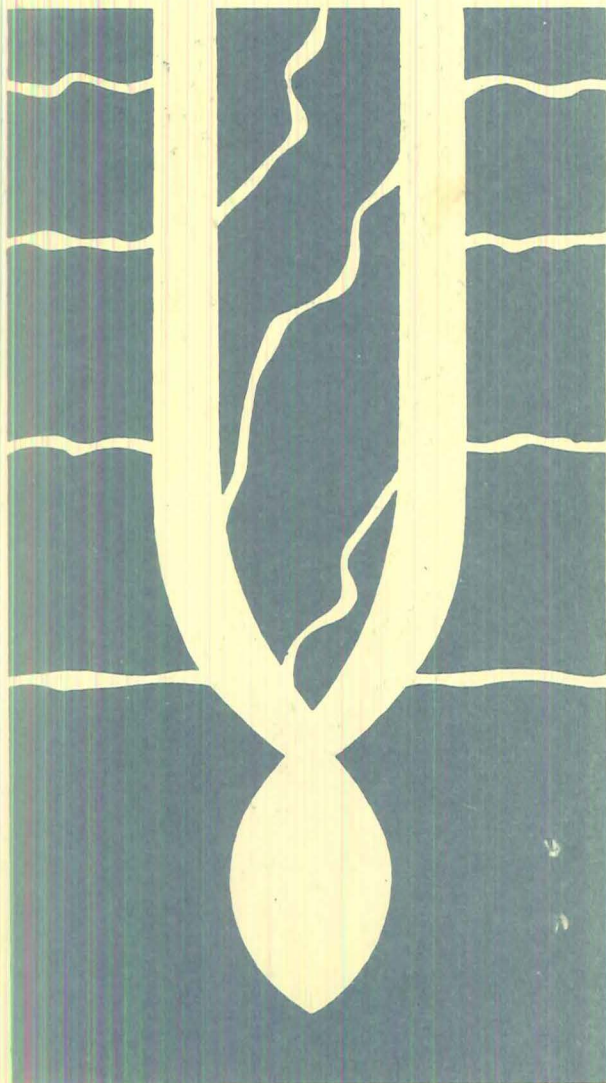


# Soil Survey Papers, No. 14

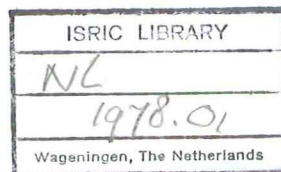
SOIL DEVELOPMENT IN  
RECENT MARINE SEDIMENTS  
OF THE INTERTIDAL ZONE  
IN THE OOSTERSCHELDE -  
THE NETHERLANDS.  
A SOIL MICROMORPHO-  
LOGICAL APPROACH



M. J. Kooistra

Netherlands Soil Survey Institute, Wageningen

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M. J. Kooistra

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SOIL SURVEY INSTITUTE, WAGENINGEN, THE NETHERLANDS — 1978

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## INTRODUCTION

Much of the surface of the Netherlands has been reclaimed from marine deposits, and marine clay soils now cover about 30% of the total area of the country. The study of subjects related to sedimentation and reclamation in the Netherlands began about 300 years ago. The first studies mainly focused on the geogenesis of the marine clay area. Later, Dutch soil scientists began to study the pedogenesis of young marine soils, especially the pedogenesis occurring during and after the embankment, drainage and reclamation of the land was studied. These studies usually dealt with specific topics such as: the decrease in volume caused by water loss; desalinization; carbonate contents; and the oxidation of pyrite-containing soils. Not much attention was paid to pedogenesis occurring during the development of coastal accretions before reclamation. The study of this pedogenesis, however, is also important. Firstly, because knowledge of soil development before reclamation gives a better understanding of phenomena present in polder soils and secondly, because coastal protection works cause marked changes in tidal ranges influencing these processes. The present study is therefore focused on soil development in recent sediments before reclamation.

There are several ways of investigating occurrence and importance of soil-forming processes. In this study emphasis was laid on the micro-morphological investigations of selected thin sections. As far as the author is aware this is the first systematic micromorphological research of recent marine sediments.

The aims of this study are:

- (i) to reconstruct processes operating in the intertidal zone with the aid of micromorphological observations, field data, physical and chemical analyses, and knowledge of the flora and fauna;
- (ii) to develop a model in which the occurrence and importance of the processes distinguished are given in a zone ranging from Mean Low Tide level to the highest levels reached by tides (the intertidal zone);
- (iii) to study the preservation of features originally formed in the intertidal zone in some reclaimed polder soils.

This study is restricted to marine sediments. In brackish or freshwater sediments the chemical processes and flora and fauna may cause very different phenomena.

The area selected for this study had to have intertidal flats and salt marshes that had developed naturally without human influence such as reclamation works or grazing. The Oosterschelde was chosen because it is the only marine inlet of the sea in the southwestern part of the Netherlands. A complete transect from Mean Low Tide level to highest saltings covered too large an area for detailed survey. Therefore two localities were selected that together comprised the complete sequence of sedimentation from Mean Low Tide level to highest saltings (see Figure 1).

To study the preservation of features originally formed in the intertidal zone, the four different soil types representing the variety of soils present in the highest saltings, were compared with equivalent soils selected in reclaimed polders. To be comparable, these 4 polder soils had to have been reclaimed from marine sediments and had to be about the same age. The soils chosen were situated in the Eerste and Tweede Bathpolder (see Figure 1).

This study is divided into four chapters. The first chapter describes the geological history of the southwestern part of the Netherlands, the genesis of intertidal zones (hydrography, sedimentation and sediment, and geomorphology) with emphasis on the Oosterschelde, and some important factors influencing the sediment in the intertidal zone (climatic conditions, fauna and vegetation). The second chapter deals with the field investigations: the survey of the se-



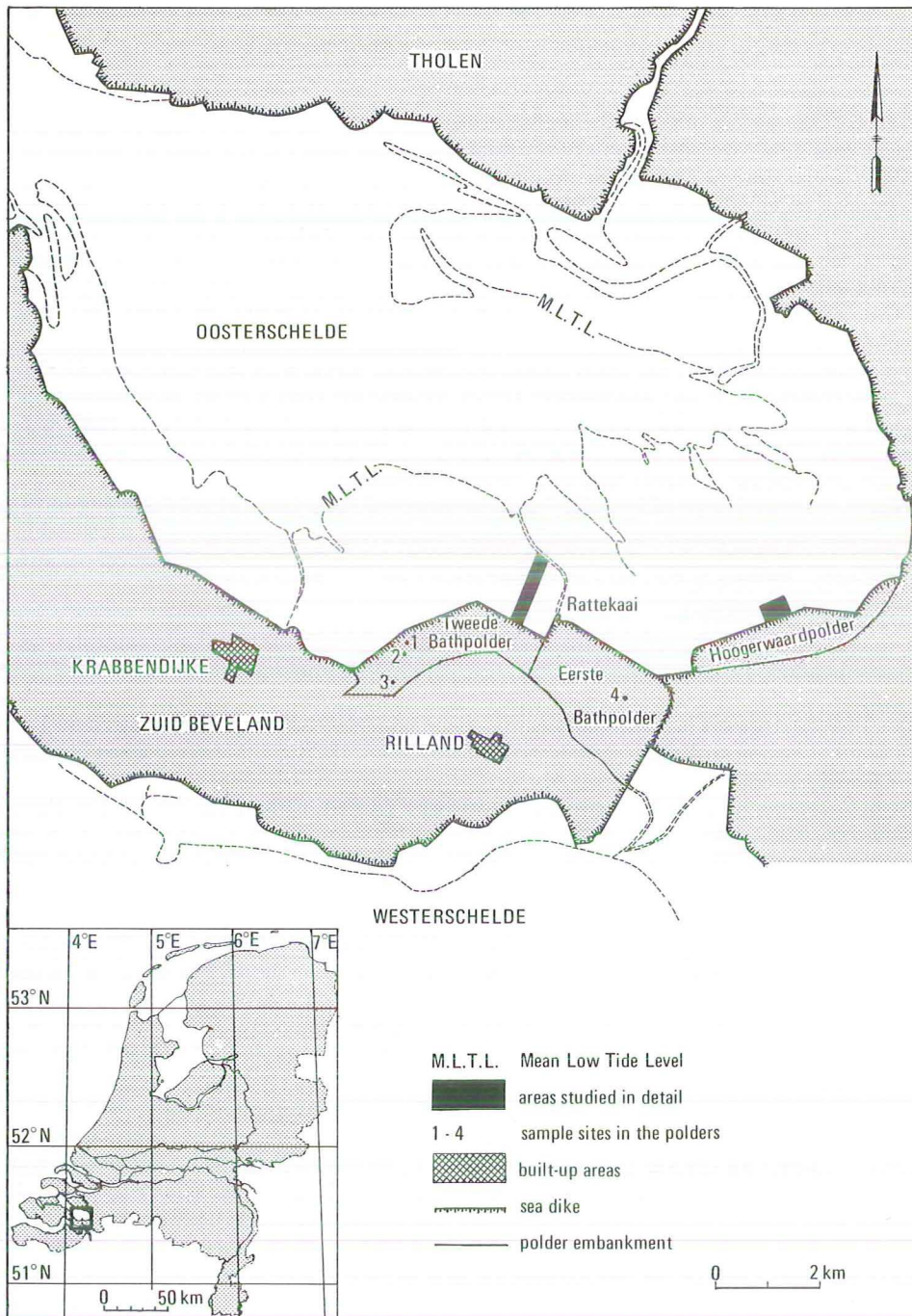


Fig. 1. Location of the study areas and polder sample sites, with inset of the Netherlands.

lected areas, the presentation of the survey in four detailed maps and the selection of the soils for further research are the main elements. The third chapter deals with the results of the physical and chemical analyses of the selected soils. These data give basic information about the soils and are important for the interpretation of phenomena visible in thin sections. In Chapter 4 the results of the micromorphological investigations are discussed. This chapter is divided into three parts. The first part deals with the interpretation of the phenomena in relation to the processes responsible (biological, physical and chemical). In the second part the occurrence and abundance of the different processes from low to high in the intertidal zone is discussed, together with a classification of the different soil fabrics occurring in the intertidal zone. In the final part the results of the study of the selected polder soils are given. Two aspects are dealt with in this part: (i) phenomena inherited from the pre-reclamation phase and (ii) phenomena due to soil development after embankment, drainage and reclamation.

# 1 ENVIRONMENTAL CHARACTERISTICS

## 1.1 GEOLOGY

### *Introduction*

This study deals with soil formation in Holocene deposits and therefore the genesis and composition of these deposits must be explained. The study area lies on the North Sea coast in the southwestern part of the Netherlands in Zeeland, an area lying on the margin of an old sedimentary basin that was frequently covered with a shallow sea and which has been infilled with Mesozoic and Caenozoic deposits (see VEENSTRA, 1969). Many of the deposits are of marine origin.

### *Quaternary development*

During the glacial periods in the Pleistocene, sea level was about 100 m lower than in interglacial times when it reached present level or higher (PANNEKOEK (Ed.), 1973). At the end of the Weichselian a sandy plain built up of fluvial and periglacial deposits existed on the site of the present coastal area.

Sea level rose continuously throughout the Holocene and several transgressive phases have been recognized. At first the rise in sea level was rapid and at the end of the Boreal ( $\pm 7500$  B.P.) the coastline of the North Sea approximated to the present coastline of the Netherlands (JELGERSMA, 1961; HAGEMAN, 1969). In front of the encroaching sea peat began to accumulate on the sandy Pleistocene sands. This peat is known as Lower Peat. The sea drowned the lower parts of the peat covering it with a clay layer. Locally the Lower Peat was eroded and gullies were cut into the Pleistocene deposits. On the clay layer extensive intertidal flats\* and salt marshes\* were developed. During the late Atlantic and early Sub-Boreal the rate at which the sea level rose decreased. By then a fairly well-closed system of coastal barriers had developed in the southwestern coastal sector, protecting the land from further incursions by the sea and conditions were temporarily stabilized (HAGEMAN, 1969; ROELEVELD, 1974). Marine sedimentation ceased and new peat formation started on these deposits. Protected by the coastal barriers the peat developed extensively: it is known as Holland Peat. The deposits overlying the Lower Peat and covered by the Holland Peat are called the Calais deposits (see Table 1). The maximum extent of the Calais deposits was further inland than the present coastline. In Zeeland the landward limit was situated near the southern bank of the Westerschelde and bent northwards near Bergen op Zoom (see HAGEMAN, 1969; Rijks Geologische Dienst, 1975).

Since the latter half of the Sub-Boreal and throughout the Sub-Atlantic, local marine transgressions have occurred when the sea has breached the weakest parts of the coastal barriers and low dunes or has entered via river estuaries. These transgressions caused local erosion of the peat and underlying Calais deposits and laid down new sediments (PONS, 1965; HAGEMAN, 1969). These deposits are referred to as Dunkerque deposits. In the Netherlands several Dunkerque transgressions are known (see Table 1). The deposits of the Dunkerque 0 transgression have not been found in Zeeland and the Dunkerque I deposits are only locally present in the most western parts of the islands (VAN RUMMELEN, 1970, 1972). The younger Dunker-

---

\* Terms indicated with an asterisk are explained in the glossary.



Table 1. The chronology of the Holocene.

EPOCH	AGE	TIME SCALE B.P.	MARINE TRANSGRESSIVE INTERVALS	DATES B.P.
H O L O C E N E	SUB-ATLANTIC	0	DUNKERQUE III B	0
		1000		700
			DUNKERQUE III A	800
				1100
			DUNKERQUE II	1400
	SUB-BOREAL	2000	DUNKERQUE I	1750
				2200
		3000	DUNKERQUE 0	2500
	ATLANTIC	4000		3000
			CALAIS IV	3500
		5000		4000
			CALAIS III	4700
				5300
BOREAL	6000	CALAIS II	6300	
			6300	
PRE-BOREAL	7000	CALAIS I		
			8000	
		8000		
		9000		
		10000		

(mainly after Rijks Geologische Dienst)

que deposits determine the present landscape in large parts of Zeeland. The Dunkerque II deposits are the result of the post-Roman transgressions that occurred between 250-650 A.D. The sea breached the coastal barriers and a low strip of dunes so creeks were formed. Where peat remained, a clay-rich sediment was deposited. Salt marshes developed and large creeks filled up, mainly with marine sands. In this landscape people settled and built low dams. During subsequent invasions large parts of this landscape were eroded. The surface remnants of the Dunkerque II deposits form the nuclei of the present-day islands and are known as 'oldland'. Dunkerque II deposits have rather high percentages of clay, 43-50%, and the upper layer contains little or no carbonates.

The next phase of invasions of the sea occurred between 900 and 1200 A.D. After rather superficial erosion and gully formation a new cycle of sedimentation took place ending with the development of salt marshes. The upper layer of these deposits contains carbonate. These Dunkerque IIIa sediments can be visualized as oldland with a younger top layer of varying thickness: they are called 'middleland'. During a new period of marine transgressions, the Dunkerque IIIb, which includes all incursions of the sea after 1300 A.D., much of the land was eroded. In the late Middle Ages storm tides were probably very frequent and many low dams collapsed. Particularly notorious are the Elizabeth floods of 1404-1421 and the incursions of 1531, as a result of which the island of Noord-Beveland, the Land of Reimerswaal and Saaftinge were drowned and deep gullies were formed. Locally the Holland Peat, Calais deposits and Pleistocene sediments were eroded. The highest parts of the landscape remained as many small islands (VAN RUMMELEN, 1970, 1972). Subsequently new sedimentation started. Along the coasts new intertidal flats and salt marshes were formed. Many of them have subsequently been reclaimed.

The study area lies mainly in the drowned Land of Reimerswaal, parts of which have been reclaimed. Figure 2 shows two geological cross-sections through the study area (unpublished data, placed at my disposal by the Rijks Geologische Dienst, Haarlem). Calais deposits are present locally underground, indicating that this area forms the landward limit of the Calais deposits. One of the creeks formed during a Calais transgression eroded a part of the Lower Peat and cut into the Pleistocene sands. The Lower Peat coincides with the Holland Peat over a large area. Dunkerque II and IIIa deposits only occur in the subsoil. The sediments on the surface belong to the Dunkerque IIIb deposits and all the soils studied are situated on these deposits.

## 1.2 CLIMATIC CONDITIONS

The Netherlands have a marine west-coast climate which is controlled by both tropical and polar air masses. Locally and seasonally either tropical or polar air masses may dominate in this region, but neither has exclusive control (ZEEMANSGIDS, 1974).

The mean monthly temperature along the southwestern coast varies between 2.5°C in February and 17.2°C in August<sup>1)</sup>. Due to the exchange of heat between seawater and land the mean diurnal variation in air temperature during the year is 30% less than that of De Bilt, 56 km inland. Maximum temperatures occur in August. Frost are rare on the coast and there are few days when maximum temperatures exceed 25°C.

The coast is windy and the wind velocities are often high. The wind velocities are higher in winter than in summer, corresponding to greater cyclonic activity. For 50% of the year the wind blows from directions between south and west.

<sup>1)</sup> Data selected from the Klimaatatlas van Nederland (1972) and reports of the Royal Netherlands Meteorological Institute, at De Bilt.

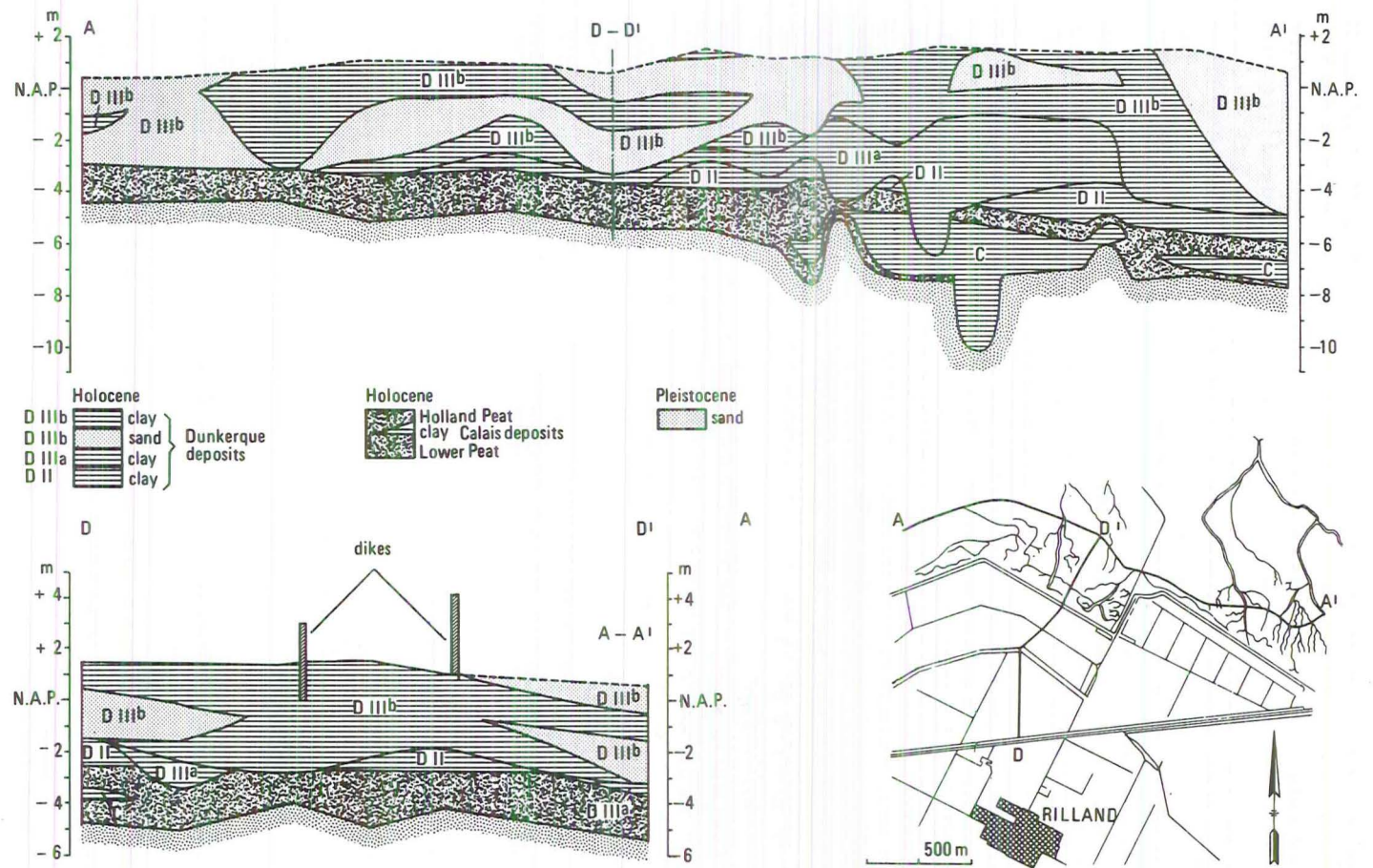


Fig. 2. Geological cross-sections through the study area and location of the cross-sections.



The coastal area is the sunniest part of the Netherlands. May and June usually are the sunniest months.

The average annual rainfall in the zone studied in Zeeland is about 700 mm, with an autumn maximum and a spring minimum. The average annual amount of evaporation in this zone, according to Penman, is about 725 mm. After correction for the estimation of potential evapotranspiration there is a mean effective precipitation of 200 mm per annum. This is either available for water requirements or is superfluous and must be drained off.

### 1.3 HYDROGRAPHY

#### *General*

In the southwestern part of the Netherlands the tides, which are normally regular and predictable, are very important. The most disturbing effect on tidal range is caused by the wind, which acts irregularly. The direction and strength of the wind in relation to the orientation of the coast is critical. Onshore winds help to generate local waves and produce currents that have an important effect on the movement of material. They also tend to raise the sea level above normal, while offshore winds tend to reduce the height of the tide and local waves (KING, 1972). Strong onshore winds cause storm tides enabling the waves to reach parts of the coasts usually beyond their reach. This can have a very damaging effect on lowland coasts. During the stormtide of 31 January 1953, the sea level in the southwestern part of the Netherlands was 3 m above the predicted level at high water.

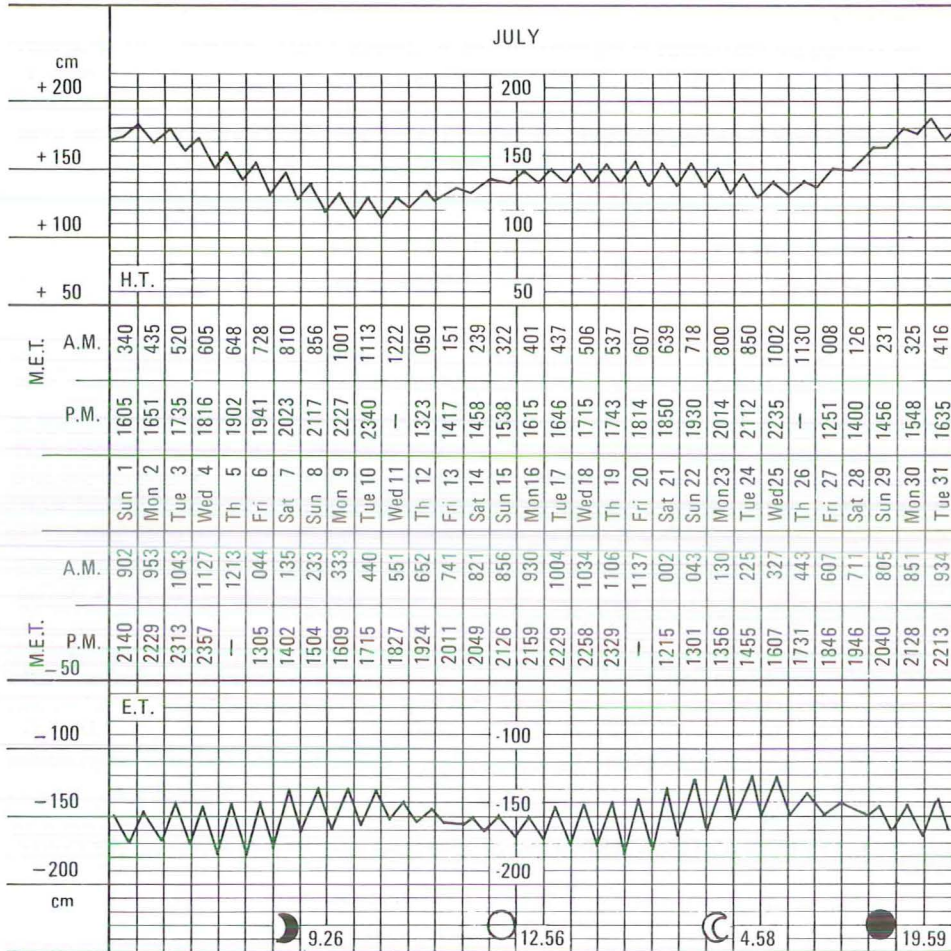
Tides also cause currents, and these have a very specific character. The direction of the currents reverses after each high and low tide reducing their capacity to move material over long distances. When they have sufficient velocity they can pick up material from the seabed and transport it together with material that has been thrown into suspension by waves. When the velocity of the tidal currents is low, deposition occurs. The sediments can form intertidal flat and salt-marsh deposits. The suspended load may also be derived from material transported by rivers or brought in by the sea. It may even originate from the tidal basins or from estuaries, either by erosion of older deposits in the channels or by biological activity (TERWINDT, 1967).

The tide in the southwestern part of the Netherlands is a semi-diurnal type with two maxima and two minima daily. Figure 3 shows the course of the tides in relation to the phases of the moon for Zierikzee, Oosterschelde (for location of Zierikzee, see Figure 9). The mean daily difference in the successive high tide levels is 15 cm, in low tide levels it is 20 cm<sup>1)</sup>. The monthly variation in successive high tide varies from 0-30 cm, in low tides it varies from 0-40 cm. North of the Tweede Bathpolder near one of the areas studied in detail, Mean High Tide level is 1.97 m + N.A.P.\* (Dutch Ordnance level = approximately mean sea level), it increases to 2.24 m + N.A.P. at spring tide and decreases to 1.62 m + N.A.P. at neap tide. The heights reached at spring tides and other unusually high tides determine the maximum heights sediments can be laid down by tidal currents. The highest velocities of the tidal currents are usually recorded at the entrance of the tidal inlets. In the eastern part of the Oosterschelde, between the island of Tholen and Zuid-Beveland, the maximum velocities during high tide vary between 0.8 and 1.1 m s<sup>-1</sup> and occur half an hour before high tide. The highest current velocities during ebb vary between 0.9 and 1.0 m s<sup>-1</sup> and occur about 3.5 h after high tide. In both cases the direction of the tidal currents reverses an hour after high or low tide.

According to DE GROOT (1963) the sediments found in the Oosterschelde are of marine ori-

<sup>1)</sup> Data given in this section are provided by the Rijkswaterstaat, unless otherwise stated.

ZIERIKZEE 1973



Source: RIJKSWATERSTAAT

M.E.T. = Middle European Time  
 H.T. = High Tide  
 E.T. = Ebb Tide

Fig. 3. Part of the tide-table for Zierikzee (Oosterschelde).

gin and are derived from the Oosterschelde itself and from the North Sea. The suspended load in the tidal currents is not constant throughout the year. As the discharge of river water has practically no influence in the eastern part of the Oosterschelde any fluctuation in the content of the load suspended in the seawater will depend on stormy weather and biological action (TERWINDT, 1967). Up to 50% of the mud in the Oosterschelde is of organic origin (DRINKWAARD, 1957, 1958, 1959). As part of the suspended load, mud is defined as all matter whose rate of fall in still water is less than that of a quartz grain 50  $\mu\text{m}$  in diameter.



### *Tidal range, current velocities and suspended load in the study area near the Rattekaai*

With the aid of the Rijkswaterstaat, Zierikzee, a series of measurements was made at certain points along a major water course at spring tide on 2 July 1973. The measurements were taken at three sites in the bed of the main water course; one in the low intertidal flat, I (gully), one in the low salt marsh, II (creek), and one in what is nearly a high salt marsh, III (creek) (see Figure 4). At these places seawater level was measured every five minutes. In addition, at point II current velocities were measured and water samples were taken to enable the suspended load to be calculated. The current velocities were measured with Ott current meters affixed to three vertical rods A, B and C in the creek bed. Water samples were taken every 10 minutes during high tide and every 15 minutes during ebb tide at the sites of the vertical rods.

Using the observations of sea level made at the three points, three tidal curves were drawn up (see Figure 5). Several facts are evident. Towards the end of the main water course seawater arrives later and the period of flooding is shorter because of the greater altitude of the salt marsh. The mean velocity of the water in the main water course with high tide is approximately  $0.3 \text{ m s}^{-1}$ . The greatest height of the sea water was observed near the beginning of the gully at the branching of the tidal channel; this is usual under normal conditions without superimposed wind. The decrease in high tide height is due to hydraulic resistance (the increasing friction between the water and the configuration of the creek which increases with distance up the water course). Hydraulic resistance is also responsible for the decrease in current velocities with depth. For example the current velocities at maximum ebb tide on vertical B of sampling point II were  $0.66 \text{ m s}^{-1}$  at 50 cm depth,  $0.55 \text{ m s}^{-1}$  at 80 cm depth and  $0.40 \text{ m s}^{-1}$  at 130 cm depth (50 cm above the creek bed).

The highest level of the seawater observed at point II was  $2.34 \text{ m} + \text{N.A.P.}$  At that time large parts of the salt marshes were covered with water. Tidal curve II is asymmetrical. The rise in water level was quicker than the fall of the water. The irregularities in all three curves result from the large amounts of drifting seaweed blocking the apparatus, and the distance between the tide gauges.

The mean current velocities measured at verticals A, B and C at point II are given in Figure 6 (for position of the verticals see figure 7). This figure shows that from the beginning of the high tide the current was fast and that it decreased about 45 minutes before the direction of the current reversed. The highest current velocities were recorded at ebb tide, within an hour after the current had changed direction. The highest velocities measured occurred in mid-creek and attained  $0.50 \text{ m s}^{-1}$  with high tide and  $0.55 \text{ m s}^{-1}$  with ebb tide.

Figure 7 shows the pattern of current velocities for the total cross-section at several half-hour intervals. With the high tide the maximum velocity occurred near the eastern bank, with the turn of the tide it shifted more to the middle of the gully. During ebb tide it moved still further to the middle of the stream, moving back to the eastern bank just before the end of the ebb tide. Thus the shape of the cross-section is determined by the course followed by the fastest currents near the eastern bank. This bank has a steep gradient: the opposite bank slopes more gradually and has small step-like slumps. At point II in the tidal gully there is no difference in ebb or flood gully bed.

In Figure 8 the curve of the discharge in the cross-section of the creek at point II is given. The figure shows that the total inflow was equal to the total discharge. With high tide the maximum inflow was  $11.2 \text{ m}^3 \text{ s}^{-1}$  and occurred 45 minutes before the turn of the tide. About the same time after the turn of the tide a maximum discharge  $11.5 \text{ m}^3 \text{ s}^{-1}$  occurred. During the period before the arrival of the next high tide, very small quantities of water were drained off via the main water course to the tidal channel. The suspended load is also shown in the figure (sediment transport along the bottom is excluded). In summer small quantities of suspended load are present in the Oosterschelde (TERWINDT, 1967). Therefore the quantities measured in



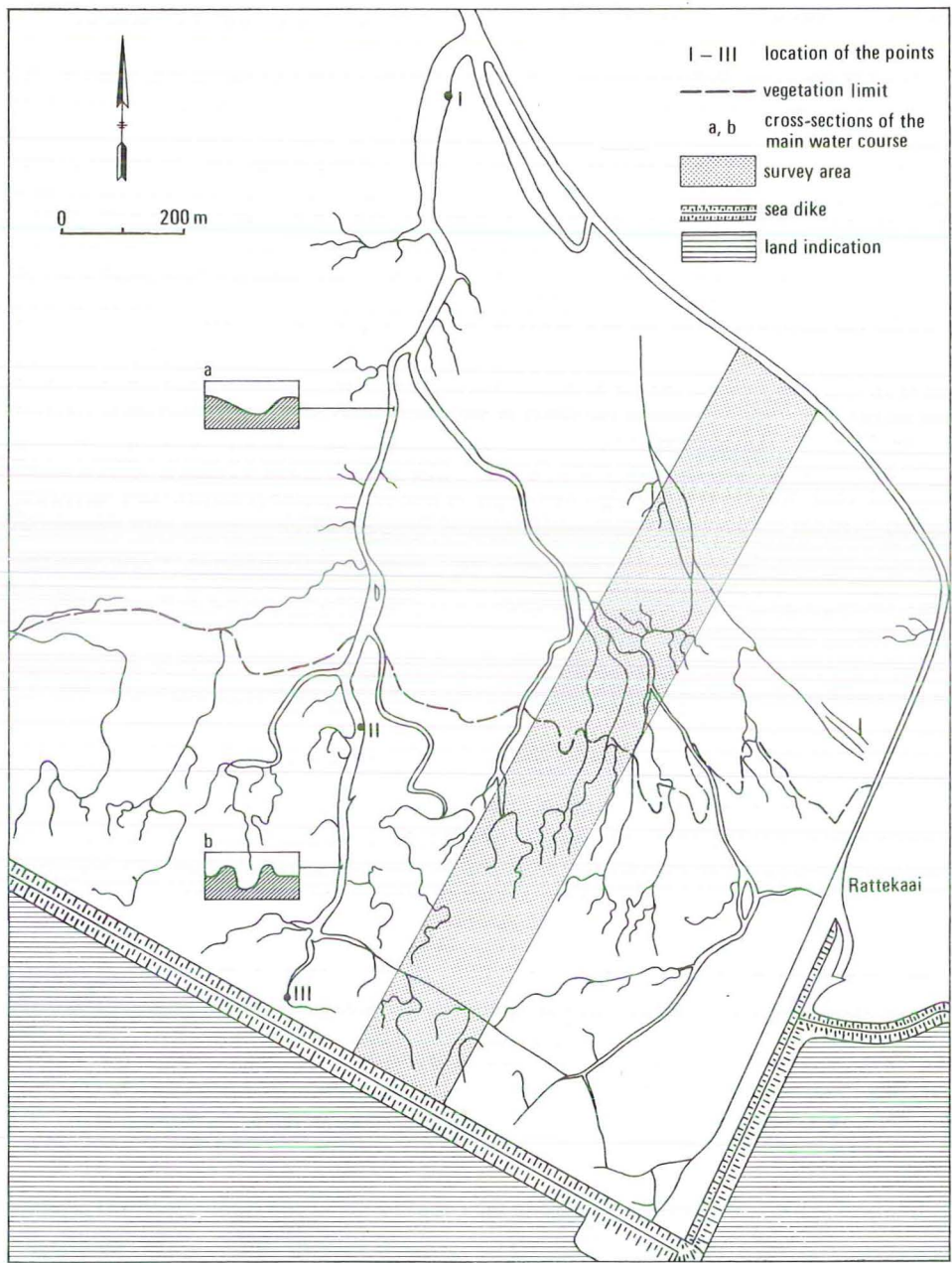


Fig. 4. Location of the points of measurements in the main water course, Rattekaai (Oosterschelde).

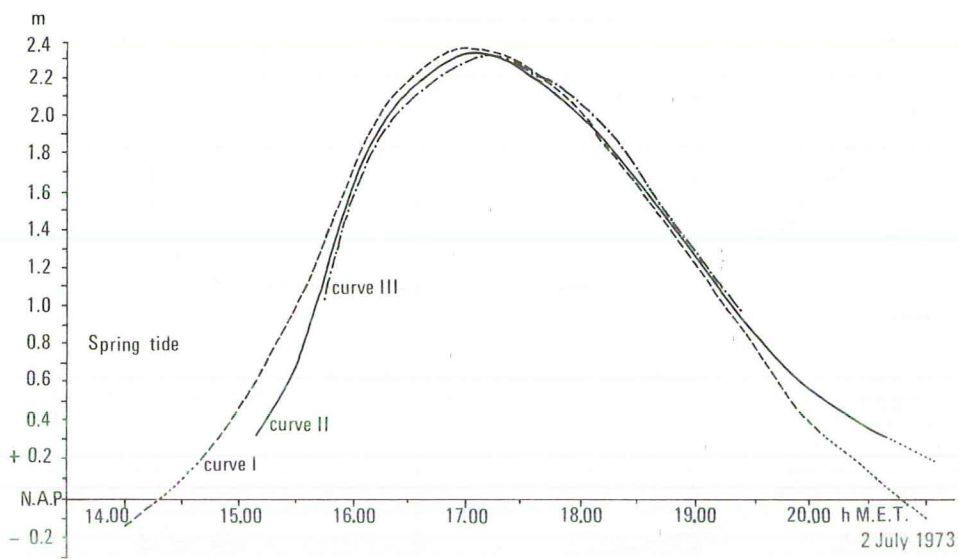


Fig. 5. Tidal curves at the points of measurements.

