probability exclusively of detrital character. A part of the iron, finally, may enter authigenically into organic compounds.

## B. Relation of iron content to clay material

The iron content of the Wadden sediments shows a close relation to the quantities of the material with grain sizes smaller than 16 $\mu$, see Tables 3

TABLE 3

| | Material $< 16\ \mu$ in percentages of whole dried (samples) | $F_2O_3$, dissolved in 10 % HCl, in percentages of whole dried (samples) | $F_2O_3$, dissolved in 10 % HCl, in percentages of material $< 16\ \mu$ | Total $F_2O_3$ in percentages of material $< 16\ \mu$ |
|---|---|---|---|---|
| Samples from | 31,8 | 2,90 | 9,12 | 10,36 |
| surface of tidal | 38,7 | 3,49 | 9,02 | 10,31 |
| flats in | 44,3 | 3,61 | 8,15 | 9,28 |
| Dollard | 54,4 | 4,31 | 7,92 | 8,88 |
| | 68,8 | 5,30 | 7,70 | 8,55 |
| „Old Sea clay" (Groningen) | 60,4 | 3,12 | 5,17 | 9,52 |
| „Old Sea clay" (Wieringermeer) | 68,3 | 3,53 | 5,17 | 7,20 |

(Data from van der Spek (1948). The last column gives the quantities of the material dissolved in 10 % HCl + the iron present as $FeS_2$)

and 4 and Fig. 17. The relation is, however, not directly proportional, since a small part of the iron is present in larger elements.

TABLE 4

| | Zone | Material $< 16\ \mu$ in percentages of whole (dried) samples | $Fe_2O_3$, dissolved in 25 % HCl, in perentages of whole (dried samples | $Fe_2O_3$, dissolved in 25 % HCl, in percentages of material $< 16\ \mu$ |
|---|---|---|---|---|
| Samples from | P | 1,2 | 0,81 | — |
| tidal flats | L | 1,4 | 0,52 | — |
| South of Nes | M | 3,6 | 0,68 | — |
| (Ameland) | M | 16,5 | 1,58 | 9,6 |
| Analyses by | L | 22,0 | 1,95 | 8,9 |
| Dr. J. van der | P | 23,7 | 1,91 | 8,1 |
| Spek. | P | 26,3 | 1,98 | 7,5 |
| (August 1949) | L | 39,5 | 2,84 | 7,2 |

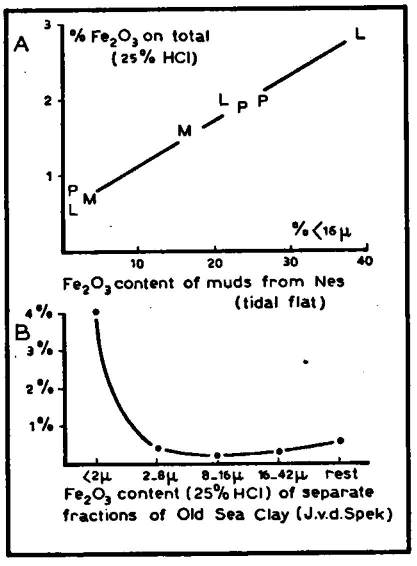


Fig. 17. **A.** Relation between iron content (dissolved in 25 % HCl) and quantities of material $< 16\ \mu$, in samples from tidal flats South of Nes, Ameland (analyses by J. VAN DER SPEK). Both quantities are expressed in percentages of the whole (dried) samples; L: Hydroxidic zone, M: Monosulphuric zone, P: Pyritic zone. — **B.** $Fe_2O_3$ content (dissolved in 25 % HCl) of successive fractions of sample from Dutch Holocene marine deposits (after J. VAN DER SPEK, 1948).

## C. The state of the authigenic iron

1. *Sediments of tidal flats and channel floors.* In the sediments of the tidal flats and the channel floors three zones may be distinguished, according to the state of the iron. They are, from the surface downwards: (a) Hydroxide zone, (b) Monosulphuric zone and (c) Bisulphuric zone. This

is the same order in which, under circumstances of continuous deposition, the zones develop out of each other.

a) *Hydroxide zone* (L). This corresponds to the zone of oxidation (aeration). The sediments are of a brownish or yellowish grey colour, unless tinted otherwise by accidental admixtures [1]. The colour is due to the presence of ferri-hydroxides (limonitic iron).

A part of this iron hydroxide is distributed as tiny, brownish-yellow or orange-coloured specks on the surface of the sand grains. With the microscope no crystal forms could be detected on this material. It is probably in colloidal or rather "colloform" state. Some of the specks may have been originally present on the sand grains. For a great part, however, they seem to be of authigenic origin (see character of sand grains in pyritic zone and transformation of P- to L-sediments). The colloidal precipitation of the hydroxide material on the quartz grains is perhaps due to electro-chemical attractions. Iron bacteria may also be involved (cf. ZOBELL, 1946. p. 124).

The part of the iron which is attached to the surface of the sand grains is, of course, only very small. The bulk of the iron content is present as colloidal or very finely divided material in the mass of the clay fractions.

The thickness of the hydroxide zone depends on many factors, such as the porosity of the sediment, the activity of burrowing animals and the rate of sedimentation. Fresh oxygen is supplied by exposure to the atmosphere, or, during the stages of submergence, by contact with the covering sea water. Small amounts of oxygen are moreover produced by $CO_2$-assimilating diatoms. The burrowing action of bottom dwelling organisms helps to distribute the oxygen further down into the sediment. Where the velocity of deposition is small or even zero, as on most tidal flats, the thickness of the hydroxide zone is comparatively slight. In muds it may vary between a few millimeters and a few centimeters, in sands it is usually not more than a few centimeters. The oxidation zone may show much greater thicknesses at places where the sedimentation has been very rapid (Pl. 11, No. 109, 110), but these thicknesses are only of temporary character. In a relatively short time the aerated state becomes restricted again to the uppermost few centimeters. The demarcation between the L-zone and the underlying M-zone is mostly rather sharp.

b) *Monosulphuric zone* (M). Below the oxidation zone all sediments are in anaerobic condition. The upper parts of the anaerobic deposits are characterized by a more or less intensely black colour. Microscopical investigation of the sand grains shows that they are covered with the same, structureless specks as in the oxidation zone, the only difference being that now their colour has become pitch black. It is probable that a chemical reaction has taken place in situ, without transport of ions through the sediment. Analyses, carried out by VAN DER SPEK, show that an important part of the iron in this zone is in monosulphuric state. It is of colloidal character and contains varying amounts of water: $FeS \cdot nH_2O$.

Another part of the iron in this zone is present in the form of pyrite ($FeS_2$), as is proven by chemical and röntgenographical analyses and by microscopical examination, both of fresh samples and of thin sections. It

[1] e.g. dark brown to violet by benthonic diatoms, green by filament algae, pink by *Noctiluca miliaris*, red by sulphur bacteria, white by elementary sulphur.

is found in small, globular crystal aggregates, with diameters of 5 to 25 $\mu$, lying isolated in the sediment (or, very subordinately, in the shape of crystalline "specks" on the surface of the sand grains). The globules are often concentrated in and around remains of plant roots, peat detritus etc. (cf. also VAN BEMMELEN, 1886, WETZEL, 1931, VAN DER SPEK, 1934 and many others).

The thickness of the monosulphuric zone is normally some 20 to 40 cm. On the banks and floors of channels and gullies it is often much more (Pl. 10, No. 83), up to many meters. The monosulphuric zone is, although anaerobic, still rich in benthonic life: crustaceans, worms, mollusca and other animals abound. The walls of their burrows are, however, mostly in oxidized state, over a thickness of 1 or a few mm.

c) *Bisulphuric or pyrite zone* (P). All Wadden sediments below the monosulphuric layer belong to the pyrite zone. It is characterized by a (more or less light) grey colour, owing to the absence of the strongly pigmenting hydroxides or monosulphides of iron. Here, the "natural" colour of the sediment is seen. The iron is nearly exclusively present as pyrite, in globules of 2—25 $\mu$ diameter. The sand grains in this zone are mostly free of surface specks. If the formation of pyrites has taken place as a precipitate-reaction, the material of the specks must have become loosened soon after the transformation started.

It was shown above (Ch. IV) that the deeper layers of the sediment are often distinctly poorer in organic matter than the superficial deposits. It might be thought that the difference in colour between the grey P-zone and the black M-zone were due chiefly to this difference in organic content. This is, however, not the case. Sands with only minor contents of clay and with correspondingly low organic contents, of 0,5 % or less, may be pitch black, whereas clays from the P-zone, with more than 2 % of organic material may show very light grey colours.

2. *Marsh deposits.* In the marsh sediments, formed above the level of high tides, a great part of the iron is in hydroxidic state, at least in the more sandy layers. These hydroxides are not infrequently concentrated around the roots of marsh plants. When such marshes are eroded by the waves, the concretions (usually not greater than a few mm) may become sorted out on the beachlets at the base of the marsh cliffs (see Ch. II).

In thin sections of marsh clays, especially the older deposits (as well as in those of the typical "Old Blue Sea Clay"), a greenish colour is usually observed, which is absent from the muds and clays of the tidal flat and channels floor environments. It may be due to the presence of iron-rich montmorillonite and illite (cf. KELLER, 1953). It is not known, however, whether the unequal distribution of the green colour is due to a primary concentration of these clay minerals in the marsh and Old Sea clay environments, or to neo-formation.

3. *The deposits of the "Old Sea Clay".* In the typical brackish-water facies of the "Old Sea clay" the pyrite is present in globules of distinctly greater dimensions: 5—40 $\mu$ in diameter (Pl. 11, No. 24). They are concentrated in and around organic material, such as fragments of peat detritus and remains and negatives of the roots of reed plants. Normal tidal flat deposits of the same age, formed in more saline environment, show pyrite globules of the same sizes as those in the recent Wadden sediments. In recent

brackish-water deposits, on the other hand, the coarser type of globules is found (e.g. in the swampy marshland sediments near Oude Schild on the island of Texel, and in the brackish estuarine marshes from the Easter Scheldt, near Woensdrecht, the Wester Scheldt (Braakman) (Pl. 11, No. 142), and from the former IJ near Velzen[1].

### D. Transformation of L-, M- and P-zones into each other

1. *Transformation* $L \rightarrow M$. When samples taken from the oxidation zone are kept under sea water in partially or wholly closed jars, they are transformed in the course of a few days into the monosulphuric state. At first the yellowish tinges of the sample disappear, the whole sediment becoming evenly dark greyish brown. Then the black colour of the $FeS \cdot nH_2O$ is developed. It starts in a few scattered centres, which increase rapidly in number. Eventually the whole mass of the deposit is of a black colour, with a profusion of tiny specks of more intense colouring. The following processes have taken place: The oxygen which was enclosed in the sediment at the time of sampling is consumed by benthonic organisms and by bacteria, for the combustion of the organic material on which they are feeding. The main product of this process is $CO_2$. Small quantities of $H_2S$ are also formed, but this gas is oxidized at once, so long as oxygen is still present. At a given moment the oxygen is used up. Anaerobic conditions set in and sulfate reducing bacteria start their activity. They reduce the sulfates which are dissolved in the enclosed sea water, partly with the aid of $H_2$, which is liberated by the decomposition of organic matter. In this way considerable quantities of $H_2S$ are produced, which react immediately with the iron hydroxides, resulting in the formation of the black coloured, colloidal $FeS \cdot nH_2O$.

It was stated above that $H_2S$ is produced also in the zone of oxidation, by the decomposition of organic matter. The process is continued after the anaerobic conditions have commenced. The production of $H_2S$ by this process, however, is of negligible importance for the formation of iron sulphides, at least in comparison to the $H_2S$ production by the sulphate reducing bacteria, the organic matter containing in the average not more than 2 % of sulphur.

The bacteria which decompose the organic material in the sediment use a part of it (30 to 40 % of the assimilated quantities, according to RANKAMA and SAHAMA, for the building up of their own protoplasma. After their death this material is partly re-used by other organisms. For another part it is preserved as relatively stable humic compounds.

It is sometimes seen, in the Wadden Sea, after storms or periods of rough weather, that certain ebb gullies have become silted up completely. The filling sediments may then preserve their oxidized state for a long time. In small artificial gullies, made by the author himself in the mud flats of the Lauwerszee (northern bank of Babbelaar), the filling deposits were, after a period of 26 days (August 25 to September 20, 1950), still completely in the hydroxidic state. The cause of this long delay, as compared to the rapidity of the transformation in the bottled samples, may perhaps be sought in the

[1] The presence of these coarse pyrite globules seems to be completely independent of the carbonate content. They are found both in clays which are highly calcareous and in clays which lack all traces of carbonate of lime.

larger dimensions and the slow migration of benthonic organisms, decomposing the organic matter, into the new sediments.

2. *Transformation $M \rightarrow L$.* When, by erosion of the surface layers, the sediments of the monosulphuric zone are exposed to the atmosphere or to aerated sea water, a rapid oxidation of the $FeS \cdot nH_2O$ takes place. Iron hydroxides are formed, together with $H_2S$. Unless the reactions occur in precipitated conditions altogether, the newly formed iron hydroxides are deposited as gels. Iron bacteria may use the energy which is liberated by this oxidation, for their own assimilation processes, but the oxidation, of course, takes place in any case, whether they are present or not (cf. WAYNE GALLIHER, 1933).

Samples from the M-zone which are exposed to the air, are oxidized at their surface in a few hours. The same reaction velocities are observed for the castings of the lugworm, *Arenicola*, which have been brought to the surface out of the underlying monosulphuric zone.

The oxidation of $H_2S$ may result in the precipitation of elementary sulphur. This phenomenon is notably seen at places where, without the influence of erosion, $H_2S$ escapes to the surface in large quantities. It may be occasioned by the outflow of ground water in the sides of ebb gullies, during the stages of low tide. Thin, brittle films of white sulphur are then produced on the water surface. Elevation of the temperature is possibly another cause of the escape of $H_2S$ to the surface. It is often noted, on warm, sunny days, that such films develop on the water of small pools or on the surface of the muds themselves. Sometimes small but undeniable mud volcanoes are even formed. This happens especially at places where great masses of dead sea weeds or *Zostera* plants are buried in the sediment (e.g. South of Schiermonnikoog; see also WOHLENBERG, 1937).

The precipitation of elementary sulphur by oxidation of $H_2S$ may involve the activities of (colourless) aerobic sulphur bacteria. Whereas these — autotrophic — bacteria acquire the energy for their assimilation processes from the chemical oxidation phenomena, other sulphur bacteria use photo-energy. These photo-synthetic autotrophic organisms may produce sulphur from $H_2S$ in anaerobic environment. They develop in bottled samples which are exposed to the light. Both green and purple bacteria are observed. Owing to the absence of illumination these colours are never formed *in* the sediments of the tidal flats. In consequence of their anaerobic character, their distribution on the sediment surface of the tidal flats is, of course, extremely limited. The only indication of their activity in natural circumstances, known to the author, was found South of Nes (Ameland). Here, the muds showed numerous stains of red colour, which proved to be caused by unicellular organisms (? Euglenoids), which owed their colour presumably to the consumption of purple bacteria.

3. *Transformation $M \rightarrow P$.* In contrast to the above mentioned transformations, this is a process requiring much longer time. The deposits, formed in a gully in the Lauwerszee (Blikplaat), which was silted up shortly after the year 1933, were, after a period of 20 years still completely in monosulphuric condition. The channels South of Ameland, which were filled up after the construction of a dam near Ballum in 1854 show only a partial change of M- into P-material. Deposits below the Ruigezandster Polder South of Zoutkamp, which was dyked in 1795 are still in monosulphuric condition.

The length of the time, required for the complete transformation may be estimated as varying between 50 years and many centuries, in the average perhaps 1 to 2 centuries.

The transformation takes place earlier in sandy deposits than in clayey ones. Laminations of sand and mud are found in the transition zone between M and P, in which the mud laminae are still quite black, the sand showing already light grey colours. This is easily understood, since the sand contains much less iron, and much less additional sulphur is accordingly needed for its transformation into pyrite.

At those places where sedimentation proceeded more or less continuously, and where the activity of burrowing animals is not too intense, quite gradual transitions are found between the pitch-black M-zone and the subjacent, grey-coloured P-zone (Pl. 10, No. 68, Pl. 11, No. 168). At other place the demarcation between the two zones is on the contrary very sharp. This is often the result of discontinuous sedimentation, and of the alternation of periods of sedimentation with periods of erosion. The latter is then usually due to the shifting of gullies and channels. The boundary between the two zones corresponds, in such cases, to the former floors of these water courses. They may be recognized as such by the presence of bivalves e.g. of *Petricola pholadiformis*, in the position of growth or comparatively large numbers of burrows of worms and crustaceans in the top layers of the P-sediments. Other indications are mud pebbles and shell beds at the base of the M-sediments. "Large" stratigraphic hiatuses are marked also by the different states of compaction in the two zones [1].

A sharp limit between the M- and the P-zones may be brought about also by the work of burrowing animals causing a homogenization of the material in the uppermost 20 to 40 cm of the sediment, which is kept constantly in monosulphuric condition (cf. VAN STRAATEN, 1952, and Pl. 10, No. 125).

4. *Transformation P → M?* Pyritic deposits are often re-aerated, by erosion, or by the work of burrowing animals. After passing through this L-state they may become transformed again into the M-conditions. No evidence has, however, been found for the occurrence of direct transformations of sediments from P- to M-conditions.

5. *Transformation P → L.* Samples from the P-zone which are exposed to the atmosphere show also oxidation phenomena. The yellow-brownish colours do not appear so quickly, however, as in the case of the M-material. The coarser pyrite globules may resist oxidation for long periods. The same observations were made on the castings of *Arenicola*, which had been brought up from the P-zone.

6. *Transformation L → P?* No data are available from which the possibility of direct transformations of L into P can be deduced. Numerous instances are known, of marsh deposits, which were originally in aerated conditions, but have sunk subsequently, owing to the relative bottom subsidence, below the ground water table, resulting in the eventual development of pyritic conditions (Pl. 11, Amsterdam). Intervening M-stages may, how-

[1] A curious phenomenon is sometimes observed, viz. that the basal parts of channel fillings are still in monosulphuric state, whereas the overlying sediments have been transformed already into P-material (see Fig. 15, left core).

ever, have occurred. In some cases at least such transition stages could be recognized, e.g. in old marsh deposits of the Kooigrie on the island Ameland, which have been depressed, relatively to the ground water table by an amount of some 50 cm. The bulk of the material was, in these sediments, in pyritic state, but numerous small blueish-black specks were also present, partly around the remains of marsh plants.

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# VI. CARBONATES

## A. Origin and character of carbonates

The carbonate content of the deposits of the Wadden Sea and of the Dutch estuaries is of various origin:

1) Carbonate grains, derived from glacial till and other sediments of the older formations, which are eroded in the tidal flat areas themselves;
2) Carbonate grains, supplied from the land;
3) Grains of carbonate of inorganic and organic origin, brought in by the flood currents from the North Sea;
4) Grains, formed by wear of skeleton remains of calcareous organisms, living in the Wadden Sea and in the estuaries;
5) Carbonate, formed by precipitation from the sea water.

The bulk of the carbonate material is due to supply of material out of the North Sea and the biological production in the tidal flat environments.

The carbonates are mainly of three kinds: carbonate of lime, dolomite and siderite. Siderite seems to be of quite subordinate importance. Dolomite is found in greater quantities, but its percentages show sometimes large variations from one locality to another. It may be partly of authigenous formation (CROMMELIN, 1943). By far the greater part of the carbonate material is made up of carbonate of lime. Both calcite and aragonite are present, in correspondence with the composition of the skeletons of the calcareous organisms, inhabiting the tidal flat areas (see Table 5).

TABLE 5. Composition of calcareous skeletons, after H. WOODS, 1947.

| Calcite | Aragonite |
|---|---|
| Foraminifera: Vitracea | Foraminifera: Porcellanea? |
| Echinoderms | |
| Most Polyzoans | |
| Ostrea | Many LLamellibranchs |
| Outer layer of *Mytilus* | Inner layer of *Mytilus* |
| Outer layer of *Littorina* | Most Gastropods |
| Most Crustaceans | |

## B. Deposition

Carbonate of lime is deposited by mechanical processes (detrital elements of inorganic and organic character) and by chemical or biochemical action (e.g. a part of the fine grained material). Chemical precipitation due to evaporation of the water is frequently observed on salt marshes and on the highest parts of the tidal flats. Thin crusts of white material are formed in these areas, which are composed chiefly of sodium chloride. Since the sequence of deposition by evaporation of normal sea water is: 1) carbonates of lime, 2) gypsum, 3) sodium chlorides, these crusts must contain also a (small) admixture of carbonates.

MASCHHAUPT (1948) believes that chemical precipitation or deposition by micro-organisms takes place very generally in the Wadden Sea environment, on account of the constant association of small quantities of $MgCO_3$ with the $CaCO_3$ in the Wadden deposits, a fact which cannot be explained by the composition of the Mollusc shells, which are very poor in magnesia. The argument looses much of its value when it is considered that a significant part[1] of the carbonates is secreted by other animals than molluscs, e.g. by foraminifera, echinoderms and crustaceans. From the data given by CLARKE and WHEELER (1922) it follows that the skeletons belonging to these other groups are mostly much richer in magnesia (see Table 6).

TABLE 6. $MgCO_3$ of skeletons of marine animals calculated as percentages of total carbonate content, after CLARKE and WHEELER (1922). — These data are based on analyses of skeletons, sampled from all latitudes, from the Arctic down to the Tropics. It is noted that the $MgCO_3$ content generally increases with decrease of latitude.

| | | | |
|---|---|---|---|
| Foraminifera | 9—12 | Barnacles | 1—2 |
| Echinids | 6—14 | Lamellibranchs | 0—1 |
| Star fishes | 8—15 | Gastropods | 0—2 |
| Various Crustaceans | 4—36 | | |

Biological precipitation of carbonate of lime may be due also to the assimilation processes of algae and bacteria. These organisms take up $CO_2$ from the sea water, thus causing supersaturation of the $CaCO_3$. It may be possible, moreover, that calcium carbonate is deposited also as a secondary phenomenon during other biochemical processes, such as the activities of sulphate reducing bacteria. Very little is known, however, about the actual importance of these processes.

No data are available concerning the occurrence of recrystallization of the $CaCO_3$. Secondary growths of calcium carbonate around detrital grains were never observed, nor cementation of calcareous deposits.

## C. Grain size distribution of carbonates

Only few investigations have been made of the grain size distribution of the carbonate elements in the Wadden deposits. MASCHHAUPT (1948, 1950; cf. also DOEGLAS, 1950) observed that the particles of $CaCO_3$ show about the same granulometrical distribution as the remaining part of the sedimentary material. The precipitation of carbonate of lime, owing to chemical or biochemical processes, cannot be of predominating importance, according to this

[1] Tests of Foraminifera and spines of Echinids are found in nearly every cubic centimeter of sediment, and often in great numbers. Only the coarse sands of channels and beaches and the decalcified marsh deposits may be free or nearly free of these carbonate elements.

author, since in that case much more fine grained carbonate material would be present. From the data of the present author it follows, meanwhile, that the $CaCO_3$ of recent tidal flat muds and sands is concentrated in the fine grain size fractions (see Table 7 and Fig. 18).

TABLE 7. Analyses or samples from tidal flats of Dutch Wadden Sea, South of Nes (Ameland) and North of Noordpolderzijl (Prov. of Groningen).

| Depth | $CaCO_3$ | Org. Cont. | NaCl | $< 16\ \mu$ | $> 16\ \mu$ | Total |
|---|---|---|---|---|---|---|
| 30 cm | 1.5 | 0.– | 0.6 | 1.2 | 96.7 | 100.0 |
| 5 cm | 1.2 | 0.– | 3.1 | 1.4 | 94.3 | 100.0 |
| 25 cm | 3.8 | 0.5 | 0.9 | 3.6 | 91.2 | 100.0 |
| 50 cm | 9.2 | 1.2 | 1.2 | 12.4 | 76.0 | 100.0 |
| 25 cm | 9.3 | 1.2 | 1.3 | 13.2 | 75.0 | 100.0 |
| 85 cm | 8.0 | 0.9 | 1.2 | 14.6 | 75.3 | 100.0 |
| 75 cm | 9.2 | 1.1 | 1.3 | 16.0 | 72.4 | 100.0 |
| 25 cm | 9.3 | 1.7 | 1.9 | 16.5 | 70.6 | 100.0 |
| 65 cm | 9.8 | 1.3 | 1.5 | 17.9 | 69.5 | 100.0 |
| 5 cm | 8.9 | 2.1 | 3.6 | 22.0 | 63.4 | 100.0 |
| 90 cm | 12.1 | 0.9 | 1.5 | 23.7 | 61.8 | 100.0 |
| 15 cm | 9.5 | 2.4 | 2.1 | 24.2 | 61.8 | 100.0 |
| 5 cm | 10.7 | 3.0 | 3.5 | 25.8 | 57.0 | 100.0 |
| 15 cm | 10.3 | 4.8 | 2.2 | 25.9 | 56.8 | 100.0 |
| 90 cm | 12.5 | 1.0 | 1.5 | 26.3 | 58.7 | 100.0 |
| 85 cm | 11.6 | 1.7 | 1.9 | 26.8 | 58.0 | 100.0 |
| 45 cm | 12.3 | 1.7 | 1.8 | 27.1 | 57.1 | 100.0 |
| 5 cm | 11.6 | 3.6 | 2.6 | 31.2 | 51.0 | 100.0 |
| 35 cm | 11.8 | 4.4 | 2.8 | 34.5 | 46.5 | 100.0 |
| 5 cm | 12.8 | 4.8 | 3.0 | 37.5 | 41.9 | 100.0 |
| 5 cm | 12.5 | 4.2 | 7.6 | 39.5 | 36.2 | 100.0 |

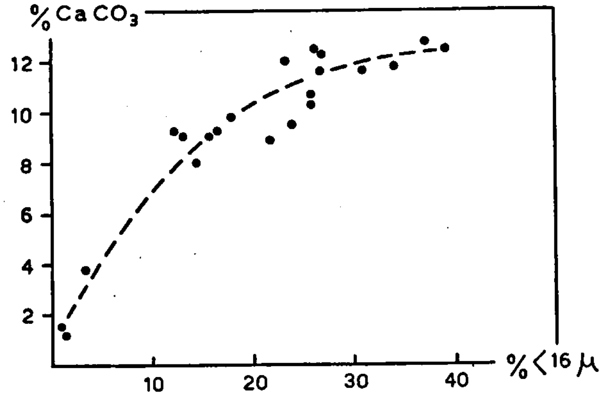


Fig. 18. Relation between total carbonate content of samples from Wadden Sea and percentage of material $< 16\mu$; see also Table 7.

Direct analyses of the carbonate content of the separate fractions were published by ZUUR (1936), see Table 8.

TABLE 8. Carbonate content of separate fractions from tidal flat deposits in Wieringermeer (Old Sea Clay), after ZUUR, 1936.

Grain size distribution of whole samples:

| Fractions (μ): | 0—16 | 16—43 | 43—74 | 74—104 | 104—147 | 147—1651 | 0—1651 |
|---|---|---|---|---|---|---|---|
| Sample A (%) | 6,6 | 4,6 | 11,6 | 22,6 | 35,5 | 19,1 | 100 |
| — B — | 13,4 | 16,4 | 28,6 | 19,3 | 15,6 | 6,7 | 100 |
| — C — | 28,6 | 25,5 | 27,0 | 8,8 | 6,4 | 3,7 | 100 |
| — D — | 55,1 | 22,3 | 11,3 | 2,6 | 2,5 | 6,2 | 100 |

Percentages of $CaCO_3$ in each fraction:

| Fractions (μ): | 0—16 | 16—43 | 43—74 | 74—104 | 104—147 | 147—1651 | 0—1651 |
|---|---|---|---|---|---|---|---|
| Samples A (%) | 13,9 | 14,5 | 9,4 | 6,7 | 5,2 | 7,9 | 6,6 |
| — B — | 10,5 | 15,3 | 9,6 | 7,4 | 6,2 | 8,2 | 9,6 |
| — C — | 11,9 | 15,6 | 11,8 | 8,6 | 6,4 | 9,9 | 12,1 |
| — D — | 10,1 | 14,4 | 10,4 | 9,6 | 9,0 | 10,7 | 11,1 |

From ZUUR's data it would appear that the maximum abundance of the carbonates is found in the fractions 16—43 μ. New analyses, carried out by VAN DER MAREL on mud samples from the present Wadden Sea flats [1] show a maximum of the carbonate content in the fraction 2—16 μ: see Table 9.

## D. Decalcification of marsh deposits

Many papers have been published on the problem of the decalcification of the marine deposits at the surface of the northern and western parts of the Netherlands, notably by BENNEMA, EDELMAN, HISSINK, MASCHHAUPT, DE SMET, VAN DER SPEK and ZUUR. The results, obtained by the various authors gave rise to a controversy between the Groningen pedologists and the school of EDELMAN, with regard to the velocity of the decalcification processes. According to EDELMAN (1950) the average loss in carbonates of the ploughed layer [2] of the Dutch clay soils amounts to about 1 % per century. HISSINK (1952) and MASCHHAUPT (1952) are, on the other hand, of the opinion that it is impossible to give a single average value, the velocities showing too large variations from one area to another. On the whole the velocities would be somewhat greater than the value suggested by EDELMAN.

Details on the manner of decalcification can be observed by thin section analysis and by the investigation of samples under the binocular microscope. It is seen that the smallest carbonate particles are the first to be attacked by solution. The more or less decalcified marsh deposits contain often only comparatively coarse carbonate elements, whereas the muds of the tidal flats and of the channel floors, where no solution has taken place, are always rich in very fine grained carbonate material. The clay laminae of marsh sediments

[1] Personal communication; the samples were collected by the present writer.

[2] This value refers therefore to the decalcification of embanked marsh deposits, which are no longer under the direct influence of the sea.

TABLE 9

Sample tidal flat Hornhuizen (Groningen)

| Fractions ($\mu$) | < 2 | 2—16 | 16—80 | 80—210 | 210—500 | > 500 | Total |
|---|---|---|---|---|---|---|---|
| % of fractions *) | 24.1 | 11.6 | 22.8 | 41.4 | 0.1 | traces | 100.0 |
| % of calcite in fractions | 7.1 | 19.9 | 12.1 | 4.3 | ? | ? | |
| % of calcite + dolomite in fractions | 8.1 | 22.2 | 14.7 | 5.6 | ? | ? | |
| % of calcite in sample | 1.81 | 2.30 | 2.76 | 1.78 | | | 8.65 |
| % of calcite + dolomite in sample | 1.95 | 2.57 | 33.5 | 2.32 | | | 10.19 |
| $100 . \frac{\text{calcite + dolomite}}{\text{calcite}}$ | 108 | 112 | 121 | 130 | | | 118 |

Sample tidal flat Nes (Ameland)

| Fractions ($\mu$) | < 2 | 2—16 | 16—80 | 80—210 | 210—500 | > 500 | Total |
|---|---|---|---|---|---|---|---|
| % of fractions *) | 36.4 | 24.4 | 24.8 | 14.2 | 0.2 | traces | 100.0 |
| % of calcite in fractions | 8.4 | 23.3 | 13.5 | 7.8 | | | |
| % of calcite + dolomite in fractions | 8.6 | 25.3 | 16.6 | 9.0 | | | |
| % of calcite in sample | 3.06 | 5.69 | 3.35 | 1.11 | | | 13.21 |
| % of calcite + dolomite in sample | 3.13 | 6.17 | 4.12 | 1.28 | | | 14.70 |
| $100 . \frac{\text{calcite + dolomite}}{\text{calcite}}$ | 102 | 108 | 123 | 115 | | | 111 |

*) Grain size composition of whole samples, after removal of salts soluble in water (NaCl).

are in some cases wholly free of lime, the intercalated sand laminae, in which the lime was originally present in coarser particles, still showing a notable carbonate content.

In sections of marsh sediments which are in the process of being decalcified, the following zonation can often be recognized (cf. Pl. 10, No. 53 (Zoutkamp) and Pl. 11, No. 142 (Braakman); see also Pl. 11, Amsterdam).

a) an upper zone, which is quite free of carbonate of lime;
b) a zone with a low carbonate content in which no clearly identifiable remains of calcareous organisms can be observed under the binocular;
c) a zone of greater carbonate content, with well preserved tests of foraminifera, but still free of spines of echinids;
d) the underlying sediment, in which both tests of foraminifera and spines of echinids (mostly *Echinocardium cordatum* L.) abound.

The fact that the distribution of the foraminiferal remains extends higher upwards, in these sections, than that of the spines of echinids, may be partly due to a difference in floating properties between these two elements, the foraminifera being deposited originally at higher levels than the echinid spines. Yet, it appears that their distribution reflects only weakly the intensity of the movements of the water in which they were deposited. There is often little or no correspondence between the presence or absence of these two kinds of microfossils and the size grades of the admixed sand grains. In many cases no difference at all is found between the coarseness of the sand above and below the upper limit of the echinid spines. Unequal resistance to solution and increase of the decalcification from below upwards seem to give a better explanation. A difference in solubility between foraminifera and spines of echinids could not be understood, meanwhile, on account of the crystalline structure. If this latter were responsible, the tests of foraminifera, composed of aggregates of fibrous calcium carbonate would disappear much sooner by solution, than the spines of Echinids, which are built up of single crystals of calcite. The cause of the different behaviour may probably be sought in the higher Mg-content of the echinid remains.

The carbonate content of marsh deposits is highly dependent on the rate of sedimentation (cf. BENNEMA and VAN DER MEER (1952), BENNEMA (1953a), MASCHHAUPT (1948), ZUUR (1936). Where deposition is slow, the surface layers may become decalcified already to a large extent before they are covered by new sediments. The variations in the carbonate content which are found in marsh areas are partly the result of these differences in sedimentation velocity. The vertical accretion of the marshes as a whole is slowest in those parts which lie at the greatest distance inland from the high tide line. It is in these same parts, accordingly, that the lowest carbonate values are found. The sticky clays of the Dutch lowlands which usually do not contain any $CaCO_3$ at all have perhaps been formed under such circumstances. It is possible that the brackish water conditions and the special character of the vegetation in these more inland lying areas are also partly responsible for the absence or at least the scarcity of carbonates.

A striking difference in carbonate content, moreover, is often found between the sediments of the raised banks and the bottoms of creeks and those of the enclosed marsh depressions, the latter being relatively poor in carbonate of lime, or even quite free of it: see Fig. 19.

It can hardly be supposed that this unequal distribution of the carbonate material is a primary feature, i.e. that the sediment which was supplied originally to the depressions was already free of calcium carbonate. Decalci-

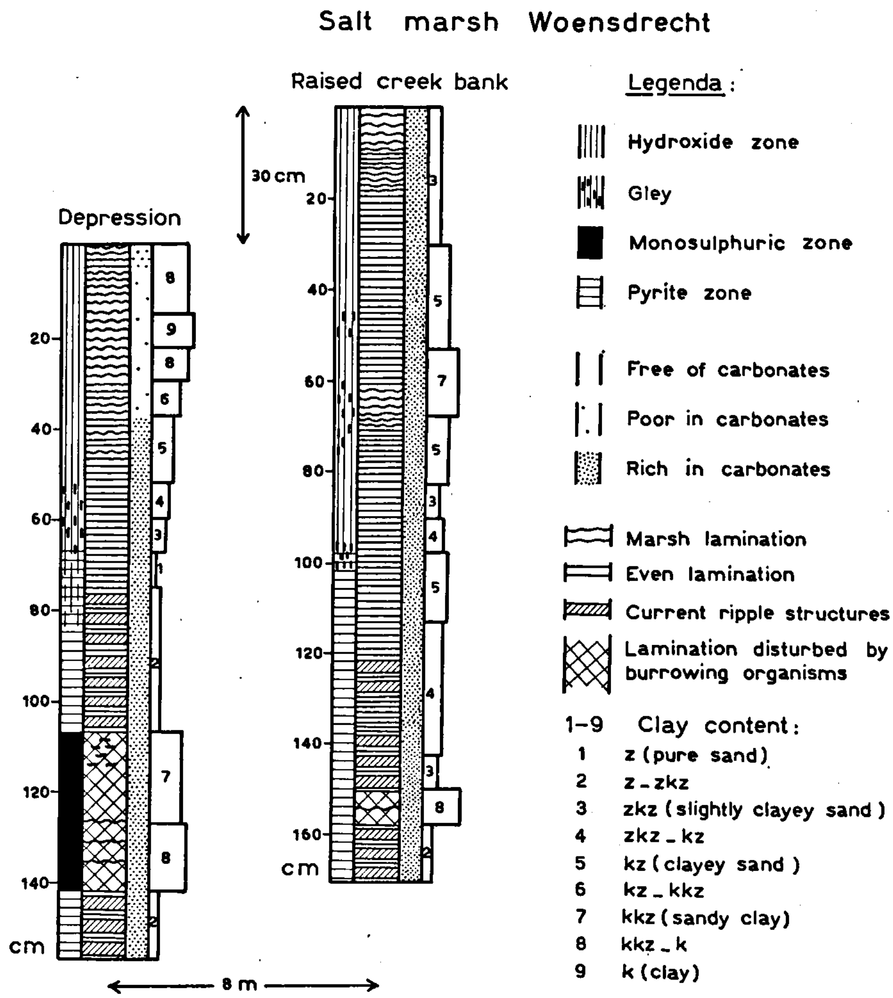


Fig. 19. Diagram of composition of cores from marsh depression (left) and raised bank of creek (right); Salt marsh of Easter Scheldt (Prov. of Zealand) near Woensdrecht.

fication seems to be the only possible explanation. The greater intensity of this process in the depressed areas may then be due to several factors:

a) The lower rate of vertical upgrowth;
b) The circumstance that the sediments of the depressions are much poorer in coarse carbonate particles than the more sandy banks of the creeks, so that they are correspondingly sooner decalcified (cf. p. 50).

c) The fact that the sediments of the depressions, in connection with their higher clay content, are richer in organic matter, which yields, upon decomposition, $CO_2$ and other carbonate-dissolving acids;

d) The fact that the more clayey deposits in the marsh depressions are richer in iron than the sediments of the creek banks. The possibility of solution of carbonates of lime by iron sulphates and sulphuric acid, which are liberated by the oxidation (aeration) of deposits containing iron sulphides has been given much attention by VAN DER SPEK (1934, 1952). This author arrives at the conclusion that it plays a very important part in the production of soils which are free of calcium carbonate.

The differences in carbonate content between the creek deposits and those of the depressed areas between them are found especially in the more brackish [1] marsh environments. The average composition of the two types of sediments in the older (Atlantic) marsh lands of the Mijdrecht polder (Prov. of South Holland), investigated by BENNEMA (1953b), is as follows:

Creek deposits: 11 % $CaCO_3$ — 4 % Organic matter — 1½ % Sulphur ($I_1$). Sediments of marsh depressions: 0 % $CaCO_3$ — 7 % Organic matter — 3 % Sulphur ($II_4$).

A few comments may be given on the question of the solution of carbonates by acids formed by the oxidation of iron sulphides. As has been stated earlier (Ch. V), the sulphur content of organic matter is very small. The comparatively large sulphur values found in the marsh depressions must therefore have been derived chiefly from the sulphates, dissolved in the sea water, in consequence of the activity of sulphate reducing bacteria. These bacteria require anaerobic conditions and cannot start their work in the newly formed sediments, before the amount of oxygen originally present has been consumed. Then $H_2S$ is produced, which reacts with the iron hydroxides, under formation of iron sulphides. At first $FeS \cdot nH_2O$ is formed, which is transformed subsequently into $FeS_2$. By the action of burrowing organisms and by lowerings of the ground water table these sulphides may become re-exidized, thereby liberating the acids which attack the carbonate particles in the sediment. A subordinate part of the sulphides may have been supplied directly, by sedimentation from the sea water in the shape of particles of $FeS_2$, which may become oxidized after deposition. The major part of the newly deposited iron has, however, been transported as iron hydroxides (cf. Ch. V). When the ground water table is subject to periodical oscillations, the sediment will be alternatingly oxidized and reduced. At every new anaerobic stage, fresh quantities of sulphur are then taken up from the sea water and fixed to the iron. At every subsequent aerobic period these sulphides will give new supplies of acids, dissolving a further part of the carbonates. In this way, the lime might soon disappear altogether. It is, however, far from certain whether such periodical movements of the ground water really take place to any important extent.

### E. Decalcification of tidal flat deposits

No indications were found for decalcification of sediments below the high tide level in the Dutch tidal flat environments. In the tidal flat muds of

[1] i. e. less saline.

the Basin of Arcachon (S. France), on the contrary, the solution of carbonates is a rather common phenomenon: see Pl. 11, No. 168. In this case, the decalcification can hardly be due to oscillations of the ground water table and the ensuing alternations of aerobic and anaerobic conditions. The deposits are permanently in the anaerobic state (except for the work of bottom dwelling organisms). The cause of the solution has to be sought probably in the large amounts of *Zostera* detritus, which are embedded in the sediment. Decomposition of this organic matter must yield considerable quantities of various acids, among which $CO_2$ probably predominates. The *Zostera*-remains are found in the sediment at depths down to several meters and in deposits which vary at least some 100 years in age (as may be gathered e.g. from the monosulphuric and bisulphuric states of the iron (cf. Ch. V)). Their abundance is in harmony also with the present day conditions in the Basin. In contrast to the Wadden Sea, the tidal flats of the Basin of Arcachon (Pl. 4, fig. 8) are nearly everywhere covered by a dense mat of *Zostera nana*, the deeper parts, such as pools, gullies and channels being rich in *Zostera marina*. The area has been affected also by the disease which attacked the *Zostera* vegetation all along the coasts of Western Europe, but it has recovered shortly after. In the Wadden Sea recovery is still only in its first stages. It is most unlikely, moreover, that the Wadden Sea has ever possessed such a large abundance of *Zostera* plants as the Basin of Arcachon, or else the remains of these plants would be much more widespread in the older deposits. [1]

The solution of carbonate of lime in the Arcachon muds is usually only partial. The finer carbonate particles, concentrated in the clay laminae of the sediment may have disappeared, but the coarser elements ,like the shells of molluscs, the spines of echinids and the tests of foraminifera are mostly still preserved ,although often severely attacked by solution. In many cases thick mollusc valves are so much weakened by the acids that they can be cut with a knife like cheese or butter.