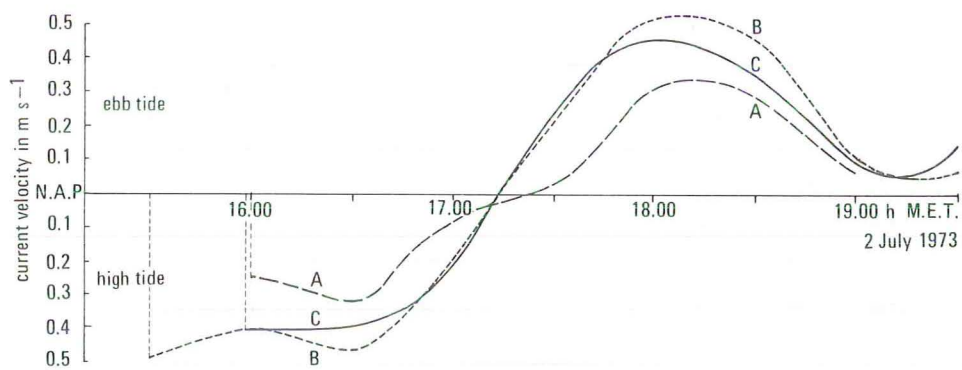


Fig. 6. Mean current velocities at the verticals A, B and C at point II (for location of the verticals see Fig. 7).

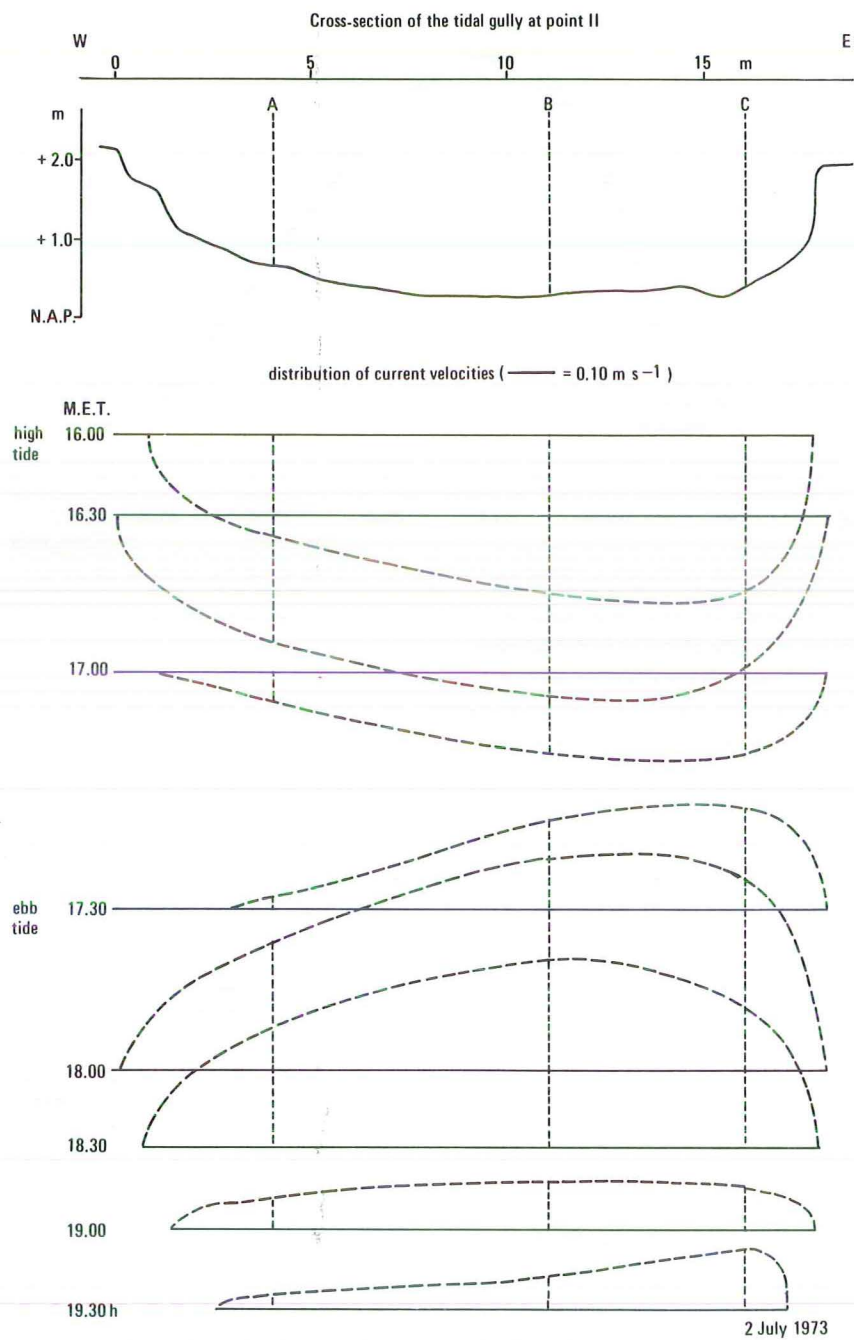


Fig. 7. Cross-section of the creek at point II and distribution of the current velocities over several half-hour periods.



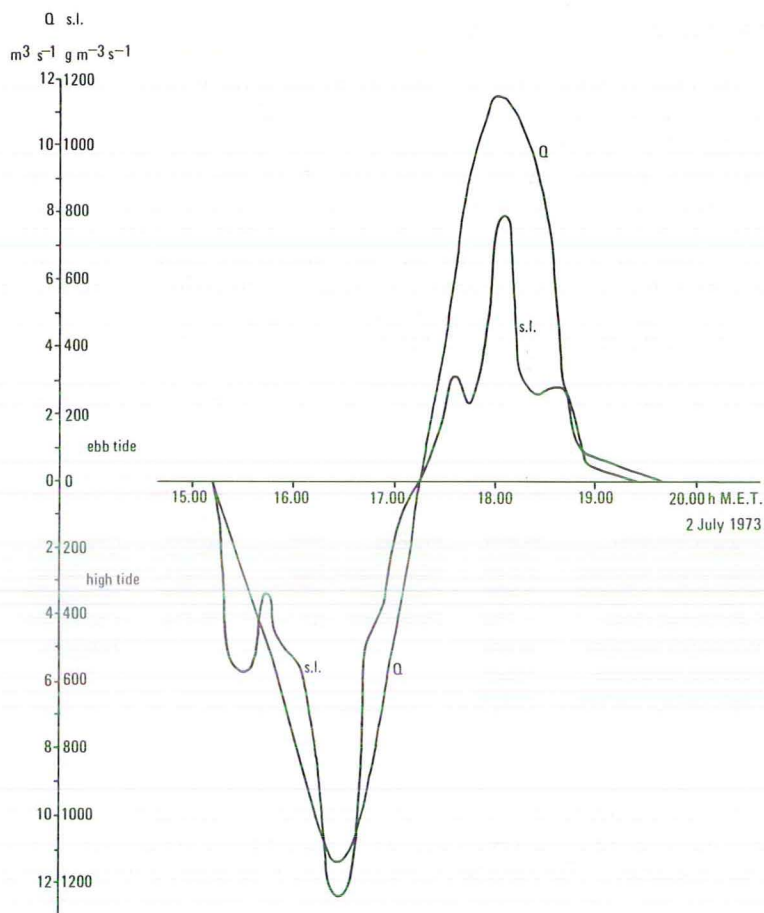


Fig. 8. Discharge (Q) and suspended load (s.l.) during a high tide and an ebb tide at point II.

the present study must be considered as being low: the greatest content measured was 13 mg dry material per litre. The curve shows that more suspended matter was brought in than was removed (about half the amount brought in was removed). With ebb tide it can be clearly seen in the drained water that there is still suspended matter present. The catchment area of the main stream is about 125 000 m<sup>2</sup>, so assuming that the same quantity of suspended load is deposited with every tide, its surface should be built up by approximately 6 cm each year. This indicates the possible rate at which the land-surface could be built up. However, the sediment deposited is not equally distributed over the surface: more sediment is deposited on the natural levees than on the backland.

### Chemical data on the seawater<sup>1)</sup>

The Oosterschelde is the only inlet of the sea in the Province of Zeeland that contains salt water. The other inlets are less saline because of the large amount of fresh water they discharge (PEELEN, 1967). The salinity of the Oosterschelde fluctuates. The highest salinities have been recorded near the entrance to the North Sea. The Oosterschelde is most saline in the last three months of the year when the surface salinity measured in the centre of the eastern part contains an average of  $17\,305\text{ mg l}^{-1}\text{ Cl}^{-}$ . Salinity is lowest in the spring:  $16\,605\text{ mg l}^{-1}\text{ Cl}^{-}$ . Tidal currents ensure that the water masses are usually well mixed vertically. Vertical gradients in salinity, temperature and oxygen are normally not clearly developed.

According to the Rijkswaterstaat the following quantities of ions and ion-combinations are present in the North Sea (see Table 2).

Table 2. Chemical composition: the most important ions and ion-combinations in North Sea seawater.

	g per kg			g per kg			g per kg
Sodium chloride	26.688	Sodium	Na <sup>+</sup>	10.515	Chloride	Cl <sup>-</sup>	18.964
Magnesium chloride	3.734	Magnesium	Mg <sup>2+</sup>	1.275	Sulphate	SO <sub>4</sub> <sup>2-</sup>	2.053
Magnesium sulphate	1.026	Calcium	Ca <sup>2+</sup>	0.409	Bicarbonate	HCO <sub>3</sub> <sup>-</sup>	0.095
Calcium sulphate	1.236	Potassium	K <sup>+</sup>	0.174	Carbonate	CO <sub>3</sub> <sup>2-</sup>	0.007
Potassium sulphate	0.846				Bromide	Br <sup>-</sup>	0.065
Calcium carbonate	0.121						
Magnesium bromide	0.074						

The annual temperature amplitude of monthly averages of the water of the Oosterschelde is over 16°C (KORRINGA, 1941). The lowest temperatures occur in February and the highest in July and August. The minimum temperature of the water is often below 3°C. Values below zero are rare. The maximum temperatures of the water may exceed 20°C for several days. Offshore in the North Sea the annual fluctuation in water temperature is less than 10°C and ranges approximately between 6 and 16°C (ZEEMANSGIDS, 1974). The distribution of the mean temperature in three monthly periods over two years is given in Figure 9. Seawater temperature is critical for biological activity in the intertidal zone. Low water temperatures in spring discourage vegetation growth and faunal activity and these start later than on land.

The water of the Oosterschelde and that of the North Sea is normally totally saturated with oxygen. Oversaturation to 120% is not unusual.

The pH of the water in the Oosterschelde is high and reasonably stable. It varies between 7.7 and 8.2.

#### 1.4 SEDIMENTATION AND SEDIMENTS

Intertidal flats and salt marshes can develop along gently sloping seacoasts that have marked tidal rhythms and where enough sediment is available and wave action is hampered. In shallow marine environments a process of sorting during transport is active.

<sup>1)</sup> Data provided by the Delta Dienst - Rijkswaterstaat, 's Heer Arendskerke, unless otherwise stated.

quarterly averages of samples taken twice monthly during 1972-73 (after data from the Delta Dienst, Rijkswaterstaat)

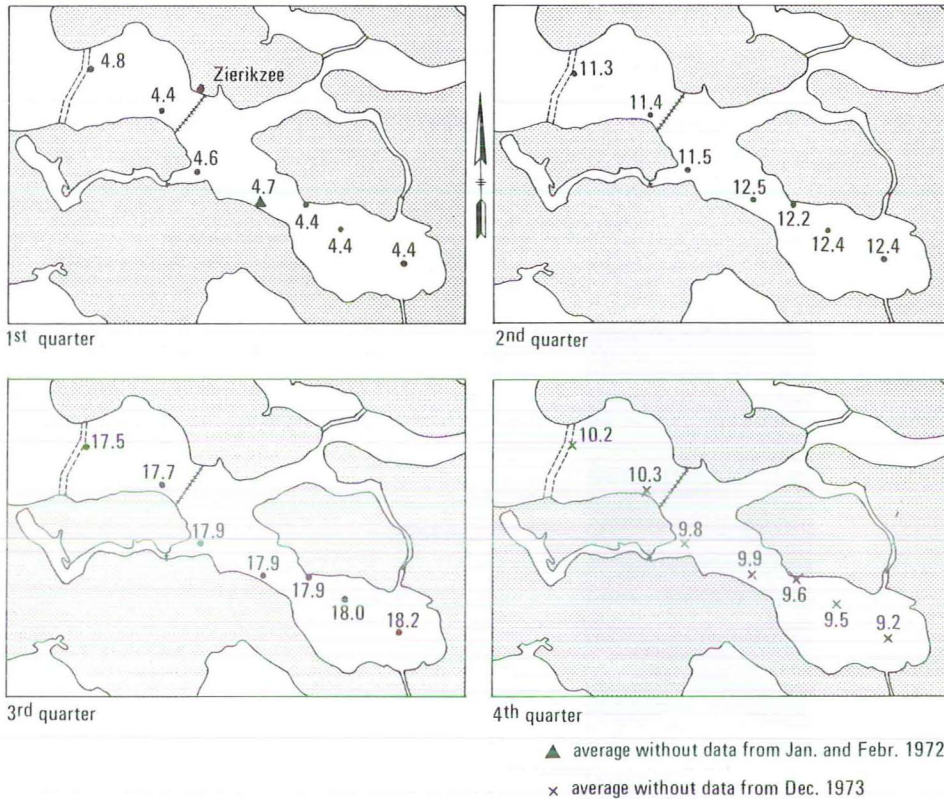


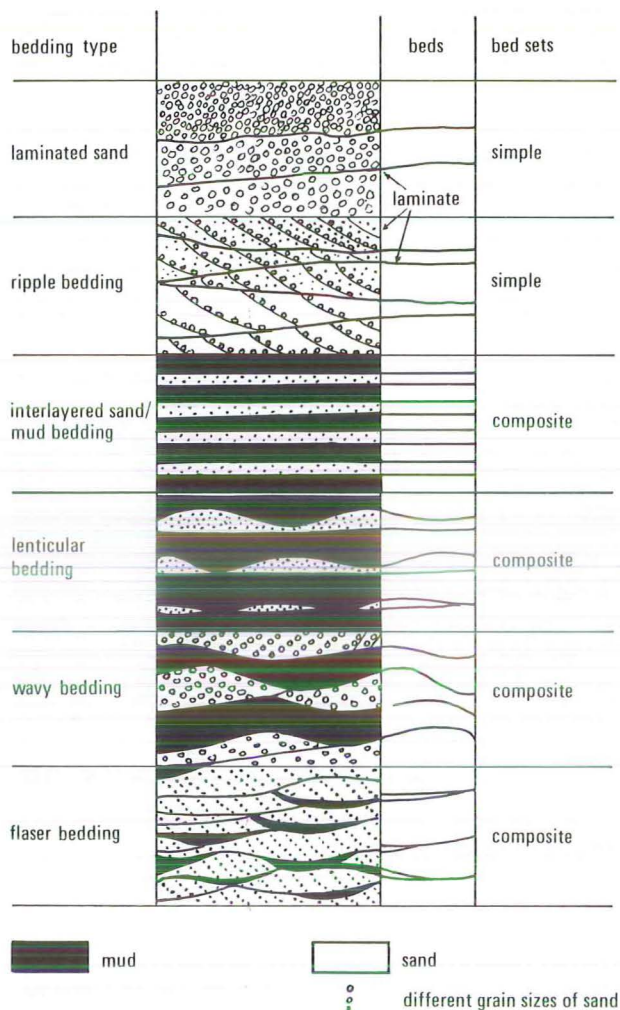
Fig. 9. Mean temperature of the seawater in the Oosterschelde in °C.

With the decrease in energy and capacity of the transporting medium, coarser sediments are deposited and only finer material is transported further. Lower intertidal flats are composed of well sorted sands, normally fine to very finely grained. Mud\*<sup>1)</sup> is occasionally deposited on the lower intertidal flats. As altitude increases, still finer particles are deposited and mud becomes predominant (ALLEN, 1970). This process of particle sorting as one moves from sea to land also operates from the source of sediment supply (gullies and creeks) to their backlands. The effect of sorting becomes more pronounced in higher salt marshes.

This sorting process only represents the general trend. In the intertidal zone the hydrodynamic conditions are very variable. The variation in water depth resulting from the tides, the varying current energies and superimposed wave energies, all cause considerable differences in successions of deposited laminae (REINECK & SINGH, 1973). Figure 10 shows several types of successions of laminae. The bedding types shown are mainly composed of successions of laminae, the sandy material of which was transported over the bed in various ripple patterns (see ALLEN, 1970; REINECK & SINGH, 1973). The varying successions of laminae are revealed if sections are cut normal to the surface.

<sup>1)</sup> The term 'mud' is used for soft clay-rich sediments that contain comparatively high amounts of water. When the water content decreases and the sediment becomes firm, this material is termed clay (VAN STRAATEN, 1954).





(Adapted from Reineck, Singh, 1973)

Fig. 10. Some important types of bedding.

The sediment in the study area in the Oosterschelde is rich in carbonate grains, containing many shells, snails, peat grains and pebbles of different sizes. These grains and pebbles originated from the erosion of exposed peat deposits in tidal channels (see Figure 2). Some of the shells, snails and peat are so fragmented and rounded that they are included as grains in the sand. Flattened and rounded-off bits of mud may also be embedded in the sediment. They are derived from blocs of soil material worked loose (for example after steep creek walls in the salt marshes have been undercut and have slumped into the creeks).

As these sediments are deposited from seawater the initial packing is very loose and all pores are filled with water. The consistence of the sediment (particularly the muddy sediment) is

weak because of its high water content. The higher the sediment is deposited above Mean Low Tide level the longer it is exposed to the air and the firmer it becomes. This is particularly important for the muddy sediments in the study area: they extend from the higher parts of the intertidal flat to highest saltings. The decrease in water content resulting in a firmer consistence is known as 'physical ripening' (ZUUR, 1958).

The thickness of the deposits above Mean Low Tide level is related to the tidal range. Generally they vary between 3 and 5 metres. The deposits in the intertidal flats vary between 2 or 3 metres; the deposits in the salt marshes usually vary between 1 and 2 metres in depth (ALLEN, 1970).

## 1.5 GEOMORPHOLOGY

### Introduction

The area above Mean Low Tide level up to and including the highest saltings can be subdivided into several zones. Usually this area is subdivided into two main subzones. In literature different terms are used for these main zones: tidal flats and salt marshes (VAN STRAATEN, 1954); eulittoral and supralittoral (BEEFTINK, 1965); and intertidal zone and supratidal zone (ALLEN, 1970). In all cases the subdivision is based on the apparent coincidence of the lower limit of the closed vegetation of halophytic phanerogams with Mean High Tide level. In the study area, however, the subzone with a closed vegetation starts between 1.30 and 1.40 m + N.A.P., while the Mean High Tide level is situated at 1.97 m + N.A.P. (see Figure 11). The occurrence of a closed vegetation below Mean High Tide level is known from other areas along the North Sea coast; for example Scheffer and Schachtschabel (1966) mention the existence of a closed vegetation 20-40 cm below Mean High Tide level in the north of Germany, De Glopper (1967) gives data from 20-30 cm below this level in the Wadden area north of the Netherlands. Also on other locations in the Province of Zeeland the vegetation continues 30-40

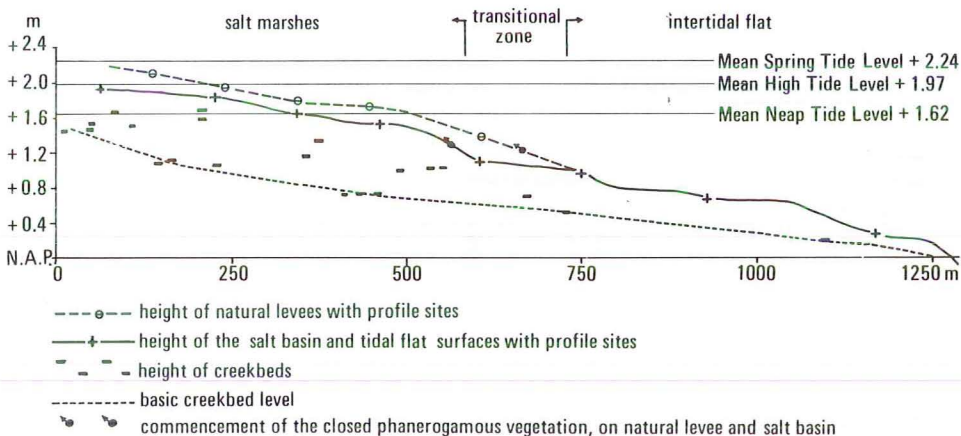
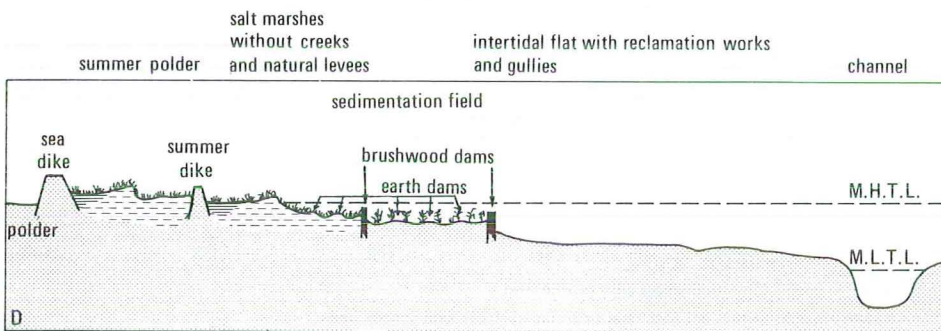
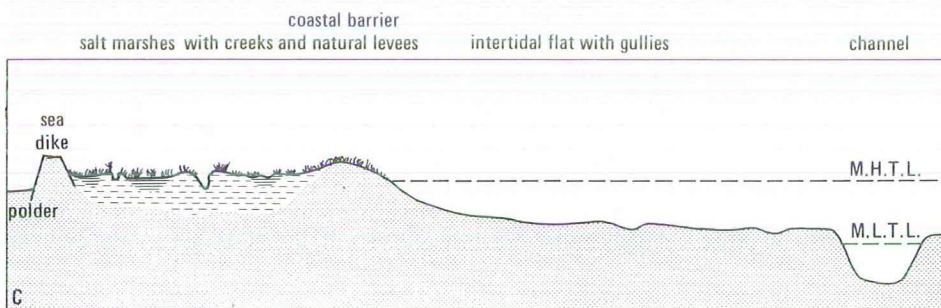
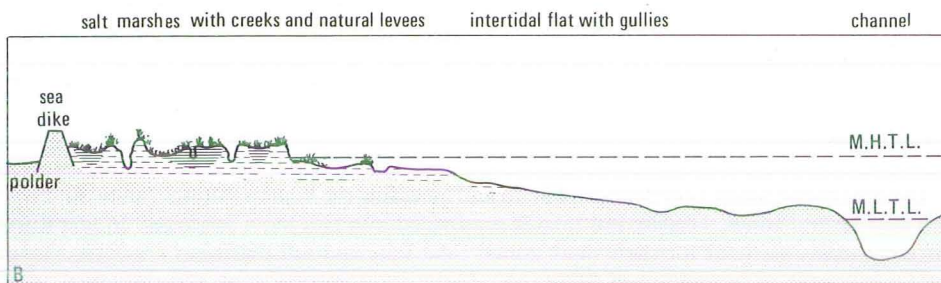
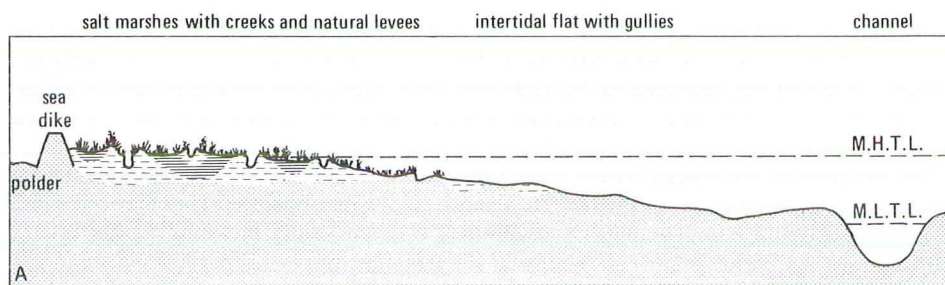


Fig. 11. Relation between different phenomena of the landscape and some mean tidal levels in a traverse near the Rattekaai (for location of the traverse see Map 5A, Appendix 3).



clay loam, silty clay loam and silty clay     
 
 sandy loam and loam     
 
 sand

M.H.T.L. = Mean High Tide Level      M.L.T.L. = Mean Low Tide Level

Fig. 12. Major shore types on sheltered coasts in the Netherlands.



cm below this level. So it is incorrect to correlate the boundary of the proper salt marshes with the Mean High Tide level and to base the terminology on this. Moreover it is incorrect to base all data on one type of shore. The type of shore present depends on local hydrodynamic conditions, presence of sediment and wind and wave action.

For the Netherlands four types of sheltered shores can be distinguished (see Figure 12). In all cases the occurrence of the closed vegetation will vary, with respect to the Mean High Tide level. In type A the surface level slopes gradually and the salt marsh proper starts below Mean High Tide level. In type B a distinct cliff edge is present marking the Mean High Tide level and generally also the limit of the salt marshes, although occasionally the vegetation may continue below the level of Mean High Tide (VAN STRAATEN, 1954). Type C is characterized by the occurrence of a distinct barrier. Behind this barrier salt marshes are developed. This barrier separates the two zones and no relation of Mean High Tide level with the vegetation limit can be given. Type D represents a shore in which the sedimentation is regulated by people in land reclamation works. In this case the vegetation continues below Mean High Tide level. This type prevails in the Wadden area in the north of the Netherlands (DE GLOPPER, 1967), but it does not occur in the Delta area. Types A, B and C occur both in the southwestern and in the northern part of the Netherlands. Type B is most common in the north; in the southwestern part no single shore type predominates. The shore of the study area belongs to type A.

Considering the above given shore types it is preferable to subdivide these shores according to morphological phenomena without relation to tidal levels. From now on the two subzones will be referred to as intertidal flats and salt marshes. Both subzones are not only characterized by absence or presence of a closed vegetation, but also by absence or occurrence of natural levees. They have different drainage densities and different granular compositions. In the study area (type A) a transitional zone can be distinguished between these two main subzones. Here, phanerogams occur locally, incipient natural levees develop and the mud content of the sediment shows a large increase. In this zone the density of water courses is higher than in the intertidal flats but lower than in the salt marshes. The two main subzones are further divided: the intertidal flats into low and high parts and the salt marshes into low, middle-high and high parts. Some of these subdivisions may even be absent.

The whole shore is indicated as intertidal zone, because it is governed by the tides; from now on in this study it will be referred to as the intertidal zone.

### *Intertidal flats*

In the intertidal zone the intertidal flats are usually most extensive. The surface of the intertidal flat undulates slightly and all kinds of ripple marks may be present on it. The intertidal flats are dissected by few tidal gullies. Some of them continue into the salt marshes on one side and end in the tidal channel on the other side. When the gullies have distinct natural levees they are called creeks. Some of the creeks disappear rapidly after debouching on the intertidal flat. Towards the tidal channel along the seaward edge of the intertidal flats small rather short gullies are found, which result from downcutting to the lower base level in the tidal channels at ebb-tide. The rather broad and shallow gullies in the intertidal flats meander and change course in the same way as rivers may do. They often have asymmetrical cross-sections. On the inner banks in the curves lateral deposits are present which usually rest on a residual deposit of shells that have accumulated on the gully floor as a result of erosion of the outer bank. Gravity faults can be found in the lateral deposits (REINECK & SINGH, 1973).

In the intertidal flats desiccation cracks are found. There are single, bifurcated or trifurcated cracks, as well as complete polygons. The polygons usually 3-6 sides and are generally 20-40 cm in diameter. On the lower flats the polygons may attain about 100 cm in diameter.

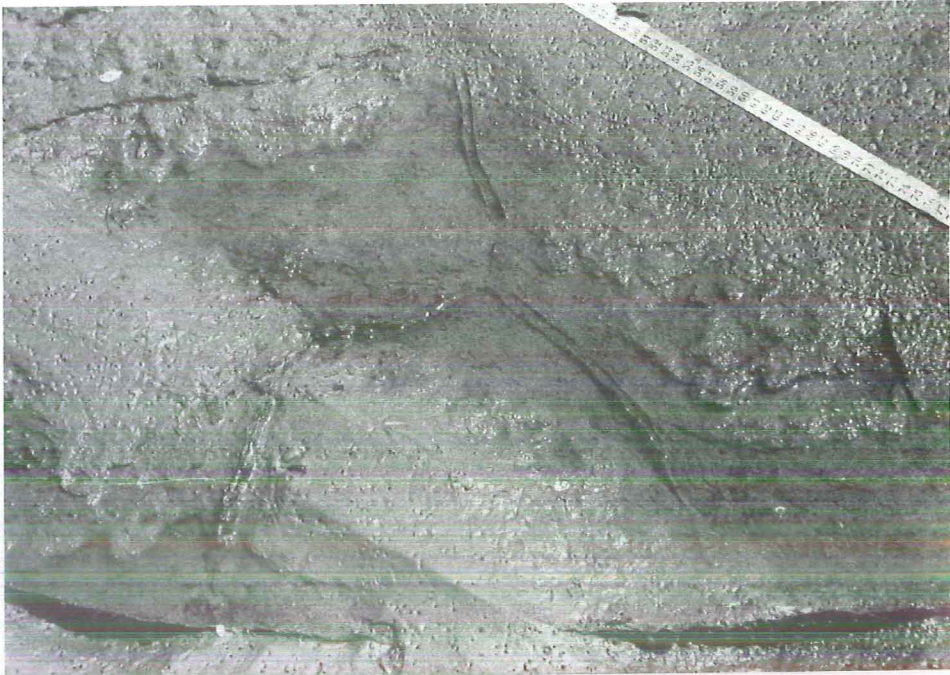


Fig. 13. Close up of polygons in sediment.

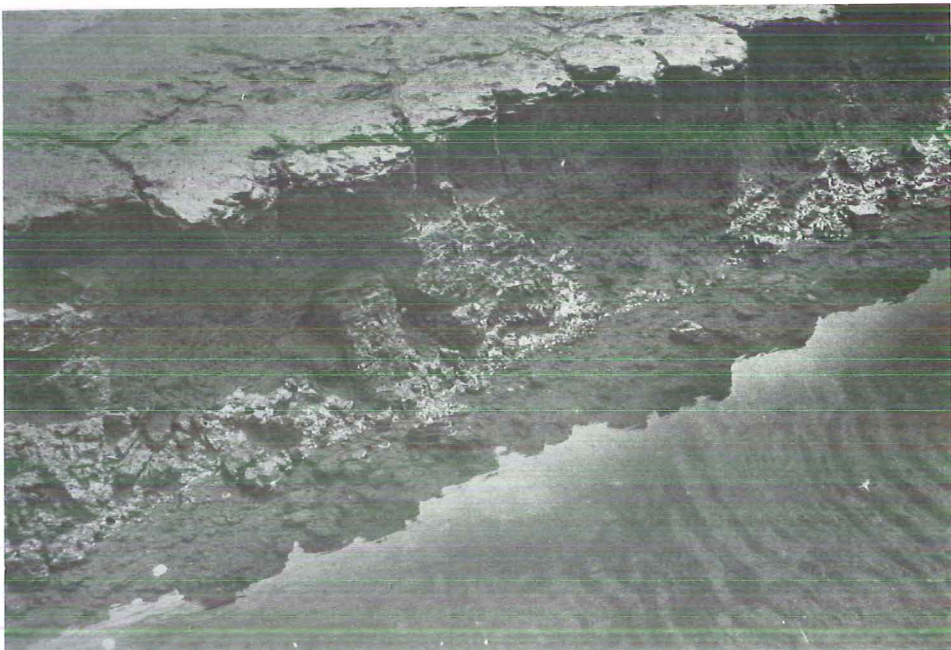


Fig. 14. General view of an area of intertidal flats, showing polygons.



The cracks themselves are 5-20 mm wide and 5-30 cm deep. Both sides often have ferruginous coatings that are several millimetres thick (see Figure 13). These polygon patterns are common in the intertidal flats. At normal low tides they are only visible at the surface locally, usually on the higher parts of the slightly undulating surface. In fact they are quite extensive, but because they are covered with recent sediment they are only revealed when strong desiccating winds coincide with low tides, causing shrinkage cracks. At such times salts also crystallize at the surface. The polygons are clearly visible in the steep walls of the asymmetrical gullies (see Figure 14). Individual polygons can be eroded and fall to the gully floor, where they become fragmented and subsequently disintegrate. Similar polygon structures are often visible in the cliff-edges of shores of type B (see Figure 12).

### *Salt marshes*

The salt marshes are dissected by numerous creeks, which often have well developed meanders. The creeks often form dendritic patterns (see Figure 4). Along the main creeks well developed natural levees are found. Progressing away from the larger water courses the levees are less well pronounced. Because of the relatively large vertical range of the tides the natural levees are clearly visible in the landscape. The differences in height from salt basin to natural levee increase from a few centimetres for the small creeks to 35-40 cm for the main creeks (see Figure 11).

Headward erosion and stream capture are common processes in the creek systems and are intensified by the segregation of flood and ebb currents along different paths in the creek beds. Undercutting of the creek walls by ebb or flood currents causes the banks to slip and the creek to change course. Slumping and slipping of the creek walls results in the formation of terraces on the slip-off slope. In most cases the soil material has slipped on oversaturated layers deeper in the profile, that have been intensified by water-draining sedimentary layers. The slumped soil is usually back-tilted. Often the extent of the slumped material is controlled by the distances between desiccation cracks in the more aerated upper parts of the natural levees. These terraces occur frequently (see also the 'steps' on the west side of the cross-section at point II, Figure 7). They are discontinuous and may occur on one bank or on both banks. Individual terraces rarely extend for more than a few metres along the wall and are several decimetres wide. These slidings often initiate meander formation and play a role in the process of stream capture.

In summer and autumn tributary creeks can be dammed up by heaps of seaweed pushed into the mouth by strong floods. The seaweed remains there as the ebb-current is incapable of removing it. Soon the seaweed is covered with fresh, mainly clay-rich, sediment and the closed off part of the former creek is filled with seawater.

Desiccation cracks are also found in the basins of the higher salt marshes. They are much smaller than the polygon structures in the intertidal flats and lack pronounced ferruginous coatings.

### *Transitional zone*

The transitional zone between intertidal flats and salt marshes has largely the characteristics of the intertidal flat, but locally a vegetation of salt-tolerant plants occurs and in this zone incipient natural levees are found as well as the first real natural levees.

In the transect across the study area near the Rattekaai given in Figure 11 (for location see Map 5, Appendix 3) the elevations of the natural levees and of the basins, are related to some



mean tidal levels. Natural levees are formed above 1.05 m + N.A.P. Distinct natural levees are found where the level of the flat reaches an elevation of about 1.20 m + N.A.P. So in this case the natural levees are found even below Mean Neap Tide level. Natural levees found above Mean Neap Tide level are soon covered with vegetation. When the flats between the natural levees are higher than 1.20 m + N.A.P., a closed vegetation cover is found. Above this level the salt marshes proper begin. So the transitional zone can be defined as the zone from the first incipient natural levees ranging to the salt marshes proper (here ranging approximately between 1.05 and 1.30 m + N.A.P.). Below this zone intertidal flats are found.

The levels of the highest salt basins and natural levees are not represented in Figure 11. The highest salt basins are situated at about 2.05 m + N.A.P.; the natural levees attain 2.35 m + N.A.P., which is about 11 cm above Mean Spring Tide level.

## 1.6 FAUNA

This account deals essentially with the fauna permanently associated with the sediment above Mean Low Tide level. Emphasis is laid on the macrofauna which cause the greatest changes in the sedimentary structures that are important for soil development. The individual specimen does not greatly influence the sediment, but the effects of high populations of macrofauna can be impressive. These fauna must be regarded as food for the fauna that is not permanently associated with this environment. During high tide the area above Mean Low Tide level is visited by bottom feeding fish, shrimps and prawns for their food supply. When the tide is out, various shore and wading birds search for their food here.

The environmental conditions set many limits to the permanent macrofauna. They have to be adapted to (i) a continuous fluctuation from wet to dry; (ii) large differences in amounts of oxygen and salts present; (iii) extreme and rapid changes in temperature and (iv) the force of the water and resulting erosion or deposition in various sequences. Few forms of life are adapted to these extreme conditions. But the populations of these forms of life are often very large. The most important species belong to the Mollusca, Vermes and Crustacea. In the marine sediment of the Oosterschelde these are: *Macoma balthica*, *Cardium edule* (cockle), *Mya arenaria*, *Scrobicularia plana*, *Hydrobia ulvae*, *Littorina littorea* and *Assiminea greyana* of the Mollusca; *Arenicola marina*, *Heteromastus filliformis*, *Nereis succinea*, *N. diversicolor*, *Scoloplos armiger*, *Eteone longa*, *Polydora ligni*, *Pygospio elegans* of the Vermes, and *Corophium volutator*, *Carcinus meanas* (shore crab), *Crangon crangon* (shrimp), *Orchestia gammarella* of the Crustacea (WOLFF, 1973).