It was stated above that in the Dutch marsh deposits laminations may be found, in which the clay laminae were completely decalcified, the sands still showing a certain carbonate content. Similar conditions were observed in laminations of the tidal flat muds of the Basin of Arcachon. Whereas in the former case this phenomenon could be accounted for by the fact that the carbonate particles in the clay laminae are so much finer than those in the sand laminae, and are accordingly earlier removed by solution, this explanation cannot (always) be applied to the case of the Arcachon muds. In the latter it may be observed that the mollusc shells in sand laminae are hard and well preserved, while the same shells in the carbonate-free mud laminae are more or less dissolved. Apparently the solution takes place with different velocities depending on the nature of the surrounding sediment. Accordingly, the main factor, responsible in these cases for the differential decalcification seems to be the greater amount of organic material which is present in the clays.

The decalcification of the muds in the Basin of Arcachon increases with the distance from the tidal inlet. The marsh sediments in this area

[1] The shells of *Rissoa membranacea* J. Adams, a gastropod which inhabits preferably the *Zostera* meadows, are likewise very rare in the Dutch tidal flat deposits. In the older Holocene marine sediments they reach a certain abundance only in the top beds of the lagoonal *Hydrobia*-clay (VAN STRAATEN, 1954).

are, as a rule, quite free of carbonates and show frequently in their general character a resemblance to the Dutch sticky clays (cf. VEENENBOS and VAN SCHUYLENBORGH, 1951) (see Pl. 11, No. 174).

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# VII. SILICA

Most of the silica of local origin seems to have been formed by organisms. Authigenous formation of silica by chemical precipitation has never been observed in the tidal flat deposits. The following siliceous elements of organic origin are encountered: skeletons of diatoms and of radiolarians, spicules of sponges and also very small spicules which are probably derived from reeds or other plants.

The *radiolarians* are extremely scarce.

The *diatoms*, on the contrary, may be extremely abundant. A marked difference is found between the occurrence of benthonic and planktonic diatoms. The latter are very evenly distributed throughout all kinds of sediments; in the deposits of the tidal inlets, the channel floors, the low flats, the high flats and the marshes. This applies especially to the species with coarse skeletons. The benthonic diatoms, on the other hand, are encountered much less universally. In the channel floor deposits and in the sediments of the lower tidal flats they are usually of comparatively subordinate importance. In the high flat deposits they may attain a greater profusion, but their maximum abundance is normally found in the marsh sediments, especially in the lower parts. As to the distribution of the living benthonic diatoms, this is somewhat different. They do not exclusively inhabit the marsh environments and the high parts of the flats, but are also found in great quantities on the lower tidal flats. Frequently they form more or less close films, covering the bottom. Usually these films are of a brownish colour, but in some cases, especially in the early spring and in the fall the abundance of the diatoms is so great that their colour is deep violet.

The fact that, notwithstanding the profusion of the living forms, so few skeletons are preserved in the sediments of the low flat environment, is probably due to solution phenomena. The $p_H$ of the sediment in the tidal flat areas which are submerged at every high tide is kept rather constant, at slightly alkaline values, owing to the buffering capacity of the sea water. Since silica is much better soluble in alkaline than in acid environments[1], the skeletons of the dead benthonic diatoms may soon disappear by solution or peptization, or at least, they will loose their shapes and structures by absorption of additional water. Only the coarse skeletons of planktonic diatoms may be left intact. In the marsh sediments the soil reaction is less alkaline and possibly, from time to time, it becomes even somewhat acid. The possibilities for the preservation of the tiny benthonic diatom remains are therefore much greater in this latter environment. It may be noted, in this connection, that very large quantities of fossilized benthonic diatoms are often found in acid, decalcified deposits of the "old sea clay", and in the more or less sapropelitic brackish water sediments which are encountered at depths

[1] See for example CORRENS (1949).

between 1.25 and 3.25 m below the surface of Westergoo (Prov. of Friesland).

Spicules of *sponges* are comparatively rare in the Wadden Sea deposits. They are much more common, however, in the older tidal flat deposits of the province of South Holland and near Velzen (North Holland). Here they are met with in all subfacies: channel floor deposits, deposits of tidal flats (s. s.) and marsh sediments.

The last significant group of siliceous elements of organic origin is formed by *minute spicules of opal*, with cross sections of only about 5 $\mu$. They are always of straight shapes and do not seem to possess axial canals like those of the (much coarser) sponge spicules. Mostly they are terminated by irregular (fracture?) surfaces. These spicules are very evenly distributed in all kinds of deposits (channel floor-, tidal flat- and marsh sediments, sticky clays and in lagoon- and swamp deposits). In some cases (*Hydrobia* clay at Velzen) such forms are apparently derived at least in part, from silicified remains of *Phragmites communis.*

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## VIII. MICRO-STRUCTURES AND MICRO-TEXTURES

### A. Introduction

Important conclusions regarding the manner of formation of the tidal flat sediments can be drawn from their structures, textures and fabrics [1]. The large scale structures, which can be studied only in the field, such as unconformities, wash-outs and megaripple-bedding, will not be treated in this paper. The minor features, the study of which is done on core samples, with the naked eye or with the aid of a binocular microscope, are dealt with later (Ch. IX). The present chapter gives some results of the investigation of still finer details, visible only in thin sections. Over 200 slides were prepared, chiefly of muds and clays.

### B. Method of preparation of thin sections

The method used for the preparation of the slides was as follows: Small blocks of about ½ × 2 × 2 cm were cut out of the (partially dried) sediment of undisturbed core samples, and carefully enveloped in thin wire gauze. They were then dried completely and, subsequently, immersed in a solution of canada balsam and shellac, at 170°C. The impregnated blocks were ground on glass plates, in the ordinary way (see e.g. WEATHERHEAD, 1947). It was found that this method gave generally very good results for muddy and clayey material. No good slides were obtained for the more purely sandy and the coarse grained sediments. Since the structural and textural properties of these latter could be studied already quite satisfactorily by direct examination with a binocular microscope (see Chapter IX), the above mentioned manner of preparation was preferred over other, more elaborate ones.

### C. Distribution of sand grains in muds

It was mentioned before (Chapter II) that, for a good understanding of the grain size distributions in the tidal flat deposits, it is necessary to take into consideration also their structures. Muds which, in the original wet state, may have the appearance of completely homogeneous mixtures of clay and sand material, show, after drying, frequently an alternation of thin laminae of mud and sand. The grain size distributions of the separate sand laminae may differ greatly among each other. As to the mud laminae, it appears from the examination of thin sections that normally they do not consist of clay substance alone, but contain sand as well (Fig. 20, No. 157, 167, 70, 150). The amount of psammitic material may vary between very

[1] It should be noted that the terms *texture, structure* and *fabric* are used in this paper as defined by modern American authors. In earlier papers by the present author they have been employed according to their original meaning as defined by ROSENBUSCH.

little and very much. A decrease in sand content is often observed from the base of the mud laminae towards the top. All grain sizes may be found, but the mean size of the sand particles, enclosed in the mud laminae is in general smaller than that of the intervening sand laminae (Fig. 20, No. 167).

Whereas no upper grain size limit of the sand grains in the mud laminae is found, a distinct lower limit is observed for the particles of the sand laminae, viz. at about 40 $\mu$. When the current velocities in the water have diminished so far that sand grains of smaller sizes than 40 $\mu$ are deposited, the bulk of the mud is laid down at the same time (cf. Ch. IX, B, 2). This is probably partly due to the flocculating effect of the electrolytes dissolved in the sea water. In brackish[1] or fresh water sediments this lower limit lies at smaller values: down to 20 $\mu$ and less.

The mud of faecal pellets is often very poor or even altogether lacking in sand grains (Fig. 20, No. 70). The organisms, which produce these pellets, either suspension- or deposit feeders, take up only the finest material.

### D. Fabric of mud laminae

A difference is found between the fabric of most muds of fresh- or brackish water origin and that of the normal Wadden muds. The first are characterised, in general. by a highly parallel orientation of mica flakes, organic debris and other constituents of flattened or elongated shapes, each of them having been deposited individually (Fig. 20, No. 76). In the muds of the Wadden Sea this parallel orientation is less pronounced. A preferred orientation of the flakes of micas and clay minerals parallel to the bedding planes is practically always present as is seen by using the gypsum blade between crossed nicols, but the mean deviations to both sides from this direction are usually much greater. The cause is that the major part of the Wadden muds has been formed by sedimentation of floccules, granules and faecal pellets, in which the separate flakes have a more or less random orientation (Fig. 20, No. 157, 167, 70). These larger elements have usually been pressed together, after deposition, to a homogeneous mass, so that their original outlines have been obliterated altogether. Firm faecal pellets, however, may be preserved without change of shape (Fig. 20, No. 70).

### E. Coating of sand grains

It was mentioned in Ch. V (C) that the sand grains in the superficial and most recently deposited sediments (L- and M-zones) of channel floors and tidal flats, are usually covered with specks of iron hydroxides and sulphides. In the older and deeper (P-) sediments of the same environments, only occasional minute crystals of pyrite adhere to the surface of the grains. Apart from these specks and crystals the surface of the sand grains normally appears to be quite "clean". The grains in marsh sediments, on the other hand, at least those in the more clayey parts are often entirely surrounded

[1] e.g. on landward parts of the Braakman marshes, Zealand (Pl. 11, No. 142); in sticky clays of Westergoo, Friesland (Pl. 10, No. 18); in the sapropelitic sediments, underlying the marsh clays of Westergoo (Pl. 10, No. 20) in the deposits of the former Zuiderzee and its beginning stages of the "Sloef" (Pl. 10, No. 23) (cf. MULLER en VAN RAADSHOVEN, 1947, EDELMAN, 1950); in many "Old Sea Clay" deposits (Pl. 10, No. 24), in the Hydrobia clay at Velzen (N. H.) etc.

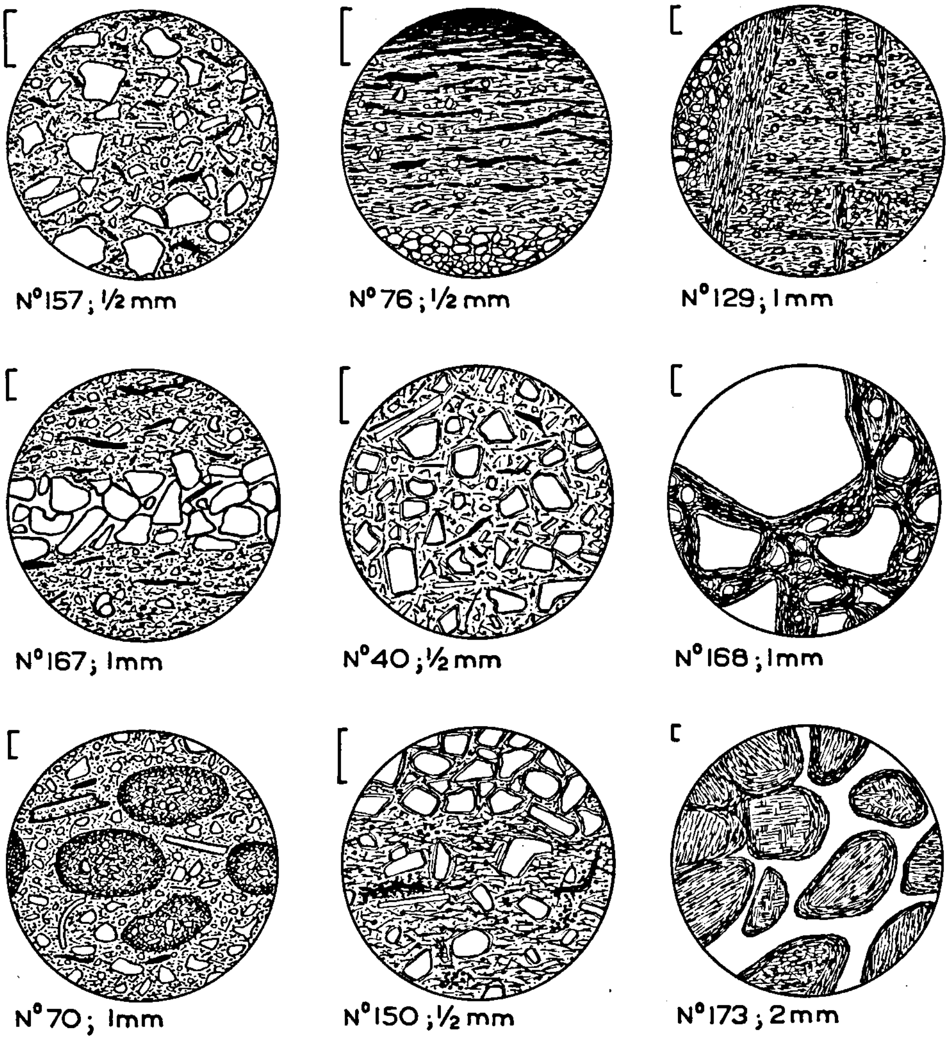


Fig. 20. Drawings (somewhat idealized) from thin sections of sediments of Wadden Sea area (1 nicol). The real diameters are given below the figures. The length of the vertical lines in the upper left corners of each figure is 100 $\mu$.

**No. 157.** Newly deposited mud from channel floor, Slenk, Lauwerszee, water depth 6.35 m — N. A. P. (Dutch Ordnance Datum); sample from 75 cm below surface (= 7.10 m — N. A. P.).

**No. 167.** Newly deposited mud from outer tidal delta, Plaatgat, 4 km N. of N. W. corner of Schiermonnikoog, water depth 7 m — N. A. P.; Core 77 (see Pl. 11); sample from 40 cm below surface.

**No. 70.** Newly deposited mud from low tidal flat, Blikplaat, Lauwerszee; sample from 65 cm below surface.

**No. 76.** Brackish water clay; "Old Sea Clay" with intercalations of peat, forming substratum of recent Wadden Sea deposits; Tidal flat W. of West Polder (Lauwerszee). Sample from 140 cm below surface, or 20 cm below top of "Old Sea Clay".

**No. 40.** Brackish water clay: "Old Sea Clay", from Panser polder, N. W. of Zoutkamp (Prov. of Groningen). Sample from 65 cm below surface.

**No. 150.** Brackish water clay: "Old Sea Clay", forming substratum of recent Wadden Sea deposits. Channel floor, Vlinderbalg, Lauwerszee, water depth 3.60 m — N. A. P. Sample from 60 cm below surface, or 25 cm below top of "Old Sea Clay".

**No. 129.** "Sticky Clay" (marsh clay), from Kubaard, Prov. of Friesland. Sample from 90 cm below surface.

**No. 168.** Glacial till, forming substratum of recent Wadden Sea deposits. Slenk, Lauwerszee, water depth 7.50 m — N. A. P. Sample from 70 cm below surface, or 10 cm below top of till.

**No. 173.** Fresh water clay, "Pot Clay" (Pleistocene), from floor of Zoutkamperlaag; water depth 14.80 m — N. A. P. Sample from 60 cm below surface.

For explanation of figures see text.

N.B. The orientation of the thin sections was vertical in all examples, given here.

by thin films of foreign material (cf. Fig. 20, No. 40). Microscopical examination of these coatings shows that they are composed of a birefringent substance (or substances), with moderately high refraction indices. The exact nature of the material(s) could not be ascertained owing to the very small thickness of the films: only up to 5 $\mu$. In recent marsh deposits they might consist of iron hydroxides, or humic iron compounds. Similar coatings are found, however, in pyritic sediments of the "Old Sea Clay" (Fig. 20, No. 150), which are in strictly anaerobic conditions and in which the presence of iron hydroxides seems most unlikely. Micaceous material or clay minerals (whether iron-bearing or not) may be responsible for the coating in these latter cases. It is possible also, that the films are composed of authigenous silica, mixed up with other material. Pure silica is not very probable, on account both of the refraction indexes and of the birefringent character.[1]

From the distribution in the recent Wadden Sea environment one would be inclined, perhaps, to suppose that the essential condition for the formation of the coatings is the position of the sediments above the ground water table: The phenomenon is restricted to the marsh deposits; the best developed films are often found near the base of the marshes; and they seem to be of greater thickness in old marsh sediments than in new ones. Now it is an interesting fact that the Old Sea Clay, in its typical brackish water facies, with abundant remains and negatives of reeds, shows the same coating phenomenon at all depths and in all thin sections which have been prepared (Fig. 21). A great part at least of these deposits must have been formed below the ground water table. It can hardly be assumed that all of them have passed (either during their formation, or afterwards by temporary lowerings of sea level) through stages in which they were lying above the ground water. It is much more likely that the coating of the sand grains has something to do with the brackish nature of the environment in which both these Old Sea Clay deposits and the recent marsh sediments were formed.

The phenomenon of the coating of sand grains has been given much attention by KUBIENA (1938). The character of the deposits on grain surface varies, according to this author, with the original state of division of these substances in the ground water. *Flocculated* complexes cannot spread, upon deposition, over the whole surface of the sand grains. "They are pulled either into the intergranular angles, or remain attached somewhere at some point on the grain surface." This corresponds to the deposition in "specks" of the iron compounds on the sand grains in the L- and M-zones of channel floors and tidal flats. *Peptized* and *suspended* substances become evenly distributed over the surface of the grains, although slight concentrations may be formed in the angles of the intergranular spaces, where the grains are pressed against each other. Since the nature of the coating material in the marsh deposits and in the Old Sea Clay seems to exclude the possibility of the formation out of suspended material, it must then have been originally present in a *peptized* state. As a matter of fact it is known that the material of brackish water clays is comparatively easily peptized.

[1] Not a single example was observed where the silica of diatoms etc. in the investigated sediments had become anisotropic. This is in accordance with the hydrophilous nature of the silica gels.

Another kind of sediment showing coating of sand grains is the so called "knip" clay ("sticky clay") well known for its poor agricultural properties. The clay shows a strong tendency towards peptization phenomena. VEENENBOS and VAN SCHUYLENBORGH (1951) who investigated the knip soils

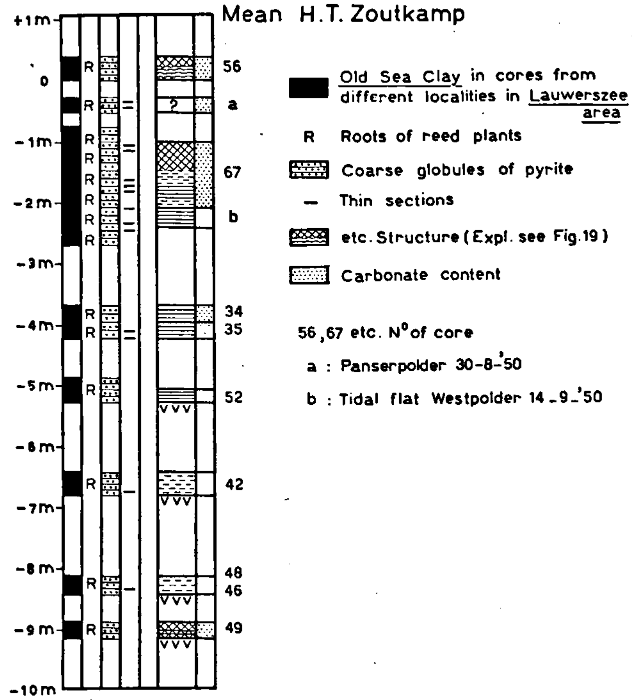


Fig. 21. Brackish water facies of "Old Sea Clay" in cores from Lauwerszee area.

of the northern parts of the Netherlands came to the conclusion that this ready peptization was presumably due for the greater part to the brackish water origin of the clay, which brought about a much greater amount of adsorbed Na-ions and a smaller amount of adsorbed Mg-ions than is found in purely marine sediments.

## F. Other types of structures and textures

The above mentioned "knip" clays show a type of structure, pictured in Fig. 20, No. 129. It is characterized by the presence of planes of sub-parallel mineral flakes, transsecting the mass of the clay in all directions. The planes look like slickensides and must be of more or less related origin. Owing to their peptizability, the knip clays are very fluid in wet seasons, but dry out to stone-hard pillars, blocks and granules in periods of aridity. It is easily understood how the peptized clay material is smeared out over the sides of the fissures originating during the preceding dry periods.

The fabric with coated sand grains should not be confused with that of certain glacial tills (Fig. 20, No. 168), in which the elements of the clayey matrix show a preferred orientation with their long axes parallel to the surfaces of the enclosed sand grains. It is a purely mechanical phenomenon, due to internal movements of the material before the final deposition. It may be compared to the fluidal structures in eruptive rocks.

Another kind of "coating", although wholly different from that of the sand grains in brackish water clays, is shown in Fig. 20, No. 173. It was found in a sample from the surface of the pleistocene "pot clay", encountered in the bottom of the Zoutkamperlaag. This clay is of lacustrine origin. At a certain moment, possibly long after the original deposition, but before the end of the Pleistocene [1], it must have been eroded, whereby small clay granules were formed. By rolling around these granules became covered with loose clay flakes of the same composition and of the same origin, which adhered to their surface, in the manner of snow balls.

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[1] The clay is covered by sands of Pleistocene or early Holocene age.