In the upper part of the intertidal flat, the species *Heteromastus filliformis*, *Eteone longa*, *Nereis diversicolor*, *Hydrobia ulvae*, *Macoma balthica* and *Scrobicularia plana* of the marine fauna are more dominant. The populations of *Mya arenaria*, *Cardium edule*, *Nereis succinea* and *Pygospio elegans* increase with the time of immersion and sand content of the sediment. The juvenile specimens of *Arenicola marina* grow up in the high intertidal flat. In their second winter they migrate to lower intertidal flats. Thus this species occurs equally in both zones of the intertidal flats, as do other species, for example *Scoloplos armiger* (WOLFF, 1973).

Few species inhabit the salt marshes. This environment has extreme conditions of moisture content, salinity, etc., so terrestrial species and aquatic species are limited. The upper zone of marine species is marked by gastropods such as *Littorina littorea*, *Hydrobia ulvae*, *Assiminea grayana* and the Crustacea *Orchestia gammarellus*. In natural levees *Nereis diversicolor* and *Carcinus meanas* occur. A few species of a terrestrial invertebrate fauna belonging to the Arthropoda can also be found.

The faunal species permanently associated with the sediment have developed several modes of living. They can be divided into three groups: (i) true burrowing forms that are normally

present below the surface (*Cardium*, *Macoma*, *Nereis* spp., *Heteromastus*, etc.); (ii) forms that live freely exposed on the surface, though at times retreating into the sediment (*Hydrobia*, *Littorina* spp. and *Carcinus*) and (iii) surface dwellers, which make use of any available cover, such as algal mats, shell deposits etc. (*Gammarus*, *Carcinus*, *Idothea*, *Littorina*). The latter group is particularly likely to include species that are not strictly characteristic for the intertidal zone. At ebb tide the intertidal flats look bare and abandoned. The mussel beds (the only mollusc living permanently above the surface) are obvious as are numerous small accumulations of faecal matter.

The fauna of the intertidal zone can be distinguished by their feeding habits (HUNT, 1926; SANDERS, GOUDSMIT, MILLS & HAMPSON, 1962 in: WOLFF, 1973): (i) suspension-feeders; (ii)

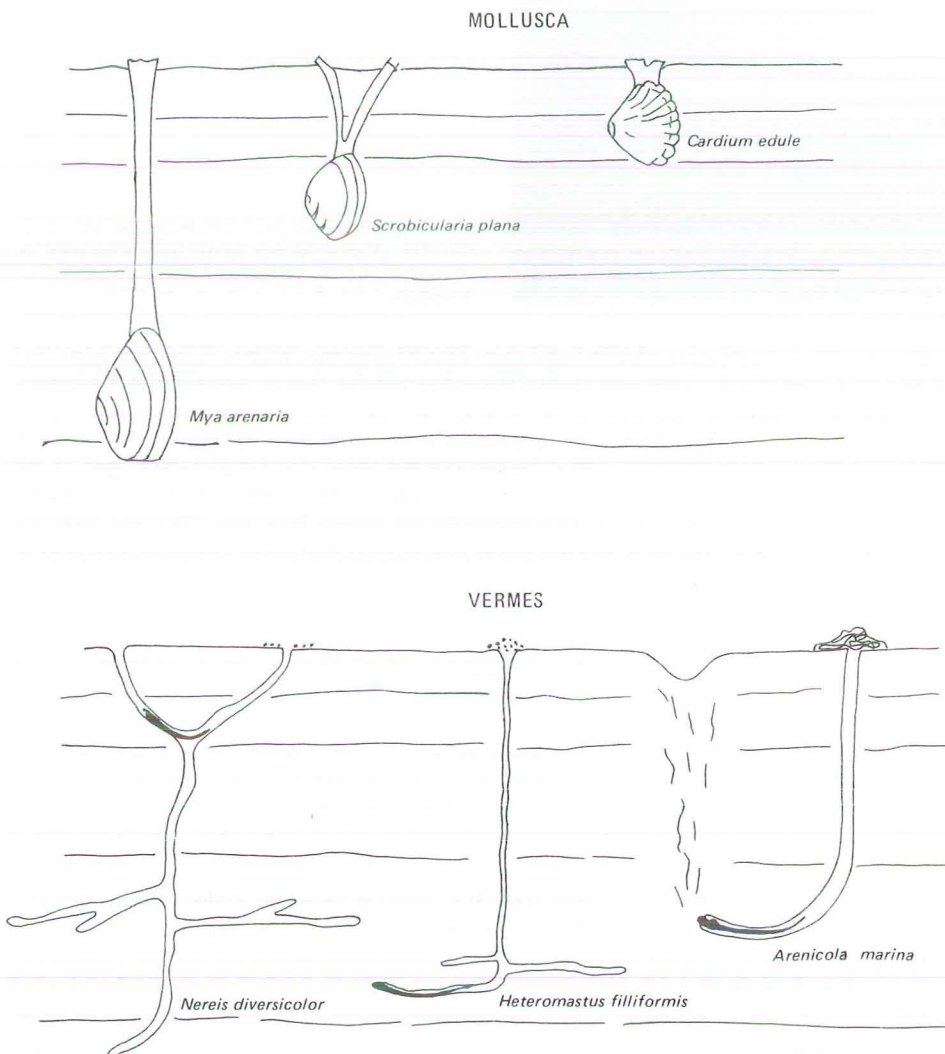


Fig. 15. Location of several faunal species in the sediment of the intertidal flat.





Fig. 16. Characteristic micro-relief produced by *Arenicola marina*, peppered with holes of *Hydrobia ulvae*.

deposit-feeders, divided into selective and non-selective deposit-feeders; (iii) scavengers; (iv) carnivores; (v) herbivores; (vi) omnivores. Omnivores employ two or more of the feeding types mentioned. The most frequent combinations are predator and scavenger, predator and deposit-feeder and deposit-feeder and suspension-feeder. True suspension-feeders include *Mytilus edulis*, *Cardium edule* and *Mya arenaria* of the Mollusca and *Polydora ligni* of the Vermes. *Hydrobia ulvae* is an example of a selective deposit-feeder. *Macoma balthica* also belongs to this group but may act as suspension-feeder during high tide. The non-selective deposit-feeders include *Arenicola marina* and *Heteromastus filliformis*. *Nereis diversicolor* is an omnivore.

The marine macrofauna influence the sediment in several ways. Firstly, their mode of life results in all kinds of channels, burrows and trails. The best known are the channels made by species that are sessile to a greater or lesser degree mainly the Pelecypods of the Mollusca and several species of the Vermes. Some examples are given in Figure 15. The depths that the Pelecypods are found below the surface vary from only a centimetre for *Cardium edule* to about 30 cm for *Mya arenaria*. The syphons of these animals may be separated or joined together, and therefore the channel to the surface may be single or bifurcated. The channels of the Polychaeta show more differences. *Arenicola marina* inhabits rather deep U or J-shaped channels. This worm swallows sand in the lower part of its burrow, causing the surface to cave in; at the other end of the tube the castings accumulate at the surface. High populations of *Arenicola* cause special hummocky relief (see Figure 16). *Nereis diversicolor* makes a rather complicated system of connected irregular channels, which reach to 30-40 cm depth. The upper part is generally Y-shaped. This worm compresses fallen sediment against the channel walls (REINECK, 1958). *Heteromastus filliformis* makes channels 20-30 cm deep and 1 mm wide, perpendicular to the surface. In the deepest parts the channels branch in several directions. The small U-shaped channels of the amphipod *Corophium volutator* are often found near tidal gullies. The common shore crab (*Carcinus maenas*) excavates large horizontal channels that end in a hollow in the walls of tidal gullies and natural levees.



Apart from channels, other disturbances caused by animals can be found in the sedimentary layers. Animals that only retreat into the sediment for short times also cause disturbance. At ebb tide the high intertidal flat can be peppered with small holes produced by the gastropod *Hydrobia ulvae* which has retreated into the sediment (see Figure 16).

These disturbances are barely visible to the casual observer. Secondly, the macrofauna produce excreta that are deposited on the surface or in the sediment. The excreta of the suspension-feeders add clay-rich material to the sediment that could not have been deposited by the currents.

Indirect effects of faunal activities can also be observed. For example, local accumulations, usually of entire shells and snails, can be found in the sediment. When these accumulations are washed up during storms or are derived from residual deposits, many broken shells are present. The genesis of these so-called *Hydrobia* beds is ascribed to the activity of *Arenicola marina*. This animal swallows sand at a depth of about 20-30 cm. The shells and snails are not consumed and become accumulated (VAN STRAATEN, 1952).

## 1.7 FLORA

The salt marshes are the part of the intertidal zone which is covered with a closed vegetation of halophytic phanerogams (see Section 1.5). In the intertidal flat, Seagrasses (*Zostera marina* var. *stenophylla*, *Zostera noltii*) occur locally. In the transitional zone between these main zones (see Figure 12, type A) an open vegetation is found. Here clumps of *Spartina townsendii* and more widely spaced individual plants of *Salicornia europaea* grow. The first more continuous vegetation is encountered on the incipient natural levees.

The vegetation of the salt marshes proper has a characteristic spatial differentiation: in zonation and successions of different vegetations (BEEFTINK, 1965). The zonation runs parallel to the creeks. Generally, in the different zonation one species predominates. The most im-



Fig. 17. Deposits of detritus and snails lying between ripples.

portant species are *Salicornia europaea*, *Spartina townsendii*, *Puccinellia marina* and *Halimione portulacoides*. Less abundant but also characteristic are *Aster tripolium*, *Plantago maritima*, *Triglochin maritima*, *Suaeda maritima*, *Festuca rubra* and *Elytrigia pungens*. Several major succession series have been determined in the intertidal zones in the southwestern part of the Netherlands. In the salt marshes two series coexist, one in the salt basins and one in the natural levees (BEEFTINK, 1965).

Many lower organisms are present in addition to phanerogams. Both intertidal flats and the salt marshes are inhabited by several species of green, brown, red and blue-green algae. The most common genus in these habitats is the *Enteromorpha*; *Enteromorpha prolifera*, a green alga, can be found most frequently, especially on fine-grained sands, either attached to solid substrata (e.g. shells) or anchored in the sediment. On higher parts of the intertidal flat *Enteromorpha prolifera* may completely cover many square metres with their light green threads (NIENHUIS, 1967, 1970). Irregular patches of *Ulva lactuca* are also common.

The upper layer of the sediment is inhabited by diatoms and flagellates. Diatoms give the surface of the sediment at low tide a brownish colour. Several algae produce gelatinous secretions to fix themselves to the surface of the mud and in this way the surface is protected from erosion to some extent. Many algae have developed optimal growth patterns out of phase with the growing season of most salt-marsh plants. This enables them to exploit improved light conditions beneath taller salt-marsh plants (NIENHUIS, 1969).

Bacteria are by far the most numerous of all organisms and are the most diverse. These bacteria determine many reactions in the soil. In less oxygenated environments they are responsible for nearly all biochemical reactions (SCHEFFER & SCHACHTSCHABEL, 1966). They play an important role in all kinds of reactions in accumulations of vegetative matter deposited by tides. The resulting fragments of vegetative matter are again removed by tides. These microscopic fragments and accompanying bacteria form a detritus that is often visible as thin brown deposits, for example between ripples in the high intertidal flat (see Figure 17). This detritus, unicellular vegetational plankton and clay particles comprise the suspended material in the seawater that forms the food of suspension-feeders present in the intertidal flat (see Section 1.6). When deposited as detritus or as mud this material is important food for deposit-feeders.



## 2 FIELD INVESTIGATIONS

### 2.1 GENERAL

To enable soil development in the intertidal zone to be studied in detail, adequate soil maps had to be prepared. These maps had to have a scale large enough (i) to indicate significant topographical features, such as creek systems, and (ii) to permit the data to be plotted and recorded accurately. The scale 1:2 500 proved to be the best. This scale is also used by the Rijkswaterstaat to indicate the topography of a small zone on the seaward side of the dike for dike protection. There are no soil maps of the study area at this scale, and therefore a survey had to be made. The resulting maps were used to select sites for detailed survey and sampling. When selecting polder soils for comparison with the intertidal and salt-marsh soils, existing soil maps were used.

The following Sections describe and discuss the survey, the maps and the selection of soils for further research.

### 2.2 THE SURVEY

Topographical base maps were prepared by taking information from enlarged aerial photographs supplied by the Topografische Dienst and using it to supplement the available Rijkswaterstaat maps. The resulting base map was checked in the field against the actual courses of the creeks. The absence of height indications was compensated for by levelling along selected traverses that crossed the survey areas.

Two rectangular plots totalling about 38 ha were mapped, comprising a complete sequence from Mean Low Tide level to the highest saltings (see Figure 1). The survey was carried out in the winter of 1972/1973 during ebb tides and was performed by sampling with a soil auger and making creek and gully cuts. In unripened material a special soil auger was used that could take a slightly tapering core with a diameter of about 7 cm up to one metre long at one time. The observations recorded the consistence of the soil, granular composition, carbonate content and aeration depth. The density of soil observations in the salt marshes was 18 per ha; for the intertidal flat it was about 1 per ha. The sample sites mainly lay along lines perpendicular to the creeks and gullies: they were deliberately selected to reflect the morphology of the landscape.

The vegetation was also mapped to ascertain its influence on soil development. The different zonation was mapped directly in the field on topographical base maps. It was found that the individual zones usually had distinct boundaries and often consisted of only one species. When more species were present, the characteristic distribution of the individual species was estimated in percentages of the covered surface. Rare species were omitted.

### 2.3 THE MAPS

#### 2.3.1 Classification and mapping units

The information gained from the survey was used to draw four maps: soil map, aeration-depth map, map of carbonate deficiencies and vegetation map (see Appendix 3, Map 1-4). In addition, the information gained from the surveys was combined with data from the levelling to produce a cross-section of the intertidal zone. A series of representative parts is given in Figure 20.



The soils in the intertidal zone were classified at several levels. First they were grouped in landscape units, as distinguished in Section 1.5: soils of the intertidal flat, transitional zone soils, and salt-marsh soils. These groups of soils were divided into sandy soils and loamy and clayey soils (Soil Survey Staff, 1975). Further classification was based on ripening classes and granular composition. The ripening classes rank the consistence of soils that have been formed under wet conditions or that are periodically or permanently saturated with water. According to DE BAKKER and SCHELLING (1966) five ripening classes can be distinguished (see Table 3). In this system, sand is considered to be completely ripened. During the survey it became evident that the consistence of sand did not always correlate with class 5. Therefore when sand did not have a firm consistence, it was assigned to the appropriate class.

Table 3. Ripening classes (DE BAKKER & SCHELLING, 1966).

Code	Class name	Consistence
1	wholly unripened	very weak, material runs through the fingers
2	nearly unripened	weak, material can be squeezed through the fingers
3	half ripened	rather weak, material can still be squeezed through the fingers
4	nearly ripened	rather firm, material can be squeezed through the fingers with difficulty
5	ripened	firm

The granular compositions were also assigned according to the nomenclature of the same system. These classes are listed in Table 4 together with the corresponding classes of the American classification (Soil Survey Staff, 1975). Figure 18 shows the location of the granular composition of the sediment in the diagram of the basic soil textural classes (Soil Survey Staff, 1975). The Dutch classification is shown on the left.

Table 4. Classification of the granular compositions.

Code	% clay	Nomenclature	Roughly equivalent to
0	0 -8	sand	sand to loamy sand
1	8 -17.5	light 'zavel'	sandy loam
2	17.5-25	heavy 'zavel'	loam
3	25 -35	light clay	clay loam to silty clay loam
4	> 35	heavy clay	silty clay loam to silty clay

The sands were further subdivided into: the fine sands, code 0 in the mapping units; and the very fine sands, code 00. When varying clay percentages belonging to codes 3 and 4 were found in the salt basins, the soils of these basins were given code 8 for their granular composition. The complete legend of the mapping units is given with the soil map (see Appendix 3).

The soil maps show the ripening class and granular composition of the topsoil, thus enabling the successive development of the sedimentation and ripening to be followed.

The schematic cross-sections (Figure 20) along the traverses give complementary information on the distribution of the granular compositions. In these schematic sections the aeration boundary is indicated.

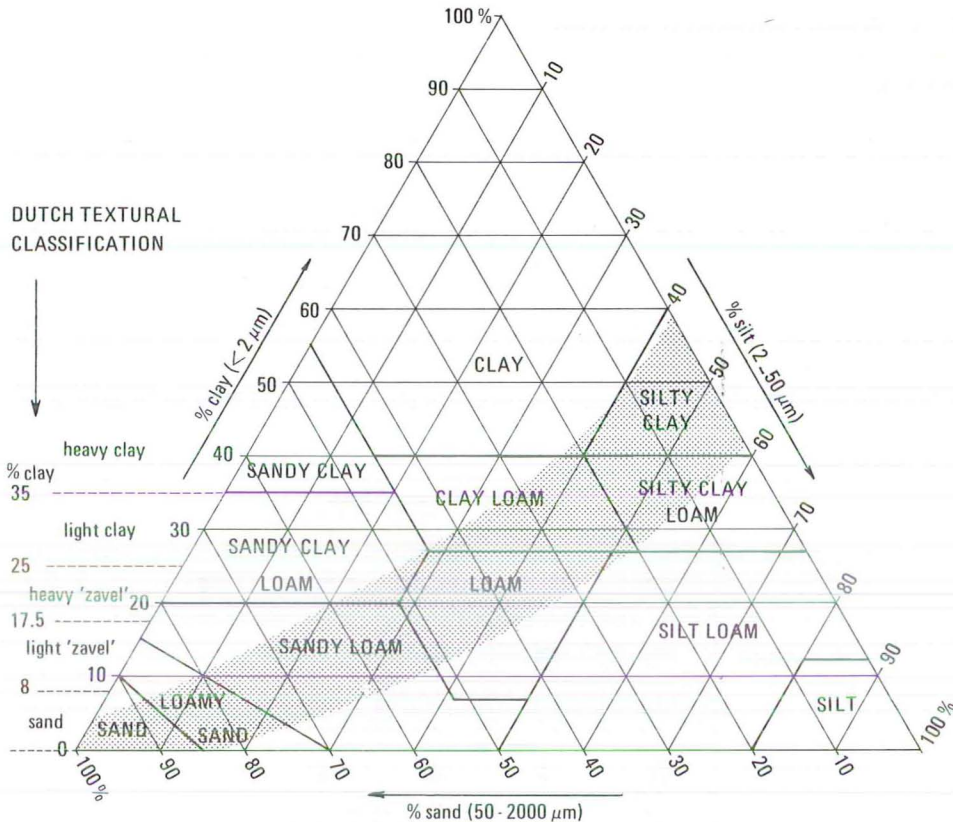


Fig. 18. Classification of the granular compositions: the U.S.D.A. triangle and the Dutch classification (left) based on clay content. The shaded zone represents the area in which the granular compositions of the samples fall.

The aeration depths are represented in 6 classes (see Legend Map 2, Appendix 3).

In the intertidal zone a marked decrease in carbonate content was found. The carbonate deficiencies were detected with diluted 10% HCl and classified in 3 categories (see Legend Map 3, Appendix 3). No finer differentiation was possible as the carbonate-deficient zone varied in thickness.

The units of the vegetation map represent the species according to their occurrence in the zonations. It is important to remember that some species are annuals and therefore their distribution may vary from year to year. The complete legend is given in Appendix 3.

### 2.3.2 Remarks pertaining to the maps

#### Soil map

The pattern of the ripening classes in the intertidal zone is related to two main factors (i) the clay content of the sediment and (ii) the length of time the sediment is exposed to the air in between tides. Generally, under the same conditions the sediment with the highest clay content has the weakest consistence. The most finely grained sediments are deposited in the higher salt basins situated at and above Mean High Tide level. These sediments are exposed to the air for a longer time and therefore dry out to some extent. Thus the most unripened sediments are found in the transitional zone and low salt marsh situated below Mean High Tide level, where sandy loams, loams and clay loams predominate. A third factor influencing the pattern of the ripening classes is the presence of creeks. They influence the hydrologic conditions in such a way that near creeks the soil consistence remains firm while the clay content varies greatly. So

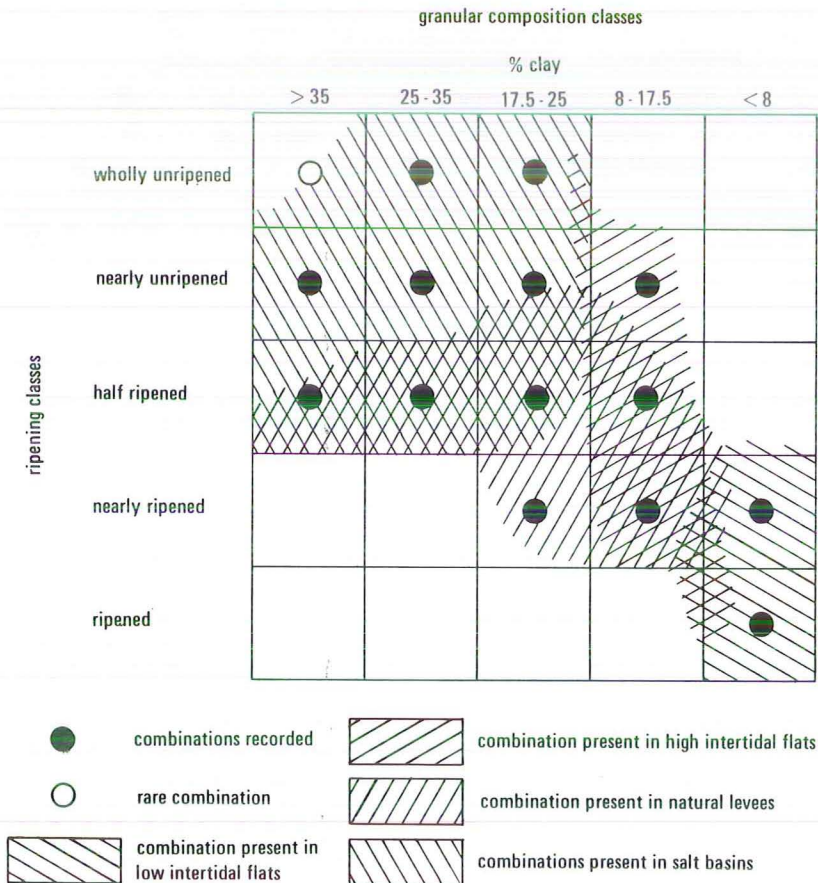


Fig. 19. Relation between ripening and granular composition in the soils of the intertidal zone.



the combinations 3,1; 3,2 and 3,8 can be found in the natural levees belonging to the same creek system, while in adjoining basins the ripening class may be 1 or 2 (see Map 1A, Appendix 3).

The distribution of the granular composition classes over the intertidal zone shows the general expected trend. The results of sorting from sea to land and from creeks to their backlands are evident (see Section 1.3). With increasing height of the surface finer grained sediment can be deposited and the range in granular composition is greater. The clay content of this sediment may be as high as 60%. Near large creeks, zones of different granular compositions are found, resulting from sorting from creek to backland. Towards the end of the creeks in the salt marshes the clay content of the natural levees increases.

The distributions of ripening classes and granular compositions do not coincide, so more than one combination of both attributes can be found. The combinations recorded are given in Figure 19, together with the landscape units in which they most often occur. Most combinations have higher clay content and weaker consistence. This is because fine-grained sediment soon loses water after deposition and therefore its consistence can vary. This water loss depends on the height at which the sediment was deposited and on its proximity to creeks. This trend must be considered as characteristic for clay-rich sediments in an intertidal zone, and contrasts with the situation found in underwater deposits of, for example, the former Zuiderzee in which the ripening classes of newly reclaimed areas are directly related to their clay content (ZUUR, 1958).

#### *Cross-sections (Figure 20)*

The cross-sections give information about (i) the succession of the granular compositions horizontally and vertically and (ii) the absolute and relative differences in height of the deposits. From these data the geogenesis of the sediment and the development of the relief can be followed.

The fine sands present at the surface in the lower parts of the intertidal flat continue in the subsoil of the whole cross-section. Relief elements (e.g. asymmetrical gully incisions and broad depressions) of a former intertidal flat can be seen in the subsoil over the whole cross-section. The former surface features have been buried by further sedimentation. The maximum height attained by these deposits is 1.40 m + N.A.P.

In the higher flats a thin mineral layer with higher clay contents occurs. At first it is only found in depressions, but higher up it becomes thicker and follows the relief of the previous deposit. When this mineral layer is more than 20 cm thick its upper boundary has its own slightly undulating relief, filling depressions in the underlying material. This deposit reaches a maximum height of 1.50 m + N.A.P. in salt basins; in natural levees it is higher because of sorting from creek to backlands instead of from sea to land.

The first loams occur in the transition from intertidal flats to salt marshes. The upper boundary of these deposits correlates more with the present-day relief. In the low salt basins these loams are present at the surface; higher up they occur in zones along creeks. Where they are overlain by younger sediment they form a deposit 30-40 cm thick that often continues to the surface near natural levees. The height of the upper boundary of this loam deposit in the subsoil varies between 1.20 and 1.50 m + N.A.P.

In the low salt basins the first clay-loam deposits can be found. Deposits with a clay content over 25% can be more than one metre thick in the basins and attain a level of about 2.15 m + N.A.P.

The change in the shape and dimensions of the water courses and banks can also be followed from the cross-sections. In the intertidal flats asymmetrical gully incisions are visible. In the transitional zone and salt marshes more symmetrical creeks with natural levees are developed. The largest creeks are incised into the underlying sand and have natural levees with a zonation of about 2.40 m + N.A.P. These natural levee deposits reach a level of about 2.40 m + N.A.P. Smaller creeks are incised into superficial deposits and lack the distinct zonations of granular composition classes. In the cross-sections the shifting of the posi-

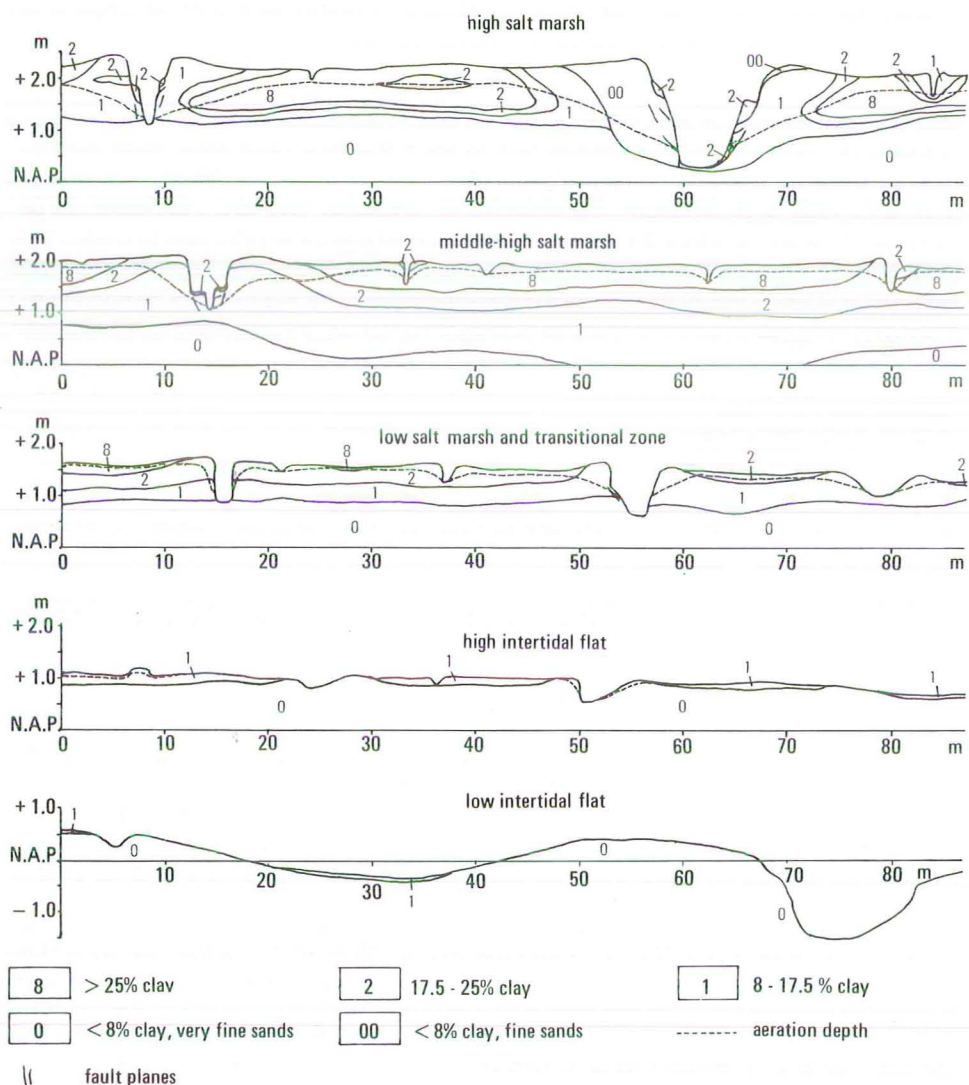


Fig. 20. Cross-sections showing the granular compositions and aeration depths: representative parts of each zone taken from the line of traverse.



tion of creeks and changes in their function and age can also be observed. These changes result in (i) asymmetrical natural levees; (ii) in different vertical successions of granular compositions on both sides of the creeks and (iii) the presence of younger coarser sediments. These phenomena indicate the age of the water course and eventual changes in its position.

The walls of the larger creeks show gravity slides, which give them a step-like relief. On these slides a younger sediment with a higher clay content is often found (see Section 1.5).

The successions outlined above indicate that in most cases the sediment in the salt basins becomes sandier with depth. Near present-day or buried natural levees other successions are found.

#### *Aeration depth map*

The aeration depths indicated show that an increase in aeration depth generally correlates with the height of the terrain, the granular composition of the sediment and the drainage conditions. The six classes also indicate the course of the aeration depth which, however, is not easy to interpret as the surface levels of natural levees and salt basins differ. Figure 19 gives a more detailed picture: here it is indicated that air penetrates the deposits through the walls of the natural levees. Aeration depth can vary locally in the same morphological unit. Along pores and cracks aeration can penetrate more deeply depending on the pore diameters and the width of the cracks. For this reason the aeration depths have been generalized.

Distinct ferruginous colours can be found coating pores and cracks in the aerated zone. The formation of these colours takes some time. After a creek has been captured the dimensions of that creek soon adapt to its new function, but it takes longer for the aeration phenomena to adjust. Therefore buried natural levees or the natural levees of formerly important creeks still show ferruginous coloration along pores and cracks not related to the present situation. However, these zones are generally better drained than the surrounding basins, as the sediment is usually sandier and allows aeration to penetrate deeper.

#### *Map of carbonate deficiencies*

Carbonate deficiencies more than 10 cm thick are not found before the middle-high salt marshes are reached and even here the large natural levees of important creeks form an exception. The carbonate-deficient zones begin about 5-12 cm below the surface in the basins and usually at a depth of 15-20 cm in the natural levees. Accordingly, the zone of carbonate deficiencies forms a wedge between two carbonate-rich layers. In the high salt marshes the zone with carbonate deficiencies becomes thicker and lies nearer the surface. Large natural levees do not have marked carbonate deficiencies. In the high salt basins carbonate deficiencies more than 30 cm thick are found. The pattern of these deficiency zones does not correlate with other mapped phenomena e.g. ripening classes, granular composition, vegetation. These deficiencies are found in basins where the deepest aeration occurs. The zone with carbonate deficiencies is generally found on and above the aeration limit, but can also continue below this limit.

#### *Vegetation map*

This map shows the natural vegetation, as no grazing of animals takes place.

In the transitional zone *Salicornia europaea* and *Spartina townsendii* are found, the latter



occurring first in isolated clumps but soon on natural levees. On incipient natural levees isolated specimens of *Salicornia europaea* can be found but a closed vegetation cover of *Salicornia europaea* is present on higher ground between natural levees covered with *Spartina townsendii*. On distinct large natural levees in the low salt marsh *Spartina townsendii* is replaced by *Aster tripolium* and *Salicornia europaea*. On top of the natural levees *Aster tripolium* grows: on the basin side a small zone of *Salicornia europaea* is found. The basins are mostly covered with *Spartina townsendii* with local admixtures of *Salicornia europaea*. The lowest parts of the basins in the low salt marsh have local bare patches or are covered with *Salicornia europaea*. Probably the bare areas are too saline to support plant growth. The *Spartina townsendii* found in these parts of the salt marshes is stunted.

In the middle-high salt marsh *Puccinellia maritima* and *Halimione portulacoides* join those already present in the lower parts. The former species occurs in the salt basins interspersed with the *Spartina*. *Puccinellia maritima* generally grows here in dome-shaped hummocks and has many stolons radiating onto the surface (see also Figure 40). This mode of growth causes that this plant traps more sediment. The resulting hummocky relief is largely responsible for the coexistence of the ripening classes 1 and 2 in the same salt basins, shown as associations on the soil map. RANWELL (1972) mentioned the formation of *Puccinellia* hummocks in the zone near Mean High Tide level, where this species occurs as primary colonist. In this area of the Oosterschelde, *Puccinellia maritima* is not a primary colonist, but nevertheless hummocks are present at Mean High Tide level. In higher salt basins the relief is not more hummocky. On the natural levees *Halimione portulacoides* replaces *Aster tripolium*. This species is locally present in a zone along natural levees and often occurs interspersed with *Spartina townsendii* on the fringes of the basins.

In the high salt marshes still more species occur. Several zones are present from the main creeks to the salt basins. On top of the high natural levees *Elytrigia pungens* grows with some local patches of *Artemisia maritima*. The next zone is one of *Halimione portulacoides*; this is often followed by a zone in which *Aster tripolium* and *Limonium vulgare* occur. On smaller natural levees *Festuca rubra* or *Artemisia maritima* can be found locally, interspersed with the *Halimione portulacoides*. In the salt basins more differentiation has also taken place: in the lowest parts the same vegetation is found as in the middle-high salt basins, but towards natural levees other species become dominant. The most important communities are combinations of *Plantago maritima*, *Limonium vulgare* and *Triglochin maritima*.

### 2.3.3 Relations between the maps

At first glance the distribution of soils and vegetation types seem very similar: as the height of the terrain increases more diversity is found in patterns related to the water courses. Closer examination reveals that the mutual relationships between soil and vegetation are more complex. Table 5 shows the relations between the different landscape units in the intertidal zone and the mapping units on the four maps. In the intertidal flat only one or a few combinations of the codes are found. With increasing height of the terrain more and more combinations occur. The largest number of combinations is associated with the natural levees. This is because the natural levees vary greatly in size, depending on the importance of the adjoining creek. Although many combinations were recorded, certain combinations are specific to particular morphological units of the intertidal zone.

Table 5. Relation between the landscape units and the various mapping units.

	intertidal flat				transitional zone		low salt marsh			middle-high salt marsh			high salt marsh			
	low bank	low flat	high bank	high flat	(incipient) natural levees	incipient salt basins	natural levee	n.l.-s.b.	salt-basin	natural levee	n.l. s.b.	salt basin	natural levee	n.l.-s.b.	salt basin	buried sand-barrier
code soil map																
1,3									■							
1,2						▼			■							
1/2,8									■			■				
1/2,3									■							
2,8												■			■	
2,3									■							
2,2							■			▼	▼				■	
2,2 ::																■
2,1						■		▼								
3,8							▼			■					■	
3,2							■	■		■	■		■	■		
3,2 ::																■
3,1						■		■								
4,2										■						
4,1						■		■		■			■	■		
4/5,0 <sub>1</sub>		▼	■	■	■	▼										
4/5,0	■	■	■	■	▼											
5,00													■			
code aeration – depth map																
1	■	■	■	■		■			■							
2					■		■	■				■				
3							■	■		■	■	▼			■	■
4							■	▼		■	▼		▼	■	▼	
5							■			■		▼	■			
6												■				
code carbonate deficiency map																
A	■	■	■	■	■	■	■	■	■	■		■				
B										■	■	■	▼	■	■	■
C														▼	■	■
code vegetation map																
1										■			■			
2										■						
3										■			■	■		
4							■			▼	■			■		
5							■									
6						■	■	■	▼						▼	
7					■		■	■	■			▼			▼	■
8															■	
9											■				■	
10											■				▼	
11											■					■
12													▼	■		
13																■

n.l. = natural levee      s.b. = salt basin      ■ = common occurrence      ▼ = rare occurrence

## 2.4 SELECTION, DESCRIPTION AND SAMPLING OF THE SOILS

### Selection

The sites had to illustrate the sequence of soil development with continuing sedimentation upslope in the intertidal zone. Therefore, two criteria were used for the selection:

(i) Each subzone of the intertidal zone from low to high (low and high intertidal flats, transitional zone and low, middle-high and high salt marshes) had to be represented by at least one sample site.

(ii) In each zone, the common characteristic soil types and vegetation types (if present) had to be represented. Only one site was chosen in the low intertidal flat and in the high intertidal flat. Upslope from the latter, pairs of sites were selected; one in an incipient or fully-fledged natural levee and one in the adjoining basin, because these locations represent two altitudinal extremes of the landscape and therefore illustrate the different soil and vegetation types. In the low and middle-high salt marshes two pairs of natural levee and salt-basin sites were chosen, because the natural levees varied greatly in dimensions and consequently many soil types

Table 6. Information on the sites selected for detailed study in the marine intertidal zone.

Site No.	Zone	Location	Elevation (in m + N.A.P.)	Code soil map	Vegetation	Fauna
1	low intertidal flat	flat-depression	0.45	4 à 5,0		Mollusca e.g. <i>Cardium edule</i> Crustacea e.g. <i>Corophium</i> ssp Vermes, several species
2	high intertidal flat	gully bank	0.96	4 à 5,0 <sub>1</sub>	green algae	Mollusca e.g. <i>Scrobicularia plana</i> , <i>Hydrobia ulvae</i> Vermes e.g. <i>Hetermastus filliformis</i>
3	transitional zone	natural levee	1.38	3,1	<i>Spartina townsendii</i>	Mollusca e.g. <i>Hydrobia ulvae</i> Vermes, <i>Nereis</i> spp
4	transitional zone	incipient salt basin	1.10	1,2	<i>Salicornia europaea</i>	Mollusca e.g. <i>Scrobicularia plana</i> , <i>Hydrobia ulvae</i> Vermes, several species
5	low salt marsh	large natural levee	1.70	3,2	<i>Aster tripolium</i> <i>Salicornia europaea</i> 35%	Mollusca e.g. <i>Hydrobia ulvae</i> , Vermes
6	low salt marsh	salt basin	1.52	1,3	<i>Spartina townsendii</i>	<i>Hydrobia ulvae</i> , Vermes
7	low salt marsh	small natural levee	1.76	3,8	<i>Aster tripolium</i>	<i>Hydrobia ulvae</i> , Vermes
8	low salt marsh	salt basin	1.65	1/2,8	<i>Spartina townsendii</i>	<i>Hydrobia ulvae</i>
9	middle-high salt marsh	small natural levee	1.94	3,8	<i>Halimione portulacoides</i> ; some <i>Puccinellia maritima</i>	<i>Hydrobia ulvae</i> <i>Carcinus maenas</i>
10	middle-high salt marsh	salt basin	1.83	2,8	<i>Spartina townsendii</i> , <i>Puccinellia maritima</i>	<i>Hydrobia ulvae</i>
11	middle-high salt marsh	large natural levee	2.08	4,2	<i>Halimione portulacoides</i> , <i>Festuca rubra</i>	<i>Carcinus maenas</i>
12	middle-high salt marsh	salt basin	1.94	2,8	<i>Spartina townsendii</i> 75%, <i>Aster tripolium</i> 10%, <i>Puccinellia maritima</i> 10%, <i>Limonium vulgare</i> 5%	<i>Hydrobia ulvae</i>
13	high salt marsh	large natural levee	2.33	4,1	<i>Elytrigia pungens</i>	
14	high salt marsh	transition n.l. -s.b.	2.07	3,2	<i>Halimione portulacoides</i>	
15	high salt marsh	salt basin	2.00	2,8	<i>Spartina townsendii</i> 50%, <i>Puccinellia maritima</i> 45%, <i>Limonium vulgare</i> , <i>Triglochin maritima</i>	<i>Hydrobia ulvae</i>
16	high salt marsh	buried sand barrier	2.07	3,2	<i>Puccinellia maritima</i> 65%, <i>Limonium vulgare</i> 20%, <i>Aster tripolium</i> 8%, <i>Halimione portulacoides</i> 7%	

n.l. = natural levee  
s.b. = salt basin



were present in them (see Section 2.3.3 and Map 1, Appendix 3). In the high salt marsh a series of 3 sites was selected; one in a large natural levee, one in a transition of this to a salt basin and the third in a salt basin. A fourth site on a buried sand barrier was added (see Map 1 B, Appendix 3).

The information shown on Map 1-4 (Appendix 3), was used in selecting the 16 sites for further study of the soil. In Table 6 information on the selected sites is given and on Map 5, Appendix 3, the locations are indicated.

### *Description*

The soils were sampled and described in the latter half of 1973 and the spring of 1974. The soils were described in the field according to the guidelines of the F.A.O. (1966). The consistence of the soil was given in ripening classes (see Section 2.3.1). When sedimentary lamination was visible this was also recorded. The reduction and oxidation phenomena related to the G horizon were described according to the German system of soil description (KOHL (ED.), 1971) as this system is the best available for indicating these characteristic phenomena of soils in the intertidal zone. The colour indications refer to moist conditions and are given according to the Munsell Soil Color Charts (1954). Whenever possible the profile descriptions were continued down to the sand in the subsoil, which represents the intertidal flat deposits (see Section 2.3.2 and Figure 19). The soil descriptions are given in Appendix 1.

### *Sampling*

In the soil pits samples were taken for micromorphological, physical and chemical investigations. The samples for micromorphological investigations were taken in 15 cm x 8 cm x 5 cm or 15 cm x 8 cm x 2 cm metal boxes. As unripened soils of the intertidal zone are very susceptible to shrinkage, the freeze-drying method (JONGERIUS & HEINTZBERGER, 1975) was used to prepare large thin sections. The samples prepared by this method were taken in 15 cm x 8 cm x 2 cm brass boxes. The samples were taken in vertical as well as in horizontal sections, and were located not only within the different horizons but also on transitions. Soil samples were taken from different horizons for physical and chemical investigations in the laboratory. For bulk density and moisture content measurements, metal cylinders with a capacity of 100 cm<sup>3</sup> or 50 cm<sup>3</sup> were used.

## 2.5 SELECTION, DESCRIPTION AND SAMPLING OF THE SOILS IN THE POLDERS

In order to be suitable for a comparative study the soils selected in the polders had to satisfy the following criteria:

- (i) to be reclaimed from marine deposits.
- (ii) to have had the same development as the soils selected in the high salt marsh: from a former natural levee; from a former transition from natural levee to salt basin; from a former salt basin; and one with a buried sand barrier high in the profile.
- (iii) to have approximately the same granular composition as the soils selected for study in the present-day high salt marsh.
- (iv) to have been reclaimed at about the same time.
- (v) to be changed as little as possible by human activities such as levelling and reworking.

Table 7. Information on the sites selected for detailed study in the polders.

	Site 1	Site 2	Site 3	Site 4	Site 5
Region	Zuid-Beveland	Zuid-Beveland	Zuid-Beveland	Zuid-Beveland	Noord-Beveland
Polder	Tweede Bathpolder	Tweede Bathpolder	Tweede Bathpolder	Eerste Bathpolder	Rippolder
Year of embankment	1857	1857	1857	1856	1713
Inundation	1906	1906	1906	1906	—
Date of examination	October 1973	October 1973	October 1973	October 1973	December 1973
Previous location	natural levee	transition n.l.-s.b.	salt basin	covered sand flat	sand-covered clay-rich deposit
Elevation	about 1.25 m + N.A.P.	about 1.40 m + N.A.P.	± 1.60 m + N.A.P.	± 1.00 m + N.A.P.	± 1.80 m + N.A.P.
Surrounding relief	flat	flat	flat	flat	flat
Land use	farmland	farmland	farmland	farmland	farmland
Crops	grass-seeds, corn, bulbs	grass-seeds, corn, bulbs	potatoes, beets, corn	onions, maize	potatoes, beets
Moisture condition	field capacity	field capacity	field capacity	field capacity	field capacity
Human influence	ploughing, drainage	ploughing, drainage	ploughing, drainage	ploughing, drainage	ploughing, drainage

n.l. = natural levee

s.b. = salt basin

The sites were chosen using (i) existing soil maps (e.g. Acarla, 1951), (ii) old creek courses visible in the field (these enabled the identification of former levees and basins) and (iii) soil augering. A good exposure of the subsoil along a recently dug ditch in the Tweede Bathpolder greatly assisted the selection of the representative former salt-basin soil. No soil with a buried sand barrier high in the profile could be found. Instead a soil with identical coarse sands high in the profile was selected. A fifth site was chosen because here the former intertidal zone deposits were preserved by an overlying thick deposit of sand. No other soils were studied because comparison with other and older soils lay beyond the scope of the present study.

Soils from the sites selected were described and sampled in the same way as those in the present-day intertidal zone. Because of the firm consistence of these soils the samples for micromorphological investigations were not freeze-dried. Table 7 gives information on the selected soils; in Figure 1 the locations are indicated. The descriptions are given in Appendix 1.



### 3 PHYSICAL AND CHEMICAL PROPERTIES

As this study focused on the micromorphology of thin sections, the number of physical and chemical analyses was restricted. In this chapter only those properties important for the interpretation of phenomena visible in thin sections and, consequently, for relevant soil-forming processes, are discussed. The results and analytical methods are listed in the Appendix 2.

#### 3.1 PARTICLE-SIZE DISTRIBUTION

The marine sediment studied consisted mainly of fine-grained, well-sorted material. Consequently, to differentiate between sediments the material must be subdivided in grain-size fractions finer than those given in the U.S.D.A. classification (Soil Survey Staff, 1975). Therefore the following grain-size limits were used: 2, 16, 50, 75, 105, 150 and 210  $\mu\text{m}$ . Figure 21 gives the particle-size distribution of some samples, expressed in weight percentages. Less than 0.5% of the material fell in the fraction over 210  $\mu\text{m}$ . The intertidal flat deposits were characterized by a sand fraction of more than 50% of the total soil. The sediment of the high intertidal flat was finer-grained than that of the lower intertidal flat. The salt-marsh samples that contained more than 50% sand were derived from the underlying intertidal flat deposits or from the natural levees of a few main creeks. Smaller natural levees are flooded so often that many small mud laminae are formed, thereby reducing the sand fraction to less than 50%. Analyses of the intertidal flat deposits rarely gave a clay content of more than 10%. In the salt marshes the clay fraction increased to 55%. The highest clay fractions were found in samples from the middle-high salt marsh.

The fractions  $< 2 \mu\text{m}$  and 2-16  $\mu\text{m}$  were found to be positively correlated,  $r = 0.974$ . The relation between both fractions for 40 samples is given in Figure 22. The ratio  $< 2 \mu\text{m} / < 16 \mu\text{m}$  calculated from the regression line varied from 0.66 at 50%  $< 2 \mu\text{m}$  to 0.71 at 15%  $< 2 \mu\text{m}$ , which is well within the range found for marine soils in the southwestern part of the Netherlands (Stichting voor Bodemkartering, 1964). There were no differences between samples from natural levees, salt basins or intertidal flats. The nearly constant ratio  $< 2 \mu\text{m} / 2-16 \mu\text{m}$  has a geogenetic origin. The finer particles in the suspended load are mostly transported in mud flakes, in which these fractions are present in constant ratios. The constant ratios of both fractions are found in all Dutch marine sediments (ZUUR, 1954; WIGGERS, 1955). The fractions  $< 2 \mu\text{m}$  and 75-105  $\mu\text{m}$  were found to have a high negative correlation coefficient of  $r = 0.969$ . This resulted from the sorting of the sediment in the study area (see Section 1.3). The particle-size distribution of the 5 sites studied in the polders was comparable to that in the actual intertidal zone. However, there were two notable differences.

(i) Though the fractions  $< 2 \mu\text{m}$  and 2-16  $\mu\text{m}$  were still positively correlated, at a given percentage of the fraction 2-16  $\mu\text{m}$  the polder samples were found to contain more clay than the samples from the intertidal zone. As a result the ratio  $2 \mu\text{m} / 16 \mu\text{m}$  varied from about 0.70 to 0.80. As nearly all the samples from the polders were derived from the same sedimentation area, this fact suggests that these fractions behave in a different way after reclamation.

(ii) In a band below the Ap horizon about 30 cm thick, distinct increases of the fraction  $< 2 \mu\text{m}$  were found in the zones in which distinct continuous clay coatings occurred on the walls of peds and in most pores.

These increases need not have been caused solely by geogenesis; pedogenetic processes may also have been involved.

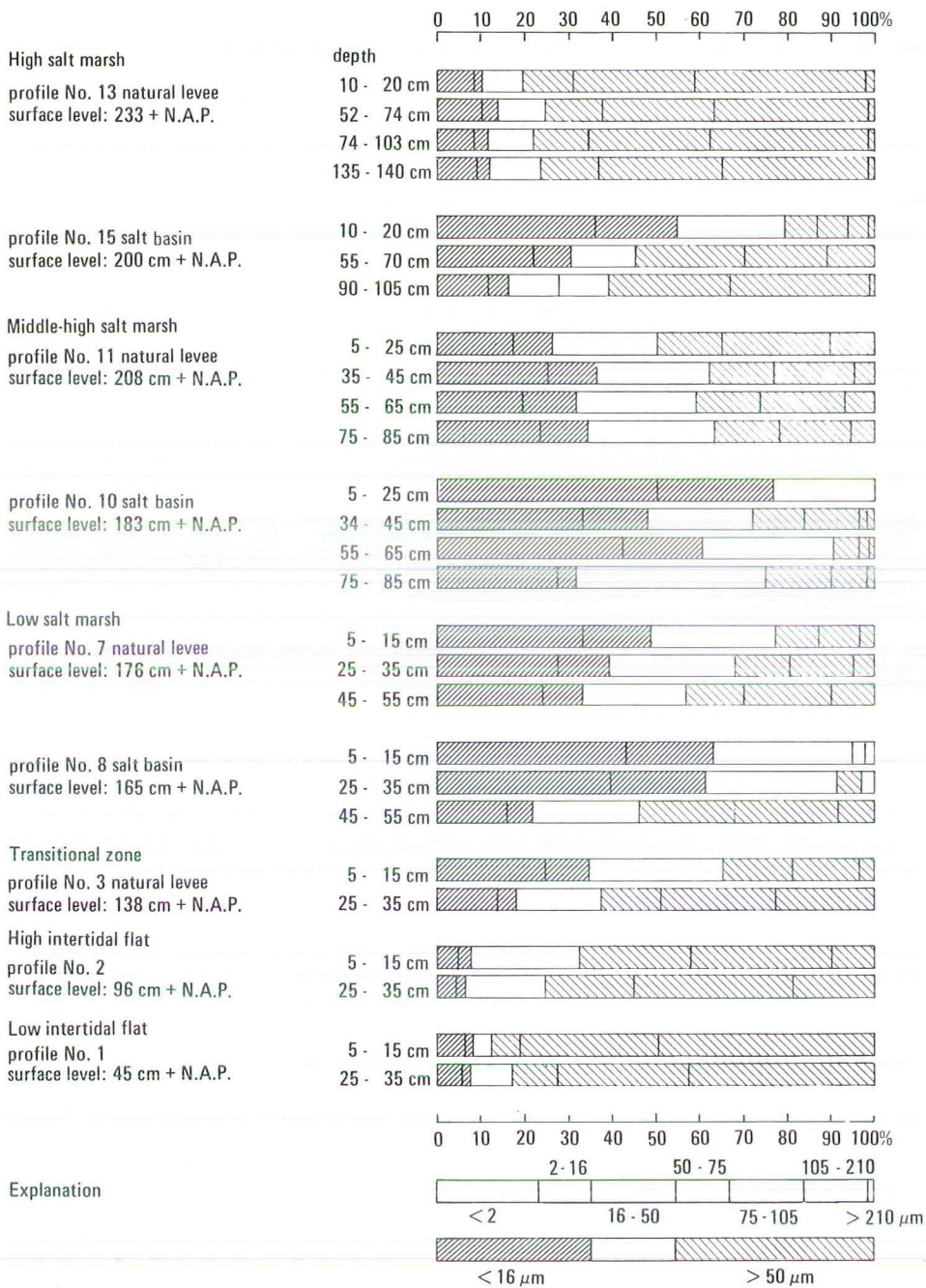


Fig. 21. Particle-size distribution in weight percentages. See Map 5A, B, Appendix 3 for location of the sites.

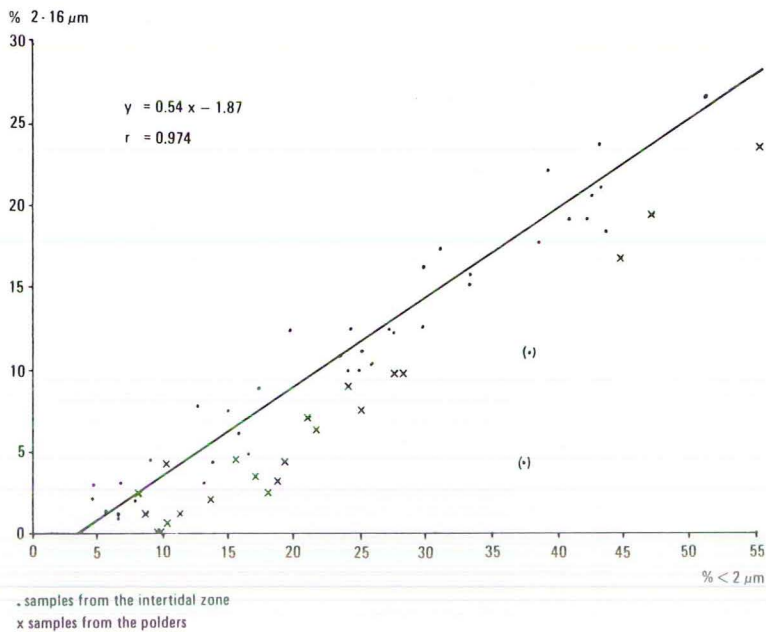


Fig. 22. Correlation between the fractions  $< 2 \mu\text{m}$  and  $2-16 \mu\text{m}$  of samples from the intertidal zone and polders.

### 3.2 MINERALOGY OF THE CLAY FRACTION

This section deals with the mineralogical composition of the clay fraction, because the types of clay minerals present greatly determine soil properties such as cation exchange capacity, moisture retention and permeability. The sand fraction was not studied because the marine sediment belongs to a young sedimentation area where weathering processes are unimportant. Data on heavy minerals of the sand fraction can be found in VAN RUMMELEN (1972). The elemental composition of the clay fraction of 38 samples, determined by X-ray fluorescence and expressed as weight percentages was found to be fairly constant (see Table 8).

Table 8. Elemental composition of the clay fraction of 38 examples.

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	TiO <sub>2</sub>	K <sub>2</sub> O	MgO	CaO	Na <sub>2</sub> O
Range:	49.19-53.09	17.78-22.00	7.08-9.52	0.07-0.50	0.69-0.81	2.87-3.62	1.85-3.40	0.10-0.47	0.00-1.44

X-ray diffraction of 43 samples showed the presence of smectite, chlorite, illite and kaolinite, as well as of mixed-layer clay minerals of illite with chlorite and/or smectite. Quartz, and to a lesser extent feldspars, were also present. Major differences in the clay mineralogical composition of the samples were not observed. These results indicate that the composition of most of the clay fraction is fairly constant; this implies that the constant composition of the fresh sediment is not altered by subsequent chemical processes.



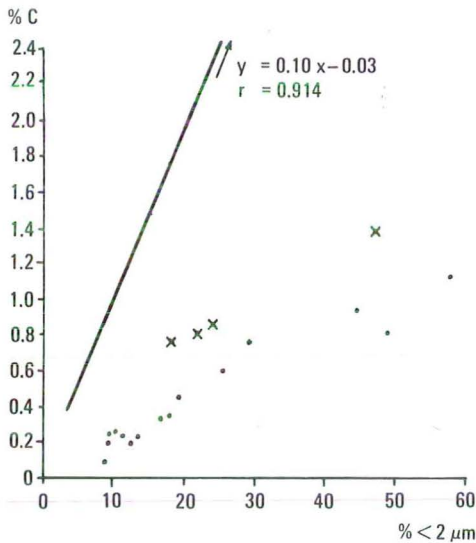
### 3.3 ORGANIC MATTER

The analyses showed that soils in the intertidal zone had a high organic matter content that was strongly correlated with clay content. The correlation coefficients for the clay content with organic carbon and nitrogen were 0.914 and 0.933, respectively. There was also a positive correlation between organic carbon and nitrogen ( $r = 0.955$ ). A linear relation between the amount of clay and organic matter is often found in recent coastal sediments in the Netherlands (see amongst others, ZUUR, 1958; VERHOEVEN & AKKERMAN, 1967). Different sedimentation areas have different regression equations. There were no differences between the correlation coefficients of the intertidal flat deposits and those of salt-marsh deposits. The dense vegetation cover does not produce a high quantity of organic matter in the salt-marsh deposits. There are two main reasons why the salt-marsh vegetation does not contribute greatly to the organic matter content.

(i) All vegetative debris on the surface is removed by high tides: some is fragmented in the seawater and incorporated in the suspended load; some is first deposited on the salt marshes as the high tide mark. Within a few weeks this material has also been fragmented by bacterial activity and most of it is again removed by the high tides (see also Section 1.7). Sometimes high tide marks are covered with sediment resulting in layers rich in organic matter.

(ii) Dead subsurface vegetative matter decays very slowly. Dead roots remain visible in their original channels for a long time. This is because the anaerobic conditions, and probably also the presence of salts inhibit decomposition. As a result of the removal and slow decomposition of organic material there is no significant development of an A1 horizon.

The organic matter present in the sediment was found to be mainly of geogenetic origin, i.e. it was derived from the mudflakes in the suspended load. Mudflakes in the Oosterschelde may contain up to 50% of organic matter (DRINKWAARD, 1957, 1958, 1959). The organic matter content of the mudflakes varies, but soon after deposition an equilibrium develops (see, for



- x samples from the Ap horizon, polders
- other samples, polders
- regression line all samples, intertidal zone

Fig. 23. Correlation between the fraction  $< 2 \mu\text{m}$  and the % C of samples from the intertidal zone and polders.

example, ZUUR, 1958); in the present study it stabilized at approximately 10% (see Figure 23). The analyses showed that the organic matter content strongly decreased after the sediment had been reclaimed (see Figure 23). In the polder soils the maximum amount of carbon was 1.36% and the maximum amount of nitrogen was 0.17%. This compares with maximum amounts of 5.6% and 0.6% respectively for carbon and nitrogen in the actual intertidal zone. In the polder soils an Ap horizon had developed which had a higher carbon content than the underlying horizons. Figure 23 suggests that there is also a relation between the percentages of carbon and of clay in the polder soils. These results indicate that after reclamation of the sediment the organic matter decomposes, resulting in a decrease in the percentage of carbon.

### 3.4 CATION EXCHANGE CAPACITY

The cation exchange capacity (C.E.C.) of the samples from the intertidal zone was highly correlated with the clay content ( $r = 0.943$ ). This confirms two conclusions that were made earlier: that in the intertidal zone the composition of the clay minerals is fairly constant (see Section 3.2), that there is a linear relation between the amount of clay and organic matter present in the intertidal zone (see Figure 23). The C.E.C. of the clay fraction would be 86 me per 100 g if the C.E.C. of the soil were assigned to this fraction only (see Figure 24). By analogy, the C.E.C. of the clay fraction in the polder soils should be about 50 me per 100 g clay (see also Figure 24). This difference in cation exchange capacity must be largely due to the lower organic matter content in the polder soils.

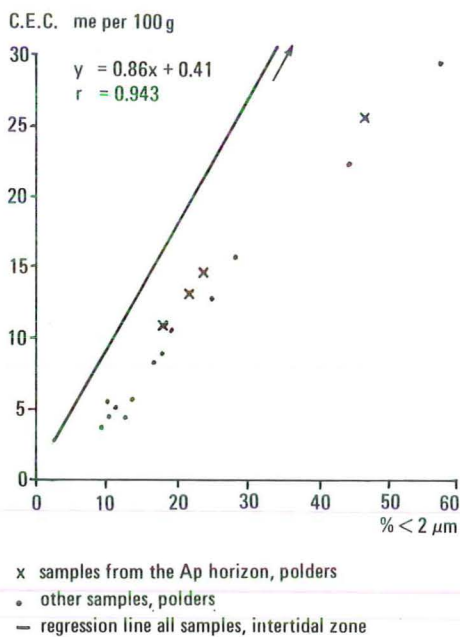


Fig. 24. Correlation between the fraction <math>< 2 \mu\text{m}</math> and the C.E.C. of samples from the intertidal zone and polders.

### 3.5 SALINITY

Electrical conductivity (E.C.) was highly correlated with the concentration of  $\text{Na}^+$  and  $\text{Cl}^-$  in solution; E.C. —  $\text{Na}^+$  in solution  $r = 0.984$ ; E.C. —  $\text{Cl}^-$  in solution  $r = 0.980$ , due to the marine environment. In seawater most of the ions comprise  $\text{Na}^+$  and  $\text{Cl}^-$  (see Section 1.3). The quantities of  $\text{Cl}^-$  varied between 7.2-94.8 me per 100 g in the 1:5 water extract. Therefore these ions govern the electrical conductivity. The E.C. values ranged from 4.9 to 20.2  $\text{mS cm}^{-1}$  (at 25°C) and were closely correlated with clay and organic matter content. The electrical conductivity was higher as the amounts of clay and organic matter increased, because the clay minerals and organic matter have a high water-retaining capacity. Therefore, high salinities were measured in clay-rich sediments. In the high salt marsh, especially in the high natural levees, salinities were lower than was expected from the clay content of the sediment. These lower salinities reflected a decrease in marine influence for, away from the sea in the Netherlands the excess of precipitation over evaporation causes desalinization of the sediment (see Section 1.2).

After reclamation it generally takes several years for excess salts to be washed away (see, for example, DIBBITS (Ed.), 1957; VERHOEVEN & AKKERMAN, 1967). So it was not surprising to find that in the polder soils the E.C. values were below 0.35  $\text{mS cm}^{-1}$  at 25°C.

### 3.6 BULK DENSITY AND WATER CONTENT

Sediments recently deposited by water have a relatively high water content and high pore space. Sediments in the intertidal zone are exposed for a varying length of time during each ebb tide. During this time they lose water and air enters. The loss of water increases the capillary potential and leads to smaller pores. Water loss and increased aeration are revealed by changes in the soil's density and water content. The density of the soil is described by the bulk density, which is the weight of oven-dry matter present in a volumetric unit of soil in its natural situation. The bulk density is expressed in  $\text{g cm}^{-3}$ . The water content is given in weight percentages of oven-dry soil. Both quantities were determined from samples taken in metal cylinders of 50 or 100  $\text{cm}^3$ , using 3-5 rings on each level in the soil pits. Samples were also taken in the polders to indicate the ripening stage of the same sediment 115 years after reclamation. The samples were taken at the same time of the year under similar, dry weather conditions.

In the intertidal zone the bulk densities varied between 0.46-1.40  $\text{g cm}^{-3}$  and the water content between 30.5 and 186.5%. In Figure 25 both quantities are plotted against each other. This yields a more or less hyperbolic function, with the most ripened soils with highest bulk densities and lowest water contents on one side, and the least ripened soils with very low bulk densities and high water contents on the other side. Bulk density and water content decreased and increased, respectively, with the clay content (see Table 9).

Table 9. Bulk density and water content compared with clay content.

	< 8% clay	8-17.5% clay	17.5-25% clay	> 25% clay
Bulk density	1.40	0.88-1.40	0.79-0.80	0.46-0.86
Water content	30.5	32.4-69.4	70.3-82.9	70.1-186.5

The ranges of the values were rather large, especially at high clay contents (see also Table 10). The water content and bulk density at the time of deposition are related to the content of clay and organic matter and the clay mineralogical composition (e.g. ZUUR, 1958; PONS &



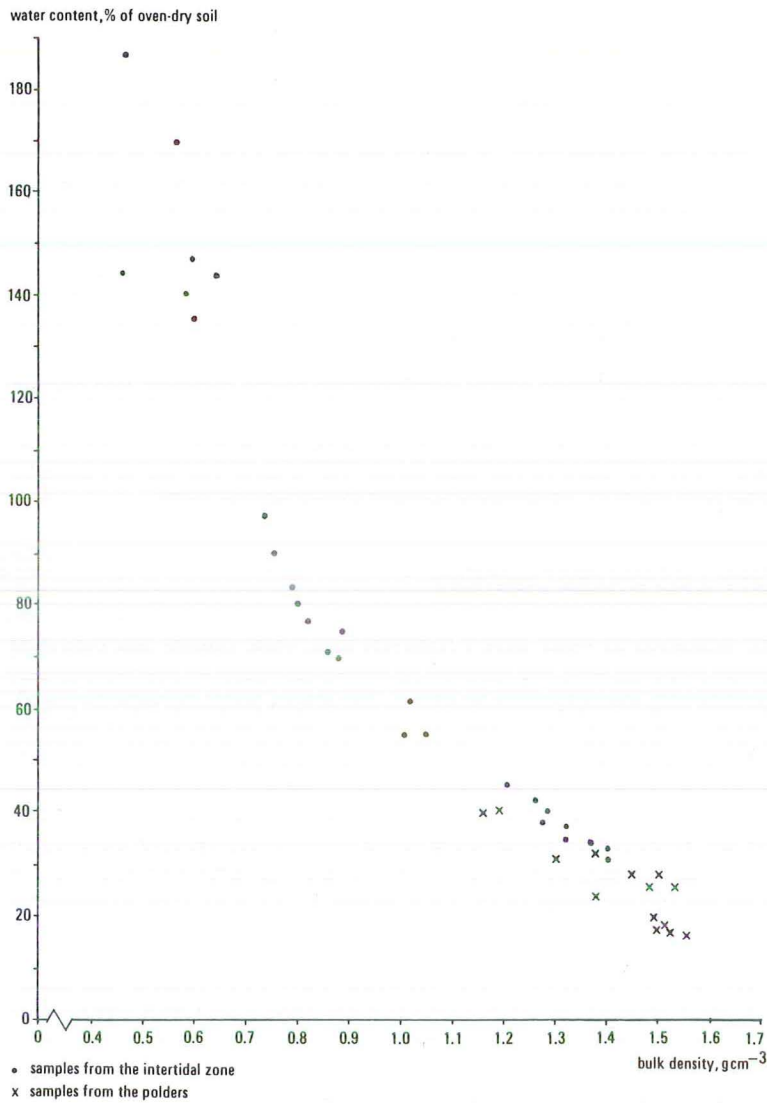


Fig. 25. Correlation between bulk density and water content of samples from the intertidal zone and polders.

ZONNEVELD, 1965; DE GLOPPER, 1967, 1973). In the intertidal zone a close correlation was found between the clay content and organic matter content (see Section 3.3). There were no distinct variations in clay mineralogy (see Section 3.2), so the variations in bulk density and water content at a given clay content could not be due to differences in organic matter content and clay mineralogy.

The distribution of the bulk densities and water contents measured over the intertidal zone typically followed the pattern given in Figure 26. This pattern (which was in accordance with

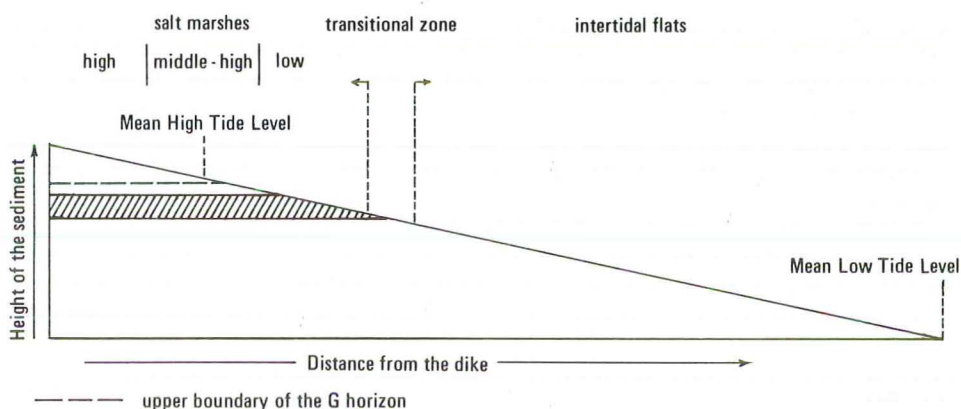


Fig. 26. Schematic cross-section of the intertidal zone showing the position of the zone with the highest water contents (hatched).

the field observations on the ripening classes of material obtained by soil auger) can be explained as follows: With increasing sedimentation in the intertidal zone the sediment becomes more finely grained and hence has a higher initial water content. However, the more the sediment is built up, the longer it is exposed at ebb tide and the less new sediment is deposited. This results in water losses which increase with increasing surface height; this first became apparent in the middle-high salt marsh. The sediments of the transitional zone and low salt marsh had the lowest bulk densities and highest water contents. These sediments lay in the G horizon (see Map 2, Appendix 3). After being buried by younger sediments they retained most of their initial water content.

The influence of vegetation on water losses from the sediments was not obvious. Since *Spartina townsendii* dominates in the low salt basins, the middle-high salt basins and in part of the high salt basins (see Map 4A, B, Appendix 3), the evapotranspiration from the vegetation must be similar in each of these zones and cannot play an important role in the differential lowering of the water content in the upper layers of the soil.

Table 10. Comparison between bulk densities and water contents at two clay contents for samples from intertidal zone and polder soils.

	Clay content %	Bulk density g cm <sup>-3</sup>	Water content % of oven-dry soil
Intertidal zone soils	9	1.21-1.37	45.0- 33.4
	39	0.47-0.60	186.5-134.6
Polder soils	9	1.50	19.0
	39	1.38	31.8

The bulk densities of the polder soils varied between 1.16 and 1.55 g cm<sup>-3</sup>. The water contents varied from 16.3 to 40.3%. The sandy soils had the highest bulk densities (1.45-1.55 g cm<sup>-3</sup>) and lowest water contents (16.3%). In contrast, clayey soils had the lowest bulk densities (1.16-1.35 g cm<sup>-3</sup>) and the highest water contents (30-40%). In Figure 25 the two param-

ters are plotted against each other together with the data from the samples of the intertidal zone. The polder soil samples form the part of the hyperbola where the lowest water contents and highest bulk densities are found. The sandiest samples from the intertidal zone had the same values as the clayey samples of the polders. This shows that even the sandiest samples from the intertidal zone change in bulk density and moisture content after reclamation. Examples of the differences of both parameters before and after reclamation are given in Table 10.

Compared with the data of the intertidal zone the increase in bulk density for sandy material in the polders varied between 20 and 25%. In clayey polder soils the bulk density increased between 2 and 3 times after reclamation. The water content could diminish more than 6 times. The largest decrease in water content and increase in bulk density occurred after reclamation.

### 3.7 pH

The pH of the soils, which is expressed as pH-H<sub>2</sub>O or pH-KCl, is influenced by many factors. The most important ones are: exchangeable bases, salt content, presence of carbonates, presence of organic matter, and formation of acids.

In the intertidal zone the pH-KCl was generally 0.2-0.3 unit lower than the pH-H<sub>2</sub>O. The pH-KCl in both alkaline and acid soils, was about 0.5-1.0 unit lower than the pH-H<sub>2</sub>O. If the differences between the pH-KCl and pH-H<sub>2</sub>O were less, this indicated that salts were present in the soil (SCHEFFER & SCHACHTSCHABEL, 1966). The presence of salts in these soils was demonstrated by the electrical conductivities measured (see Section 3.5).

The pH-H<sub>2</sub>O in the intertidal flat deposits ranged between 6.6 and 8.6, indicating slightly acid to moderate alkaline conditions. The pH-H<sub>2</sub>O of the seawater in the Oosterschelde varied between 7.7 and 8.2 (see Section 1.3). Thus it can be inferred that after sedimentation, processes take place that affect the pH. The pH changed with increasing surface level. In the intertidal flat deposits the soil was moderately alkaline with a pH between 8.3 and 8.6. In the salt marshes pH values were lower. The surface samples of the natural levees had higher pH-H<sub>2</sub>O values than those of the salt basins. In the natural levees (although less obviously) and in the salt basins, pH-H<sub>2</sub>O first decreased with depth and then was constant or rose slightly again. This feature was most distinctive in the middle-high and high salt marsh. The lowest pH-H<sub>2</sub>O values occurred in the salt basins of these subzones.

In the polders the difference between the pH-H<sub>2</sub>O and pH-KCl was 0.5-1.0 unit. These soils contained very few salts (see Section 3.5). The pH-H<sub>2</sub>O in the polders varied between 7.9 and 8.3 and was constant throughout the soil profile. This suggests that in the polders no processes influencing the pH-H<sub>2</sub>O have taken place.

### 3.8 EXCHANGEABLE CATIONS

Two aspects were studied: (i) the base saturation and (ii) the adsorbed cations.

(i) The base saturation gives the sum of the adsorbed bases as percentages of the C.E.C. In the intertidal zone the base saturation varied from 62% to over 100%. Base saturation was more or less related to pH. In the sediments of the intertidal zone from Mean Low Tide level to the middle-high salt marsh, the base saturation exceeded 100%, indicating that the salts had not been completely removed before the analyses of the exchangeable cations were done. With increasing distance upslope the base saturation decreased; this was most conspicuous in clay-rich sediments.

(ii) Of the adsorbed cations, exchangeable Mg<sup>2+</sup> and K<sup>+</sup> strongly correlated with the clay con-



tent, organic matter content and the C.E.C. The other adsorbed cations  $\text{Na}^+$  and  $\text{Ca}^{2+}$  had a weak correlation. Because there is a high concentration of  $\text{Na}^+$  in marine environments this ion replaces other adsorbed ions. The adsorbed sodium in the intertidal zone varied between 4 and 24%, whereas it was less than 1% in the polder soils. The quantity of adsorbed  $\text{Mg}^{2+}$  was also high in marine environments, in contrast to the polder soils. A decrease of the salt concentrations results in the  $\text{Na}^+$ , and also  $\text{K}^+$  and  $\text{Mg}^{2+}$  being replaced by available  $\text{Ca}^{2+}$  (Stichting voor Bodemkartering, 1967). In contrast to the intertidal zone, the base saturation in the polder soils was always about 100%. Over 80% of the adsorbed cations on the complex were  $\text{Ca}^{2+}$  ions.