## IX. MACRO-STRUCTURES

### A. Coring method and preparation of samples

Most data concerning the structures and the composition of sediments, recorded in this paper, are based on investigations of core samples. The cores were taken with brass tubes of a length of 1 and 2 m and with a diameter of 6 cm (Fig. 22). The thickness of the walls was 1,2 mm. The lower ends of the tubes were sharpened by grinding of the outer edges.

When a tube of this kind was pushed into the bottom, the compaction of the core was usually slight, or even zero, owing to the relatively wide inner diameter and the small thickness of the wall. In some cases, compaction of the cores could be avoided by rotating the tube alternately to and fro, over a small angle. It would often happen, that a special state of settling of the sand grains prevented suddenly any further pushing down of the corer. Hammering on the upper end of the tube was, in such cases, mostly of no avail whatever. When, however, the corer was then given a rapid succession of alternating short pulls and pushes, it usually could be made to slide down into the sediment without too much difficulty.

After forcing the tube into the bottom, the space remaining above the core was filled up with water and closed off by a brass lid with a disc of rubber on its lower side. The tube was then pulled up, and, in consequence of its being entirely filled with sediment and (not expanding) water, the whole core was drawn up with it. After removal of the disc, the core slid out, either by its own weight, or helped by tapping on the outside of the tube, or by pushing with a "core-pusher". Cores of clayey or muddy composition were as a rule easily pushed out of the tubes. For sand, the best results were obtained with the tapping method, either or not combined with gentle pushing. Pushing alone, without tapping, resulted frequently in the pressing of the sand grains sideways against the walls, so that the cores became quite inextricably fixed in the tubes and had to be washed out with water.

The investigation of channel floors was done with a corer, the lid of which closed automatically when the apparatus was pulled upward. It was let down by means of iron rods, instead of by ropes or cables. In this way it was possible to exert the required pressure for the pushing of the tube into the bottom and to record the original orientation of the core samples.

In the dry or compact deposits of salt marshes it was mostly impossible to obtain core lengths of more than a few decimeters at a single push. Here, the cores had to be taken up in a few sections, until the level of the ground water was reached. Below this level, and in the soft deposits of the tidal flats and the channels, the coring could not be interrupted in this manner, since the bore hole would immediately sag together, both by the weight of the surrounding sediment and by the suction, exerted during the pulling up of the tube.

In the laboratory the cores were treated as follows: with the aid of small steel trays, $5 \times 7\frac{1}{2}$ cm$^2$ area and with upstanding edges of $1\frac{1}{2}$ cm, pieces were taken out of the cores. These pieces were cut through with a wet knife, in such a manner that the resulting cakes protruded about ½ cm above the edges of the trays. They were then heated on a small electric stove, until a half-dry state was reached, whereafter a thin layer was shaved off

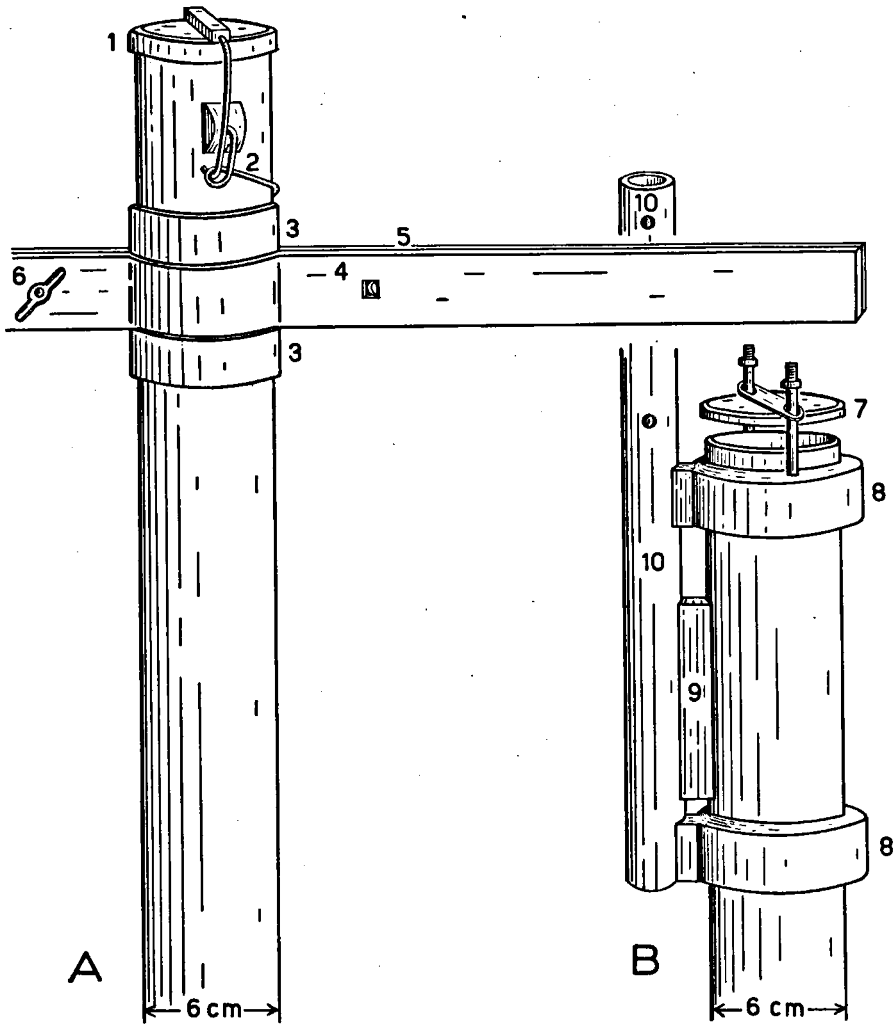


Fig. 22. Coring tubes. A: used on land and tidal flats; B: used for channel floors. 1,7. Brass lid with thick rubber plate; 2. Closing gadget; 3,8. Brass rings, soldered on tube; 4,5. Pair of iron bars, fitting around tube; 6. Winged nut, for fixing of bars; 9. Piece of brass to permit fastening of iron bars (4,5), when used for boring on land; 10. Hollow brass rod for fastening of first extension piece.

from the surface, by means of a safety razor blade. The structures appeared in this way in every detail. The degree of drying was most essential. If accomplished insufficiently, the clayey material would be smeared out by the razor blade, and the details of the structure would remain invisible. The drying could, on the other hand, not be prolonged too far, or the samples would crack and the colour difference between parts of slightly differing clay content would largely disappear.

It was found that some of the finest features could be observed only by making photographs of the half-dried samples. The photographic films are apparently of greater sensitiveness for the contrast clay—sand than the human eye.

Apart from the macroscopical analysis of the structure, the samples were investigated under a binocular, for the determination of the grain size distribution in the separate sand laminae [1], for the examination of microfossils etc.

## B. Laminations of tidal flat and channel deposits

1. *Distribution and general character of laminations* (cf. HAENTZSCHEL, 1936). The chief sediments in the Wadden Sea and estuarine channels are sands, muddy sands, muds and shell beds (Ch. II). The sand occurs in beds of greatly varying thickness: up to several meters in the thickest beds and down to less than a millimeter in the thinnest laminae, which are intercalated in muds. The mud is deposited in laminae which range between a few centimeters and fractions of a millimeter. Laminae which are composed mainly of finely divided peat detritus are also met with. Mostly they are not more than a few millimeters in thickness.

Laminated deposits of these types are not restricted to the channel sediments. They are likewise found on the tidal flats and on the floor of marsh creeks. They are of much greater abundance on the lower parts of the tidal flats than on the higher parts. In the latter places the laminations are usually disturbed, after the deposition of the sediment, by the work of burrowing organisms (cf. p. 83).

The sand laminae, considered separately, may show ripple structures, either of wave ripples (tidal flats, Pl. 8, fig. 19) or of current ripples (Pl. 9, fig. 20, 21) (floor of channels, gullies and creeks, and on tidal flats). The greatest numbers of ripple structures are always found in the channel deposits (current ripples).

The laminations are of a sublenticular character. Correlation of the detailed succession of the laminae between two sections becomes already impossible with a distance of only a few or even one meter. The regularity, known e.g. from varved glacial clays, in which the separate laminae may be traced over distances of many kilometers, is completely absent.

2. *Origin of laminations. Sand laminae* are the product, either of sedimentation or of residual concentration of sand out of original mud-sand mixtures. The processes take place under the influence of tidal currents or (on the flats) of the oscillating movements of the water due to waves, or to combinations of these two. The maximum velocity of the oscillating water

[1] The rather inaccurate determination of the grain sizes of the separate sand laminae under the binocular microscope is sometimes of more value than the accurate determination of the grain size distribution of bulk samples, taken up by grab samplers. The median diameter of such a bulk sample depends, among other things, on the thickness of the mud laminae deposited at the turn of the tides, which may vary by quite accidental causes, such as differences in the quantities of mud suspended in the water. The grain sizes of the separate sand laminae, however, give more direct information concerning the strength of the currents by which they were deposited.

particles along the bottom is often greater than that of the tidal currents. Even when tidal currents themselves are of insufficient strength to move sand grains, they may produce a considerable transport of sand if only combined with wave action (cf. LUEDERS, 1935).

The deposition of *mud laminae* takes place chiefly in quiet water conditions. Nevertheless, the water in the Wadden Sea need not be as tranquil as is required for the sedimentation of wholly dispersed mud in fresh water. Several factors are responsible for this enhanced deposition (cf. BOURCART and FRANCIS-BOEUF, 1942; FRANCIS-BOEUF, 1947; REINHOLD, 1949):

a) The dissolved electrolytes in the sea water bring about the flocculation of the smallest particles;
b) Certain elements of the microplankton, especially diatoms, tend to stick together, so that flakes are formed in which suspended clay and silt particles get caught;
c) A large part of the transported mud has passed through the intestines of invertebrate organisms, where, by secretion of a binding substance and by compression, more or less compact faecal pellets are formed (cf. SCHWARZ, 1932);
d) A part of the mud is derived by erosion from older mud and clay beds and forms particles of all grain sizes.

The sedimentation of the fine grained mud occurs mostly during the turn of the tides. Structures analyses of oriented cores from channel floors, in which current rippled sand laminae alternate with mud laminae, make it probable that such deposition occurs both during high water- and low water slack tides. It is possible, moreover, that, on the upper parts of convex banks of meanders, deposition of fine muds takes place also during the stages when the currents in the centre of the water courses are of great velocities. In the thin water cover on these banks only weak currents are present, but much suspended mud may be whirled on from the deeper, swiftly flowing water nearby.

In whatever way the fine grained mud may have been deposited, there will almost invariably have preceded a stage of stronger water movement, giving rise to a sand lamina. A more or less gradual transition in grain size from coarse sand below, via fine sand, to a covering deposit of mud might be expected. Graded bedding of this kind is found, but it is comparatively rare and *sharp boundaries* between sand laminae and the overlying mud laminae are the rule. This is sometimes the result of a hiatus in the available size grades, as appears from thin section analysis of laminated sediments. More usually it is the result of the flocculated or granular state of the mud. When the current velocities drop below the value at which material of 40 $\mu$ is no longer transported (3 mm/sec, according to HJULSTROEM), the bulk of the mud is deposited together with the rest of the sand or silt (cf. Ch. VIII)

Just as stages of relatively weak water movements, favouring the deposition of mud, are generally preceded by stages of stronger motion in the water, they are also succeeded by such stages. The erosion, starting when greater current velocities set in, may be followed immediately by sedimentation of freshly supplied sand on top of the mud, thus preserving it from further erosion. But other factors are involved as well in the preservation of newly formed mud laminae:

a) The "HJULSTROEM-effect": The minimum current velocity required for the erosion of loose sediments is always greater than the maximum velocity at which sedimentation can take place. The difference between these two critical velocities increases with decrease of the grain size of the bed material. Fine mud will therefore be relatively difficult to remove.

b) Compaction. The mud compacts under the influence of its own weight, the contained water being expelled upward. In every fresh mud layer, there is a considerable decrease of water content downwards. Although certain currents may be strong enough to erode the upper parts of such mud, they may be insufficient to remove also the lower portions.

c) Drying out. Mud which has been dried out superficially during the stages of emergence of the flats has acquired an increased resistance towards erosion. The places, where this drying is most active, are to be found on the edges of the banks along gullies and channels, because of the sinking of the water table below the surface (cf. VAN STRAATEN, 1951b, Fig. 9).

d) Benthonic diatoms (cf. HECHT und MATERN, 1930, LINKE, 1939, a. o.). The mud bottom of the flats often derives part of its usual brownish colour from a thin coating of benthonic diatoms. Because of the need of sufficient sunlight for their $CO_2$-assimilation, these organisms can live only on the surface. If sedimentation takes place, the diatoms quickly work their way through the new deposit to regain their original position on the surface. Since they secrete a binding slime, a notable cohesion of the superficial mud layer ensues. Where this superficial layer is torn, e. g. by bird's feet (VAN STRAATEN, 1951b, Photograph 12), one often notes how it is curled up along the edges of the ruptures like pieces of cloth.

## C. Marsh laminations

Marsh laminations (cf. HAENTZSCHEL, 1936) are characterized by the somewhat undulating, nodular aspect of the laminae (Pl. 7, figs. 15, 16). It is due to the fact that the marsh surface, on which the successive laminae are laid down is not so smooth as the "subaqueously" formed tidal flat and channel floor surfaces. Whereas the latter are continuously smoothed out by wave and current action, the marsh surface acquires an uneven character by the drying out during the long intervals of exposure to the atmosphere. It is true that the tidal flat and channel floor surfaces are often rippled, but the stoss sides and the lee sides of the ripples themselves are again quite smooth. The irregular thickness of the marsh laminae is also due to the presence of the marsh plants, which cause an unequal distribution of the newly deposited material.

The marsh laminations hardly ever show sub-structures of current- or wave ripples. The formation of such ripples is generally rendered impossible by the obstructing influence of the plants.

It will be seen later that the stratification of the high tidal flat deposits, lying underneath the marsh sediments, is mostly highly disturbed by burrowing marine animals. The marsh deposits themselves are normally practically free of these organisms. The result is that the base of the marshes is usually marked by a sharp change in sediment structure, from the more or less homogeneous material below to the well preserved laminations above (see Pl. 5, fig. 9).

### D. Beach laminations

The tidal inlets are bordered by sandy beaches, which are very similar to those on the North Sea side of the barrier islands. Only few data were collected concerning the structures of these beach deposits. They pertain exclusively to the upper foreshore and backshore parts.

Apart from ripple laminations, due both to subaqueously formed ripple marks and to wind ripples, a fine parallel stratification was often found, in which the separate laminae were very even and of uniform thickness over considerable horizontal distances (see also: EMERY and STEVENSON, 1950, MACKEE, THOMPSON, 1937). These laminae consisted of sands of different grain sizes and frequently also with varying amounts of heavy mineral grains (Pl. 6, fig. 11). Mud laminae are normally absent.

The heavy minerals are sometimes concentrated in such quantities that they make up more than 90 % of the total. The enriched layers are relatively fine grained. The average grain size of the chief minerals decreases in the following order: quartz (and felspar), epidote, garnet, opaque minerals, zircon (cf. DE VRIES, 1949). The grain size of the quartz corresponds more or less to that of the normal beach sands.

It seems that heavy mineral concentrations of this kind are mainly found, along the Dutch coast, at those places where the shore is cut back by erosion, due to waves and currents (see also CROMMELIN en SLOTBOOM, 1945, LAMCKE, 1937, 1938, TRUSHEIM, 1935, DE VRIES, 1949). They are usually best developed on the highest parts of the beaches, at the foot of cliffed sand dunes.

### E. Brackish water laminations

In a number of corings in the Westergoo area (Prov. of Friesland) a special kind of brackish water sediment was met with, underlying the marsh deposits. It consisted of very clayey material, which shrunk together considerably upon drying. Although in some samples no particular structure could be observed at all, other parts showed a very minute lamination, of a type which seemed to point to deposition in a quiet body (or bodies) of water (Pl. 9, fig. 22). The laminae were alternately composed of clay and of comparatively pure, clay-less silt, with grain sizes of 20 to 40 $\mu$. The presence of these latter make it probable (see Ch. VIII) that the water in which the clay was deposited, was brackish. Other data support this hypothesis: the large quantities of ostracod valves which are enclosed and the character of the foraminifera (investigation by J. VAN VOORTHUYSEN, Report of Geological Survey at Haarlem, not published).

Similar fine laminations, with the same clay-less silt laminae, were encountered in other brackish water sediments, e.g. in the deposits of the former Zuiderzee and in the "Old Sea Clay" formation. It seems that they constitute a rather characteristic feature of such deposits.

A comparable structure is that of the "sloef", a deposit which has been formed in the beginning stages of the Zuiderzee (MULLER en VAN RAADSHOVEN, 1947, EDELMAN, 1950, MIDDELHOEK and WIGGERS, 1953). Although it is much poorer in clay, the chief components being silt and very fine sand, it shows laminations which are not less fine and even than those of the above mentioned sediments (Pl. 9, fig. 23).

It should be stressed, finally, that all these fine laminations may show occasional small scale cross bedding structures, intercalations of ripple-bedded sediment and disturbances of the stratification due to burrowing organisms etc.

**F. Current ripple structures**

The most characteristic property of the channel deposits in the Wadden Sea is formed by the abundance of current ripple structures. To give rise to such a profusion, it is necessary, not only that ripples are formed in great numbers, but also that they have the chance to be preserved by rapid burial under new sediments. Both conditions are fulfilled on the channel floors, which constitute the environment where the tidal currents are strongest and of the longest duration and where the highest rates of sedimentation are attained (see Ch. I, B).

Current ripple structures are visible, mostly, by the different composition of the successive laminae deposited on the lee sides of the ripples. These inclined laminae may consist alternately of coarser and finer sand, or they may differ in clay content. A relatively greater percentage of clay material is often caused by a less turbulent state of the water. In other instances, however, the movements of the water were stronger during the deposition of the dark laminae, rich in clay, then during the formation of the light coloured laminae. This is due to the circumstance that the clay material of the current ripples is often in the state of faecal pellets or of small fragments of eroded mud and clay layers, which may be both larger and heavier than the sand grains. The sand which is deposited together with these clay fragments, in the relatively dark coloured laminae, is, accordingly, somewhat coarser than the average. Apart from such coarse sand grains, the laminae frequently show a concentration of particles of peat detritus, tests of foraminifera, spines of echinids, etc. The largest elements are mostly found near the base of the lee slopes of the ripples.

By noting the original orientation of the cores it could be deduced which current ripple structures had been formed by ebb currents and which by the currents of the flood. Sometimes "herring bone patterns" were found, pointing to an alternating deposition of sand by ebb- and by flood currents. More commonly, however, the sedimentation by one of the two dominates more or less strongly over the other, for instance ebb sands on the landward side of convex bends of channels, or in "ebb channels" (see p. 15) and flood sands on the seaward side of the same bends, or in "flood channels".

The current ripple structures are usually cut off by erosion on their upper sides (cf. Pl. 9, fig. 21). These erosion surfaces may be quite flat, or they may be gently curved or undulating. Cases in which the ripples have been preserved entirely are much less frequent (e.g. VAN STRAATEN, 1951b, Photograph 10). They are then mostly covered by a comparatively thick deposit of mud.

In sandy channel sediments the current ripple laminations are often the only structure elements which are visible. Yet, it is not so, of course, that each bed or lamina of channel sands necessarily shows these ripple laminations. It is frequently seen that the sands are free of such structures over core lengths of many decimeters.

Current ripple structures are encountered also in the deposits of tidal flat gullies and of marsh creeks, although in the average less abundantly than in the channel sediments. The surface of the tidal flats is likewise very commonly covered with current ripples. In accordance with the low rate of accretion they are however comparatively seldom preserved in the sediment. No current ripple structures have been found, up till now, in the deposits of the marshes (s. s.).

### G. Wave ripple structures

Cross sections of newly formed wave ripple marks may show various types of structure. Sometimes these are symmetrical, the sand laminae being thickest under the ripple crests and thinnest, or wedging out altogether, in the troughs. The coarsest grains are, in these cases, usually concentrated in the crests. The mud laminae show a thickening, either in the crests, or, more usually, in the troughs. Combinations of these different possibilities are also encountered.

Other wave ripples show distinctly asymmetrical structures, which are hardly or not at all distinguishable from those of current ripples. All transitions are found between the latter and purely symmetrical structures. The symmetry or asymmetry of the ripple structures corresponds as a rule to that of the ripple shapes, but exceptions are also met with, e.g. symmetrical ripples with asymmetrical structures.

In numerous instances, meanwhile, the wave ripples consist of pure sand in which no trace of minor laminations can be detected. They can then be recognized only if they are of pronounced symmetrical shape, or if they show characteristic relations between wave length and height (cf. VAN STRAATEN, 1954a).

No difference in structure is seen between the cross sections of true wave ripple marks and those of the longitudinal wave current ripples (Pl. 8, fig. 19) (VAN STRAATEN, 1951a). Both types of ripples are mainly produced on the lower parts of the tidal flats.

### H. Structures of mud pebble beds

The mud pebbles in the Dutch Wadden Sea are mostly of flattened shapes, with more or less oval outlines (see also HAENTZSCHEL, 1936, RICHTER, 1922, 1924). They frequently show imbricate arrangements, with inclinations directed upstream. Spindle-shaped mud pebbles are much less common. They have been found in gullies, lying with their long axes parallel to the currents, and on the sand beaches of the Borndiep, the tidal inlet between the islands Terschelling and Ameland. In the latter case they were derived from clay beds, cropping out on the beach and had acquired their elongated ellipsoidal shape by rolling up and down the slope with the swash and backwash.

### I. Structures of shell beds

The floor of the channels and gullies is often paved by residual concentrations of washed mollusc shells. The valves lie for the greater part with their convex sides upward (cf. LUEDERS und TRUSHEIM, 1931, RICHTER, 1922, 1942) and form usually imbricate structures (see also HAENTZSCHEL, 1936). Oblong shells like those of *Mytilus edulis* may show a preferred orientation with their long axes parallel to the current.

Concentration of shells is also caused by the action of waves, viz. on beaches. Here, a pronounced orientation is sometimes observed of the oblong valves of *Mytilus edulis* parallel to the slope of the beach, i.e. parallel to the alternating currents of swash and backwash (VAN STRAATEN, 1950). This orientation is then at right angles to that of the spindle-shaped mud pebbles, also encountered on beaches (see above). The position of the latter corresponds, however, essentially to their rolling motion, the pebbles being transported up and down the beach with the slightest movement of the water. The *Mytilus* shells, on the other hand, acquire their most stable orientation when lying with their convex sides turned upwards, the sharp edges of the valves resting on the bottom, so that they are in more or less fixed position. The two positions might perhaps be referred to as kinetic and static.

The orientation of the mollusc shells is not always predominantly convex-upward. Accumulations, in which the greater part of the valves has been deposited convex-downward, may be encountered in the seaward parts of marsh sediments. The valves lie sometimes nested conformably in each other (HAENTZSCHEL, 1936). Up to 5 valves, belonging to one (e.g. *Mytilus edulis*) or more species (e.g. *Cardium edule* and *Macoma balthica*) may be assembled in this manner into a single packet.

The phenomenon of the "nested" arrangement is not limited to loose valves. An interesting example of closed shell *pairs*, enveloping each other, was found in the lower peaty clay which covers the younger tidal flat series in the excavation at Velzen (N.H.) (VAN STRAATEN, 1954b). The shell bed has been formed, in all probability, on the floor of a shallow brackish pond. It was chiefly composed of small bivalves of *Cardium edule* and of *Macoma balthica*. The shells pairs, mostly two or three together, fitted rather closely into one another.

The orientation of loose valves with their convex sides downward was also (rarely) observed on the beaches of the barrier islands, bordering the North Sea and the tidal inlets. These cases seem to be due to the effect of a gentle swash. Out of a deeper zone, with a more random orientation of the shells, only those valves are taken up by the weak water movements, which were lying on their convex sides. During the transport this orientation remains unchanged. Part of the valves are transported by traction over the bottom, another part is carried floating on the water surface. With the beginning of the backwash the thickness of the water sheet diminishes rapidly down to zero, both by the seaward flow at the surface and by the soaking of water into the sand, and the shells are left on the beach in their reversed position.

A special kind of shell-concentration takes place in the case of the "*Hydrobia*-beds" (VAN STRAATEN, 1952). These beds are rich in the tests of *Hydrobia ulvae*, but contain also varying amounts of larger mollusc valves. They are found at different levels above each other. The uppermost one, situated at depths of 20 to 30 cm below the surface of sandy tidal flats, is present in wide areas throughout the Wadden Sea. Similar shell beds were encountered in the estuary of the Easter Scheldt. It seems very probable that the shell concentration is, in most cases at least, the result of the activities of the lug worm, *Arenicola marina*. This animal, which inhabits the sand flats in enormous numbers (Pl. 4, fig. 7), swallows sand, at a level of about 20 to 30 cm below the surface (Fig. 24). After digestion of the nutritive admixtures, the sand is pushed back on the surface in the shape of loose castings, which are disintegrated and spread out again over the flats by the action of waves and currents. The sand describes, therefore, a complete circle. The shells and the other coarse materials, sinking down along the feeding shafts, together with the sand [1], are not swallowed by the animal and move only in a downward direction. They thus become concentrated in a separate bed, with a thickness of one to several centimeters. Numerous facts support this hypothesis, e.g. the low content of broken shell material (in contrast to that in the concentrations formed by waves or currents), and the malacological composition of the beds, which corresponds closely to the mollusc assemblages living at the same localities.

The *Hydrobia* beds are characterized by a pronounced gradation of the grain sizes, from fine material at the base (mostly *Hydrobia* shells and peat detritus) to coarse material at the top (e.g. bivalves of *Cardium edule*). The finer elements have sunk through the openings between the coarse materials. No special orientations, such as convex-upward or with subparallel longer axes, are found in these beds, nor imbricate positions of the valves.

## J. Load casts

Structures due to the sinking down of sand masses into the underlying mud are not at all rare in the muddy channel deposits. SHROCK (1948) has called these features "flow casts", but KUENEN (1953) later suggested "load casts". They occur also in the muds of the low tidal flats. Usually they are of rather irregular appearance. In some cases it is seen that the base of rippled sand laminae, which must have been approximately flat at the time of deposition has become undulated by the sinking down of the sand at the places of the ripple crests, the top of the sand laminae thereby becoming more or less flattened out.

The observed structures were always of comparatively small dimensions, not exceeding a few millimeters. Large sand balls like those found in fossil deposits (e.g. the Psammites du Condroz in the Belgian Ardennes, (cf. VAN STRAATEN, 1954a) have not been met with, up till now, in the Wadden sediments. Load casts, which may be compared to these fossil forms, both in size and in internal structure, have been noted, however, in the "sloef" deposits in the former Zuiderzee area (MACAR, 1951).

## K. Slump structures

It would seem likely, on account of the muddy composition and the steep inclination of many channel banks, that slump structures are of rather common distribution in the Dutch tidal flat sediments. The actual occurrence of large-scale sliding phenomena, damaging embankments, has, in fact, been noted both in the Wadden Sea area and in the estuaries in the province of Zealand. Minor slumpings and collapse phenomena occur regularly on the sides of ebb gullies in tidal flats (cf. HAENTZSCHEL, 1938, a). No unambiguous examples of slump structures have, however, been found by the author in core samples or in exposures in recent marine sediments along the Dutch

[1] The sinking movement of these larger elements is proven by the sediment structures (Fig. 25).

coasts [1]. It must be admitted that it is somewhat difficult to form an idea about their real distribution. Many of the large. scale structures, unless they show minor foldings and corrugations, may remain unnoticed in the core samples, which have a diameter of only 6 centimeters. Excavations in the older deposits of reclaimed areas, where large sections of the sediments can be studied, are rare. On the other hand, it should be borne in mind that most slumping phenomena will take place on those sides of channels and gullies, which are cut back by erosion. This involves that, in many cases, the slumped masses themselves will also be removed by the currents.

## L. Normal desiccation cracks

Shrinkage cracks, resulting from the desiccation of muds and clays are a very common feature in those parts of the Wadden Sea area, which lie above, or slightly below mean high water level. They are especially found in the floors of salt pans and on the highest parts of muddy tidal flats, bordering the marshes. They are not limited to horizontal surfaces. The vertical faces of marsh cliffs show these cracks as well.

The cracking may be "complete" (cf. SHROCK, 1948), so that the whole surface is divided into separate polygons, or it may be "incomplete", with most of the fissures wedging out laterally in the mass of the mud or the clay, before abutting against each other. Sometimes combinations of the two are formed: a system of first order cracks of the complete type separating polygons which are incompletely cracked by fissures of a second order. Cracks of the same order form mostly comparatively regular patterns, with polygons, which are dominantly of about the same size, generally ranging in diameter between a few centimeters and a few decimeters (Pl. 2, fig. 3).

The fissures have depths of up to several centimeters, their width varying from a fraction of a millimeter to 1 or 2 centimeters. They may be filled up with mud or with sand. It is sometimes seen, moreover, e.g. in salt pans which have become dry by evaporation of the water, that small gastropods have assembled in great numbers in the upper parts of the fissures, searching for the last traces of moisture (*Hydrobia ulvae* in the Wadden Sea, *Littorina saxatilis* on Scolt Head Island, Norfolk etc.).

## M. Mud cracks of subaqueous origin

It has been mentioned before (p. 20 and VAN STRAATEN, 1954a), that mud cracks can develop both by exposure to the atmosphere and by processes which are active under a permanent cover of water. The sand filled fissures due to the latter kind of cracking, which are found in muds of channel floors, present a somewhat different character from that of the desiccation cracks of marsh areas. The patterns are mostly less regular and vey often of the incomplete type (Pl. 6, fig. 12). The fissures are of comparatively small dimensions, not more than a few millimeters wide, not more

[1] The structure which has been illustrated in Photograph 9 of the paper: Texture and Genesis etc. (VAN STRAATEN, 1951b) may be the result of slumping, but, since it was encountered in a channel where much fishing was being done with the aid of drag nets, it may as well as be of artificial origin.

than 1 to 3 centimeters deep, and at the most a few decimeters in length. Normally they have straight or gently curved forms, with smooth walls. Serrated cracks seems to be rather rare. Downward they wedge out sharply. The fillings are sometimes folded by differential compaction and may resemble ptygmatic veins in crystalline rocks.

Although the possibility of cracking of certain muds by shrinking processes, taking place under a permanent cover of water has been proven, e.g. by JUENGST (1934), the present author still feels greatly reluctant to assume a similar origin for the fissures in the Wadden muds. Yet it seems very difficult to account for them otherwise than by shrinking phenomena. The patterns of the cracks are much too irregular to be compared with systems of ice crystal imprints (cf. HAENTZSCHEL, 1935, SHROCK, 1948). Tension cracks, formed in sliding or creeping masses of mud, are of a far more parallel orientation. The sharp-edged downward terminations of the sand filled fissures preclude the possibility of an origin by benthonic animals creeping along the surface of the muds.

Some of the fissures could perhaps have been formed by temporarily deposited mollusc shells, which cut with their sharp edges into the bottom. By traction over the channel floors these shells could even produce comparatively long fissures. As a matter of fact, several of the cracked mud beds are directly overlain by shell beds. The patterns of the cracks seem, however, to be of another type than what could be expected if this phenomenon was solely responsible. Although it might be possible that the cracking was initiated by the cutting by these shells [1], it appears that the major part of the fissures must have been formed in another way. The fact that they are frequently found in muds underlying shell beds may, apart from the possibility of the initiating by cuttings due to mollusc valves, have something to do also with the following circumstances. Many of these shell beds can be considered as basal conglomerates, i.e. they have been deposited on the floor of channels which were freshly scoured out in older sediments. The latter are characterised by a more or less advanced state of compaction for the muds, which, in any case, must be far more favourable for the development of cracks, than the soft conditions of recently deposited mud layers. It is also possible that the cracking is caused by changes in the composition of the water. During periods of non-deposition the mud of the channel floors, whether covered by a shell bed or not, will have been exposed to the influence of considerable variations in salinity of the water, flowing in and out with each successive tide.

### N. Structures due to escaping or entrapment of air

Structures of sandy deposits, which are the result of the movements of air in the sediment, have been investigated by a number of authors: BAUDOIN (1949, 1951a, 1951b), EMERY (1944, 1945), JOHNSON (1938), KINDLE (1936), LARSEN (1936), PALMER (1928), SHROCK (1948), WOHLENBERG (1937) and many others. They are of different types: sand domes, cavernous sand structures and air holes (terms used by EMERY, 1945).

Air holes are formed by the escaping of entrapped air along separate

[1] Compare the initiating of subaerial shrinkage cracks by imprints of bird's feet, as described by SCHAEFER, 1954.

vertical channels, of 1 to 10 mm diameter. Their mouths may be sharp edged, or surrounded by raised rims, or widened into crater-like shapes (EMERY). They are of common occurrence on the beaches of the barrier islands, both along the North Sea and on the sides of the tidal inlets.

Sand domes are formed in the same environments, but are less frequently met with.

Cavernous sand, on the other hand is a most common feature. It is not restricted to the areas mentioned above, but is also found on sandy tidal flats, notably on those which border the broad beach plains at the ends of the barrier islands (Pl. 5, fig. 10). It is mainly formed in the vicinity of the high tide line, but may be encountered also at lower levels. Although a pure, sandy composition of the sediment offers the best conditions for the formation of this structure, the author saw typical examples also in laminated muddy sands, in the estuary of the Wester Scheldt near Ellewoutsdijk.

The cavernous sand structure has only little chance of being preserved in the fossil state. Unless the sand is cemented beforehand, the cavities will disappear sooner or later by compaction. No examples were found, in the Wadden Sea, of cavities at depths exceeding 30 cm. The lower cavities are usually considerably flattened. BAUDOIN (1951b) mentions examples from the French coast of repetitions of cavernous sand strata with more or less spherical bubbles in the top parts and flattened cavities at the base.

### O. Other inorganic structures of primary or secondary origin

The inorganic features described in the foregoing are far from being the only ones. Many other types of structure are observed on the surface of the tidal flats:

*Ripple marks* of other kinds than the normal current- or wave ripples, such as linguoid ripple marks and rhomboid ripples;

*Swash marks* and *foam marks,* mainly encountered on the sandy beaches along the tidal inlets;

*Rill marks* and *drag marks*;

*Gas pits,* e.g. those due to bubbles of $O_2$ adhering to the surface ($O_2$ liberated by the assimilation processes of benthonic diatoms);

*Ice crystal imprints*;

*Impressions of rain drops and hail stones,* etc.

Many of these structures may, after burial, be preserved in every detail, as is proven by the examination of bedding planes of fine grained fossil rocks. They are, however, mostly of so small relief that, in vertical sections, they are normally overlooked. To study them, it is necessary to start with the inspection of the bedding planes. Whereas this presents no special difficulties in the case of indurated sediments, which split comparatively easily along these bedding planes, it is often quite impossible for recently deposited soft material. No information can be given here concerning the preservation of these structures in the Holocene sediments.

### P. Burrows of Molluscs and shell pairs in the position of growth

Shell pairs of molluscs in the position of growth are found in the sediments of channel floors, tidal flats and marsh creeks. Their distribution, as observed by the writer in the Dutch tidal flat areas, is as follows:

TABLE 10

| | Channel floors | Low flats | High flats | Marsh creeks |
|---|---|---|---|---|
| *Barnea candida* | × | | | |
| *Zirphaea crispata* | × | | | |
| *Mya truncata* | × | | | |
| *Petricola pholadiformis* | × | × | | |
| *Mytilus edulis* | × | × | (×) | |
| *Scrobicularia plana* | × | × | × | × |
| *Paphia pullastra* | | × | | |
| *Mya arenaria* | | × | × | × |
| *Cardium edule* | | × | × | × |
| *Macoma balthica* | | × | × | × |

Of the species mentioned in Table 10, only *Mytilus edulis* belongs to the epi-fauna. The others live in burrows in the bottom. An abnormal case of *Cardium edule,* living *on* the surface, was noted in a marsh pool on the island of Schiermonnikoog. The shells of these animals were very thin (var. *paludosa*) and had a maximum length of 25 mm.

The growth of the mollusc is, of course, strongly dependent on the rate of sedimentation, or of erosion. Adult individuals are only found at places where deposition is slow or absent. *Mytilus edulis* is able, by small movements, to keep its position on the surface, even though a moderate sedimentation is going on, but for most other species the deposition of new material means the end of their existence. Erosion of the bottom is not less dangerous for the life of most molluscs. Some species, like *Cardium edule* can dig themselves rapidly into the bottom after they have been washed out by current- or wave action, at least when the water is not too cold. Other kinds, such as *Mya arenaria* and *Scrobicularia plana* are more helpless, and die when the erosion has been too rapid or has removed too much sediment. [1]

It will be seen accordingly, that the channel floors, where the average velocities of sedimentation and erosion are the highest of all Wadden Sea environments, offer the least favourable circumstances for the development of a rich fauna of bottom dwelling molluscs. Nevertheless, intervals occur in the history of the channels in which neither deposition, nor erosion is active, or in which the two are in equilibrium. In other cases the erosion is very slow, owing to the resistance of the bottom material: peat, clay or glacial till. In such conditions, the channel floors may become inhabited by large numbers of boring molluscs, especially *Petricola pholadiformis* and *Barnea candida* [2]. SCHAEFER concludes from his observations in the Jade-Busen (1939), that these latter species burrow preferably in peat bottoms. Yet, they are very often found in clay beds. In many cases this is due to the fact that they are able to react, in response to erosion, with a deepening of their bore holes. They may thus burrow primarily into peat surfaces, coming to rest eventually, after removal of the covering layers, in the underlying clays.

The burrows of molluscs are nearly always vertical. Of the Wadden Sea species, listed in Table 10, only *Zirphaea crispata* seems to bore holes in other directions, more or less dependent on the inclination of the surface. The shell pairs of the vertically burrowing molluscs are, however, not always preserved in their original position. In the excavation at Velzen (VAN STRAATEN,

[1] The following observation is described by HECHT (1930). Bivalves of *Mya arenaria* were washed out from the tidal flats of the Jade-Busen and thrown up onto the surface of the salt marsh borders. Many of the individuals (a few centimeters in diameter) which had come to rest in the water-filled depressions of this marsh surface had made new burrows and resumed their normal position of life. However, examples of this kind must be comparatively rare.

[2] The first mentioned species was imported on the Dutch coast only in the beginning of this century. It seems that it is taking the place of *Barnea candida.*

1954b) an example was seen of a channel floor which had been cut down a little deeper after great numbers of *Scrobicularia plana* had bored into the sediment. Many of the bivalves protruded, in consequence, about halfway above the new, lower lying surface and were pushed into inclined positions by the effect of the currents.

Burial of shell pairs results normally in their filling up with sediment. The fillings may show downward curved laminae of alternately muddy and sandy composition. When the valves fit more or less closely together (e.g. in the case of *Scrobicularia plana*) the filling is often restricted to the lower part of the enclosed cavities. It may also occur that the bivalves contain only water (*Cardium edule*).

On their outer side, the valves of most shell pairs do not rest immediately against undisturbed sediment. They are surrounded by a zone of usually rather structureless material, ranging in thickness between about 1 mm and 1 cm. It is the filling of the original hollow, due to the opening and closing movements of the shells.

### Q. Burrows of (marine) worms and crustaceans

Burrows in which no skeleton remains have been preserved must be ascribed largely to the work of worms and crustaceans. They are met with both in the sediments of the flats and in those on the floors of creeks, gullies and channels, and are of greatly varying dimensions. Most of them are of a vertical or slightly inclined position. Horizontal burrows or parts of burrows are also formed, but they are only rarely preserved. Unless they are filled

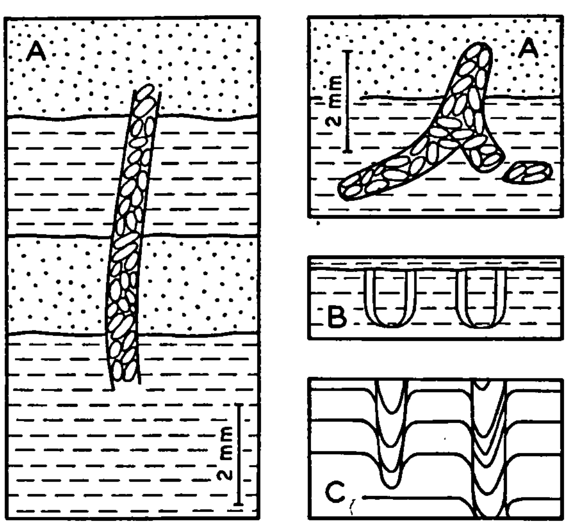


Fig. 23.

A: Pellet-filled burrows from tidal flat of Nes, Ameland;
B: U-shaped burrows from older tidal flat series in excavation at Velzen (N. H.), ca 7 m below Dutch Ordnance Datum. The vertical parts of the tubes have been left open, the horizontal parts are pressed together by compaction;
C: Dragging structures along burrows.

up with sediment, directly after they have become abandoned, they are easily pressed together by the weight of the overlying sediment.

The fillings of the borings are usually characterized by a downward curvature of the laminae (Pl. 8, fig. 17). Burrows are also observed in which the fillings consist entirely of faecal pellets (see Fig. 23 A, cf. SCHWARZ, 1932).