### 3.9 CARBONATE CONTENT

The carbonate content of the samples from the intertidal zone varied between 0.7 and 12.7%. The carbonate content increased concomitantly with the clay content. The increase in clay content from 4.6 to 33.2% corresponded to an increase in carbonate content from 7.7 to 12.7%. This has also been found by other authors, e.g. VERHOEVEN (1962), DE GROOT (1963), VAN DER SLUIJS (1970). Expected maximum values of carbonate contents were only found in some of the samples. In many cases, especially in clay-rich samples, lower values were measured in the subsoils (see Section 2.3). In nearly all cases, as also found in the survey, the largest decrease of carbonates was measured just above the G horizon. The zones in which no visible and audible effervescence could be detected in the field had carbonate contents of less than 1.6%. Distinct carbonate deficiencies were found in the middle-high and high salt marshes, occurring over broader zones in the high salt marsh (see Map 3, Appendix 3). This shows that after sedimentation, processes occur to cause marked decreases in carbonate content in the subsoils. Carbonates dissolve in the soil solution under slightly acid conditions. In the sediment the carbonate, as part of the mineral framework, is in contact with the mobile liquid and gas phases. When carbonates dissolve, bicarbonate ions are formed. This reaction is intensified when gases, such as  $\text{CO}_2$ , or acids enter solution. As long as solid carbonate is present the pH will not fall below 6 to 7 (STUMM & MORGAN, 1971). Several processes might be responsible for the carbonate being dissolved after the sediment has been deposited:

- (i) The influence of atmospheric  $\text{CO}_2$  gas in the soil solution increases with the height of the surface. This would result in the largest deficiencies being near the surface, especially in sandy sediment, but in fact they occurred much deeper, generally just above the G horizon.
- (ii) When organic matter in aerated or in non-aerated environments decomposes,  $\text{CO}_2$  is produced. Because there is no decrease in percentage carbon in zones with carbonate deficiencies, the amount of carbon present in the sediment is related to the clay content (see Section 3.4). Therefore the dissolution of carbonates cannot be ascribed to this process. Moreover, if the decrease in carbonate content is also related to the content of organic matter and clay content, then large decreases in carbonate contents over broad zones should also be found in the middle-high salt basins. This is not the case (see Map 3, Appendix 3).
- (iii) The vegetation does not play a major role either. It does not add large quantities of organic matter to the soil which can be decomposed, thereby producing  $\text{CO}_2$  (see Section 3.3).

None of these three processes satisfactorily explains the distribution of carbonate deficiencies. However, the oxidation of sulphides, discussed in the next section, is probably an important factor. In the polder soils the carbonate content varied from 6.0 to 11.7%. So, these soils are still rich in carbonate.

### 3.10 REDUCTION AND OXIDATION PHENOMENA

Reduction and oxidation occur with elements that exhibit multiple valence states. In this respect, the most important elements in soils after iron and manganese are carbon, nitrogen and sulphur. The photosynthesis of plants results in reduced states of higher free energy for the latter three elements. Therefore, organic matter in soils is bound to be oxidized. If oxygen is not available, other reducible compounds may function as electron acceptors. Under soil conditions these are nitrate, manganese, ferric oxide and sulphate. Decomposition of organic matter under anaerobic soil conditions is thermodynamically possible, but proceeds slowly. Enzyme systems in bacteria and other organisms can surmount kinetic activation-energy barriers and can accelerate otherwise slow reactions (BERNER, 1971). As  $H^+$  ions are frequently involved in redox reactions, pH values are often influenced by such processes. An important aspect of redox reactions is the difference between the mobility of certain elements in reduced and oxidated state.  $Fe^{3+}$  and  $Mn^{4+}$  generally form very insoluble compounds. Their reduced counterparts  $Fe^{2+}$  and  $Mn^{2+}$  are much more mobile.  $S^{6+}$  is very soluble, but  $S^{2-}$  is easily precipitated. The differences in mobility of iron, manganese and sulphur influenced by the redox potential ( $E_H$ ) and pH are mainly responsible for marked depletion and accumulation of these elements in certain horizons (VAN BREEMEN, 1976). The depletion and accumulation of these elements in different horizons results in distinctive soil colouring. The soil of the predominantly reduced zone is usually rather uniformly black, dark (olive) grey or grey, because of the presence of  $FeS$  and  $FeS_2$ . When the reduced soil material is black there is usually an accompanying smell of  $H_2S$ .

#### *Discussion of the data*

During the fieldwork and study of the thin sections ample evidence of the presence of pyrite and accumulations of ferric oxides was found. In the soil pits at the interface of the reduced and oxidized environment a strong mottling of brownish to reddish colours due to ferric compounds was visible. In this zone black mottles of manganese oxides were also found. Yellow mottles of jarosite were not observed, probably because the pH was too high for jarosite to be formed (VAN BREEMEN, 1976). The different colours due to redox reactions were recorded in the soil descriptions (see Appendix 1). In the thin sections studied, pyrite was observed in the form of spheroidal aggregates of microcrystallites, known as framboidal pyrite. For the formation of this type of pyrite, periodical aeration is thought to be necessary (SWEENEY & KAPLAN, 1973; RICKARD, 1975). Most of the pyrite present in marine deposits was originally formed in the upper few centimetres of non-aerated sediment.

The reduction of e.g. ferric iron and sulphate results in the formation of  $HCO_3^-$  (BERNER, 1971). The  $HCO_3^-$  may be concentrated locally. In a solution containing equivalent amounts of  $Ca^{2+}$  and  $HCO_3^-$ ,  $CaCO_3$  will start to precipitate if the pH rises above 7.3 at  $P_{CO_2} = 10^{-2}$  (GARRELS & CHRIST, 1965). In thin sections of deposits from the intertidal flat, local accumulations of  $CaCO_3$  were indeed found. Generally the bicarbonates had been removed by the seawater via internal drainage and the creek systems.

In three profiles in the high salt marsh, samples were taken in which pH,  $E_H$ , total iron, total sulphate and water-soluble sulphate were determined. The results are given in Table 11, together with the clay content, percentage carbon and carbonate content. The measured redox potentials fell between  $-0.20$  V and  $+0.20$  V, while the pH- $H_2O$  varied between 6.6 and 8.6. In these ranges of  $E_H$  and pH, ferric oxide, goethite and pyrite may be present in the solid phase (VAN BREEMEN, 1976). The highest percentages of total  $SO_4$  were found in fine-grained sediments in the upper part of the G horizon. The percentage water-soluble sulphate was also



higher in fine-grained sediments, but the highest values were found just above and in the uppermost part of the G horizon. The highest percentages of total iron were also found in fine-grained sediments. The increase in total sulphate just inside the G horizon indicates an accumulation of reduced sulphur, mainly as pyrite (BERNER, 1971). Pyrite formation was most pronounced in fine-grained sediments for two reasons: the microbiological activity is greatest (because of the high organic matter content); and the clay fraction contains the free iron oxides and silicate iron that are necessary for the formation of pyrite. In seawater an excess of sulphate is generally present. The highest quantities of total iron were found above the G horizon.

Table 11. Some data on the accumulation of pyrite and ferric iron measured directly in fresh soil samples from the high salt marsh.

Depth in cm	pH-H <sub>2</sub> O	E <sub>H</sub> (V)	Fe (tot) %	SO <sub>4</sub> (tot) %	SO <sub>4</sub> (dil. in H <sub>2</sub> O)	% < 2 μm	% C	% CaCO <sub>3</sub>
<i>Natural levee, site No. 13</i>								
10- 20	7.9	-	1.50	0.23	0.064	7.8	0.77	3.8
74-103	7.8	+0.2	1.40	0.09	0.084	8.2	0.46	5.5
104-123	8.0	+0.2	1.18	0.35	0.087	8.7	0.46	5.1
135-140	8.0	+0.1	1.35	0.98	0.098	8.9	0.54	7.1
G horizon from - 104 cm								
<i>Transition, site No. 14</i>								
5- 15	7.7	+0.2	2.17	0.39	0.109	17.0	1.54	3.3
25- 40	7.4	+0.1	3.05	0.41	0.175	23.7	1.93	1.3
55- 65	7.7	-0.1 - +0.2	2.74	2.42	0.187	23.4	2.16	2.5
75- 85	7.9	-0.1	2.12	2.80	0.141	15.6	1.23	7.0
95-105	8.0	+0.1	1.90	2.10	0.120	14.9	1.16	6.7
G horizon from - 41 cm								
<i>Salt basin, site No. 15</i>								
10- 20	7.2	+0.2	4.30	0.77	0.314	36.3	3.31	2.5
55- 70	7.8	-0.2	2.84	3.65	0.177	21.8	1.77	8.7
90-105	7.9	-	1.66	1.64	0.106	11.7	0.85	7.7
G horizon from - 24 cm								

Dithionite-extractable iron, Fe(dith.), was determined in 40 samples taken in the intertidal zone up to the high salt marsh. The iron measured by this method was mostly derived from iron oxides. Higher quantities were found in fine-grained sediment than in coarse-grained material. In the intertidal flat very small amounts of Fe(dith.) were present. In contrast, the values increased to about 3% in the salt marshes. There was always more Fe(dith.) above the G horizon than in the G horizon, but the maximum values occurred just above the G horizon.

The distribution pattern of the phosphorus present resembled that of the Fe(dith.), but the amounts present were much lower (< 302 ppm). As ferric iron has a strong tendency to interact with phosphate, all the phosphate present had probably precipitated (RICKARD, 1973). Therefore, a minor part of the ferric iron may have been present as iron phosphate.

Field observations and chemical data showed that in the middle-high and high salt marshes the zone with the largest amounts of ferric iron, just above the G horizon, generally cor-



responded with the zones where the lowest carbonate contents were found. The ferric iron precipitated in these zones may have been partly derived from oxidation of iron sulphides. The type of pyrite present indicated an alternation of reduction and oxidation. The oxidation of iron sulphides also causes the release of hydrogen and sulphate ions. Iron sulphides were oxidized in the middle-high and high salt marshes, because:

- (i) these salt marshes are situated at and above Mean High Tide level, where aeration facilities are increased and
- (ii) because here leaching of the reaction products is possible.

The lower limit of the decalcified zone (less than 1.6%  $\text{CaCO}_3$ ) had many tongues, some penetrating far into the reduced subsoil, indicating the routes followed by the sulphuric acid and products produced by the dissolution of carbonates. This feature is also mentioned by VAN DER SLUIJS (1970). As a result of leaching, the zone of carbonate deficiencies was not necessarily restricted to the zone above the G horizon where the oxidation occurred. In fine-grained sediment the dissolving of carbonate was more pronounced than in sandy sediments. This is because of the small particle size, which allows easy solution. Also, the larger amounts of iron sulphides present in fine-grained sediments can oxidize to acid sulphates and dissolve the carbonates. The sulphate formed can again be transformed to sulphides and be fixed as pyrite. In the soil pits, black root channels were often visible extending far into the grey reduced subsoils. This probably resulted from the reduction of leached sulphate.

### Hypothesis

Redox reactions may play an important role in the development of the carbonate deficiencies. In the zone just above the G horizon, reduction and oxidation periodically occur related to spring tides, neap tides and the seasons. As a result, the sulphides formed during reduction may shortly afterwards be oxidized, and during this process carbonates will dissolve. The quantity of iron present is not sufficient to cause the carbonates to be dissolved in one cycle. Calculation from data given by VAN BREEMEN (1973) shows that circa 1.66% calcium carbonate is needed to neutralize 1% pyrite. More than one reduction-oxidation cycle would be necessary to produce the carbonate deficiencies measured (see Figure 27). This mechanism resembles ferrolysis, the iron-induced dissolution of clay minerals described by BRINKMAN (1969).

A number of facts can be explained by assuming that several reduction-oxidation cycles involving iron can be important, perhaps the most important factor, for the formation of dis-

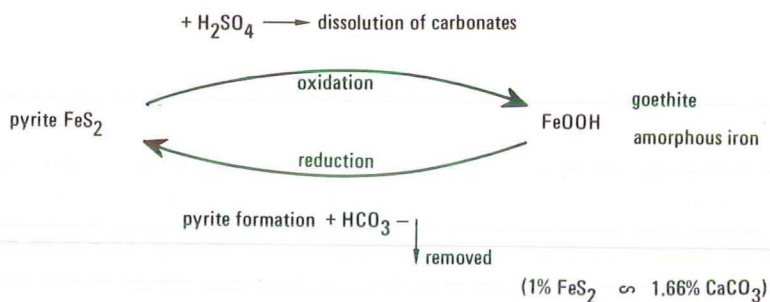


Fig. 27. Schematic representation of the reduction-oxidation cycles involving iron, resulting in carbonate dissolution.

tinct carbonate deficiencies. These facts are: (i) The occurrence of carbonate deficiencies in soils where the upper boundary of the G horizon was found below the surface; i.e. in the middle-high and high salt marsh (see Map 2 A, B, Appendix 3) (field observations). (ii) The presence of the lowest carbonate contents just above the G horizon (field observations, chemical analyses). (iii) Large carbonate deficiencies were always found in soils where much newly formed pyrite had already been observed (micromorphological observations). (iv) In these soils oxidation of pyrite was observed (micromorphological observations). Also, the irregular topography of the lower boundary of the zones with carbonate deficiencies, the occurrence of carbonate deficiencies in the G horizon, and black root channels in the reduced subsoils are phenomena that can be explained by the leaching of the products formed by the oxidation of sulphides. The carbonate contents measured in the soil and the changes in content with depth are very similar to the data given by VAN DER SLUIJS (1967, 1970), but different processes are thought to be responsible for these phenomena.

## 4 MICROMORPHOLOGICAL INVESTIGATIONS

### 4.1 GENERAL

#### *Introduction*

After deposition of marine sediment in the intertidal zone, two active factors of soil formation, climate and organisms (HOLE, 1961), soon cause changes in the sediment. In this environment the climatic factors temperature, wind and rain, together with the benthic macrofauna, micro-organisms and vegetation, are the main elements inducing different soil-forming processes. Processes of soil formation include (SIMONSON, 1959):

(i) *additions* of organic and mineral materials to the soil;  
(ii) *removals*, losses of materials from the soil;  
(iii) *transfers*, translocations of materials within the soil from one point to another; and  
(iv) *transformations* of mineral and organic substances within the soil. These events may occur simultaneously or in sequence to mutually reinforce or conteract each other (RODE, 1962; SIMONSON, 1959), and as a result the effects of these four kinds of changes in a soil are expressed in two trends, a horizonation and a haploidization (HOLE, 1961; BUOL et al., 1973). Horizonation includes the proanisotropic processes and conditions by which the original materials are differentiated into soil profiles with many horizons. Haploidization includes proisotropic processes and conditions by which horizonation is inhibited or decelerated or by which horizons are mixed or disturbed. Both trends are of equal importance. Generally one of the trends dominates. Viewed in this light the aims of this micromorphological study are:

(i) to ascertain the changes caused to the original material of the intertidal zone by flora, fauna, physical and chemical processes and to relate these changes to the four groups of changes mentioned earlier.  
(ii) to draft a model to represent the occurrence and relative importance of faunal, floral, physical and chemical processes during upward growth of the sediment.  
(iii) to study the preservation of features originally formed in the intertidal zone, in some reclaimed soils.

#### *Terminology*

Several features observed in thin sections and processes can be described by terms derived from different sciences, such as pedology, sedimentology and biology. As the approach used in this thesis is pedological, pedological terms are preferred. If there is no pedological term for a feature or process, an appropriate term from another science is used. In most cases these terms are derived from sedimentology. Sedimentological terms, however, should be used with care because the interpretation and approach in sedimentology are essentially different from those in pedology. This study deals with a theme for which the common pedological and micromorphological terms and concepts are not very satisfactory. Several times the terms available for specific features could not be used as they are associated with a genetic interpretation, which in this case may not be correct. The micromorphological observations are described following the terminology of BREWER (1964), unless otherwise stated. Features not previously defined are, whenever possible, indicated by descriptive terms. The introduction of new terms is avoided as much as possible. A glossary of the terminology used is given at the end.



## Framework

This chapter is divided into four sections. In the first section (Section 4.2) the methods of preparing thin sections, the microscopic and submicroscopic techniques used and the resulting interpretation are described. Section 4.3 presents a reconstruction of the biological, physical and chemical processes occurring in the intertidal zone, based on the micromorphological observations. In the third section (Section 4.4) the development of soil fabrics in the intertidal zone is discussed. In this section the soil fabrics are classified and a model of fabric development during the accumulation of sediment is presented. Finally, pedogenetic fabrics in the reclaimed soils are described in Section 4.5.

## 4.2 METHODS

The large thin sections were prepared according to the method developed by JONGERIUS and HEINTZBERGER (1975). Because of their susceptibility to shrinkage, nearly all the samples taken in the intertidal zone were freeze-dried before being impregnated. The other samples and those from the polders were air-dried before impregnation.

The thin sections were studied in plain transmitted light, under crossed polarizers, and in reflected light with magnifications up to x250. By means of an epidiascope (LEITZ/WETZLAR, IIL) the thin sections were also projected on a wall in plain transmitted light or with crossed polarizers. In this way images of nearly the whole thin section were obtained at magnifications up to x20. This method enabled information on differences in granular composition and on the distribution of several features e.g. voids, organic matter and carbonates, to be gained. The composition of some amorphous, microcrystalline and opaque materials present in thin sections was studied by a combination of scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDXRA) on small parts of thin sections. These methods are described in BİSDOM *et al.* (1975 and 1976).

The interpretation and determination of the effects of biological processes on the soil matrix were not only based on literature and on evidence from thin sections, but also on many field observations. Faunal channels were followed, and the position of several animal species in the sediment, their movement, way of feeding, and the shape and composition of their excrements were studied. Some known excrements were studied with the scanning electron microscope (SEM), which enabled topographical images to be obtained. Some effects of physical and chemical processes were also studied in the field e.g. polygon structures, occurrence of ferric iron.

## 4.3 SOIL-FORMING PROCESSES IN THE INTERTIDAL ZONE AND THEIR MICROMORPHOLOGICAL CHARACTERISTICS

### 4.3.1 General

In this section the results of the micromorphological investigations are presented in conjunction with the processes that caused them. These processes can be identified in thin section from the features they have caused. The thin sections prepared from vertically and horizontally oriented samples taken from the soil profile, when combined with many field observations

made it possible to present three-dimensional reconstructions. In the introduction to this chapter it was mentioned that the active factors of soil formation are climate and organisms. The effects of these active factors can be translated into biological, physical and chemical processes. Although the activities of organisms have physical and chemical aspects, their total effect usually results in such a specific and complex pattern that they are dealt with as a separate group. The role played by organisms is subdivided into a faunal and floral part, each with distinctive micromorphological characteristics. Before dealing with the soil-forming processes and their micromorphological characteristics it is necessary to redefine the concept for the constituents of the soil material. KUBIENA (1938) and BREWER & SLEEMAN (1960) developed a plasma/skeleton (grain) concept in which the soil material was separated into plasma and skeleton grains mainly on the basis of the stability and size of the mineral part. The organic material considered by BREWER (1964) was restricted to humified organic matter and resistant organic bodies. The plasma/skeleton (grain) concept is inadequate for soils in the intertidal zone because it does not give sufficient emphasis to the composition of newly deposited mud and sand laminae.

The sediment of the intertidal zone showed alternations of laminae with different grain sizes. The clay-rich laminae were to a varying degree formed by the accumulation of mud-flakes deposited under quiet-water conditions. Thin sections made of mud in suspension (see also Section 1.3.1) filtered from the seawater during high tide in a tidal channel near the Rattekaai revealed a complex composition of colloidal mineral material, dead organic matter (e.g. peat fragments), living organisms (e.g. diatoms), fine mineral particles (e.g. quartz grains and other mainly light minerals), many carbonate particles, and a few pyrite spheroids and iron oxides. The mineral and organic particles did not usually exceed  $30\mu$  m. This complex composition gave the mud-flakes and mud laminae in the sediment the appearance of a clay-sized, carbonate-rich loosely packed groundmass in which much organic matter of different kinds was present and mineral grains of  $2-30\mu$ m were embedded. In newly formed sand laminae, many organic bodies and carbonates were found. If the plasma and skeleton grain concepts of KUBIENA (1938) and BREWER & SLEEMAN (1960) are used, the composition of the mud and sand laminae is ignored. As a result the geogenetic origin is obscured and the description of the effects of the soil-forming processes on the sediment becomes complicated.

In this case it is more useful to make a distinction in the lowest fabric units of the soil between fine and coarse material, independent of the stability and form of organic matter present, as proposed by STOOP & JONGERIUS (1975). The boundary between both groups can be fixed at  $30\mu$ m: then the fine material will mostly consist of particles smaller than  $2\mu$ m, in which a limited number of particles from  $2-30\mu$ m is embedded. Both groups, the fine and the coarse material, contain mineral as well as organic particles.

#### **4.3.2 Changes in the sediment caused by biological processes**

As the lowest part of the intertidal zone comprises intertidal flats, where animals, rather than plants, predominate, the fauna will be dealt with first.

##### *4.3.2.1 Faunal activities*

Brief descriptions of the species of benthic macrofauna in the intertidal zone, their mode of life and way and kind of feeding were given in Section 1.7. In this study the effects of faunal activities were mostly clearly distinguishable from those of the flora. The fauna produced specific effects depending on their mobility and characteristic feeding habits. Their excrements



and skeletal remains were distinctive. The features in the sediment resulting from the mobility of the fauna were related to the animals' feeding habits and adaptation to the environment. They can be grouped under three headings: channels, pedotubules and passage features (this latter term will be defined later in this Section). Usually several species producing different traces of mobility, accentuated by differences in size, occurred in the same locations; this gave rise to complex patterns in the thin sections. Excrements and skeletal remains, e.g. shells, did not always occur in association with faunal channels, pedotubules and passage features. Occasionally they were displaced and deposited elsewhere, incorporated in sedimentary layers. These dislocated elements of faunal activity are dealt with in more detail in Section 4.4.1. To understand the features produced by the fauna in the intertidal zone some knowledge of the characteristics of the animals' excrements is required. Therefore, before describing the different channels, pedotubules and passage features encountered, an account of the different faunal excrements present in the sediment will be given. As the intention of this study was solely to reconstruct the faunal processes and their effects on soil formation, no specific research was done to identify the species involved. However, if the faunal species responsible for the different feature is known, it is mentioned by name.

### *Excrements*

All excrements recognized in thin section were initially three-dimensional distinctly shaped pellets, identical to the modexi of Bal (1973). They were often easily detectable in the thin sections because they were more compact than the surrounding sediment. The shape, size, composition and occurrence of the excrements in the thin sections and, if known, the names of species that produced them, are given in Figure 28.

All excrements had an organo-mineral composition, in which the mineral part dominated. The excrements found in the intertidal zone fall into four categories:

(i) *composed of clay-sized material (less than 2  $\mu\text{m}$ )*: This common type was nearly always found in passage features. They must have been produced by more than one species, as they varied in size and shape.

(ii) *composed of fine material (less than 30  $\mu\text{m}$ )*: A very abundant type found in all types of channels, pedotubules and passage features, and produced by many species.







(iii) *compound*: This type comprised a thin layer of clay-sized material, rarely containing particles between 2-30  $\mu\text{m}$ , surrounding a core of mainly coarse grains. It was common, predominantly occurring in passage features and only rarely in striotubules. Several species produced excrements of this type.

(iv) *composed of coarse grains*: Droppings of this type were not found in the thin sections. They were common at low tide on the surface of the intertidal flats where they were deposited by *Arenicola marina*, but were usually swept away by high tides (see Figure 16).

Types 1 and 2 were generally found in bio-geogenetic laminae (see Section 4.4.1).

In the scanning electron microscope photos given in Figure 29, three different shapes and sizes of excrements of known species are shown, together with three details of the surface. These excrements were air-dried and therefore had shrunk; cracks had formed and the outer layer of fine material had contracted, revealing the interior part. The excrement of *Hydrobia ulvae* is a biconical long cylinder composed exclusively of clay-sized material; the excrement of *Cardium edulis* is ellipsoidal, composed of fine particles; that of *Macoma balthica* is a cylinder consisting of a thin layer of clay-sized material, rarely with a few particles of 2-30  $\mu\text{m}$  surrounding a core of mainly coarse grains. The surface details of the excrements indicated their composition. As well as mineral parts composed of clay-sized material and coarse grains, fragments of peat, algae and diatoms, as well as living species of algae and diatoms attached



	Shape	Size in $\mu\text{m}$		Composition			Occurrence			Remarks
		length	width	< 2 $\mu\text{m}$	< 30 $\mu\text{m}$	compound	channels	pedotubules	passage features	
1.	 sphere (Bal, 1973)	160 - 300	140 - 300	x	x		x		x	several species, incl. <i>Vermes</i>
2.	 ellipsoid (Bal, 1973)	200 - 800	100 - 500	x	x	x	x	x	x	many species, e.g. <i>Cardium edule</i>
3.	 bacillo-cylinder (Bal, 1973)	200 - 1100	60 - 400	(x)	x		(x)	x	x	many species
4.	 biconical long cylinder	340 - 450	90 - 125	x					x	only <i>Hydrobia ulvae</i>
5.	 cylinder (Bal, 1973)	700 - 1100	400 - 550		(x)	x			x	several species, e.g. <i>Macoma Balthica</i>
6.	 polled cone $\otimes$	700 - 800	390 - 510			x			x	probably one species

$\otimes$  polled - derived from to poll = cut off the top of

Fig. 28. Characteristics of excrements present in thin sections of samples taken in the intertidal zone.

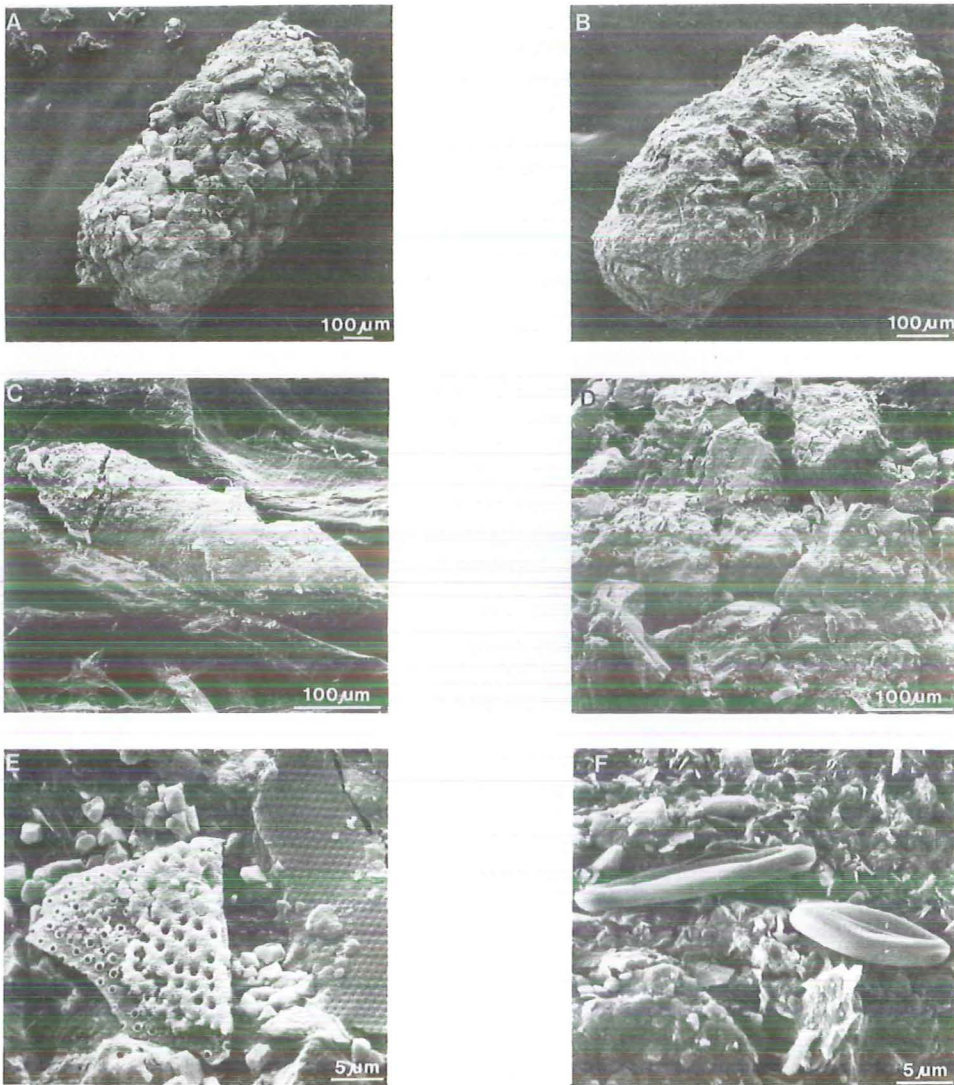


Fig. 29. Shapes and compositions of some excrements and details of their surface.

A. *Macoma balthica* excrement; shape: cylindrical; length: ca. 1040  $\mu$  m; composition: a thin layer of usually clay-sized material surrounding an interior of coarse grains.

B. *Cardium edule* excrement; shape: ellipsoidal; length: ca. 750  $\mu$  m; composition: fine particles.

C. *Hydrobia ulvae* excrement; shape: biconical cylinder; length: ca. 420  $\mu$  m; composition: clay-sized material.

D. detail of excrement of *Macoma balthica*; interior of coarse grains visible, with an organic grain (peat) and fragments of algae.

E. detail of excrement of *Macoma balthica* with fragments of algae.

F. detail of excrement of *Hydrobia ulvae* with diatoms.

afterwards, were identified. Figure 37 shows the appearance in thin sections of some excrements of differing shapes and compositions.

All excrements contained many fine particles of carbonate, uniformly sized and evenly distributed throughout the fine material. These carbonate particles generally had more uniform sizes and were often smaller than those present in mud-flakes and mud laminae. This suggests that a part of the carbonate becomes fragmented in the animal's digestive tract.

The excrements in the thin sections associated with phenomena produced by burrowing were, when not modified by the animal itself, only incidentally deformed by externally applied pressures. The only other noteworthy changes that affected these excrements were chemical and resulted from oxidation. In contrast, excrements present in bio-geogenetic laminae often showed serious deformations and/or coalescence, eventually including other sedimentary material. After excretion, the excrements undergo morphological changes as result of microbiological, chemical and physical processes termed 'ageing' by BAL (1973). It is doubtful whether the deformations and disintegrations found in excrements in bio-geogenetic laminae are caused by ageing. Mechanical destruction due to locally exerted external pressure and/or dislocation due to external forces, should be excluded from ageing.

The composition of the excrements reflected the kind of food the animal had ingested. Excrements composed of clay-sized material must have been produced by selective deposit-feeders, such as *Hydrobia ulvae*, who only ingest the finest material (see also Section 1.7). The excrements of suspension-feeders were composed of fine material and therefore resembled the original composition of mud-flakes. This was obvious from the excrements of *Cardium edule*, which is a true suspension-feeder (WOLFF, 1973). Excrements with a compound composition must also have been excreted by selective deposit-feeders, such as *Macoma baltica*. The food of selective deposit-feeders as well as of suspension-feeders mainly consists of micro-organisms and detritus, but the mode of life and the animal's size probably determine which part of the sediment is selected.

Whether the excrements are deposited on the surface or in the sediment depends on the animal's mode of life, rather than on its way of feeding. The sessile Pelecypods and Vermes deposit their excrements on the surface. Most of these excrements are soon washed off by high tides and subsequently incorporated in sedimentary laminae. Excrements embedded in sediment in this way will be discussed in more detail in Section 4.4.1. The excrements deposited directly in the sediment are described in detail in conjunction with the following discussions on individual features produced by the burrowing fauna.

### Channels

Many of the species living in the sediment made channels. The channels were straight, curved or very convoluted with or without branching and chambers. They had diameters varying from some dozens of micrometres to several centimetres.

In the area under the direct influence of tides the channels tended to be vertical except where the surface was inclined, e.g. the slopes of the tidal gullies and walls of natural levees. The channels in this zone were generally simple: many were unbranched, straight or U-shaped and opened out to the surface. These simple channels were used for a longer time and were made by Mollusca, several species of the Vermes and some Crustaceae, all species with a more sessile way of life. Some species of the Vermes, such as *Heteromastus filiformis* and *Nereis* spp. made simple, rather straight channels that bifurcated in the sediment (see Figure 15). The channels made by the shore crab (*Carcinus maenas*) were found in inclined surfaces and were horizontal and straight, ending in a small chamber. In the natural levees of the salt marshes they were not very conspicuous, as the entrance was often located in vertical shrinkage cracks.



Juvenile specimens of crabs were often found in the voids between the polygons in the intertidal flat and in the high salt basins. In the voids between the large polygons in the intertidal flat the crabs dug shallow holes, generally not larger than 15 mm in diameter. In Figure 45 part of a void between two polygons with such a 'crabhole' is given.

In areas that were only sporadically flooded, such as the highest parts of the natural levees, the faunal channels had no distinct dominant orientation. These channels were also more branched and convoluted than those in the lower regions of the intertidal zone.

This difference in channel patterns can be attributed to the instability of the sediment and to the continuous deposition with or without alternations of erosion.

In a small zone around the channels the sediment was often deformed. Here the ground-mass was more compact, elongated particles were oriented more or less parallel to the channel and when the sediment was laminated the laminae were bent up or down. The laminae did not necessarily bend in the same direction all along the channel: sometimes the laminae changed direction within short distances, without any apparent relation to the direction the animal burrowed. These changes in direction resulted from pressure exerted by the burrowing animal. They were clearly developed in sediment with a weak consistence. In this study such zones are called pressure-affected zones. JONGERIUS (1970) described the same type of feature as faunadocompaction. The pressure-affected zones, however, have a greater extent than the type of faunadocompaction described by JONGERIUS (see Figure 30).

Channels in use for longer times in the zone permanently influenced by the tide often had several types of cutans, as a result of the instability of the sediment and the deposition of fresh material.

Generally the walls of the channels were stabilized by being cemented with slimy secretions. In this sediment, because of the high water contents and different granular compositions, very unstable conditions prevail. The periodic sedimentation of fresh material alternating with periods of erosion increases the instability. In reaction, to strengthen their channel walls, many animals plaster them, mainly with mineral material, locally or over longer distances. The cutans directly formed by the animals themselves to stabilize the walls or to clear away loose material, are from now on termed zoocutans\*. Several types of predominantly mineral zoocutans (from now on called mineral zoocutans) were observed:

(i) *Simple mineral zoocutans composed of fine material (mud)*. The mud used was usually derived from faecal matter: deformed excrements, composed of fine material were observed several times in the mud plaster, and undeformed excrements were found locally attached to the channel walls (see Figure 31). It is proposed to term these cutans mud-zoocutans\*. They are certainly produced by species of Vermes and Pelecypods. DOEKSEN & MINDERMAN (1963) mention mud-zoocutans in *Nereis* channels.

(ii) *Compound mineral zoocutans, of which the individual cutans were composed of fine and coarse material*. The fine material was found furthest away from the channel walls. Usually, several of these compound cutans were found on the same channel wall, usually overlapping each other. These compound zoocutans typically exhibited the following characteristics (see Figure 31):

- \_ the individual cutan was not extensive
- \_ the individual cutan had a compound composition, i.e. coarse grains nearest to the wall covered with a thin layer of fine material, together forming an elongated thin layer
- \_ individual compound cutans usually overlapped each other
- \_ the composition of the mud present in the compound zoocutans was always the same; the composition of the coarse particles varied.

The compound zoocutans were formed as follows. The coarse particles were derived from

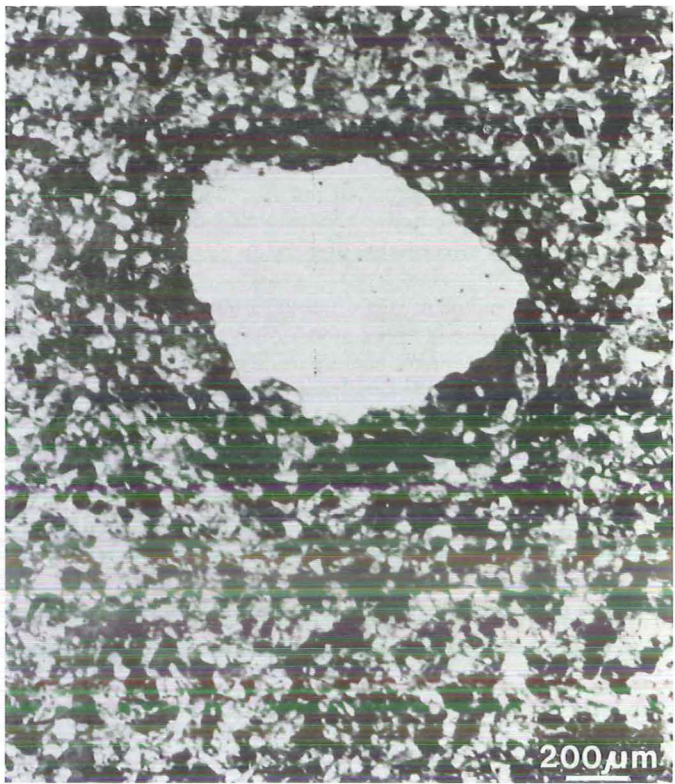
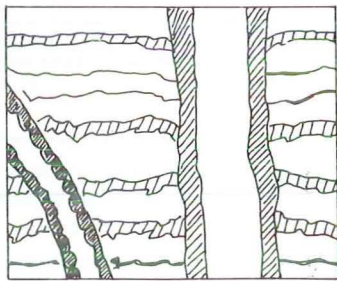
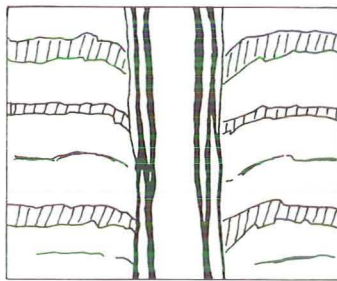


Fig. 30. Pressure-affected zone around a cross-section of a faunal channel.



mud-zoocutans



overlapping compound zoocutans



Fig. 31. Zoocutans with pressure-affected zones.



material that had fallen or flowed into the channel (e.g. during high tide, when sediment is transported along the surface, or when birds disturb the channel entrance). This material was pressed against the channel walls by the animal and was then covered with mud, usually derived from excrements. This process may be repeated several times. It is proposed to term this type 'overlapping compound zoocutan'\*. REINECK (1958) used the term 'multi-layered coatings' to describe the same phenomenon, and attributed their formation to *Nereis* species.