Sometimes there is no filling at all (Fig. 23, B). The burrows may cut

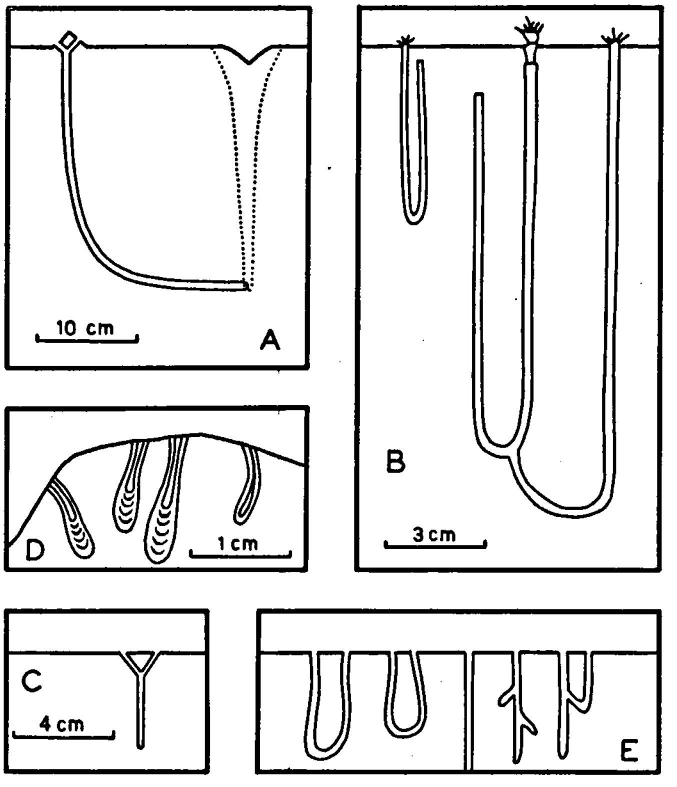


Fig. 24. Types of burrows made by various animals:
A: *Arenicola marina* (partially after THAMDRUP, 1935);
B: *Laniae conchilega* (after SEILACHER, 1951);
C: *Pygospio elegans* (after THAMDRUP, 1935);
D: *Polydora* (after RICHTER, 1928);
E: *Corophium volutator* (after HAENTZSCHEL, 1939 and THAMDRUP, 1935).

cleanly through the sediment, without further disturbing influence on its stratification. In other cases they are surrounded by a narrow zone in which the material has been dragged along with the burrowing animal (Fig. 23, C).

The knowledge of the various structures produced by the great number of species, inhabiting the sediment of the Wadden Sea area, is still far from complete. Only a few types will be mentioned here.

A species which has received a great deal of attention is *Arenicola marina* (see THAMDRUP, 1935 a.o.). This animal lives preferably in sand and makes, at least in normal conditions, a more or less L-shaped burrow (see Fig. 24, A). When feeding, the animal is lying in the deepest part of this gallery, its head inmost. Above its head a shaft is developed, through which the sand sinks down. The sinking movement results in the formation of a funnel-shaped pit at the surface.

The living gallery of *Arenicola* has walls that are hardened by the secretion of slime and enriched a little in iron hydroxides. The surface of the walls may show a transverse relief, due to the impression of the body segments (HAENTZSCHEL, 1938b). The material along the head "shaft" is generally kept quite loose [1]. The sinking of the sand in this zone appears to be not only the result of gravity, but it is also helped by movements of the worm. The sand which has passed the body and from which the nutritive admixtures have been extracted, is pushed through the other end of the burrow, to be accumulated on the surface in small heaps of excrements (Pl. 4, fig. 7).

The burrow, with a diameter of up to about 8 mm, is dug down to depths of 20 to 30 cm. Even when, during prolonged conditions of extremely low water, the ground water sinks down to 50 cm below the surface. the worms do not try to extend their burrows any deeper. The horizontal parts of the galleries may be branched (RICHTER, 1924, THAMDRUP, 1935).

No unquestionable examples of fossilized burrows of *Arenicola marina* are known to the author. The recognition of these structures in older sediments is, however, hampered by the fact that the horizontal parts are normally pressed together by compaction. Structures of the sediment below the funnel-shaped pits, made by recent worms, are given in Fig. 25. They indicate that not only sand, but also coarser material, like leaves of *Zostera*, small pieces of wood and mollusc shells are lowered into the bottom.

The structures of *Lanice conchilega* (Fig. 24, B) have been studied, among others, by SEILACHER (1951). This species makes long, flexible U-tubes of up to a few decimeters length. The walls consist of specially selected sand grains and/or fine debris of shells, held together by a binding substance. The growing individuals may form secondary tubes of successively larger diameters, which branch from the original ones. The latter then become abandoned and are filled up with excrements or other sediment material, or they are simply closed off by a septum.

*Pygospio elegans* (Fig. 24, C) builds usually single, vertical shafts, the walls of which are cemented by a hardening slime. The tubes are of small dimensions: some 3—7 cm in length and with inner diameters of about 1 mm. The upper ends may be bifurcated.

Sling-shaped burrows are made by *Polydora* (e.g. *P. ciliata*), a worm which lives both in rocks (limestones) and in clay or compact mud. The burrows of the mud-dwelling individuals have diameters of 0,3—0,8 mm and depths of 3—4 cm, sometimes even 8 cm (LINKE, 1939). The slings, at least those of the rock-boring types, may be enlarged in the manner indicated in Fig. 24, D. The successively abandoned parts of the structure are closed off by septa (RICHTER, 1928). The distribution of this species, as well as that of *Corophium volutator*, mentioned below, is not restricted to horizontal surfaces. Both animals bore also into inclined or vertical walls of creeks, gullies and channels, at approximately right angles to the surface.

[1] According to HAENTZSCHEL (1938b) this is not always the case. He observed several examples of hollow feeding shafts with firm walls, of about the same diameters as the living galleries, and with a similar transverse sculpture.

Simple U-shaped burrows, without enlarging structures like those of *Polydora,* are formed by *Corophium volutator* (cf. HAENTZSCHEL, 1939), a small crustacean, which is found in muds and clays as well as in sands. The branches of the U are not always strictly parallel to each other, but may diverge from the surface inward (Fig. 24, E). The structures attain depths

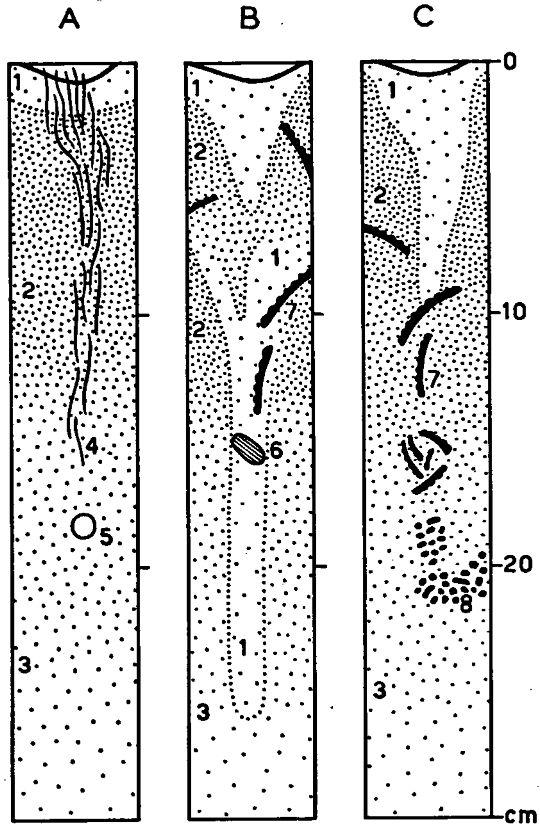


Fig. 25. Sediment structures below pits of recent individuals of *Arenicola marina.* Basin of Arcachon, May 1953.

1: Hydroxide zone;
2: Monosulphuric zone;
3: Pyritic zone;
............ Limit of Hydroxide zone;
4: *Zostera* leaves;
5: Cross section of horizontal gallery of *Arenicola*;
6: Piece of wood;
7: Shell fragments;
8: Accumulations of shells of *Bittium reticulatum, Hydrobia ulvae* etc.

of up to about 4 cm. Although the normal shape of the burrows is of the U-type, other forms are also met with: single vertical shafts (going to depths of as much as 10 cm) and forms with secondary branches, made by young individuals (HAENTZSCHEL, 1939, SCHWARZ, 1929, THAMDRUP, 1935).

The influence of the whole fauna of burrowing animals upon the sediment structure in the Wadden Sea environment is considerable. This influence is strongest on the high parts of the tidal flats. The burrowing has often been so intense that the original fine lamination of the deposits has been completely obliterated (Pl. 8, fig. 17, 18). Only the major stratification, of layers of several centimeters thickness, differing from each other in average clay content etc. remains visible. On the low flats, on the other hand, the laminated structures are usually well preserved, notwithstanding the fact that these areas may also be inhabited by great numbers of burrowing animals. The cause of this difference in structure must be sought in the types of sedimentation processes, prevailing in these areas. The high parts of the flats are as a rule only poorly dissected by ebb gullies, and reworking of the sediment owing to lateral migrations of the incisions is of little effect. The sedimentation is dominantly of vertical and low-angle lateral types (see Ch. I). Accretion is accordingly slow, but mostly fairly continuous, so that the bottom dwelling animals have time to disturb the depositional lamination with their burrowing activities (Fig. 26). On the low flats, which border the major

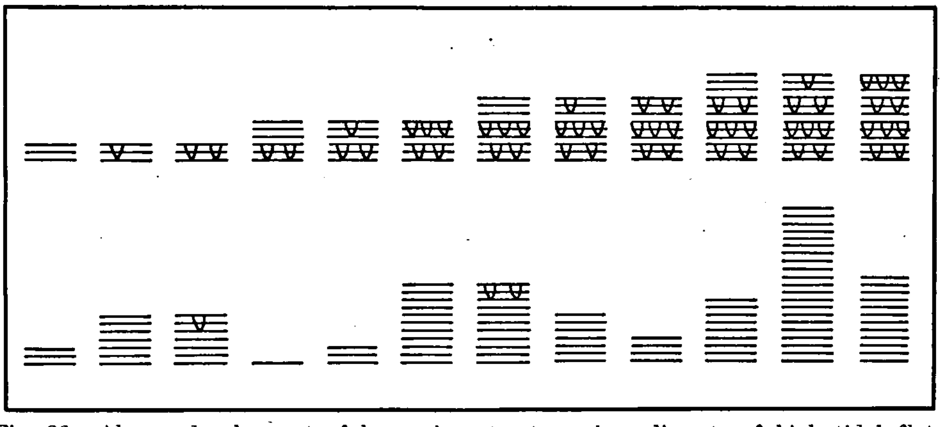

Fig. 26. Above: development of burrowing structures in sediments of high tidal flats (sedimentation slow but continuous). Below: development of laminated structures of low tidal flat deposits (rapid sedimentation, alternating with periods of erosion).

channels and which are dissected by numerous ebb gullies, much reworking of the sediment takes place by the displacements of the currents. The sedimentation is much less regular than on the high flats, stages with rapid deposition alternating with stages of rapid erosion. Just when the effect of burrowing animals upon the sediment structure begins to be of some importance, the whole material is removed and replaced by a freshly laminated deposit[1].

## R. Structures due to burrowing land animals

The influence of the marine bottom dwelling animals on the sediment structure is limited to the areas which lie below a level, coinciding ap-

[1] When the periods between such reworkings of the low tidal flat sediments by migrating gullies or channels are of longer duration, the laminations of the greater part of the sediment are still left comparatively undisturbed by burrowing organisms, because at each of these reworkings the sediments are deposited in relatively thick beds and most of the burrowing animals do not penetrate the sediment deeper than a few centimeters below the surface.

proximately with the level of mean high tide. The animals cannot live in the normal salt marsh deposits[1], owing to the too infrequent submergence by salt water. The frequency of the marine inundations is still too high, on the other hand, to permit the development of a burrowing land fauna, with earth worms, mole rats etc. The latter pervade the deposits only in the very last stages of marsh formation, when the floodings have become phenomena of exceptional occurrence. The diminishing of the frequency of submergence by sea water is. in normal circumstances, the result of the vertical accretion of the marshes itself. This implies that, at the time of the establishment of the land fauna, the marsh deposits have reached already a considerable thickness. Since the land animals, as a rule, do not burrow to great depths, it follows that the laminated structure of the lower parts of the marsh deposits is usually left intact.

The homogenization of sediment by the work of burrowing land animals has been investigated, in the Netherlands, by HOEKSEMA (1953).

As regards the structures, resulting from the work of the land animals, they appear to be somewhat different from those of the high tidal flat sediments. This is possibly connected with the greater compactness of the marsh deposits and to the scarcity of the inundations. Burrows containing fillings which contrast sharply with the surrounding material, and which show downward curved laminations, are more the exception than the rule. Instead, a peculiar granulate structure is often produced (Pl. 7, fig. 13). In other cases, the structure becomes remarkably homogeneous, vertical sections showing only indistinct streaks of relatively clayey or sandy material, oriented in random directions. This latter type of structure is also found in the "sticky clays" (cf. EDELMAN, 1950). It is not known, however, in how far other factors are also responsible for this structure, e.g. primary lack of stratification owing to deposition in close carpets of vegetation or in scrubs.

### S. Structures due to plant roots

Where sediment is penetrated by plant roots, various disturbances of the lamination may arise. In the marsh deposits, especially in the lower parts, the effect of plant roots is mostly rather small, much smaller at least than that of the burrowing animals in the underlying sediment of the high tidal flats. The material of the marsh laminae may be dragged along in a narrow zone around the downward pushing plants roots. After the death of the roots their organic substance may disappear completely by oxidation, owing to the aerated condition of the marsh sediments. The resulting hollows are filled up with clay or sand, forming minute tubes which contrast with the surrounding material.

In the deposits of marsh creeks and of high tidal flats much larger structures may befound. Very often they are produced by the roots of reed plants: *Phragmites communis*. They may have the shape of thick tubes, filled with a comparatively homogeneous mass of clay or sandy clay, in the centre of which the roots themselves are still present. The fact that the tubes are so much wider than the roots by which they were formed may be caused by the swaying to and fro of the reed plants under the influence of the wind. The structures made by plant roots in the high tidal flat

[1] Creek bottoms and the floor of salt pans, of course, excepted.

deposits resemble sometimes closely to worm burrows. They are then filled up, just like the latter, with downward curved laminae of mud and sand, and can be recognized as plant root formations only when the organic material of the roots is actually preserved.

## T. Other structures of organic origin

The surface of the tidal flat sediment shows often a great profusion of imprints, tracks and trails, made by various crawling and feeding organisms, such as crustaceans, worms and gastropods. They are best developed in the surface of muds. Two types of markings may be distinguished: those made by animals which normally live on the surface, e.g. *Littorina littorea*[1], and, secondly, the impressions formed by species which dwell in the sediment, but come out of their burows for feeding purposes, either partially or with their whole body: *Scrobicularia plana* (markings of ventral shipo), *Nereis diversicolor*, *Corophium volutator* etc. (HAENTZSCHEL. 1934, 1939, THAMDRUP, 1935, LINKE, 1939 a.o.). Tracks of the first catagory may be of great lengths. Those of the other kind are short and radiate from a central hole.

Other imprints are produced by crabs, birds (feet, wings, beaks), seals etc. Most of the impressions, mentioned above, affect the sediment only very superficially. Owing to the difficulties, connected with the investigation of bedding planes in unconsolidated material (see p. 77), no data can be given concerning their distribution in older, deeper sediments.

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[1] *Hydrobia ulvae* creeps freely about during submergence of the flats, or when the surface is very wet. During the period of emergence it usually takes shelter in the uppermost layer of sediment (THAMDRUP, 1935).

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## X. CHARACTERISTICS OF SEDIMENTS IN RELATION TO THEIR ENVIRONMENT OF FORMATION

Many of the sediment properties, discussed in the foregoing chapters, are more or less characteristic for a special area of formation such as channel floors, tidal flats etc. Very few of them, on the other hand, are sufficiently typical to be used separately as indicators of these environments. More certainty is obtainable in this respect when, instead of a single one, all properties are considered together. To this purpose they have been regrouped in the following lists (compare with Plates 10 and 11).

1. CHANNEL FLOOR ENVIRONMENT (comprising all areas between the deepest places of the channels and the level of mean low tide).

a. *Large scale structures:*

- Unconformities and normal, multidirectional cross-lamination.
- Wash-outs (caused by renewed scour and by displacements of currents).
- Large scale unilateral cross-lamination (due to transverse mega-ripples and to "lateral deposition").

b. *Minor structures:*

- Abundance of laminations of mud and sand.
- A b u n d a n c e o f c u r r e n t r i p p l e s t r u c t u r e s, in thick masses of sand as well as in thin laminae.
- Imbricate position of mud pebbles and mollusc shells (inclination of elements directed upstream).
- Preferred orientation of washed mollusc valves with convex sides upwards.
- Presence of mud cracks of subaqueous origin and of minute load cast structures.
- Limitation of burrowing structures and shell pairs of molluscs in position of- growth to certain beds, which have formed the floor of the channel during prolonged periods of non-deposition.

c. *Composition:*

- Occasional presence of hard rock gravels.
- Occasional presence of boulders of peat.
- Abundance of mud pebble beds.
- Abundance of shell beds (material washed together by currents). The malacological composition of these beds is mostly more diversified in large channels than in small ones.
- Frequency of coarse grained sand layers. The average grain size of the channel sands diminishes often from below upwards.

Frequency of mud layers, especially in those areas where the tidal flats, above the level of low tides, are also of pronounced muddy composition (e.g. bay heads).

Presence of spines of *Psammechinus miliaris* (these are almost exclusively limited to channel floor deposits).

Richness of sediments in carbonates (coarse sand may nevertheless show (primary) low carbonate contents). Decalcification not known from channel sediments of present Wadden Sea.

Presence (in the most recent deposits) of discontinuities in colour gradation (transition M → P), and in state of compaction. These discontinuities are often marked by layers with burrowing structures or shell pairs in the living position (former floors) and/or by deposits of washed mollusc valves or mud pebbles (first sediments of new series).

d. *Biotic characteristics:*

Presence of shell pairs in position of life, belonging to *Petricola pholadiformis, Barnea candida, Zirphaea crispata, Mya truncata,* (*Mytilus edulis*).

Abundance of skeletons of bryozoans on washed mollusc valves.

2. TIDAL FLAT ENVIRONMENT (between levels of mean low and mean high tide levels).

A. Low parts of tidal flats.

a. *Large scale structures:*

Unconformities, cross-lamination and wash-outs less common than in channel floor sediments, but more common than in high tidal flat deposits.

b. *Minor structures:*

A b u n d a n c e  o f  l a m i n a t i o n s  o f  m u d  a n d  s a n d.

Current ripple structures not so abundant as in channel floor deposits ,but more common than in high tidal flat sediments.

Occasional presence of wave ripple structures.

Imbricate position of mud pebbles and washed mollusc valves.

Preferred orientation of washed mollusc valves with convex sides upwards, sometimes also with longer axes parallel to currents.

Mud pebbles sometimes with preferred orientation of longer axes parallel to currents.

Presence of mud cracks and of minute load cast structures.

Rare occurrence of cavernous sand structures.

Burrowing structures and shell pairs in position of growth more abundant than in channel floor sediments, but less than on high parts of tidal flats.

Occasional presence of structures due to penetration of sediment by plant roots.

c. *Composition:*

Peat boulders rather rare.

Mud pebble beds common, but less frequent than in channel floor deposits.

Abundance of shell beds. Concentration of shells mostly due to currents (gully bottom pavements) or waves, rarely to burrowing animals (*Hydrobia* beds). The current-formed shell beds show sometimes a concentration of the valves of a single species, e.g. *Mytilus edulis* or *Scrobicularia plana*, or even of only the left valves: *Mya arenaria.*

Average grain size of sand layers often distinctly smaller than on channel floors and on high tidal flats.

Abundance of mud beds, especially in bay heads and other sheltered areas.

Presence of faecal pellets, often concentrated in separate laminae or as fillings of worm burrows etc.

Richness of sediments in carbonates. Decalcification not known from Wadden Sea flats (but observed in Basin of Arcachon, France).

Presence (in recent deposits) of discontinuities in colour gradation (transition $M \rightarrow P$) and in state of compaction (see under Channel floors).

d. *Biotic characteristics:*

Presence of shell pairs in position of growth, belonging to *Cardium edule, Macoma balthica, Scrobicularia plana, Mya arenaria,* (*Petricola pholadiformis*), (*Mytilus edulis*).

B. HIGH PARTS OF TIDAL FLATS.

a. *Large scale structures:*

Unconformities, cross-lamination and wash-outs still less frequent than in low tidal flat deposits.

b. *Minor structures:*

Laminations of mud and sand much less frequent than in low flat sediments.

Current ripple and wave ripple structures comparatively rare.

Imbrication of washed mollusc valves (not seen in typical *Hydrobia* beds).

Preferred orientation of washed mollusc shells with convex sides upward (not seen in *Hydrobia* beds).

Occasional presence of normal desiccation cracks.

Occasional presence (in deposits of actual Wadden Sea) of cavernous sand structures.

B u r r o w i n g s t r u c t u r e s e x t r e m e l y a b u n d a n t.

Shell pairs of molluscs in position of growth very frequent.

Occasional presence of structures due to penetration of sediment by plant roots (e.g. reeds).

c. *Composition:*

Mud pebble beds comparatively rare.

Shell beds much less frequent than in low tidal flat deposits (except for *Hydrobia* beds, which are of great extension in uppermost sediment layers of actual Wadden Sea). Concentration of shells due to currents, (gully bottom pavements) or waves, or to burrowing animals (*Hydrobia* beds).

Average grain size of sands often larger than on low tidal flats.

Mud beds in general of somewhat smaller importance than on low tidal flats.

Presence of faecal pellets, often concentrated in burrows of bottom dwelling animals.

Richness of sediment in carbonates. Decalcification not known from present Wadden Sea.

Presence (in recent deposits) of discontinuities in colour gradation (transition M→P) and in state of compaction. They are partly caused by the alteration of periods of erosion and of sedimentation (then often marked by normal shell beds); for another part they are the result of the work of burrowing animals.

d. *Biotic characteristics:*

Presence of shell pairs in living position belonging to *Cardium edule, Macoma balthica, Scrobicularia plana, Mya arenaria.*

3. MARSH ENVIRONMENT.

3A. ENVIRONMENT OF MARSH CREEK BOTTOMS. The floor of the major creeks normally lies below mean high tide level. When the creeks are not continued over the forelying flats as ebb gullies, they may retain a cover of stagnant water during ordinary low tides. Small creeks usually run dry at ebb tide.

b. *Minor structures:*

Laminations of mud and sand, and

Current ripple structures of greater frequency (especially in estuaries of Zealand) than on high tidal flats.

Occasional presence (in higher parts, and in small creeks) of marsh laminations.

Occasional presence of brackish water laminations.

Imbricate structure of shell beds.

Occasional presence of normal desiccation cracks.

Abundance of burrowing structures and presence of shell pairs in position of growth.

Presence of disturbance of stratification due to plant roots (e.g. reeds).

c. *Composition:*

Occasional presence of shell beds (concentration by currents), often composed for the greater part of valves of a single species, e.g. *Scrobicularia plana.*

Greatly varying amounts of mud.

Average grain size of sands mostly equal or slightly smaller than on forelying tidal flats.

Richness of sediment in carbonates.

d. *Biotic characteristics:*

Presence of shell pairs in position of growth of *Cardium edule, Scrobicularia plana, Mya arenaria, Macoma balthica* (sometimes in brackish water varieties).

3B. MARSH (SURFACE) ENVIRONMENT (above mean high tide level).

a. *Large scale structures:*

Presence of wash-outs (due to creeks) and (rare) unconformities resulting from cutting back of marsh cliffs, followed by new accretion.

Thinning out of sand laminae from creek banks inward.

b. *Minor structures:*

Marsh laminations.

Occasional presence of desiccation cracks.

Burrowing structures of marine animals and mollusc shells in living position only rarely present (formed in marsh pans; shell pairs then often of very young individuals).

Abundance of structures due to burrowing land animals, mainly in upper parts of sections.

Presence of structures caused by plant roots.

Frequency of coated sand grains.

c. *Composition:*

Occasional presence of shell beds (especially at the back of former marsh cliffs) and of gravels composed of small iron hydroxide concretions (in recent marshes also in vicinity of cliffed outer edges).

Richness of sediment in clay material. The base of the marsh deposits is usually marked by a sudden transition of sandy sediments of high tidal flats to clayey material of marsh origin.

Average grain size of sand laminae mostly smaller than in underlying tidal flat or marsh creek deposits and decreasing from marsh base upwards.

Presence of iron in hydroxidic condition (unless marsh deposits have sunk below ground water table by relative subsidence).

Decalcification phenomena usually present; decreasing from surface downwards. Upper parts of sections (especially those of greater age) sometimes free of carbonates.

Occasional presence of thin laminae composed for a great part of skeletons of benthonic diatoms (especially near marsh base).

4. VARIOUS BRACKISH WATER ENVIRONMENTS (innermost parts of marshes, brackish water swamps, ponds, lagoons etc.).

b. *Minor structures:*

Brackish water laminations, with separate silt laminae of 20—40) $\mu$.

Coating of sand grains.

Pronounced parallel orientation of mica flakes as observed in thin sections of clay material.

c. *Composition:*

Presence (in anaerobic sediments) of comparatively many and comparatively large (globular) aggregates of pyrite crystals (up to 40 $\mu$ diameter).

Occasional presence of thin laminae, composed for a great part of skeletons of benthonic diatoms.

d. *Biotic characteristics:*

Abundance of ostracod valves.

Presence of mollusc shells in position of growth belonging to brackish water varieties (e.g. small, thin shells of *Mya arenaria*, shells of *Cardium edule* var. *paludosa* etc.).

# SUMMARY

CH. I. The environment of the Dutch Wadden Sea, as well as that of the estuaries in the southwestern part of the Netherlands can be divided into three sub-zones: (1) the channel floors (sensu lato), i.e. the areas below mean low tide level, (2) the tidal flats (sensu stricto), between the levels of mean low and mean high water and, (3) the salt marshes, above the level of mean high tide. The channel floors are composed, either of older sediments, which have been laid bare by erosion of the tidal currents, or by new deposits, formed in the channels themselves. The latter are predominantly of sandy character, but may show locally high contents of muddy material, especially in sheltered bays. The tidal flats consist for the greater part of sand. Slightly muddy sand is often encountered along the high tide lines and very muddy deposits, dissected by small ebb gullies, are frequently present along the sides of the channels. The marshes are usually composed of comparatively clayey deposits, which are cut through by creeks. Details are given concerning the morphology of these sub-zones, and on the processes of erosion and sedimentation, which are responsible both for the morphology and for the composition of the sediments. The chapter is based on own observations (most of them published before) and on the results of a great number of other investigators (see list of references).

CH. II. The chief sediments in the Wadden Sea are (1) sands, (2) mud and clay, (3) shell beds. "True" hard rock gravels are very rare. They occur in the vicinity of outcrops of older, psephitic deposits (glacial till). Special mention is made of the formation of gravelly sediments, composed of small, limonitic clay-rhizo-concretions (found at the base of marsh cliffs and in the mass of the marsh deposits themselves). Granulometrical analyses of Wadden sediments have been carried out by a number of authors. Several conclusions may be drawn from their work: The Wadden sands are rarely pure, but contain mostly a certain amount of material $< 16\ \mu$; the average grain size of the sands decreases usually from the tidal inlets inwards; the material which has been transported in suspension, most of the time, shows a remarkably uniform grain size distribution along the whole length of the Dutch coast (DOEGLAS, FAVEJEE, HISSINK, ZUUR) etc.

CH. III. The investigated sediments are mainly composed of psammitic and pelitic elements of the following minerals: quartz, carbonates, micas and clay minerals, felspars, glauconites and heavy minerals. The quartz percentages decrease with diminishing of the grain size of the material under consideration. Micas and clay minerals show an increase in this same direction. Grains of carbonates and felspars have their maximum distribution in the siltfractions. From the heavy mineral composition of the Wadden Sea sands it may be deduced that the greater part of the material has been brought in from the North Sea, via the tidal inlets (CROMMELIN). The same conclusion is reached with regard to the silt fractions (CROMMELIN) and the clay material (FAVEJEE).

CH. IV. The organic matter of the Wadden Sea sediments is partly derived from older peat beds which have been eroded; for another part it is produced by plants and animals living in the Wadden Sea area itself. The basic organic materials, required for the growth of the latter organisms, are probably chiefly supplied out of the North Sea (VERWEY). The organic content of the Wadden Sea sediments may show a decrease from the surface downwards, at least in the first few decimeters. This is presumably due to decomposition, under the influence of bacterial activities, by enzymes and by purely chemical processes. A notable parallelism is observed between the percentage variations of the organic matter and those of the material $< 16\ \mu$.

CH. V. A close relation exists also between the percentages of material $< 16\ \mu$ and the iron content. This element is present in various authigenous compounds: Hydroxides of iron are found in marsh deposits (above the ground water table) and in the

uppermost few millimeters or centimeters of the tidal flat and channel sediments. $FeS . nH_2O$ is formed in anaerobic environment, under the surface of the tidal flats and the channel floors. This substance tends to take up additional sulphur, thereby changing into pyrite. The pyrite is normally distributed in very small elements. Comparatively large, more or less globular aggregates of pyrite crystals (up to 40 $\mu$ diameter) are seen in brackish water sediments. The transformation of iron hydroxides into monosulphuric compounds takes place in a short time. That of the $FeS . nH_2O$ into $FeS_2$ requires at least half a century. Where the vertical accretion has been continuous, a gradual change in colour is observed between the deep black monosulphuric sediments just below the surface and the greyish, pyritic material at greater depths.

CH. VI. The major part of the calcium carbonate material is (primarily) formed by calcareous organisms (foraminifera, echinoderms, molluscs etc.). A minor amount may have originated in other ways, e.g. by bacterial activities and by chemical processes. A relation is found between the increase of the carbonate percentages and the amounts of material $< 16\,\mu$. A maximum is reached in the fraction 2—16$\mu$. Marsh sediments are subject to decalcification processes. The velocity of the solution of the carbonates depends on many factors, which require still further investigation. No decalcification phenomena are known from the normal tidal flat and channel floor sediments in the Netherlands. They have been observed, however, in the Basin of Arcachon (France). It is thought that the solution in this area is caused, at least to an important extent, by organic acids, produced during the decomposition of the large masses of dead *Zostera* remains, which are embedded in the sediments.

CH. VII. Considerable quantities of silica are formed on the surface of the tidal flats by the skeletons of (living) benthonic diatoms. The numbers of dead skeletons which are encountered in the tidal flat deposits themselves are, however, mostly very small. In the marsh sediments a more normal relation seems to exist between the amounts of skeletons of living and of buried diatoms. It is supposed that, after the death of the organisms, a solution or at least a beginning peptization of the silica takes place, which is swifter in the tidal flat environment than in the marsh deposits, probably in consequence of the higher alkalinity. The relatively coarse and less soluble skeletons of a part of the planktonic diatoms are of much more even distribution and are found in all Wadden Sea sediments. Other sources of locally formed silica are: radiolarians, sponges and plants.

CH. VIII. This chapter gives some conclusions, to be drawn from the study of thin sections of Wadden Sea sediments and of various deposits formed in more brackish water environment. The minimum grain size of separate sand (and silt) laminae is about 40 $\mu$ in the former and down to at least 20 $\mu$ in the latter. The parallel orientation of mica flakes and clay minerals is often much more pronounced in brackish (and fresh) water muds than in muds of Wadden Sea origin. Another conclusion, following from thin section analysis, is that brackish water deposits often show a coating of the sand grains, which may be due to peptization of clay material.

CH. IX. Useful evidence regarding the circumstances of sediment formation can be gathered from the structures as seen in undisturbed core samples. Several types of laminations are described. The laminae of channel floor- and tidal flat deposits have comparatively even, smooth upper and lower sides. The sand may show current or wave ripple structures. The laminae are of a sublenticular character and cannot be traced over great horizontal distances. The marsh laminations are characterized by the somewhat undulating, nodular aspect of the lamiae. The structures of beach deposits differ from the channel floor- and tidal flat laminations in that their laminae are more strictly parallel (apart from ripple mark structures). Another difference between these two laminations is that the latter are normally free of mud material. The finest laminations, with the thinnest laminae, are found in (some) brackish water deposits.

The laminations and other primary depositional structures may be disturbed by secondary influences: the burrowing of bottom dwelling organisms, the penetration of the sediment by plant roots etc. The effect of the burrowing animals is in general most pronounced on the highest parts of the tidal flats, where the sedimentation tends to be slow, but continuous. A sharp limit is often found between the disturbed deposits of the high tidal flats and the overlying marsh sediments, the lower parts of which are scarcely inhabited by bottom dwelling animals at all.

Among the other structures, which are dealt with in this chapter, special mention may be made of the fissures, developed in mud beds under a permanent cover of water. Some new data are presented concerning their distribution and character, but no satisfactory conclusion about the manner of their formation is reached.

CH. X. The sediment properties, described in the foregoing chapters, are summarized and arranged according to their distribution in the various environments of formation.

# PLATE 1

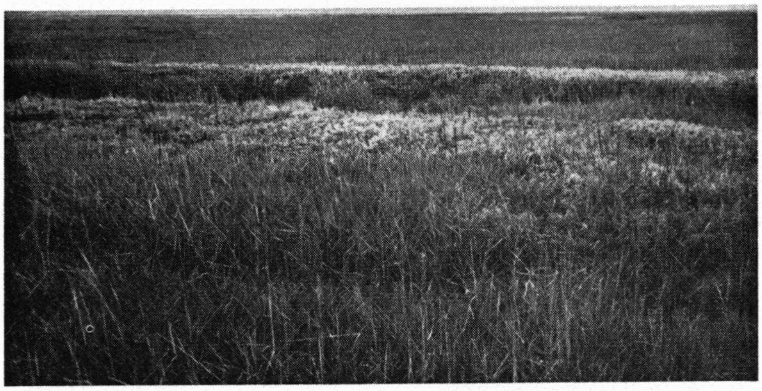

Fig. 1. Raised banks of creek, covered with *Obione portulacoides,* in *Spartina* marsh. The creek itself is not visible. Estuary of Easter Scheldt, W. of Woensdrecht.

Fig. 2. Cliffed marsh edge and clumps of *Spartina* on highest parts of tidal flats. Wadden Sea, S.W. corner of Lauwerszee-embayment.

## PLATE 2

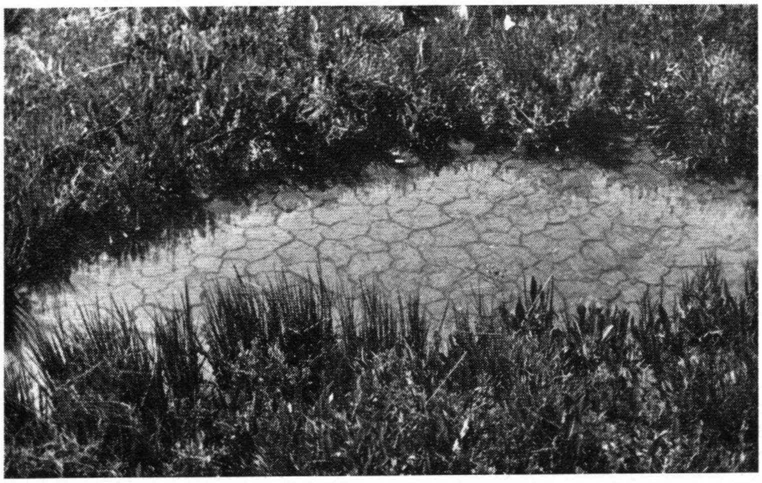

Fig. 3. Marsh pan with desiccation cracks.
Salt marsh of Ile aux Oiseaux, Basin of Arcachon, France.

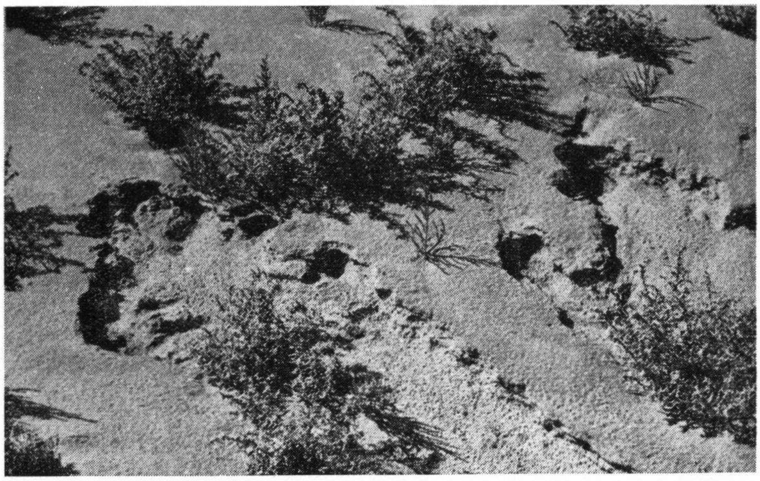

Fig. 4. Earliest stage of marsh creek formation.
Parkgate Saltings, Dee Estuary, S. of Liverpool, England.

# PLATE 3

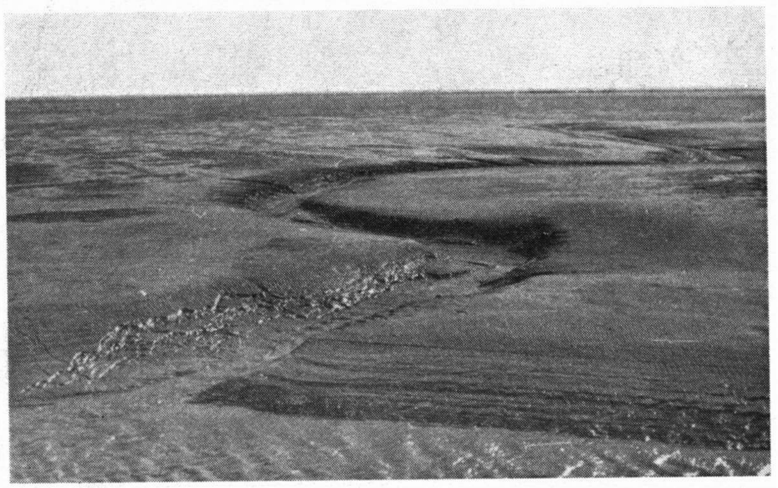

Fig. 5. Ebb gully in low part of tidal flat. Wadden Sea N. of Holwerd.

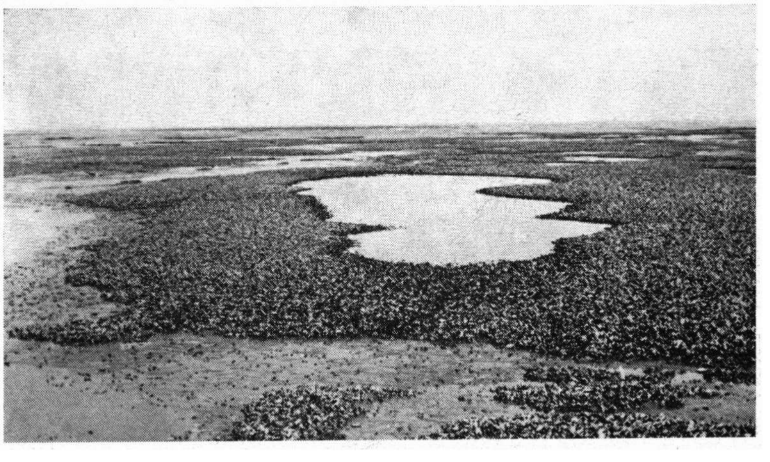

Fig. 6. Erosion of mussel bed. The central part has been removed and the resulting hollow is filled with stagnant water during emergence of the flats. Wadden Sea, S.E. of Hollum.

**PLATE 4**

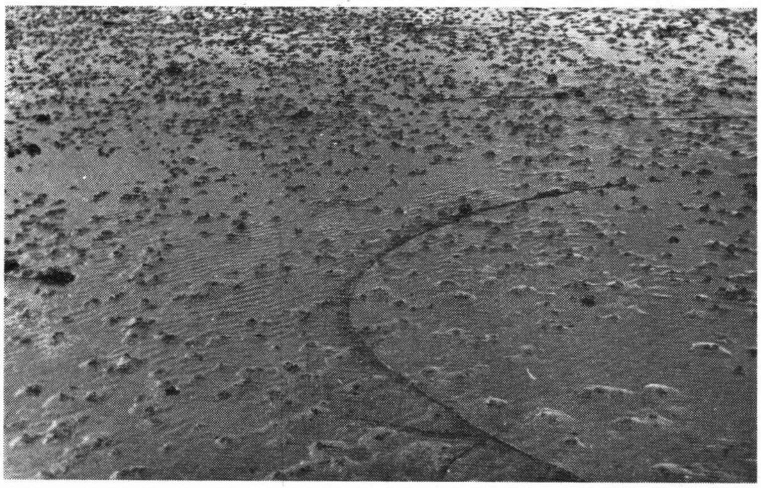

Fig. 7. High part of tidal flat with wave ripple marks, castings of *Arenicola marina* and strings of *Chaetomorpha*. Wadden Sea, S. of Nes, Ameland. The abundance of *Arenicola* has resulted in the formation of a well developed *Hydrobia*-bed at 20 cm below the surface (see Pl. 11 No. 125).

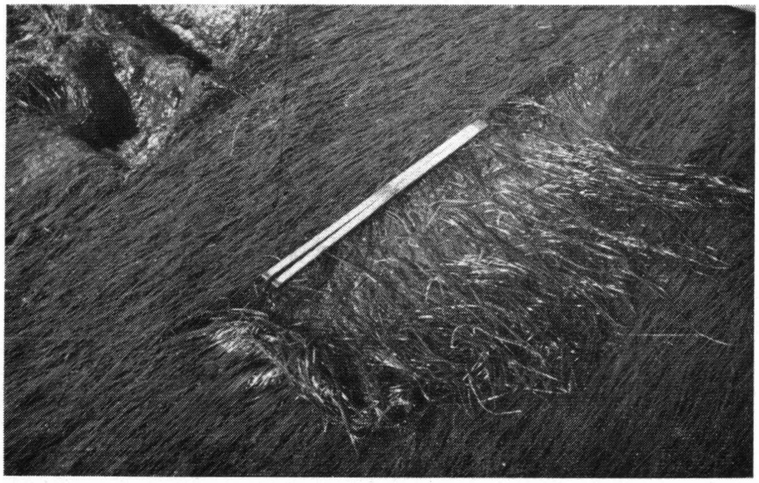

Fig. 8. *Zostera* vegetation on tidal flat in Basin of Arcachon, France, N. of Gujan Mestras.

**PLATE 5**

Fig. 9. Marsh sediments with well-preserved lamination, resting on high tidal flat sediments, the original lamination of which is disturbed by burrowing animals. Exposure in wall of deeply incised marsh creek, Somme Estuary, N. France.