The vermicutans of JONGERIUS (1970) and the skatans and modexans of BAL (1973) are also zoocutans. Vermicutans, skatans and some of the mud-zoocutans and overlapping compound zoocutans are all produced by species of the Vermes.

Another feature associated with channel walls had a chemical cause. In the upper parts of open channels in the intertidal flats and natural levees, precipitated ferruginous matter was found lining the walls (ferrans) and/or in the groundmass adjacent to the walls (neoferrans). The neoferrans were generally continuous and could be 2-5 mm wide; the ferrans were not necessarily continuous and were much thinner. Neoferrans occurred, sometimes alternating with neomangans; together they could be more than 1 cm wide. They were also found in crab-holes. These neocutans and cutans must have been precipitated as a result of the aeration, oxidation and evaporation that are possible during ebb-tides. These secondary effects, developed after the channels were formed are discussed further in Section 4.3.4.

After their formation, channels may be partly or completely infilled, mainly with coarse particles. These infillings usually result from physical processes and are dealt with in Section 4.3.3. Generally, infilled channels remained recognizable as such, and could be more easily identified if pressure-affected zones, zoocutans, neoferrans and ferrans were present.

### *Pedotubules*

According to BREWER & SLEEMAN (1963) a pedotubule is:

a pedological feature consisting of soil material<sup>1)</sup> and having a tubular external form, either single tubes or branching systems of tubes; its external boundaries are relatively sharp.

Several types of pedotubules were observed. Not all were solely of faunal origin. Pedotubules formed by the infilling of faunal channels are discussed in Section 4.3.3 (physical processes).

Two different types of faunal pedotubules were distinguished: aggotubules (BREWER & SLEEMAN, 1963; BAL, 1973) and striotubules (BREWER & SLEEMAN, 1963).

(i) Aggotubules. BAL (1973) slightly adapted the definition of the aggotubule given by BREWER & SLEEMAN (1963) as follows:

Aggotubules are pedotubules composed of soil material which occur principally as recognizable aggregates within which there is no directional arrangement with regard to the external form.

The recognizable aggregates occurring in the aggotubules were usually ellipsoidal or bacillocylindrical excrements composed of fine particles, completely filling channels. These channels were oriented horizontally as well as vertically, as was apparent from the fact that cross-sections of these aggotubules were found both in horizontal and vertical thin sections. VAN STRAATEN (1954) also observed bifurcating channels filled with excrements. Figure 32 shows a section of an inherited aggotubule composed of excrements present in the polder soils. BAL (1973) terms this type of aggotubules 'modexotubules'.

<sup>1)</sup> The constituents of soil materials are in this case defined as fine material and coarse particles, instead of plasma and skeleton grains (see Section 4.3.1).



(ii) Striotubules. According to BREWER & SLEEMAN (1963):

Striotubules are pedotubules composed of soil material that is not organized into recognizable aggregates but exhibit a basic fabric with a directional arrangement related to the external form. The directional arrangement is semi-ellipsoidal with the walls of the pedotubule approximately tangential to the semi-ellipsoid.

In the thin sections much evidence of striotubules was observed. The three characteristic varieties and their genesis are shown in Figure 33. Striotubules are produced by more sessile species living in the sediment, mainly the Pelecypods of the Mollusca but also by the Amphipod *Corophium volutator*. The striae are the result of movement of the animal. Bivalve molluscs move with their feet over short distances. During this the soil material is pressed alongside their bodies and redeposited in a strial configuration behind them. The striotubules usually contain more mud than the surrounding sediment, due to the addition of generally clearly recognizable excrements. The excrements may be embedded in the mud striae but striae may also be completely composed of excrements. The striotubules of variety A en B need not to be strictly vertical: they may also be slightly inclined. Striotubule A in Figure 33 is a result of upward movement of the animal, to keep pace with continuing sedimentation. Striotubule B is



Fig. 32. Part of an inherited aggotubule filled with excrements present in a thin section from Profile no. 2 in the Tweede Bathpolder.

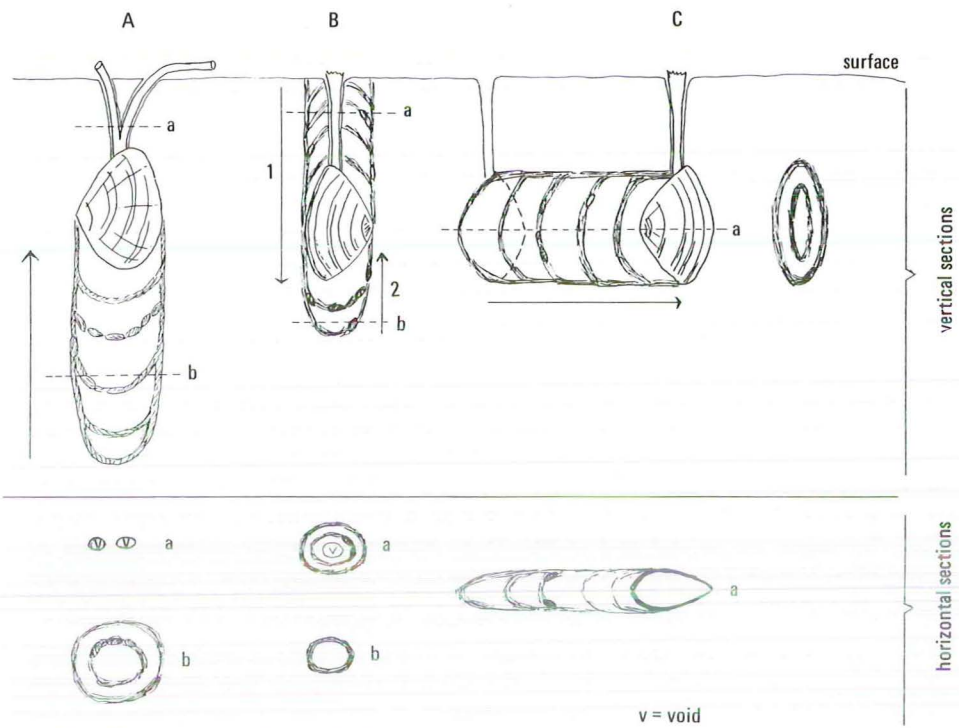


Fig. 33. Three varieties of striotubules and their genesis.



Fig. 34. Striotubule of variety A, produced by *Mya arenaria*, in which the difference in width of the tubule corresponds with a rotation about the long axis.



primarily the result of downward movement of the animal, though afterwards the animal has moved up a little. The animal may burrow down (i) because of erosion of the sediment, (ii) because it is growing or (iii) because it has migrated and retreated into the sediment in a new place. A striotubule caused by downward movement of the animal is characterized by a reverse striation around the syphonal channel to the surface. The reverse striation should not be confused with cutans due to infilling (see Section 4.3.2.3). The upper part of Figure 33 C shows a longitudinal section and a cross-section of a striotubule produced by horizontal movement of an animal. Horizontal movement may be necessary due to instability of the sediment or disturbance of the overlying soil material. In this case the striation is usually only weakly developed, as the direction of the movement is parallel to the lamination. Striae composed of excrements accentuate the presence of these striotubules. The cross-section given in vertical section in Figure 33 C is elongated because of the difference in width and length of the mollusc's valves e.g. in the case of *Scrobicularia plana*. Each species has its characteristic ratios. When the differences in width and length are small, nearly circular or circular cross-sections are formed. Horizontal striotubules were less common than vertical ones, but were not rare. Types A and B in Figure 33 have already been recorded by REINECK (1958), but the third has not previously been mentioned in the literature. The differences in length of the three dimensions of the valves are also reflected in phenomena visible in striotubules. During upward movement the animal may rotate on its long axis, thereby producing striae of different sizes. This phenomenon is clearly visible in Figure 34, which shows a striotubule produced by *Mya arenaria*. Thus changes in diameter of the striotubule are not only a result of the growth of a juvenile specimen, as REINECK (1958) suggested.

In the part of the burrow above the animals, in which the siphons reach to the surface, mud-zoocutans were often found. The zones around striotubules also showed pressure-affected zones, identical to those already described.

#### *Passage features*

In addition to channels and pedotubules a third type of zoogenic feature caused by the movement of animals was found. These features occurred in intertidal flat and salt-marsh deposits, where they were even more common than channels and pedotubules. The relevant features appeared in thin section as elongated, rather straight or curved bands running in all directions, and having no sharp external boundaries (see Figure 35). The internal fabric of these bands differed from the surrounding sediment in:

- (i) the way the particles were packed;
- (ii) the orientation of elongated particles more or less parallel to the longitudinal axis of the band;
- (iii) slight changes in grain size composition.

Furthermore, particularly in the central part of the bands, excrements that were oriented in the same direction as the elongated particles were often present. These excrements mostly consisted of fine particles. From the thin sections no relation could be established between the mud laminae present in the sediment and these excrements, and therefore it was concluded that the excrements had probably been produced by suspension-feeders, i.e. animals that ingest their food during high tide at the surface and withdraw into the sediment at ebb tide. Many animals of the intertidal zone do not live in one place for prolonged periods but move freely on the surface during high water and retreat into the sediment during ebb tide in order to be protected against dehydration and against predators such as birds. These animals move at random through the sediment. As the high tide occurs twice daily, they may move up and down twice each day too; this would explain why these bands were so abundant. After the



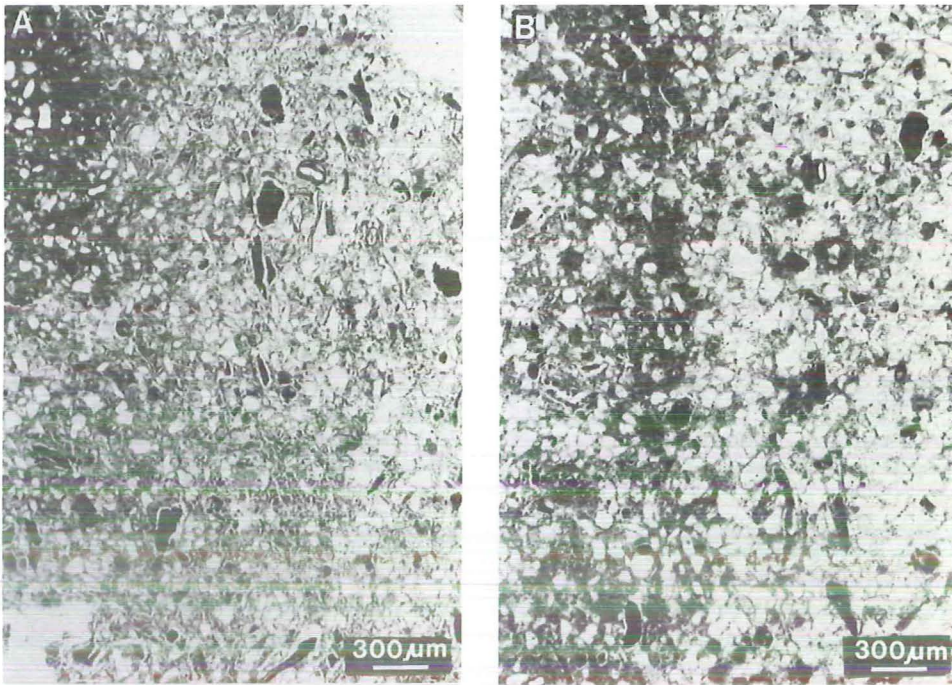


Fig. 35. Difference in external boundary of a passage feature and a pedotubule. Both phenomena have a diameter of 8 mm. A. diffuse boundary of a passage feature; elongated particles are oriented longways. B. sharp external boundary of a striotubule.

animal has passed, the sediment plastically refills the passage it leaves behind. This process was often observed in the field.

Passage features were only found in unripened soils, because there the animals find little resistance to burrow through the soil and the soil material easily deforms and infills behind them. As the burrowing animals encounter increasingly firm sediment, gradual transitions from these passage features to clearly defined faunal channels were observed. The first indication of such a transition is the appearance locally of small, vesicle-like voids, often elongated in the longitudinal axis of the passage bands. These voids gradually increase in size, until they occupy the centre of the passage and become fully-fledged channels. Transitions from passage bands to clearly identifiable channels were only found in the muddy sediments in the higher salt basins.

The passage features were found in sandy as well as in muddy sediments, regardless of laminations. They were most easily detected in sandy, laminated sediment.

In addition to excrements composed of fine particles, excrements composed of clay-sized material, or consisting of a core of coarse grains enclosed by a thin mud layer were also found. All the main shapes of excrements distinguished earlier occurred, but ellipsoids and bacillo-cylinders dominated, showing that the excrements must have been produced by several species. These excrements were not embedded as a result of the rather drastic conditions as supposed by BAL (1973), but were embedded by the refilling soil material in the place where they were produced.

Several related distribution patterns of excrements were identified in the passage features.

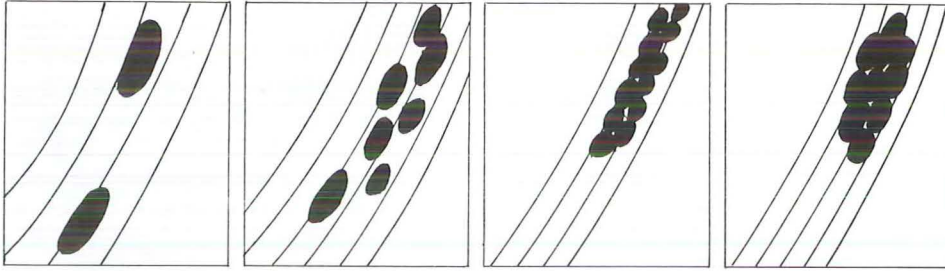


Fig. 36. Related distribution patterns of excrements in passage features (longitudinal sections).

They are schematically shown in Figure 36.

No branching passage features were found. This strengthens the opinion that only one animal is responsible for each passage track and that the passages are used only once. Often the passage features crossed each other. Complex patterns with different packings, reorientations, varying grain size compositions and distributions resulted and were common. In these complex patterns excrements of different shapes, compositions and sizes were often found (see Figure 37). They were often so abundant in the sediment that the whole of the ground-mass was turbated.

No term exists in the literature to describe this significant pedological feature that is the most obvious result of faunal activity in the deposits of the intertidal zone. Therefore the term 'passage feature' is proposed. This is defined as follows:

A passage feature is a pedological feature consisting of soil material, that has a tubular external form, consists of only one single tube and has no distinct external boundary. These tubes are recognizable by differences in packing, orientation of elongated particles along the long axis of the tube; differences in composition and/or distribution of the grain sizes compared with the undisturbed sediment; and presence of excrements oriented in the same direction as the elongated particles.

Passage features are the result of the single passage of an animal in wet unconsolidated soil material in search of food or temporary protection.

The species in the intertidal zone responsible for the formation of passage features belong to the Vermes, Gastropods, Crustacea and perhaps some small juvenile Pelecypods.

The dimensions of passage features present in the intertidal zone varied from several millimetres to about 2 centimetre in diameter, and from several centimetres to more than 15 cm (the length of a thin section) in length.

One type of passage feature will be discussed in more detail because of its great abundance in the salt basins and its specific characteristics. This is the passage feature and transition to channels typically produced by the Gastropod *Hydrobia ulvae*. *Hydrobia ulvae* was mainly found in muddy sediments of the higher parts of the intertidal zone. In the high intertidal flat and transitional zone deposits its passage features occurred among those of other animals. However, in the muddy sediments of the salt marshes, particularly in the basins, *Hydrobias* produced almost all the passage features present, as they occurred in large numbers and were probably the only species producing passage features there. Densities of up to thousands of specimens per square metre were common. Holmes (1949) recorded a maximum abundance of 16000 per m<sup>2</sup> in *Zostera* beds near the mouth of the Exe Estuary (England). In the passage features of *Hydrobia ulvae* complete snails and the characteristic excrements, i.e. biconical cylin-



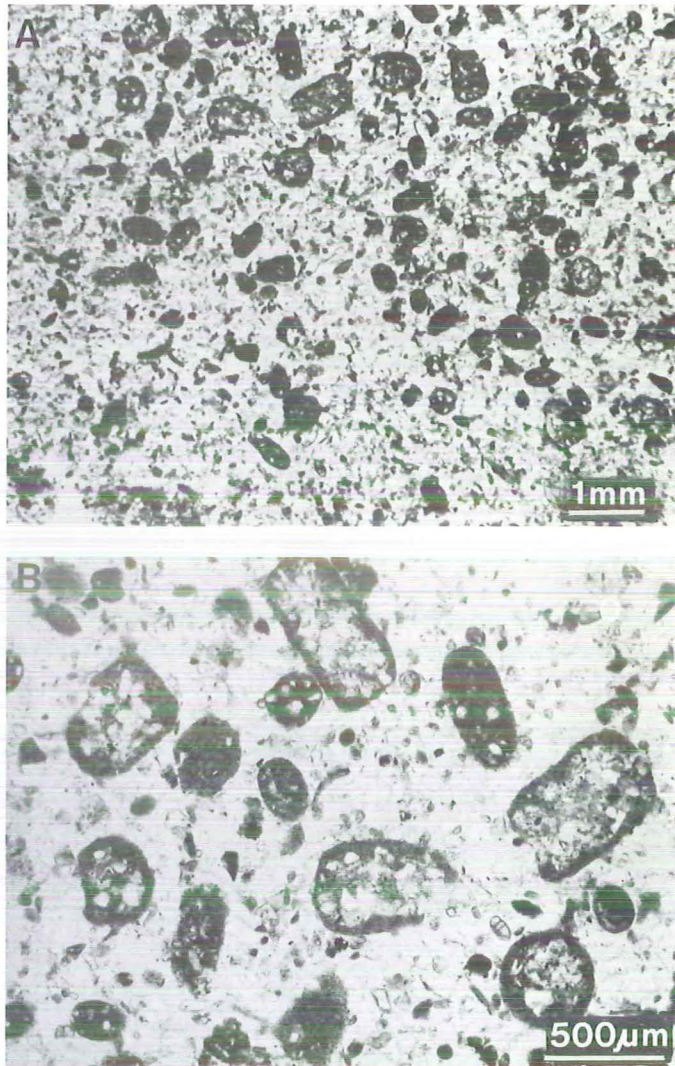


Fig. 37. Complex pattern due to crossing of many passage features. Different faunal species must have produced this complex pattern as several different shapes and sizes of excrements are present. A. general view. B. detail showing composition.

ders composed of clay-sized material, were found. Complete snails of *Hydrobia ulvae* were often observed in thin sections; the maximum number seen in one section was thirteen. Intact specimens present in passage features were usually oriented with their top upwards, indicating that the animals had been preserved in the sediment in their natural position. Although large numbers of *Hydrobias* were found, their excrements were only rarely found in passage features. This suggests that *Hydrobia* specimens excrete mainly during high tide. This assumption was confirmed by the observation that many excrements of *Hydrobia* were often present in the seawater flooding over the salt marshes at high tide, also mud laminae composed solely of



*Hydrobia* excrements, geogenetically deposited, were found in salt-marsh deposits.

Generally, *Hydrobias* move in the upper 5 cm of the sediment, though depths of more than 12 cm reached by living specimens were also observed. If sedimentation is continuous the animals congregate in the upper 5 cm, thus giving rise to thick layers showing passage features.

In the intertidal flat and transitional zone deposits only 'pure' passage features were present (no gradual transitions to faunal channels were observed). In the low salt marshes, mainly in the basins, but also in smaller natural levees where the most unripened soils with bulk densities below  $0.86 \text{ g/cm}^3$  occurred, only pure passage features made by *Hydrobia ulvae* were found in clay-rich material. Due to their great abundance and their way of life associated with the tide, *Hydrobia ulvae* may completely turbate the sediment. In Figure 38A an example is given. Sometimes in very unripened, clay-rich material the turbated matrix becomes cloudy. Partly infilled passage tracks were found with increasing frequency from the highest parts of the low salt marsh to the higher sedimentation levels. The first indication of this was the occurrence of small, spherical to elongated voids, 1-3 mm in diameter, in the central part of the passage track. These voids became longer, though still smaller than the original passage track (see Figure 38B). Passage features with central voids were so abundant that they often touched and crossed each other, and as a result the voids were often compressed, cut off, or connected. With depth these voids became smaller as a result of compaction. In this way a very typical fabric with many fine, irregular, smooth voids randomly oriented was formed (see Figure 38C). The path followed by *Hydrobia ulvae* passage features with or without small voids seemed to be unrelated to other visible phenomena. Occasionally they crossed dead roots (less often, living roots) and followed their hollow interiors. *Hydrobia* passage features were also found in association with root channels and damaged roots, fragments of which were embedded in the animal's passage track. In the high salt basins longer central voids occurred, often

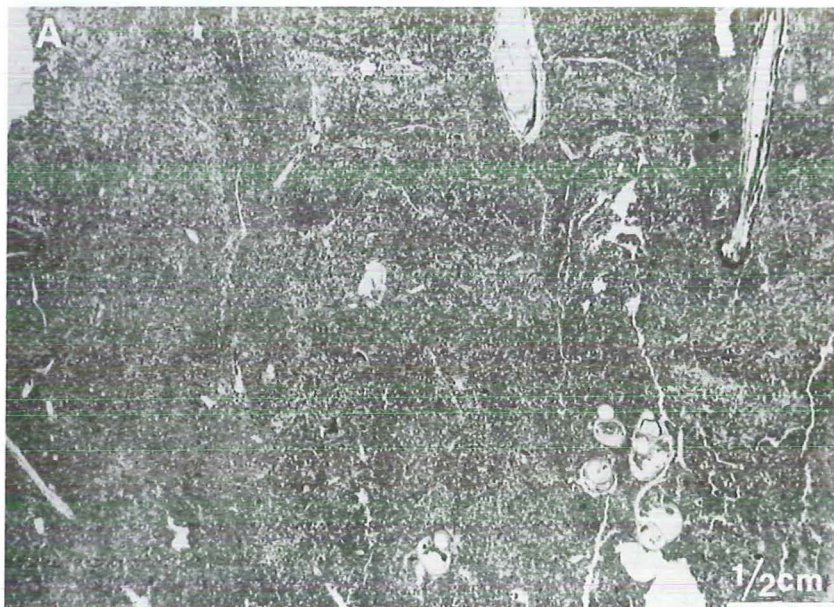


Fig. 38. Passage features produced by *Hydrobia ulvae* in salt basins. A. turbated sediment resulting from the intersection of many passage features. B. Recently formed central voids in passage features just below the surface. C. Resulting pattern of central voids in passage features deeper in the sediment.



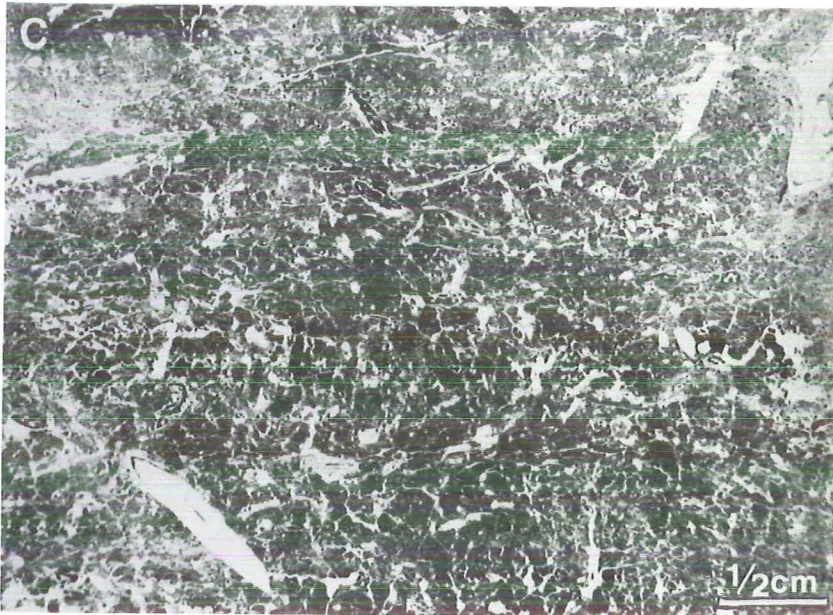


Fig. 38. *Continued.*

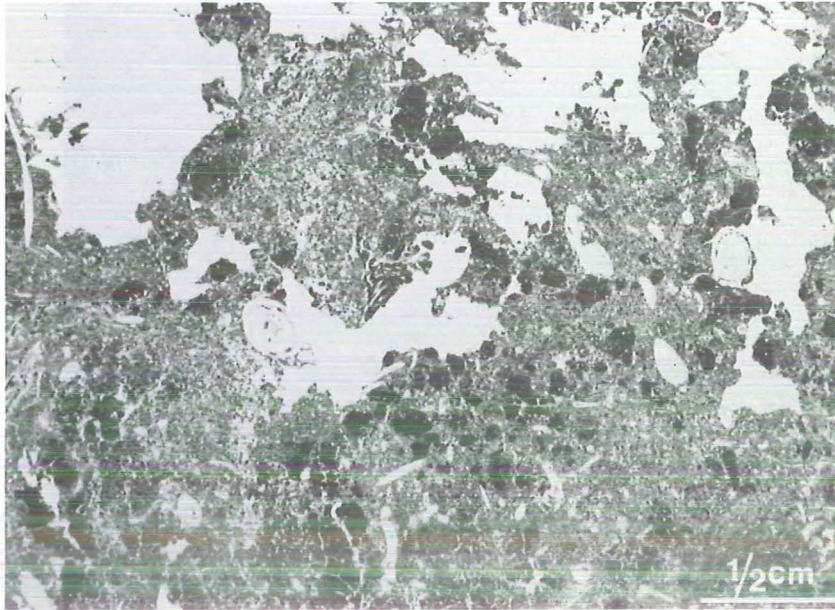


Fig. 39. Rounded fragments of a neoferran embedded in passage features produced by *Hydrobia ulvae*.

interlinked by intersecting passage features with voids. All transitions of passage features to faunal channels, including 'pure' passage features were found, but it was more common to find transitional passage features with larger central voids, and channels rather than 'pure' passage features. In the highest salt basins the activities of *Hydrobia ulvae* probably take place deeper below the surface. In these cases the animals probably enter the soil material via the walls of the polygon cracks, where the consistence of the soil material is weaker than in the superficial layers.

The central void systems of *Hydrobia ulvae* passage features could be connected with the atmosphere, either directly or via interconnected voids. This was demonstrated by the occurrence of neoferrans and (rarely) ferrans in the voids in the passage features, and by the discovery of shrinkage voids found associated with these central void systems. These indirect consequences of the faunal activities are dealt with in more detail in Sections 4.3.3 and 4.3.4. An example of this phenomenon, which occurred most commonly in high salt basins but occasionally also in middle-high salt basins, is presented in Figure 39. Fragments of neoferrans and/or ferrans that occurred adjacent to and in voids that were crossed or partly followed by *Hydrobia ulvae* were embedded there in the same way that root fragments were embedded in passage features.

#### 4.3.2.2 Influence of the vegetation

A short outline of the species, zonation and succession of the vegetation in the intertidal zone was given in Section 1.6, while in Section 2.3.2 the vegetation mapped in the areas studied in detail was discussed. This section deals with the part of the vegetation below the



surface. First some data about root systems, such as type, length, thickness and density, are given. Secondly the primary and secondary effects of roots on the soil material are discussed.

*Root systems*

The vegetation of the salt marshes mainly consists of herbaceous monocotyledons and dicotyledons, except for *Halimione portulacoides*, which is a shrub.

Monocotyledons and dicotyledons have basically different root systems. The primary root of the monocotyledon seedling is usually soon replaced by a number of secondary roots of similar length, thickness and distribution. These adventitious roots are branched and form a rather homogeneous system, often referred to as a fibrous system. Monocotyledon roots rarely have secondary growth. In monocotyledon roots the intercellular spaces that form hollow cylinders are often situated in the centre of the root, in the primary vascular structure.

The primary root of dicotyledons remains and develops into the main root which, together with a number of branching lateral roots, constitutes the root system. The main components of a dicotyledon undergo secondary growth. The roots of dicotyledons generally have intercellular spaces in the cortex, and the central vascular structure forms a rather solid cylinder (ESAU, 1960). In Figure 40 some different root systems are shown.

*Triglochin maritima* and all the graminiae recorded in the study area (of which *Spartina townsendii*, *Puccinellia maritima*, *Festuca rubra* and *Elytrigia pungens* are the most impor-

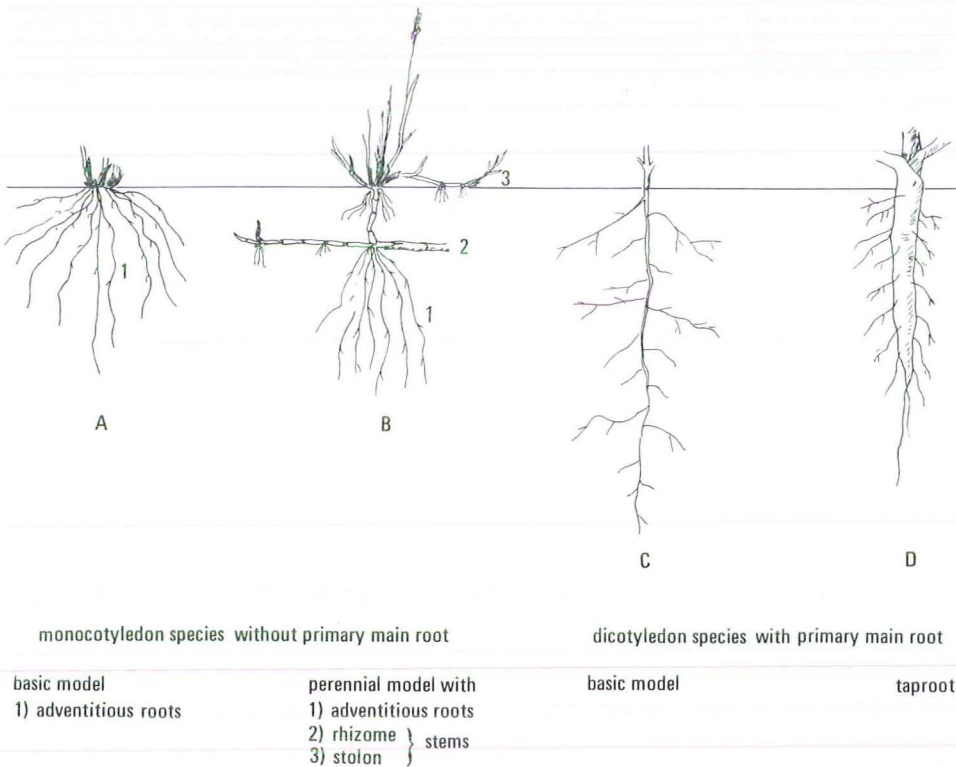


Fig. 40. Some different root systems.

tant), are monocotyledons. These species are perennials. Other species mentioned in Sections 1.6 and 2.3.2 belong to the dicotyledons. *Salicornia europaea* and *Suaeda maritima* are annuals, whereas *Aster tripolium* may be annual or biennial (see Map 4, Appendix 3). Given that the salt marshes were covered with dense vegetation, it was not surprising to find that the soil was intensively rooted. In the profile descriptions the depths of the roots were indicated, as well as the content of roots present, divided into size classes and abundance following the F.A.O. *Guidelines for Soil Profile Description* (1965). Usually, roots were present right up to the surface. Where *Spartina townsendii* grew the upper 6-8 cm of the sediment was disturbed by shoots sprouting upwards from the rhizomes. The root systems of *Puccinellia maritima*, *Limonium vulgare*, *Festuca rubra*, *Salicornia europaea* and *Suaeda maritima* usually remained within the upper 50 cm of the soil. The adventitious roots of *Puccinellia maritima* formed dense clusters, as they develop from stolons radiating on the surface forming domeshaped hummocks (see Section 2.3.2). The root systems of *Halimione portulacoides*, *Spartina townsendii* and *Aster tripolium* penetrated further into the sediment, reaching depths to about 100 cm. Roots from the last two species were even found extending some 25 cm into sandy intertidal flat deposits below the salt-marsh sediments. This means that channels present in sands belonging to intertidal flat deposits need not all have been made by animals. Roots of *Halimione portulacoides* did not reach down to the intertidal flat deposits as this species grew on higher levels; the natural levees.

Often, more roots were present than could be accounted for by the existing vegetation. Many of these roots represented the remains of root systems of former plants, often annuals such as *Salicornia europaea*. The thickness of the roots was rather variable. As mentioned above, the diameters of monocotyledon roots are more uniform than those of dicotyledons. The largest root diameters (30 mm) were measured in the upper part of the taproots of *Aster tripolium*. The roots of *Spartina townsendii*, which were often between 8-15 mm in diameter, were also important, as they usually occurred in large numbers and maintained the same order of thickness over relatively great distances, due to their monocotyledon root system.

#### *Effects of roots and stems on the soil material*

The parts of the vegetation present below the surface, which from now on will be referred to as roots, disturbed the continuity of the sediment and the tidal lamination. They formed systems of branching channels of different diameters with circular cross-sections and smooth walls. As explained in Sections 1.6 and 2.3.2, the different zonations in the vegetation mapped in the study area consist of relatively few species. As a result, in the thin sections it was unusually to find roots from more than two different species.

The differences between root systems of monocotyledons or dicotyledons usually showed up clearly in thin sections. The monocotyledon roots were more evenly distributed and varied less in diameter than those of dicotyledons. The internal organization of monocotyledon roots of the same species was very similar. Monocotyledon roots, e.g. those of *Spartina townsendii* and *Elytrigia pungens*, often had a central metaxylem vessel, i.e. a central hollow tube. In contrast, dicotyledon roots, were unevenly distributed, varied greatly in diameter and had a different internal organization. The root systems all showed a marked tendency to develop vertically rather than horizontally. In thin sections, changes in the direction of roots caused by lamination were found only rarely. The high moisture contents and loose initial packing of the soil material (see Section 3.6) were probably responsible for this. If a change in direction occurred, it was because other roots formed an obstacle.

The pressure exerted by the roots on the soil material to form channels produced a zone of compacted groundmass surrounding each root, in which elongated particles were oriented



more or less parallel to the channel and the sedimentary lamination was deflected in the direction of the growing root tip, i.e. downward. These phenomena are identical to those of the pressure-affected zones around faunal channels (see Section 4.3.2.1). The pressure-affected zones produced by roots could be distinguished from those produced by fauna by the direction in which the laminae were bent. Pressure-affected zones around root channels were found in all the vegetated areas in the intertidal zone, even in ripened soils, for example in the high natural levees. Thus the formation of pressure-affected zones depends on loose initial packing of the sediment as well as on weak consistence of the soil material.

When roots were very abundant in the soil, the pressure they exerted affected much of the soil material, resulting in a soil fabric with a striated appearance caused by the criss-crossing of the pressure-affected zones. The oriented elements were mostly elongated carbonates, present in the fine material. Oriented clay domains were not observed.

Roots form channels by exerting pressure on the surrounding soil material, and therefore, living roots must initially completely fill these channels. Subsequently, small spaces may develop between the larger vertical roots and their channel walls. These spaces allow water, soil material and air to penetrate the soil. As a result, thin zones of infilled soil material were sometimes found surrounding some living roots; also neoferrans occurred in the channel walls (see also Sections 4.3.3 and 4.3.4).

Root channels are very stable and may retain their form and associated characteristics long after the root has died. Only local disturbances produced by a burrowing animal or other roots cutting through the old root channels were found. Animal burrows and other roots were also found following parts of previous root channels. Animals probably even burrow along or across channels containing living roots.