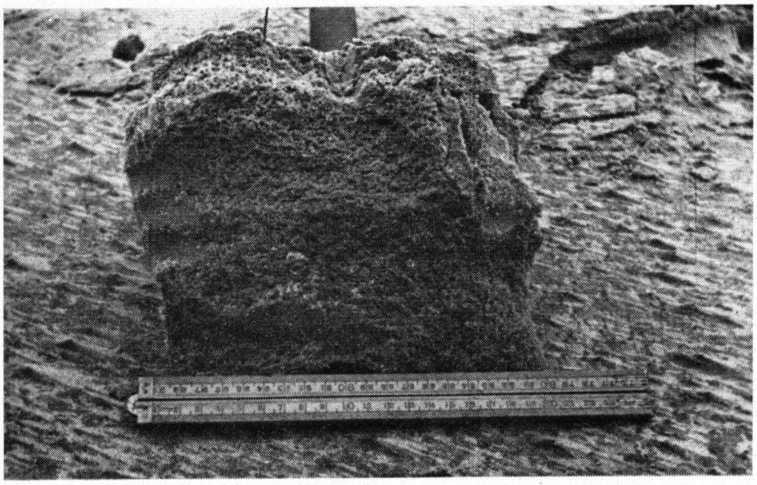

Fig. 10. Cavernous sand on beach of Wadden Sea, E. part of Ameland. The sediment is covered by a thin crust of salt, due to evaporation.

**PLATE 6**

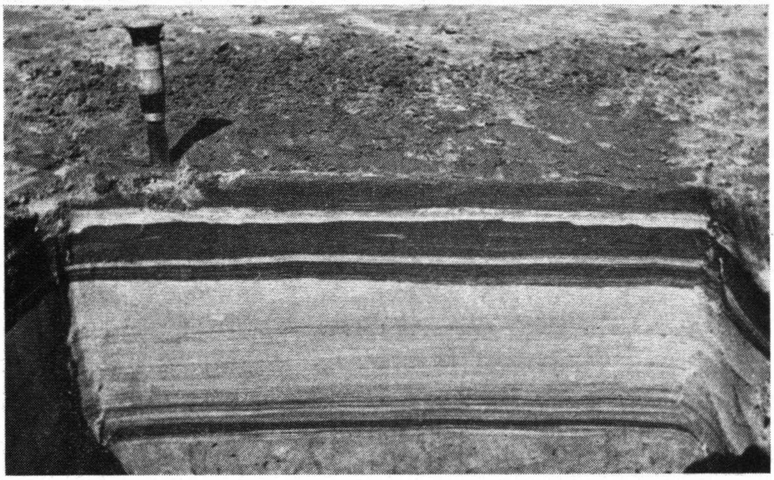

Fig. 11. Laminated beach sand on shore of tidal inlet, W. of Hollum, Ameland. The dark layers are formed by concentration of heavy minerals.

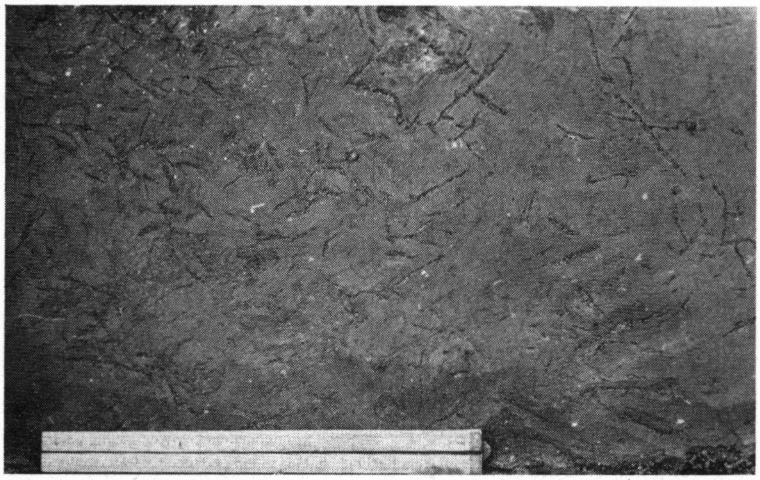

Fig. 12. Sand filled fissures in mud of channel floor. N.W. corner of excavation at Velzen (North Holland), 13.55 m below Dutch Ordnance Datum. The fissures must have been formed at a depth of some 9 meters below the low tide level.

## PLATE 7

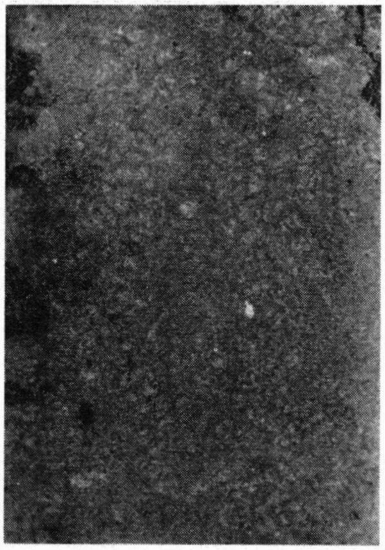

Fig. 13. Granulate structure of marsh sediments, probably due to the work of burrowing land animals. Tjummarum (Friesland), 20—27½ cm below surface. Vertical section, natural size.

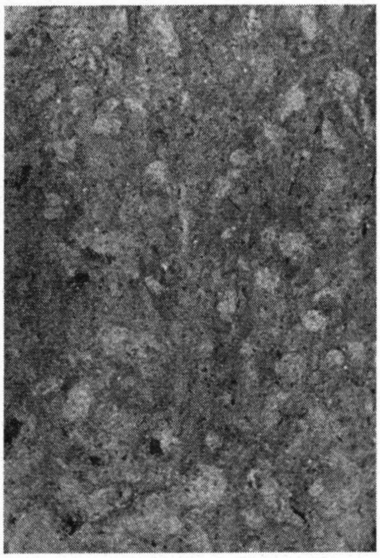

Fig. 14. Burrowing structure in recent high tidal flat deposits. Wadden Sea. *Corophium*-mud flat in S.W. part of Lauwerszee-embayment; 2 cm below surface. Horizontal section, natural size.

Fig. 15. Marsh lamination. Edge of recent marsh cliff, Zoutkamp (Groningen), 62—69½ cm below surface. Vertical section, natural size.

Fig. 16. Marsh lamination, older tidal flat series, S.W. corner of excavation at Velzen (North Holland), 287½295 cm below Dutch Ordnance Datum. Vertical section, natural size.

**PLATE 8**

Fig. 17. Burrowing structure in high tidal flat deposits. Tjummarum (Friesland), 140—147½ cm below surface. Vertical section, natural size.

Fig. 18. Burrowing structure in high tidal flat deposits of "Old Sea Clay" at 50—57½ cm below surface, or 25—32½ cm below actual top of "Old Sea Clay", Wadden Sea, N. of Ternaard (Friesland). Vertical section, natural size.

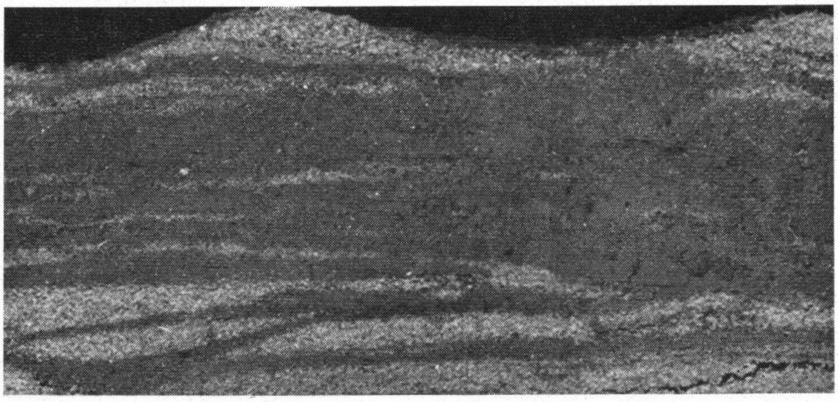

Fig. 19. Low tidal flat lamination with cross-section of longitudinal wave-current ripple marks. Wadden Sea, N. bank of Schildknoopen, 0—5 cm below surface. Vertical section, 1½ X.

## PLATE 9

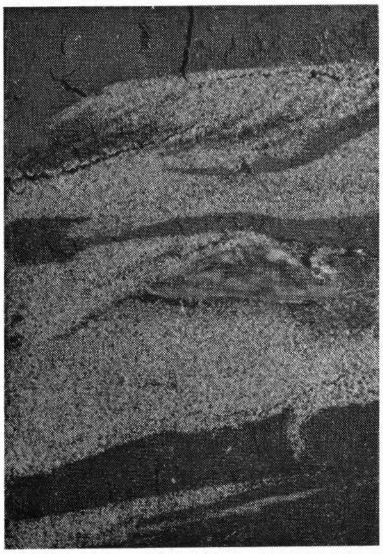

Fig. 20. Channel floor lamination. Wadden Sea, Slenk (Lauwerszee-embayment), depth of channel 12 m below Dutch Ordnance Datum; sample from 45—52½ cm below surface. Vertical section, natural size.

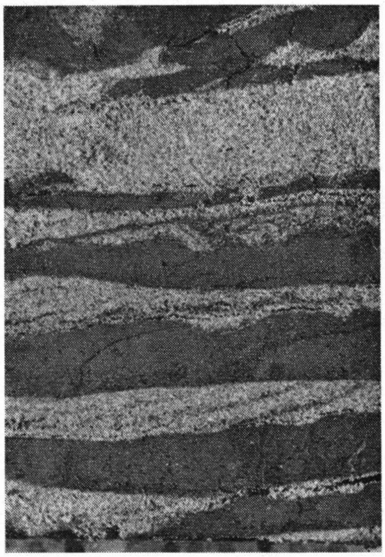

Fig. 21. Channel floor lamination. Wadden Sea, Slenk (Lauwerszee-embayment), depth of channel 8 m below Dutch Ordnance Datum; sample from 37½—45 cm below surface. Vertical section, natural size.

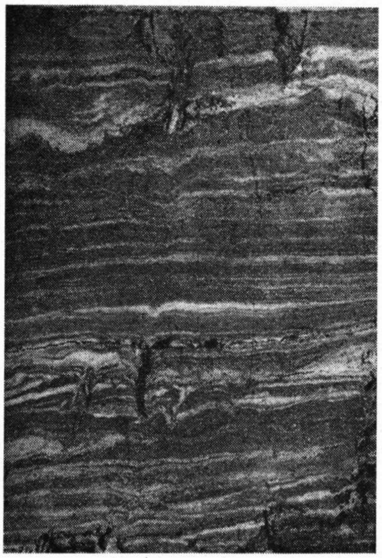

Fig. 22. Brackish water lamination. Rien (Friesland), 197½—205 cm below surface. Vertical section, natural size.

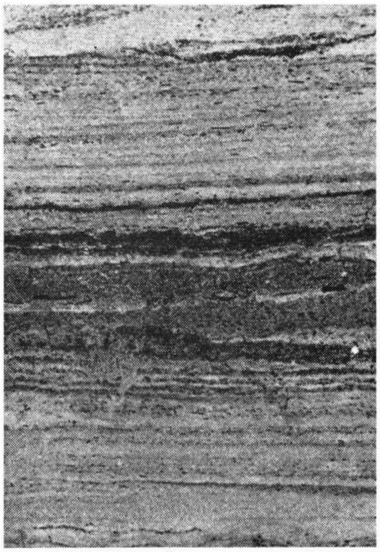

Fig. 23. Brackish water lamination in "Sloef". Noordoostpolder, J. 104, 57½—65 cm below surface. Vertical section, natural size.

## Key to Plates 10 and 11

*Deposits of marsh environment*

| | | |
|---|---|---|
| No. 18 | Hartwerd | 30—150 cm |
| No. 20 | Rien | 100—170 cm |
| No. 53 | Zoutkamp | 0—105 cm |
| No. 131 | Ellewoutsdijk | 0—80 cm |
| No. 142 | Braakman | 0—65 cm |
| No. 174 | Ile aux Oiseaux | 0—15 cm |
| | Amsterdam | 485—540 cm |

*Deposits of creek bottom environment*

| | | |
|---|---|---|
| No. 68 | Schiermonnikoog | 0—50 cm |
| No. 92 | Griend | 0—40 cm |

*Deposits of high tidal flat environment*

| | | |
|---|---|---|
| No. 20 | Rien | 240—285 cm |
| No. 53 | Zoutkamp | 135—200 cm |
| No. 125 | Nes | 0—100 cm |
| No. 131 | Ellewoutsdijk | 85—150 cm |
| No. 142 | Braakman | 120—135 cm |
| No. 174 | Ile aux Oiseaux | 15—40 cm |
| | Amsterdam | 540—710 cm |

*Deposits of low tidal flat environment*

| | | |
|---|---|---|
| No. 24 | Schildhoek | 0—130 cm |
| No. 53 | Zoutkamp | 200—275 cm |
| No. 68 | Schiermonnikoog | 102—140 cm |
| No. 124 | Nes | 0—55 cm |
| | Amsterdam | 710—750 cm |

*Channel floor environment*

| | | |
|---|---|---|
| (No. 77 | Delta Plaatgat | 0—45 cm) |
| No. 83 | Slenk | 0—60 cm |
| No. 109 | Zoutkamperlaag | 0—65 cm |
| No. 110 | Zoutkamperlaag | 0—65 cm |

*Brackish water environment*

| | | |
|---|---|---|
| No. 20 | Rien | 170—225 cm |
| No. 23 | Noordoostpolder | 75—145 cm |
| No. 24 | Schildhoek | 130—165 cm |
| No. 142 | Braakman | 0—120 cm |
| | Amsterdam | 475—525 cm |

## Explanation of Plates 10 and 11[1]

*No. 18 Hartwerd (Friesland)*

30—150 cm Marsh deposits, formed in brackish water environment (grain size of separate lenticles or laminae of silt down to 20 $\mu$. Upper part of section: "sticky clay".

*No. 20 Rien (Friesland)*

100—170 cm Marsh deposits, formed in brackish water environment (grain size of separate lenticles or laminae of silt down to 20 $\mu$, coating of sand grains);
170—225 cm Deposit with "brackish water laminations" (very thin, horizontal laminae, with grain sizes of 20—40 $\mu$); Absence (or at least scarcity) of ostracod valves not usual in sediments of this kind;

[1] "Recent" is used for deposits formed under present environmental conditions (age 0—ca. 400 years).

225—240 cm Transition zone;
240—285 cm High tidal flat deposits; At 285 cm: Shell pair of *Scrobicularia plana* in position of life.

*No. 23 Noordoostpolder, J. 104*

75—142 cm "Sloef"-deposit, formed in beginning stages of Zuiderzee;
142—145 cm Shell bed, mainly composed of *Valvata piscinalis*;
145—150 cm Peat detritus deposit, formed in practically fresh water (chlorinity not more than 0,2 %).

*No. 24 Schildhoek (Lauwerszee)* (ca 50 cm — N.A.P.)

0—130 cm Partly recent low tidal flat deposits. At 110 cm and at 130 cm; shell beds, formed on floor of ebb gullies. Both shell beds mark the places of discontinuities in the colour gradation of the sediment. The floor of the gully of 110 cm depth was for a certain period inhabited by burrowing animals.
130—165 cm "Old Sea Clay" in (?) marsh facies; upper part decalcified. Brackish water formation (grain sizes of silt laminae, coarse pyrite globules).

*No. 53 Zoutkamp (Robersum)*

0—105 cm Marsh deposits. Laminations in upper part disturbed by burrowing land animals;
105—135 cm Transition zone;
135—200 cm High tidal flat deposits;
200—275 cm Low tidal flat deposits (the limit between these two facies does not necessarily coincide with the half tide level).

*No. 68 Schiermonnikoog*

0—50 cm Recent creek bottom deposits, with same structures as normal high tidal flat sediments;
50—102 cm Transition zone;
102—140 cm Low tidal flat deposits.

*No. 77 Delta Plaatgat (N. of Schiermonnikoog; Depth 7 m)*

0—45 cm Recent deposits of front slope of outer tidal delta (locality at ca. 4¾ km from N.W. lighthouse of Schiermonnikoog in direction N. 351° E). The relatively muddy composition of this core sample seems to be rather unusual for this environment.

*No. 83 Slenk (Lauwerszee; Depth 7.50 m — N.A.P.)*

0—60 cm Recent channel floor deposits, with shell bed at base. Example of very muddy sediments, formed on floor of large channel with strong tidal currents;
60—75 cm Till.

*No. 92 Griend*

0—40 cm Recent creek bottom deposits, with same structure as normal high tidal flat sediments. At 20 cm; shell pair of living *Mya arenaria* (35 mm length).

*No. 109 Zoutkamperlaag (Depth 8.00 m — N.A.P. Wadden Sea)*

0—65 cm Recent channel deposits, for a great part composed of mud pebbles. The tests of foraminifera are of comparatively large sizes. Many of the echinid spines belong to *Psammechinus miliaris* (which are heavier than those of *Echinocardium cordatum*).

*No. 110 Zoutkamperlaag (Depth 14.00 m — N.A.P. Wadden Sea)*

0—65 cm Recent channel deposits, mainly mollusc shells, also containing some fine gravel material;
65—75 cm Older clay sediment, with shell pair of *Barnea candida* in position of growth.

*No. 124 Nes (Bank of ebb gully) (Wadden Sea)*

0—55 cm Recent low tidal flat deposits. The sediment contains great quantities of faecal pellets, often concentrated in separate laminae.

*No. 125 Nes (Ameland, tidal flat) (Wadden Sea)*

0—100 cm Partly recent high tidal flat deposits; from 15—22 cm *Hydrobia* bed formed by action of burrowing animals;
100—140 cm Transition of high tidal flat deposits to low tidal flat deposits.

*No. 131 Ellewoutsdijk (salt marsh) (Wester Scheldt estuary)*

0—80 cm Recent marsh deposits, formed in vicinity of outer marsh edge. The whole section (down to 170 cm) contains small grains of brick;
80—85 cm ? Creek bottom deposits;
85—150 cm High tidal flat deposits;
150—170 cm Transition of high tidal flat deposits into low tidal flat deposits.

*No. 142 Braakman (salt marsh) (Wester Scheldt estuary)*

0—65 cm (Recent) marsh deposits, formed in brackish water environment, at comparatively great distance from outer marsh edge;
65—120 cm ? Creek bottom deposits;
120—135 cm High tidal flat deposits.

*No. 168 La Hume (Bassin d'Arcachon; tidal flat)*

0—220 cm Partly recent deposits of high tidal flats and low tidal flats. At 95 cm and at 155 cm shell beds, formed as gully bottom pavements. At 100 cm shell pair (in position of life) of *Gastrana fragilis,* at 150 cm id. of *Scrobicularia plana,* at 172 cm id. of *Gastrana fragilis,* at 195 cm id. of *Lucina lactea.* Whole section rich in loose shells of *Bittium reticulatum,* in unhinged valves and washed shell pairs of various Lamellibranchs (many of them heavily attacked by solution) and in more or less decomposed remains of *Zostera* plants. The clay laminae are mostly very poor in carbonates. The mollusc valves, embedded in the clay, often show stronger effects of solution than those in sandy parts.

*No. 174 Ile aux Oiseaux (B. d'Arcachon; salt marsh, edge)*

0—15 cm Marsh deposits, completely decalcified;
15—40 cm High tidal flat sediments.

*Amsterdam, Dokput N.D.S.M. (Tuindorp Oostzaan; depths in this case relating to Dutch Ordnance Datum)*

475—485 cm Peat;
485—540 cm Marsh deposits, formed, at least for the upper part, in brackish water environment (large pyrite globules);
540—710 cm High tidal flat deposits, with shell pairs (in living position) of *Macoma balthica* at 625 cm, and of *Scrobicularia plana* at 630, 660, 672, 675, 680, 685, 690, 700 and 705 cm, and with a few sponge spicules;
710—750 cm Low tidal flat deposits.

# COMPOSITION AND STRUCTURE OF RECENT MARINE SEDIMENTS IN THE NETHERLANDS

BY

**L. M. J. U. VAN STRAATEN**

(Leidse Geologische Mededelingen, Deel XIX)

## ERRATA

P. 16, fig. 11, legend: open circles "Older formations covered by *less than 80* cm of recent deposits" should be: "Older formations covered by *more than 20* cm of recent deposits".

P. 16, fig. 11: The inset figure in the upper right corner gives the depths of the top of the old sea clay in relation to Dutch Ordnance Datum.

P. 28, fig. 13, caption: "Samples taken along line A—A′ of *Fig. 11* ..." should be "... of *Fig. 12* ...".

P. 33, 12th line from below "*the bulk* of the food" should be "*a substantial part* of the food".

P. 94, Summary, Ch. IV, 4th line: "*chiefly*" should be "*partly*".

Plate 12 (in pocket): Map of the Dutch Wadden Sea for the year 1943 This map was produced originally for a symposium on the Wadden Sea in the "Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap" (2e reeks, deel LXVII, no. 3, May 1950), and was financed by a grant from the Kamminga Foundation at Groningen.

Translation of the legend:
"Kwelder" = Marsh,
"Landaanwinningswerken" = Land reclamation works,
"Bij gemiddeld laagwater droogvallende gronden" = Tidal flats, emerging at average low tide,
"G.L.W. lijn" = Average low tide line,
"N.A.P." = Dutch Ordnance Datum.