Dead vegetative remains decompose very slowly and their remains stay visible for a long time. A clear example is given by the presence of buried thallus fibres of the green alga *Enteromorpha prolifera radiata*. These thallus fibres occurred as 'roots' in the upper 4 cm of high intertidal flat deposits. In Figure 41 recent thallus fibres are shown. In spite of their simple in-

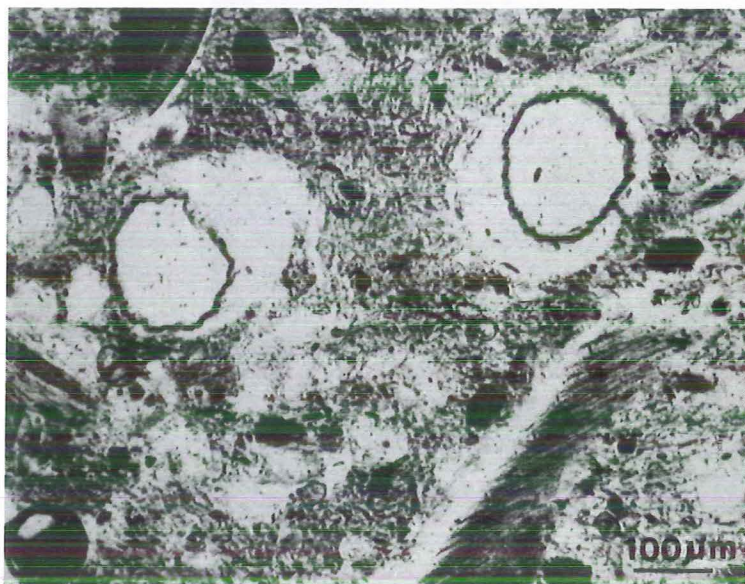


Fig. 41. Recent thallus fibres of the green alga *Enteromorpha prolifera radiata*.

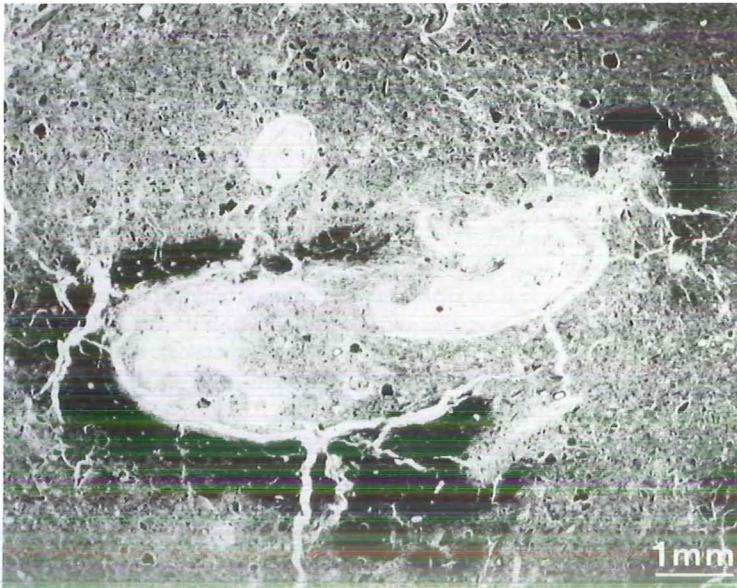


Fig. 42. Complex feature. Channel with neoferran, which has been disturbed by the passage of an animal. In the partly infilled channel a new root is visible.

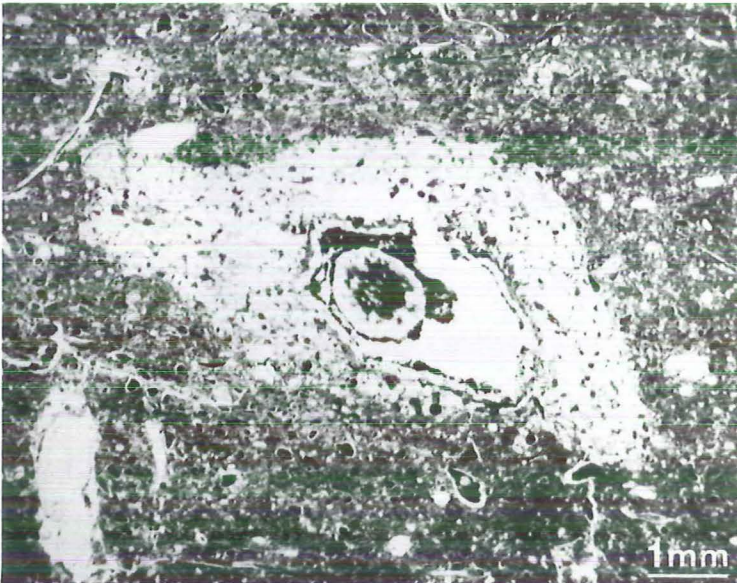


Fig. 43. Complex feature. In a channel infilled with coarse particles a root has grown, which is now a misfit and has been partly pyritized. Between the root and the coarse particles of the infilling, thin zones of fine material can be found locally.



ternal structure and the sandy composition of the surrounding material, these thallus fibres were observed buried *in situ* under low salt-marsh deposits.

Root remnants were often damaged more as a result of mastication and/or ingestion by animals. These fragmented parts were not necessarily present in the original root channel, but were found in faunal channels or, most often, embedded in passage features.

Dead roots shrink away from the walls of their channels, thereby increasing the access for water, soil material or air. Part of the channels of dead roots becomes wholly or partly infilled with soil material in which root remnants may be embedded. Infilled soil material was not only found in the gap between the root and the channel wall but also in large metaxylem vessels, especially in the central hollow cylinders of monocotyledons such as *Spartina townsendii*. The soil material present in these spaces consisted of fine particles as well as of coarse particles and mixtures. It was found to have the same composition as the surrounding soil material, or to be coarser or finer grained. The granular composition of the infilling was generally rather uniform. Differences in granular composition were only observed in a few cases. These infilling phenomena are discussed further in Section 4.3.3.

In channels (regardless of whether they were infilled with soil material) that lay near or in the zones permanently saturated with water, a reducing environment was found. As a consequence, root remains present in these zones often contained large amounts of pyrite in the form of spheroidal framboids and pseudomorphs (see Sections 3.10 and 4.3.4). These pyrite accumulations often extended beyond the root remnants even reaching into the infilling soil material or into the walls of the channels, forming pyritans and/or neopyritans. In the zone at or just above the zones permanently saturated with water, an oxidational environment was present regardless whether or not infilled soil material was present. Here accumulations of manganese were found in the root remnants in the form of pseudomorphs, and distinct neoferrans occurred in the channel walls, sometimes associated with thin ferrans. Neoferrans and ferrans were not always present together: neoferrans were much commoner than ferrans in floral channels<sup>1)</sup>. The phenomena resulting from reductional or oxidational environments are discussed further in Section 4.3.4.

In the thin sections complex features associated with floral channels were found. Channels with distinct neoferrans were often locally disturbed by the passage of an animal. In the passage feature formed in the former floral channel a new smaller root may grow, as a 'misfit' (see Figure 42). Passage features were often observed to follow or cross infilled or open floral channels containing root fragments. In several cases the presence of new roots in infilled former floral channels was observed: an example is given in Figure 43: Between the infilling of coarse grains and the new root, a thin discontinuous zone of fine material probably infilled along the living root, is found. The dead secondary root has been partly pyritized. Roots were rarely found in faunal channels because most of the faunal activity in the salt marshes results in the formation of passage features.

### 4.3.3 Changes in the sediment caused by physical processes

The features visible in thin sections as expressions of physical processes can be divided into three groups: voids caused by water loss in the superficial layers of the sediment; features resulting from compaction by the weight of superimposed younger sediments; and features caused by downward transport of soil material in voids.

<sup>1)</sup> As stem channels e.g. of rhizomes, were also present in the soil, the term 'floral channel' is used here instead of 'root channel'.

### *Shrinkage voids*

The first group includes all the cracks organized in the characteristic polygon pattern. This pattern was not always fully developed; bifurcations and trifurcations also occurred. The width and depth of the cracks and the diameters of the polygons varied considerably. The cracks were of the ortho type (BREWER, 1964), i.e. the morphology of their walls was due to the unaltered, normal, random packing of the soil constituents. Polygon patterns were found in intertidal flats, natural levees and high salt basins, e.g. in materials of different granular compositions.

In the sandy material of the intertidal flats, large polygons of 20-100 cm in diameter were found. These polygons have already been described in Section 1.5. Figure 44 shows a part of a thin section of sediment sampled in the intertidal flat, showing a shrinkage crack. In this photo the orthic morphology of the crack is evident. The two small, rather circular holes were made by juvenile shore crabs. In the steep innersides of natural levees, large shrinkage cracks

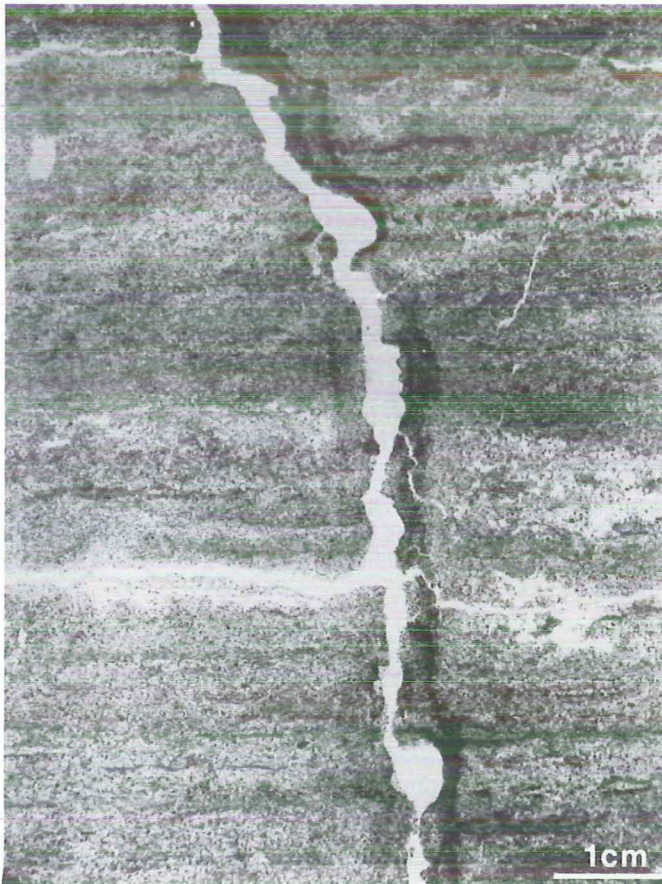


Fig. 44. Vertical cross-section of sediment in the intertidal flat showing a part of a shrinkage crack of a polygon with compound neomangan-neoferrans and two crab holes made by juvenile specimens.



were also present. Often they were not so well formed, because root systems had impeded their development. These shrinkage cracks were only interconnected to a limited degree, therefore single, bifurcated and trifurcated cracks were common. The initial polygons were rather large, i.e. 20-50 cm in diameter. As in the intertidal flat, these shrinkage cracks developed in sandy material. A third type of shrinkage cracks was found in the salt basins, where they usually formed complete polygons. The diameter of these polygons was usually less than 20 cm and the cracks did not reach more than 8 cm in the sediment. These small polygons were never found in salt basins that had a dense cover of *Spartina townsendii*.

As well as the typical polygon patterns, a very complicated void pattern, also caused by shrinkage, was found in the zone above the G horizon in the high salt marshes. This pattern was characterized by very irregular partly interconnected orthovughs, in which deformed channel-remnants were sometimes visible. These partly connected orthovughs were probably formed after small shrinkage cracks developed and enlarged from existing channels. There was generally a close relation between the width of the original channels and the size of the orthovughs: wider channels resulted in larger orthovughs. These orthovughs were most pronounced in fine-grained sediment. In this study these voids are called 'vughs'.

Shrinkage cracks are formed as the result of water loss which causes a rise of the capillary potentials. The particles that are able to move freely in relation to each other are drawn closer together and produce tensile stresses in the sediment. At a given point these stresses become so high that they can no longer be absorbed, and shrinkage cracks are formed. In the intertidal zone, the loss of water that caused the formation of shrinkage cracks is largely due to direct evaporation from the surface. Transpiration of the vegetation probably plays a minor role only in the high salt marshes. The presence of shrinkage cracks in sandy material proves that pore spaces decrease and bulk densities must increase, even in sands.

### Compaction

The second group of phenomena results from compaction of the sediment with depth. This is not a purely pedological process; compression is a phase in the course of consolidation and diagenesis of rocks. However, the first stages in consolidation which take place in recently deposited wet sediments can also be a part of the physical ripening of the soil. As a result of compression, the volume of the voids decreases, solid particles become more densely packed and the surplus water is drained off towards the creeks by faunal and floral channels and water-bearing layers. The initial packing of the sediment is very loose; this is apparent from the bulk densities given in Section 3.5. The effects of compaction on the arrangement of the soil particles are comparable with those in the pressure-affected zones (see Section 4.3.2 and Figure 30). In mud layers and several other mud accumulations the content of small grains (2-30  $\mu\text{m}$  in diameter) embedded in a groundmass of clay-sized material (see Section 4.3.1) increased as a result of compaction of the clay-sized material. These compactions were also revealed by changes in related distribution patterns, in which the quantity of small grains seemed to increase due to compaction of the clay-sized part, giving this material a porphyric fabric (STOOPS & JONGERIUS, 1975) with increasing depth. As result of compaction, voids became smaller. This feature was clearly demonstrated in the changes in diameter with depth of the partly interconnected small voids in the passage features of *Hydrobia ulvae* (see Section 4.3.2.1 and Figure 38C). Compaction also fractured snails present in the sediment. This type of compaction can be classified as stratipedicompaction (JONGERIUS, 1970). However, Jongerius does not mention this type of stratipedicompaction that is due to continued sedimentation from water.

### *Downward transport of soil material in voids*

In the intertidal zone several types of voids occurred. In the previous sections of this Chapter, packing voids, voids of biological origin (faunal channels and chambers, voids in passage features and channels formed by the vegetation), planar orthovoids (shrinkage cracks) and vughs were discussed. Yet another type of void remains to be discussed: the vesicle.

Vesicles were found in sandy sediments in the intertidal flat as well as in the walls of the creeks in the salt marshes. They varied from 0.5-4 mm in diameter and they were spherical or oblate (see Figure 45). In sandy layers the vesicles often extended over several metres and attained a maximum thickness of about 20-30 cm. They gave the sand a spongy appearance. According to REINECK & SINGH (1973), vesicles are produced by entrapped air bubbles. During rapid sedimentation from swash on slopes many air bubbles can be entrapped within the sandy sediment when wave action is reduced. If this theory is true, these vesicles are also the result of a physical process.

The occurrence and specific characteristics of infilling soil material in the various voids are set out in Table 12. Infillings were absent from vesicles and the small voids in passage features, because these voids did not form a continuous system. With the exception of packing voids, all voids with distinct infilling were oriented vertically and generally were directly linked with the surface.

Free grain cutans were rather rare. The fine particles of disturbed excrements or thin mud laminae in dominantly sandy material were sometimes transported downward over short distances. This material wholly or partly covered the surfaces of coarse grains, and was also occasionally present as 'bridges' between these grains.

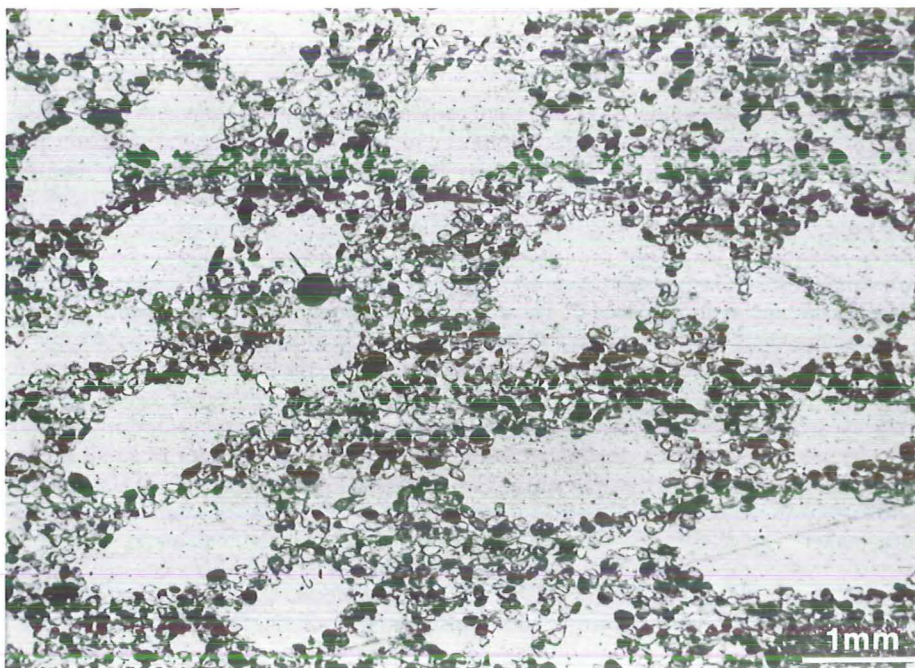


Fig. 45. Vesicles in sandy sediment.



Table 12. Occurrence and specific characteristics of soil material found in voids as a result of physical processes.

Origin of void	Group	Occurrence of infilling	Frequency	Type complete infilling		Internal fabric		Composition			Internal fabric	
				cutan	(x)	simple	compound	fine particles	coarse particles	mixtures	homogeneous	aggregates
Physical	packing voids	x	(+)	x		x		x			x	
	planar orthovoids	x	++	x	(x)		x	x	x		x	(x)
	vughs	x	+	x	x	x	(x)	x	x	x	(x)	x
	vesicles	-	-	-	-	-	-	-	-	-	-	-
Biological	faunal channels	x	++	x	x	x	(x)	x	x	x	x	x
	central voids in passage features	-	-	-	-	-	-	-	-	-	-	-
	root, stem channels	x	++	x	x	x	(x)	x	x	x	x	(x)

occurrence: x = present  
 - = absent  
 frequency : (+) = rare  
 + = few  
 ++ = common  
 - = absent

In all other voids distinct cutans or complete infillings of soil material were sometimes present. Cutans of soil material can be classified as matrans (BAL, 1973), i.e. a cutan whose composition is identical or almost identical with the composition of the s-matrix. In sedimentary parent material, where the composition of the s-matrix is not homogeneous this term is not so useful, and therefore not used in this study. Complete infillings of soil material in channels are identical with pedotubules (BREWER, 1964).

### *Cutans*

Cutans occurred in planar orthovoids, vughs and channels, and were simple or compound. In planar orthovoids they were usually compound, in the vughs and channels the cutans were usually simple. The compound cutans in the planar orthovoids were difficult to recognize as they were often disturbed by passage features and/or had neocutans (see Section 4.3.4) developed in them. The diagnostic factor was the absence of tidal lamination. Cutans were not necessarily present on both sides of the plane; often they had only developed on one side. The cutans were mostly composed of coarse grains. They were not extensive and the thickness of the individual cutans was less than 3 mm. As the cutans had a limited extent, they often overlapped each other partly or wholly, while other parts of the plane were bare or lined with one cutan. As a result the cracks varied greatly in diameter and had only a weak accommodation of their faces. Sometimes a thin, very restricted cutan of fine particles was found. These mud cutans were probably formed from excrements that had been remodelled by swelling or the passage of animals present in the cracks (some Vermes, Gastropods and juvenile shore crabs). Where parts of the cutans had flaked off, fragments were found deeper in the cracks, often together with single excrements.

The planar orthovoids in the natural levees and high salt basins did not have such compound coarse-grained cutans. Their cutans were often simple and finer grained, though still of limited extent. The vughs and channels also generally had simple, fine-grained cutans. In root channels along existing roots fine-grained soil material was also found as cutans.

### *Infillings*

Complete infillings of soil material were found in planar orthovoids, vughs, channels and chambers. Two different types of infillings were distinguished. The first type was characterized by an undifferentiated internal fabric, whereas in the second type the constituent particles were organized into distinct aggregates. The first group of infillings was found throughout the intertidal zone, but especially below Mean High Tide level, and was the more common. The second group was largely restricted to soils with rather sandy granular compositions in the high salt marsh, and occurred above the G horizon.

Complete infillings of the first type were most often found in channels. These infillings were composed of fine particles as well as of coarse particles and mixtures. The granular composition of the infilling was sometimes identical with that of the surrounding soil material, but it could also be coarser or finer grained. The pedotubules (infilled channels) were mainly isotubules (BREWER, 1964). Channels completely filled with coarse grains, which occurred mainly in the intertidal flats, could be classified as granotubules (BREWER, 1964), but in addition to the coarse grains they also contained many carbonate grains, and some glauconite and peat grains. In the salt marshes the infillings were usually finer-grained. There the infilled material formed rather homogeneous mixtures of coarse and fine particles with a porphyric related distribution pattern (STOOPS & JONGERIUS, 1975). In infilled floral chan-



nels, remnants of roots and stems were occasionally present. When open vessels occurred in the remnants, as, for example, in monocotyledon roots, they were also infilled with soil material.

The second type of infilling was usually found in channels and vughs. Infilled channels were identical to the aggotubules of BREWER (1964).

Both the cutans and the two types of complete infillings described resulted from gravitational transport of soil material in voids. This transport can take place under wet or dry conditions; soil transport under wet conditions results in an undifferentiated internal fabric, whereas soil transport under dry conditions results in a soil fabric that is composed of distinct aggregates. If the soil material is transported as a wet mass, it flows into the voids plastically, forming cutans as well as complete infillings. These cutans and complete homogeneous infillings were generally found in voids oriented vertically and open to the surface, therefore most of the transported soil material must have been derived from the surface.

In the intertidal flat a large part of the bed load is transported in ripples during high tide. Material from a sand ripple can flow into open voids, whether they are channels or shrinkage cracks. Infillings of coarse grains in faunal channels were fairly common. Small amounts of sand that had entered the channels were often plastered along the walls as zoocutans by the animal (see Section 4.3.2.1). Larger amounts of sand accumulated from a number of inflows, and occasionally completely filled channels. A combination of one or more zoocutans and an infilled central part with coarse grains was frequently found, especially in the former siphonal channels of molluscs (see Section 4.3.2.1, *Striotubules*). In the shrinkage cracks the sandy material of the ripples must flow down the wall closest to the direction from which the bed load is derived. This would only be possible when the cracks have a distinct opening at the surface, and this only occurs when evaporation is high. This theory explains: (i) the limited, sometimes compound, character of these cutans, (ii) the presence of cutans on one side of the plane only, and (iii) the coarse composition of the infilling. The hypothesis that cutans are only spasmodically formed is supported by the fact that more than one neocutan (see Section 4.3.4) can occur in the cutans. These cutans, which only occur in shrinkage cracks, can be referred to as inflow cutans. The formation of inflow cutans is a physical process restricted to intertidal flats.

Bed-load transport is an unusual phenomenon in the salt marshes. Here, especially in the basins, the very wet superficial layer is involved; it may move towards the lowest part in the microrelief and there enter open voids. This type of movement is thought to take place during high tide as well as during ebb tide, when surplus water drains away. In a slowly moving mass of sediment and water the granular composition is not always constant, and this would explain why the infillings showed slight variations in granular composition, in which fine material dominated. The locally higher concentrations of coarse particles in the porphyric internal fabric were largely due to the addition of material derived from a sandy storm-tide lamina. This wet infilling was almost entirely restricted to floral channels, because faunal channels were rare in the salt basins (see Section 4.3.2.1). Cutans were found when roots were still present in the channels; otherwise the channels were completely infilled. The infilling generally took place in a very restricted number of flows.

The second type of gravitational transport in voids was that of the displacement of soil material as aggregates of firmer material. The voids partly or completely filled with these aggregates need not be open to the surface. The aggregates are formed in the upper layers of sandy sediment in the high salt marsh when channel walls dry out and shrink and the loosened parts fall down into the voids. This drying of the sediment is most pronounced near the surface in high natural levees.

#### 4.3.4 Changes in the sediment caused by chemical processes

In thin sections distinct phenomena resulting from chemical processes were observed. These phenomena are: presence of distinct amounts of pyrite, accumulations of ferric iron, manganese and carbonate, and decrease of carbonate. All these phenomena are mainly related to redox reactions. The formation of pyrite and accumulations of carbonate were a result of reduction reactions in the sediment. Oxidation reactions are wholly responsible for the precipitation of ferric iron and of manganese, and partly responsible for the dissolution of carbonates. In this Section these phenomena will be discussed under the headings 'Phenomena due to reduction' and 'Phenomena due to oxidation'. As the processes involved have already been discussed in Sections 3.9 and 3.10 they will be referred to only briefly here.

##### Phenomena due to reduction

###### *Pyrite*

Most iron sulphides were present as framboidal pyrite. This pyrite is composed of microlitic\* pyrite crystals, called framboids (see among others PONS, 1964; BERNER, 1971). In transmitted light pyrite is absolutely black; in incident light the microlites are clearly visible. Framboidal pyrite was generally found as spherical aggregates. Some of these spherical aggregates had protuberances. These protuberances were usually smaller pyrite spheres joined to a main sphere. From now on this type of framboidal pyrite will be referred to as amoeboidal pyrite\* (see Figure 46). Framboidal pyrite was also found as a substitution substance in organic matter, preserving the original structure (see Figure 46). From now on this type of pyrite will be referred to as pyrite pseudomorphs\*. Cutans and neocutans of framboidal pyrite

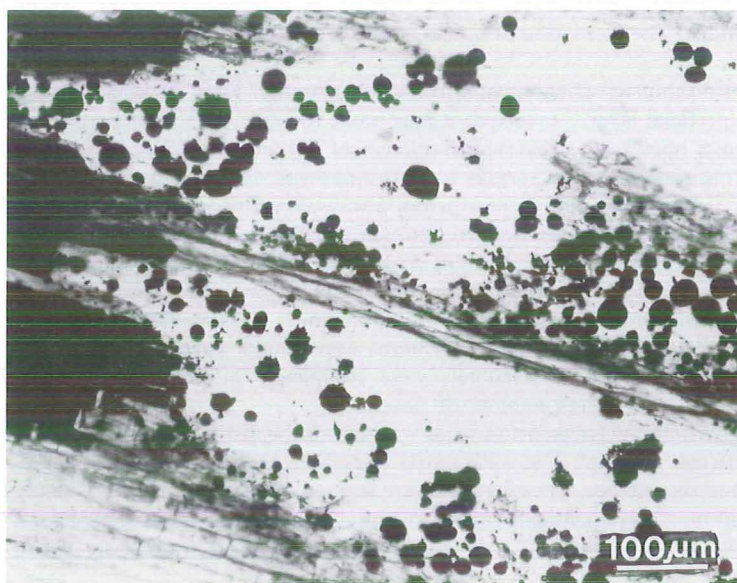


Fig. 46. Pyrite in a former root. Pyrite pseudomorphs on the left of the photo and amoeboidal pyrite and some spheres in the middle and to the right.



(pyritans and neopyritans respectively) also occurred associated with roots. The final type of pyrite that was present was idiomorphic, most probably cubic.

The sizes of spherical framboidal pyrites varied from 1-2  $\mu\text{m}$  (barely detectable) to 180  $\mu\text{m}$  in diameter. They were always found associated with organic matter. Freshly deposited sediment contains some pyrite spheres because pyrites occur in mudflakes, associated with organic matter and in peat and detritus grains. This pyrite generally had diameters smaller than 25  $\mu\text{m}$  and is termed 'primary pyrite' by PONS (1964). In the sediment studied the amounts as well as the diameters of spherical pyrite were often much larger, therefore neo-formation of pyrite must have taken place. Generally clusters of spherical pyrites were found. These occurred in organic matter such as peat, detritus, algae, diatoms, snails, shells and roots, which were sometimes completely filled with pyrite spheres; and in clay-rich sediments where much fine-grained organic matter was present (see Section 3.3). The largest amounts of pyrite were found in clay-rich vegetated sediments, because these sediments contained the most organic matter. The diameters of the spherical pyrite bodies were much larger than those recorded by PONS (1964) and MIEDEMA *et al.*, (1974). Pons distinguished four classes: less than 2  $\mu\text{m}$ ; 2-7  $\mu\text{m}$ ; 7-15  $\mu\text{m}$ , and larger than 15  $\mu\text{m}$ . MIEDEMA *et al.* (1974) recorded sizes up to 50  $\mu\text{m}$ . In thin sections taken in the higher salt basins, spherical pyrites up to 80-120  $\mu\text{m}$  were not unusual. These larger sizes were probably the result of the systematic sampling in the salt basins.

When the quantity of spherical pyrite present was higher than the original quantity in the sediment, amoeboidal pyrite was often present too. The sizes of amoeboidal pyrite bodies generally varied between 20-80  $\mu\text{m}$ . These pyrites were found in root remains and in clay-rich sediment in the reduced zone, and most probably represent a growing phase of spheres.

Pseudomorphs of pyrite were regularly present in the zones where the quantities of pyrite were greater than the original geogenetic amount. Pyrite pseudomorphs were mostly restricted to peat and detritus grains and root remnants. Many pyrite pseudomorphs of completely pyritized peat and detritus grains were found throughout the zone of pyrite neo-formation. Pyrite pseudomorphs of roots usually occurred deeper in the reduced horizon of clay-rich vegetated sediments. The root remnants were rarely completely pyritized pseudomorphs; alternation with tissues filled with spherical pyrites was common.

Neopyritans and pyritans were associated with the pyritization of roots. Around a pyritized root pyritans may have formed, which extended into the soil matrix to form a neopyritan when the root was near to the channel wall. If the root touched the channel wall, neopyritans were often formed directly. Idiomorphic pyrite was very rare, had diameters less than 25  $\mu\text{m}$  and was only found locally in high salt basins.

Generally the pyrite remained where it was formed or deposited. Local translocations were mainly due to faunal activity.

### *Carbonate*

Freshly deposited sediment was rich in carbonate. Many fine particles only a few micrometres across occurred randomly distributed in mudflakes and therefore also in mud laminae. These particles can be referred to as a dense calcic basic fabric (MULDERS, 1969; BAL, 1975). Among the fine mineral grains present in the fine fraction (less than 30  $\mu\text{m}$ ) and also among the grains in the coarse fraction (larger than 30  $\mu\text{m}$ ) many randomly distributed carbonate grains occurred. The carbonate grains were composed of numerous microlites that either had a rather homogeneous appearance or had a laminar structure produced by the rounded-off shell and snail fragments. Intact snails and shells and large fragments of broken snails and shells were present, sometimes building up complete laminae. Individual snails and shells were also found mainly in their original position in tubules and passage features; sometimes they

had been fractured due to compaction of the sediment (see Section 4.3.3).

Single idiomorphic carbonate crystals with a rhombohedral-like habit were observed locally in the intertidal zone. These idiomorphic crystals were usually complete and varied in size between 40-60  $\mu\text{m}$ , but individual crystals up to 105  $\mu\text{m}$  were also found (see Figure 47). These idiomorphic crystals were embedded in the fine fraction (usually near voids), and also among coarse grains. As the idiomorphic carbonate crystals were usually intact and also formed rather large units in the surrounding matrix, they must have been formed *in situ* after deposition of the sediment. BREWER (1964) called such crystals 'intercalary'.

Besides these idiomorphic carbonate crystals, calcitans, neocalcitans and quascalcitans also occurred, restricted to the intertidal flats. In table 13 a survey of these carbonate accumulations is given. Figure 48 shows a channel neocalcan and a SEM-EDXRA point analysis in one of these carbonate accumulations. As the analysis indicates, these carbonates are calcium carbonates. The carbonate accumulations were mainly found on or near the walls of the cracks of large polygons. They were thickest in the coarsest granular compositions and were often interrupted or disturbed by faunal activity. In the cracks the accumulations were not symmetrically developed on both sides. In channels near the shrinkage cracks, carbonate accumulations only occurred on the side away from the crack. In zones of carbonate accumulations, calcified excrements were also found.

The new formations of calcium carbonate must have been formed by precipitation from an oversaturated solution. With reduction, bicarbonate ions are formed (see Section 3.10). Due to local evaporation the calcium carbonate precipitates from the soil solution. This occurs during ebb tides. When the voids are larger or nearer to the surface, quascalcitans are formed. When the evaporation is less, neocalcitans or even calcitans may be formed. When the evaporation is too low no carbonate precipitation takes place. In coarser-grained material the capillary supply of soil solution is larger and greater accumulations can develop. In the shrinkage cracks of the polygons in the high intertidal flat covered with the macroscopic green algae *Enteromorpha prolifera*, no accumulations of newly formed calcium carbonate were observed; this was because the vegetation hindered evaporation too much. The local, single idiomorphic carbonate crystals must have been formed in the same way.

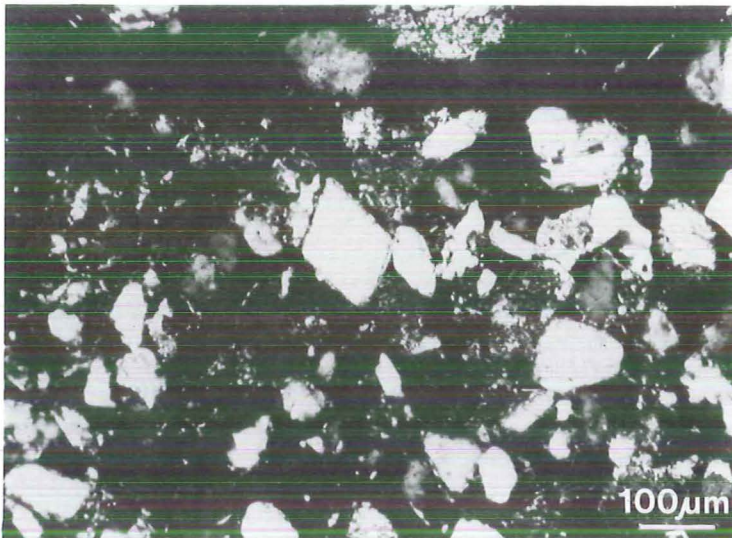


Fig. 47. Idiomorphic carbonate crystal.



Table 13. Post-depositional carbonate accumulations.

Zone	Feature	Internal fabric	Thickness in $\mu\text{m}$	Quantity	Depth in cm	Remarks
Low intertidal flat	quasicalcitan 1-2 mm from void	fine crystic	120-160	patchy	4-11	} partly associated with a quasiferran
	neocalcitan	fine crystic	80-120	nearly continuous one side	4- 5	
	calcitan	fine crystic	30- 60	patchy	4- 5	
High intertidal flat	quasicalcitan 1-2 mm from void	fine crystic	120-250	broken	3-11	} 1) partly associated with a quasiferran 2) calcified excrements present
	neocalcitan	fine crystic	120-250	broken	3-10	
	calcitan	fine crystic	30- 60	patchy	3	

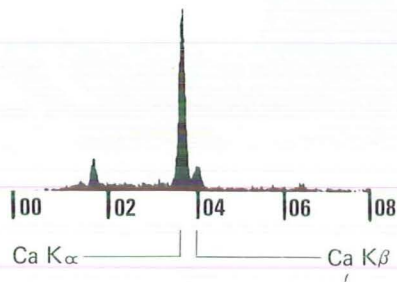
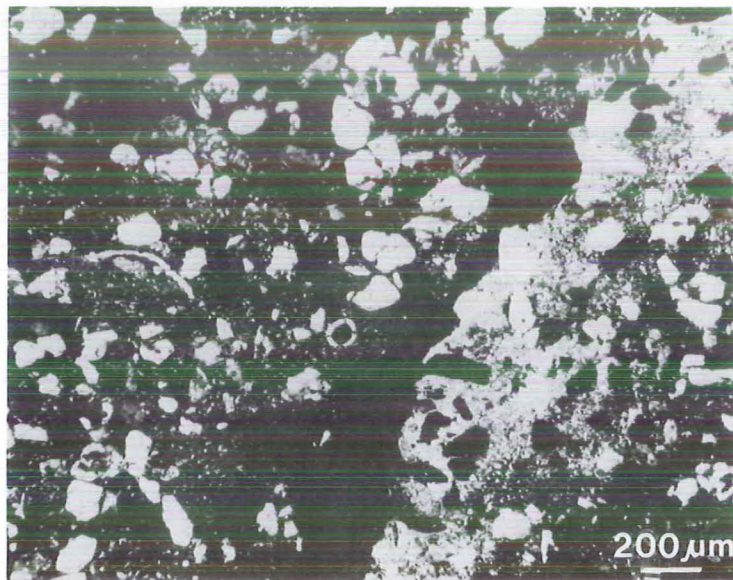


Fig. 48. Channel neocalcitan and a point analysis (SEM-EDXRA) showing the presence of calcium

## Phenomena due to oxidation

### *Ferric iron*

In oxygenated environments, dissolved ferrous iron oxidizes to ferric iron. As the aeration and evaporation of the sediment are restricted and largely limited to the surface and to voids in contact with the atmosphere, the precipitation and accumulation of ferric iron was concentrated in specific zones. In thin sections ferric iron accumulations occurred as: cutans, neocutans, quasicutans, in zones around embedded manganese pseudomorphs (see next item) of organic matter, around embedded pyrite spheres, pyrite pseudomorphs and along pyritans and neopyritans.

Ferrans were not common. They were usually thin and were often discontinuous. The same ferran sometimes varied in thickness. Two types of ferrans occurred: the first had a rather amorphous internal fabric when viewed under the microscope; the second had a distinct radial fibrous structure, which must have been caused by the presence of goethite, a stable iron mineral in the prevailing pH and  $E_H$  conditions (see Section 3.10). In the intertidal flat amorphous ferrans were only observed on the walls of small faunal channels. The ferrans present on the walls of voids (mainly channels) in the salt marshes were mostly composed of goethite (see Figure 49). These ferrans generally consisted of several thin laminae. Ferrans were usually best developed on the walls of faunal channels.

Neoferrans were the most common accumulations of ferric iron. They were usually well developed, continuous, and fairly extensive. They were most evident in sandy sediments, and best developed along shrinkage cracks and faunal channels. Along floral channels they were less evident as the possibilities for aeration were often limited by the presence of roots or root remnants. Neoferrans present in the walls of the shrinkage cracks were often several millimetres thick. Occasionally cutans of soil material also occurred in these cracks in the intertidal zone (see Section 4.3.3) and therefore several covered former neoferrans could occur in close

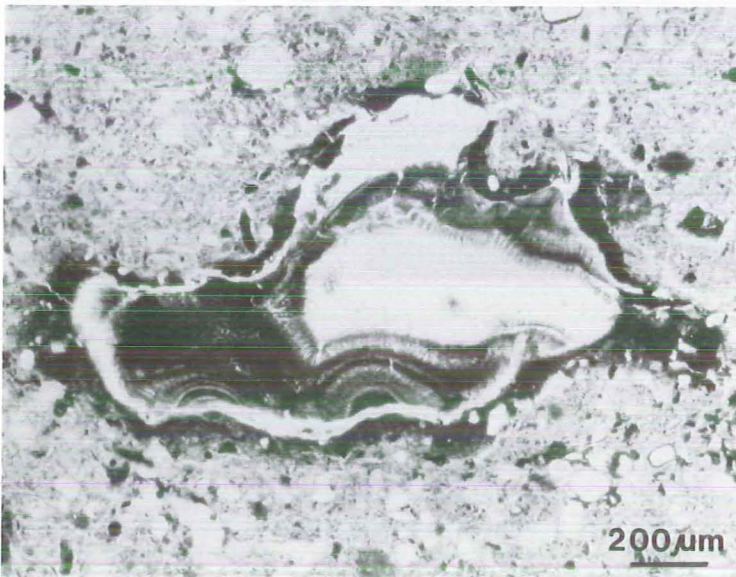


Fig. 49. Channel goethan in a recent middle-high salt-marsh deposit.



proximity. Along faunal channels no covered former neoferrans were found, even when zoocutans were present. The largest neoferrans observed were over 10 mm thick and occurred around crabholes.

Sometimes the neoferrans in the walls of the large shrinkage cracks and the crabholes alternated with neomangans (see also next item) forming compound neocutans. A selection of SEM-EDXRA data from a compound neocutan of this type is given in Figure 50. From these data it is evident that there is no distinct separation between the neomangans and neoferrans, as both elements also occur together. Secondly there is a relation between the occurrence of the element phosphorus and the element iron. When the elemental phosphorus is found, elemental iron is present too. This result of the SEM-EDXRA data is in accordance with the correlations of Fe (dith) and P (Olsen) discussed in Section 3.10. Thus there is strong evidence that iron phosphate is present in the neoferrans. As ferric iron has a strong tendency to interact with phosphate and as the quantity of iron was always in excess, the phosphate present was probably all precipitated as iron phosphates, which can be found in all the iron accumulations mentioned earlier in this Section.

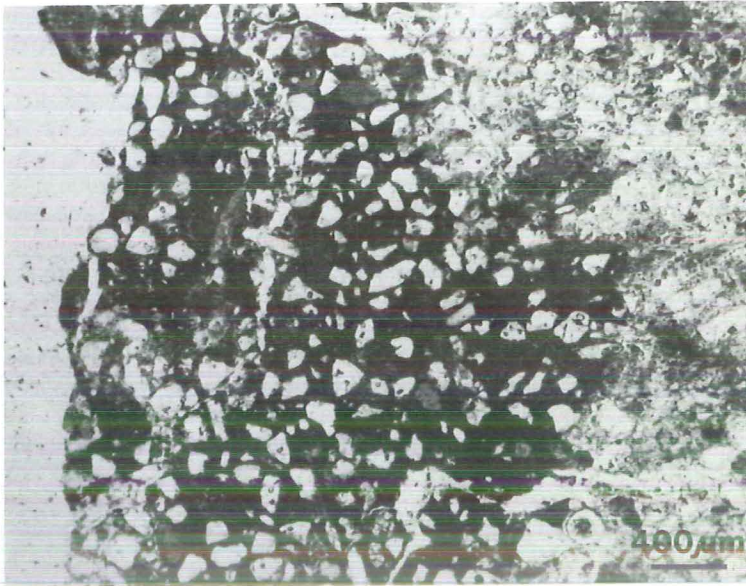
Quasiferrans were found regularly. Most of the quasicutans result from wet soil material infilling the channels along which neoferrans were formed. Only rarely were quasicutans observed in which the iron had been precipitated directly a short distance from the void. These quasiferrans were restricted to sandy sediments. Quasicalcitans (see Phenomena due to reduction) were found associated with the same voids as quasiferrans and neoferrans. When both materials occurred near the same void, the iron precipitation was always nearer to the void, sometimes slightly overlapping the quasicalcitan. This phenomenon may be ascribed to difference in formation. The carbonate is directly precipitated from the oversaturated soil solution. However, the ferrous iron present in the soil solution only precipitates after oxidation, and therefore is found nearer the voids.

Ferric iron accumulations around framboidal pyrite, whether as spheres, pseudomorphs, cutans or neocutans are due to oxidation of the pyrite. The pyritans and neopyritans most often showed ferruginous margins, probably a result of the better aeration facilities near voids. In sandy material the oxidation zones still followed the original pyrite shapes. In contrast, in muddy material the oxidation zones formed irregular, more or less adhesive, diffuse (BREWER, 1964) red-brown zones around the black nuclei of the non-oxidized pyrite remnants. These pyrite oxidation phenomena were only found locally in the superficial zones of the parts of the salt marshes at and above Mean High Tide level. The ferruginous colouring of soil material resulting from oxidation of pyrite was usually more strongly developed than the directly precipitated trivalent iron near voids. When neopyritans and pyritans were completely oxidized, very pronounced neoferrans and ferrans resulted. The black/red colours of oxidizing pyrite and of the manganese pseudomorphs with red margins produced a strong mottling in the superficial zone of the higher salt basins. Accumulations of ferric iron around manganese pseudomorphs are dealt with in the next item.

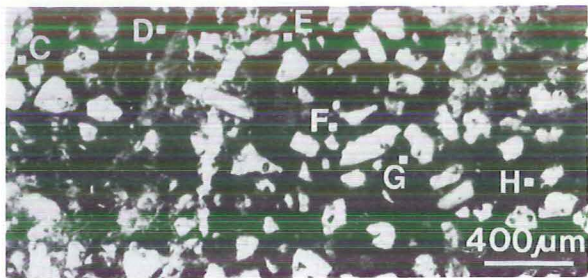
From the data mentioned above it is evident that the extent of trivalent iron precipitations depend not only on oxidation (mainly via voids directly connected with the atmosphere) but also on granular composition.

### *Manganese*

In addition to the manganese neocutans described above, many manganese pseudomorphs were also observed. Like the pyrite pseudomorphs, the manganese pseudomorphs were formed in peat and detritus grains as well as in root remnants. It seems that oxidized manganese preferentially precipitates in organic matter or is related to processes acting in organic matter.



A. General view of a section of the compound neocutan.

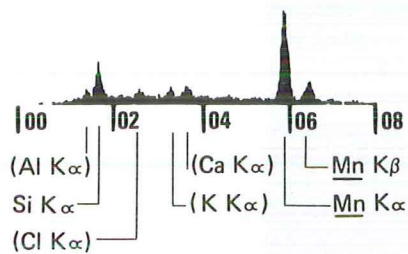


B. Location of the point analyses.

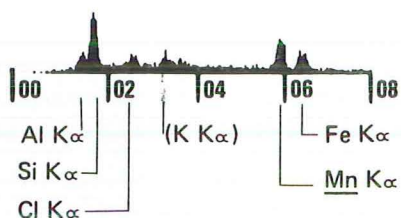
Fig. 50. SEM-EDXRA analysis of a compound neomangan-neoferran adjoining the walls of a vertical shrinkage crack in the intertidal flat.



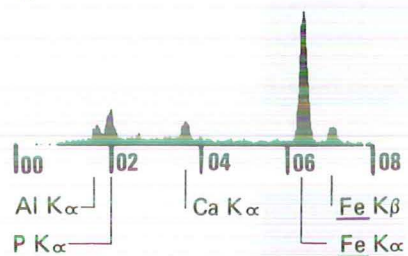
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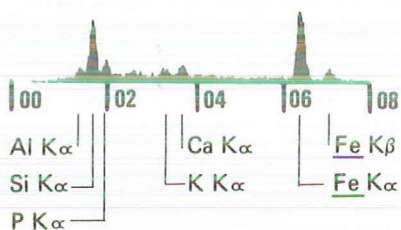
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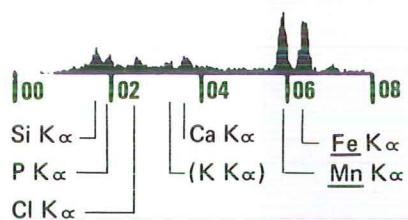
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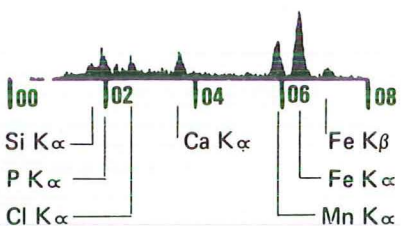
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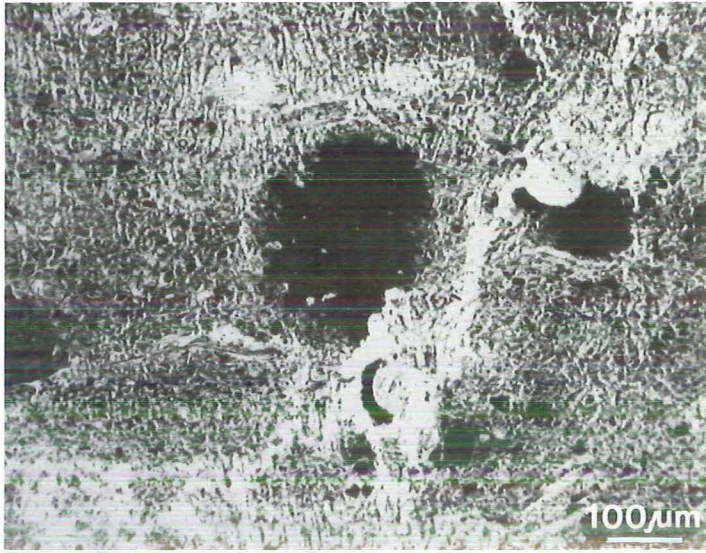


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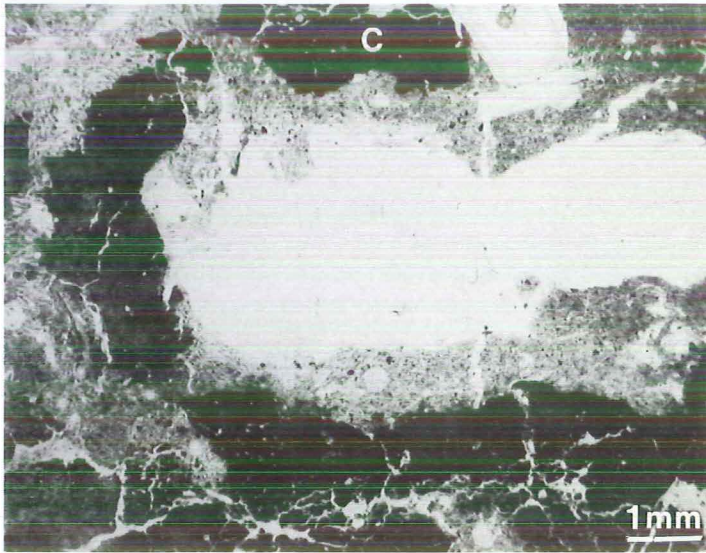


H

Fig. 50. *Continued.*



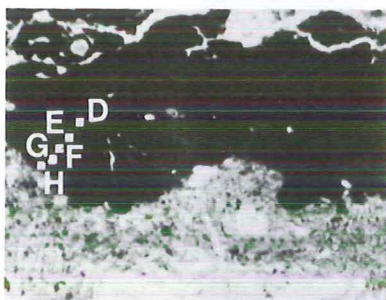
A. General view peat pseudomorph.



B. General view root pseudomorph.

Fig. 51 SEM-EDXRA analyses of a peat pseudomorph and a root pseudomorph.





C. Location of the point analyses.

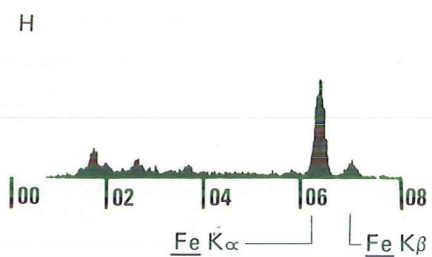
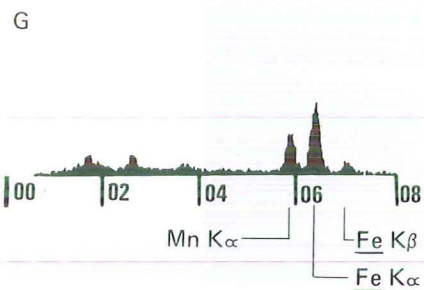
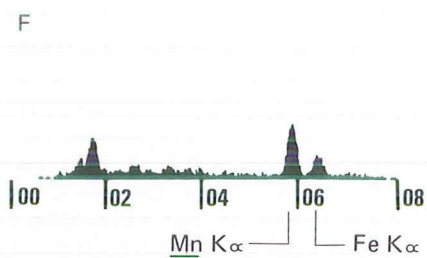
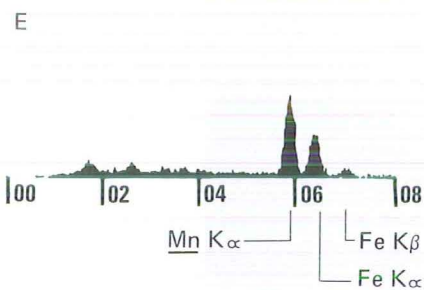
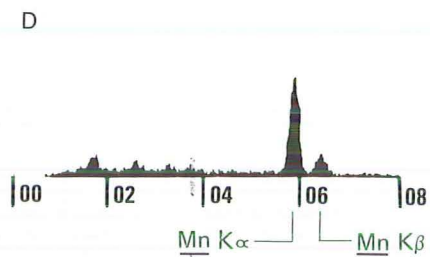
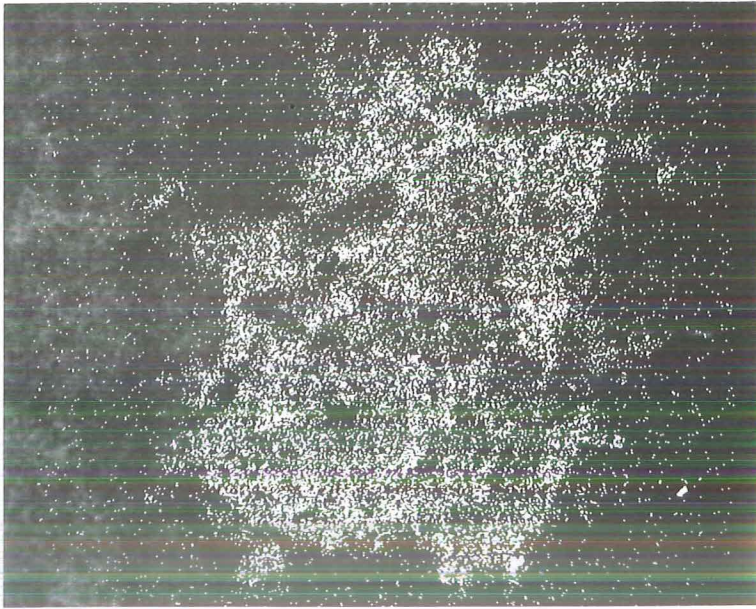


Fig. 51. Continued.



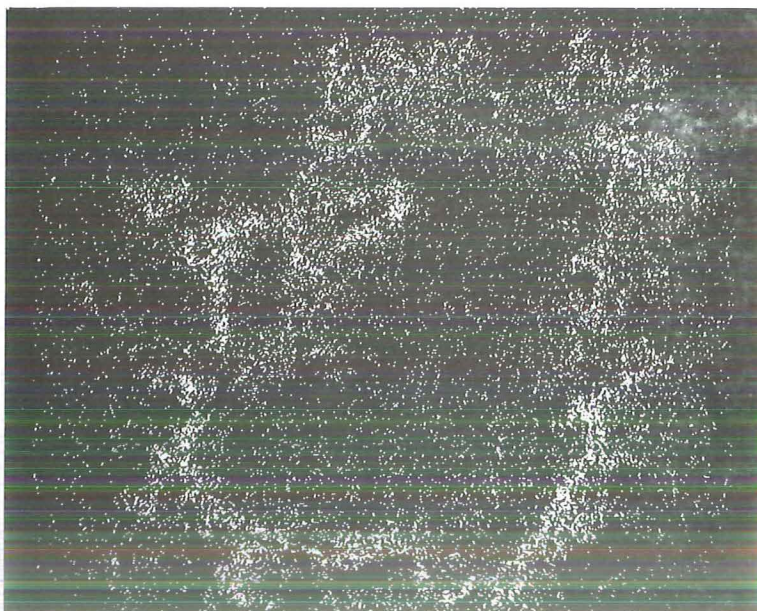
I. X-ray image of the element Mn in the peat pseudomorph.



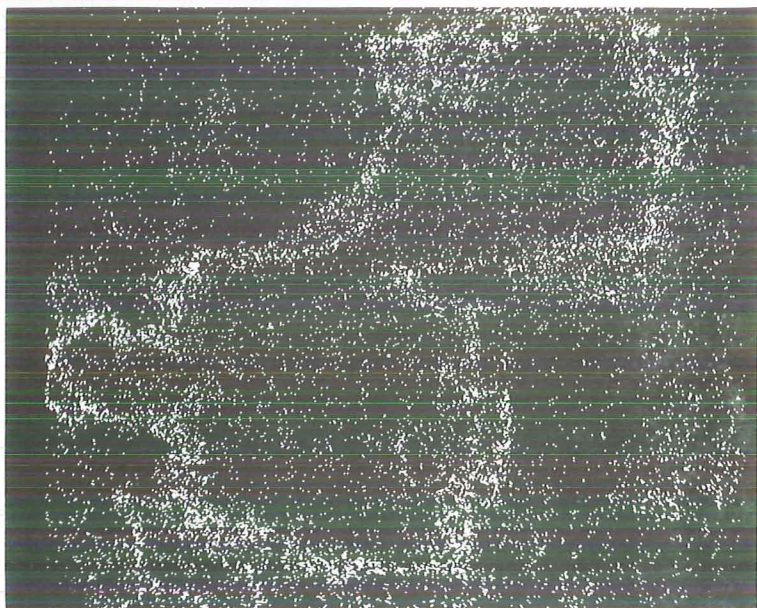
J. X-ray image of the element Mn in the root pseudomorph.

Fig. 51. *Continued.*





K. X-ray image of the element Fe in the peat pseudomorph.



L. X-ray image of the element Fe in the root pseudomorph.

Fig. 51. *Continued.*

Some black pseudomorphs were studied with SEM-EDXRA. The results from a peat pseudomorph and a root pseudomorph are given in Figure 51. The point analyses and X-ray images revealed that manganese was found in the centre of the pseudomorphs and iron on the edges. Near the edges of the pseudomorphs manganese decreased and iron first occurred and then increased. Thus the large central parts of the pseudomorphs had distinct manganese accumulations. Iron occurred on the margins of the pseudomorphs as a zone that followed the contours of the black manganese core like a cutan. Such zones showed up under the microscope in transmitted light as a faint red-brown zone around black nuclei. In other cases no such red-brown margins were found, or distinct, sometimes rather broad, ferruginous zones were visible. The latter resembled red-brown, irregular, usually adhesive glaeboles (BREWER, 1964) with black nuclei. From previous work (pers. comm. DR. BISDOM) it is known that if the manganese had completely replaced the organic matter, then the peaks revealed in the point analyses would reach a certain height. The manganese peaks in Figure 51 were not so high, indicating that organic matter was still present. When a distinct iron peak was found, a small phosphorus peak also sometimes occurred, indicating the presence of iron phosphate.

All these phenomena usually occurred in the superficial zones of clay-rich sediments in the middle-high and high salt marshes. The manganese pseudomorphs with distinct ferruginous fringes were more conspicuous in these zones than the red-brown/black features that had been caused by the oxidation of pyrite. They were more common and generally had broader, more adhesive ferruginous zones. The ferruginous zones around manganese pseudomorphs were only found on those parts of the pseudomorphs that were embedded in the soil matrix. This implies that iron is derived directly from the soil solution in the soil matrix and not via voids. Iron pseudomorphs of organic matter were not observed.

The formation of these compound phenomena seems to have taken place in two phases. Oxidized manganese is precipitated in organic matter that is usually embedded in the soil material. When a certain amount of manganese is present, this pseudomorph may function as a nucleus for the precipitation of ferric iron, which, once started, continues for as long as there is an adequate supply of ferric iron.

In lower salt basins no manganese accumulations were observed, but iron accumulations were found. This can be explained by the fact that iron is more readily oxidized than iron (VAN SCHUILENBORG, 1973).

### *Carbonate*

Although carbonate deficiencies are not solely due to oxidation, for convenience' sake they are dealt with here.

In the subsoils of higher salt marshes distinct carbonate deficiencies were found, always beginning above the G horizon. At first the number of small carbonate particles in the fine fraction diminished. Subsequently larger grains diminished and disappeared. Decalcification was not evenly distributed: it was usually most pronounced along voids, with or without roots, in zones with high concentrations of organic matter and in sandier laminae. As a result the carbonate deficiencies produced a mottled pattern. Differences in amounts of carbonate occurred even in single laminae. The pattern was further complicated because the infilling of voids with younger sediment produced higher carbonate contents in the infilling than in the surrounding material. Also, recently embedded excrements from suspension feeders or selective deposit feeders feeding at the surface had higher carbonate contents. The transition from a dense calcic basic fabric to a weak calcic basic fabric often occurred within a depth of 10-20 mm. The deficiencies were most pronounced in clay-rich sediments, especially those of the salt



basins. The higher the level of the salt basins, the earlier decalcification occurred below the surface and the deeper the decalcification proceeded. The decalcification in natural levees was less pronounced than in the salt basins and, when present, began deeper below the surface (see also Section 2.2; Map 3 A, B, Appendix 3 and section 3.9). The lower boundary of distinct carbonate deficiencies was rather irregular with many tongues. There was a rapid transition (only a few millimetres) from carbonate deficiency to almost the original quantity present in the sediment. The tongues representing leaching channels were only partly associated with root channels, which sometimes contained root remnants, and sometimes were infilled. These tongues were also often associated with zones where clear passage features were found. The lower boundary of the carbonate deficiency zone was situated at, above, or most often just in the G horizon. In distinct deficiency zones the clay-sized material was usually almost entirely decalcified, but remnants of larger carbonate grains were still present, especially in coarser laminae.

Sometimes carbonate was found in neoferrans and quasiferrans present in the carbonate-deficient zones. It seems that here locally evaporation is more important than leaching. This phenomenon was found in the high salt basins, where practically no *Spartina townsendii* grew but where the existing floral species (see Map 4 B, Appendix 3) were often lower and more shallowly rooted, probably favouring evaporation.

#### 4.3.5 Effects of the different processes on soil formation

In the preceding Sections, processes were reconstructed from micromorphological phenomena, field observations, and data of chemical and physical analyses. The phenomena can also be arranged in four basic kinds of changes, namely: additions, removals, transfers and transformations (SIMONSON, 1959; see also Section 4.1). However, voids are not represented in these groups. Yet in the marine sediment above Mean Low Tide level the formation of voids is very important. Aeration, evaporation and reduction are regulated via voids (see Section 4.3.4). Furthermore, gravitational transport of soil material takes place via voids (see Section 4.3.3). Thus most kinds of changes can be found associated with voids. Therefore voids have been added as a separate fifth group of changes.

(i) The *voids* present were of biological or physical origin (see Section 4.3.3).

(ii) The *additions* found in thin sections were restricted to the *excrements* produced by suspension-feeders directly *in situ* in the sediment as e.g. in passage features, striotubules and as aggotubules filled with excrements. Roots, shells and snails, not geogenetically deposited, may also be considered to be additions.

(iii) The *removals* were represented by the occurrence of distinct carbonate deficiencies (see Section 4.3.4).

(iv) Many changes belonged to the *transfers* such as cutans of soil material, complete infillings, isotubules and aggotubules, striotubules, and passage features.

(v) *Transformations* also took place. The accumulations of ferric iron, calcium carbonate, pyrite and manganese belong to this group. The first two items were generally associated with voids.

So in the sediment all five basic kinds of changes leading to differentiation (formation of horizons) or to homogenization and thereby determining the soil genesis, were very conspicuous. Their occurrence, abundance and combinations within the whole sequence from Mean Low Tide level to highest saltings will be dealt with in the next Section.

## 4.4 FABRIC DEVELOPMENT IN THE INTERTIDAL ZONE

Before dealing with the pedogenetic fabrics more information must be given about the geogenetic fabrics. The type, occurrence and abundance of the soil-forming processes can change in different geogenetic fabrics. Moreover, in the resulting soil fabrics relict fabrics of geogenetic origin are still visible.

### 4.4.1 Geogenetic fabrics

The geogenetic fabrics result from the deposition of material transported in seawater by currents and waves during the tidal cycle, alternated with erosion phenomena. The mechanism of the tides and the related processes of sedimentation have already been described in Sections 1.3 and 1.4. The resulting sediment, with or without distinct lamination and sorting effect on grain sizes was discussed generally in Section 1.4. The granular compositions dealt with in Section 3.2 are bulk analyses that may include many laminae of different granular compositions. Much more information about the geogenetic fabrics was obtained from studying the thin sections. Nearly all the geogenetic fabrics observed in the intertidal zone have previously been described as they have been studied by many sedimentologists such as VAN STRAATEN, 1954; ALLEN (1970); REINECK & SINGH (1973). The salt marshes, especially the basins, have received the least attention.

Because the geogenetic factors are important as the original material on which soil-forming processes act, this Section considers several of their important aspects. These aspects are: (i) lamination of the sediment; (ii) transitions of the laminae; (iii) their thickness; (iv) the composition and internal arrangement of the constituent elements of the laminae. In Table 14 some of the important data on the original geogenetic lamination are given. Disturbance and homogenization of the laminae due to soil-forming processes have been excluded. They are treated separately in Section 4.4.3.

(i) *Lamination*. Many of the thin sections of samples taken in the intertidal zone showed distinct lamination. Laminations generally occurred in samples from intertidal flat deposits and natural levees. Interlayered sand/mud bedding, wavy bedding, flaser bedding and cross-bedding were common. Many bed sets were composite (see Figure 10). It is beyond the scope of the present study to determine the different laminated patterns. In thin sections the common shapes of the different beds and laminae were parallel, non-parallel, and wavy (ALLEN, 1970). Bifurcation and termination of laminae was not unusual: these phenomena resulted from the separate and combined effects of moving wave and current ripples.

(ii) *Transitions of the laminae*. The transitions of the laminae ranged from very sharp to very gradual, but were usually rather sharp. The mud laminae often had a more gradual boundary with the preceding sand lamina than with the succeeding sand lamina, which was most often sharp. This probably resulted from the relatively large pore spaces between the sand grains: during deposition mud flakes which are composed of smaller, easily deformable elements, can settle between them.

(iii) *Thickness of the laminae*. The alternating laminae were usually thin. The sand laminae were thicker than the mud laminae. Several sandy laminae often succeeded each other with only minor differences in granular composition, but with distinct surface planes. In Table 14 homogeneous beddings are also represented. These are deposits in which no distinct lamination can be seen, but which have minor, very gradual changes in granular composition. Homogeneous beddings were largely restricted to the salt basins. These basins were built up of many thin laminae, which together had a rather homogeneous appearance. Occasionally, sand laminae of several millimetres thickness were found in the homogeneous muddy deposits.



Table 14. Characteristics of geogenetic fabrics.

Zone, location and depth in cm of the thin sections	Bedding				Dominant composition			Remarks
	laminated	thickness	sharpness	homogeneous	sand	mud	equal	
Low intertidal flat profile no. 1: 0- 15 5- 20	x x	thin thin	sh sh/clear	-	x x			peat grain l.
High intertidal flat profile no. 2: 0- 15 4- 19 near profile no. 2: 0- 15	partly partly x	thin thin/mod thin/mod	clear diff/cl/sh diff/cl	partly partly	x x		x	peat grains shell doublet peat grain l., ves.
Transitional zone n.l. profile no. 3: 0- 15 21- 36 40- 55 i.s.b. profile no. 4: 0- 15 15- 30	x x x - partly	mod/thick thin/mod thin -	diff clear/sh sh -	- - - x partly		x		detritus l. peat grain l. shell/snail l.
Low salt marsh n.l. profile no. 5: 0- 15 24- 39 45- 60 68- 83 s.b. profile no. 6: 0- 15 15- 30 30- 45 n.l. profile no. 7: 0- 15 18- 33 45- 60 s.b. profile no. 8: 0- 15 0- 15 15- 30 33- 48 52- 67	partly x x - - - x x - - - - partly	mod mod/thick mod - - - thin/mod thin-thick - - - - thick	diff clear diff - - - diff diff/cl - - - - diff	partly - - x - - - - - - - - partly			x x x	peat grain l. peat grain l. peat grains stormtide l. detritus/stormtide l. peat grain/detr.l. stormtide l. stormtide l. detritus l.
Middle-high salt marsh n.l. profile no. 9: 0- 15 23- 38 44- 59 62- 77 s.b. profile no.10: 0- 15 22- 37 39- 54 n.l. profile no.11: 0- 15 17- 32 39- 54 75- 90 s.b. profile no.12: 0- 15 17- 32 38- 53 68- 83	x - - - - partly x x x partly - x x	thin/mod - - - - mod/thick thin/mod thin/mod mod - mod/thick mod	diff - - - - diff/cl clear/sh clear/sh diff/cl diff - diff/cl clear	- - x - - first 1/3 - - - partly 1/4 x x - -		x x x x x x		stormtide l. stormtide l. stormtide l./detr.l. stormtide l. stormtide l. stormtide l. detr./peat grain l.
High salt marsh n.l. profile no.13: 0- 15 15- 30 33- 48 55- 70 75- 90 92-107 124-140 tr. profile no.14: 0- 15 38- 53 54- 69 69- 84 90-105 s.b. profile no.15: 0- 15 15- 30 55- 70 90-105 profile no.15b: 0- 15 15- 30 b.s.b. profile no.16: 0- 15 15- 30 40- 55 56- 71	x x x x x x x x x x x partly x - - partly x x x x	thin thin thin/mod thin/mod thin thin thin thin-thick thin/mod mod thin/mod - mod/thick thin/mod - mod/thick mod thin/thick thin	cl/sharp cl/sharp cl/sharp cl/sharp sharp sharp sharp cl/sharp clear cl/sharp thin clear - diff cl/sharp - - clear diff clear cl/sharp	- - - - - - - - - - - partly 2/3 - - - - upper 4/5 - - -	x x x x x x x		x x x x x x x x x x x x x x x x x x x x	peat grain l. vesicles detr./stormtide l. stormtide l. peat grain l. several detr.l. stormtide/detr.l. stormtide l. large mud pebb. peat/mud pebb.

i. = incipient  
s.b. = salt basin  
b.s.b. = buried sand barrier  
n.l. = natural levee  
l. = lamina  
detr. = detritus  
gr. = grains  
stormt. = stormtide  
pebb. = pebbles  
ves. = vesicles

thin = laminae less than 2 mm  
mod = moderate : laminae between 2-5 mm  
thick = more than 5 mm

sh = sharp = lamina boundary less than sand grain  
cl = clear = lamina boundary less than 2 sand grains  
diff = diffuse = lamina boundary more than 2 sand grains

These laminae were the result of storm tides. In contrast, primary homogeneous sandy sediments resulted more from rapid sedimentation (REINECK & SINGH, 1973).

(iv) *Composition of the laminae.* Most of the sediment was composed of sand and mud laminae. The dominance of both types, as given in Table 14, is based on their surface percentages in thin sections. The composition of the sand laminae varied little. They contained many carbonate and peat grains. High concentrations of rather randomly distributed glauconite grains were also found. Some larger carbonate parts, shell and snail remains, were also incorporated.

In contrast, mud laminae showed more internal variation. The basic concept of the composition of mud laminae has already been discussed in Section 4.3.1. Mud laminae were not necessarily completely built up from mud flakes; excrements were often incorporated and sometimes mud laminae consisted solely of excrements. The excrements were arranged as single oriented excrements at varying distances from each other, or as tightly packed clusters that could be partly or wholly compressed. In Figure 52 some examples are schematically given. Types 1, 2 and 3 were restricted to the intertidal flat. Type 3 was most common in the lower parts; in the higher parts of the intertidal zone types 1 and 2 occurred more often. Type 4 was found in the salt basins, even in the high salt marsh. In these basins the excrements had almost the same composition as the surrounding soil material and therefore were rather difficult to distinguish. The excrements in the mud laminae or composing mud laminae were detected by their typical shapes, greater compaction, orientation and composition (see Section 4.3.2.1). From now on all the laminae or bedding types composed of remains of flora and/or fauna and deposited as geogene sediment will be referred to as bio-geogenetic laminae\* and their fabrics as bio-geogenetic fabrics. These fabrics include laminae composed of or containing excrements, shells and snails or their remains, peat fragments, etc.

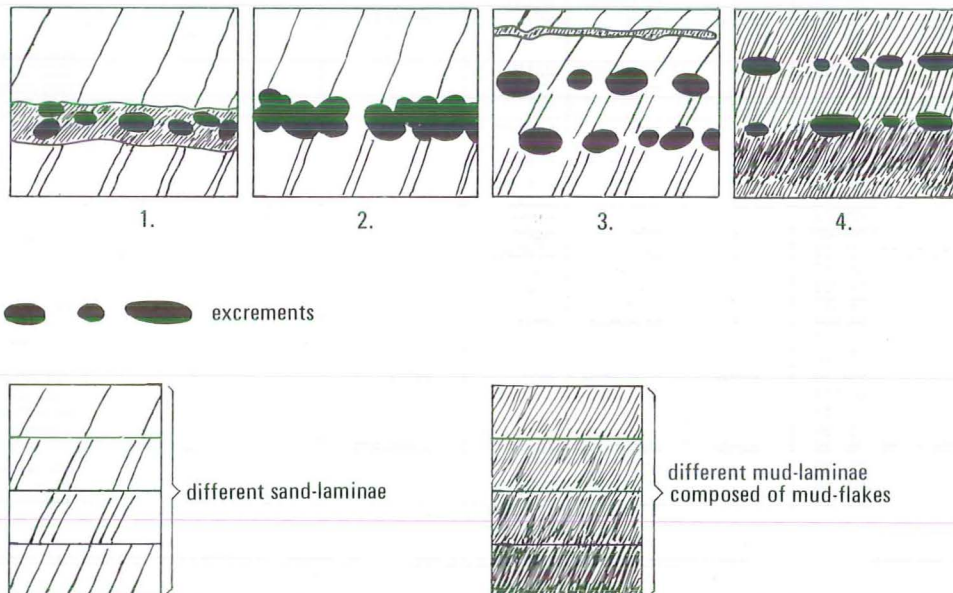


Fig. 52. Several types of bio-geogenetic fabrics of excrements.



After being excreted on the surface nearly all excrements present in bio-geogenetic fabrics were transported either as bed load along the surface, or as suspended load. The excrements deposited at the surface need not be removed over large distances. However, not all the excrements present in bio-geogenetic fabrics originated from sessile faunal specimens that deposit their excrements at the surface. Species such as *Hydrobia ulvae* and possibly some crustacea excrete in the seawater and some of these excrements are deposited and incorporated in or form bio-geogenetic laminae. Most of these excrements, however, are mechanically and chemically changed during transport and unrecognizable incorporated in mud flakes.

Types 1 and 2 of the bio-geogenetic laminae were mainly found in muddy deposits whose surface was covered by the macroscopic green algae *Enteromorpha prolifera radiata* or *Zostera* spp. These 'rooted' vegetations effectively reduce currents and therefore excrements are not displaced over great distances. Direct covering of excrements without displacement is also possible. In bio-geogenetic laminae of type 2 the individual excrements were often almost indistinguishable as they had been deformed during transport and disturbed by passage features. In type 3 the excrements had been transported as bed load. The excrements present in type 4 were mostly those of *Hydrobia ulvae* that were after excretion as part of the suspended load deposited in the salt basins.

The differences in mud flake laminae and excrement laminae were accentuated by several factors. (i) As the composition of the excrements varied according to the food ingested by the animal, in mud laminae partly or completely composed of excrements differences in granular composition were visible (see also Section 4.3.2.1). In these mud laminae the quantity of fine particles (2-30  $\mu\text{m}$ ) in the fine fraction could be less or more than that in the mud-flake laminae. Therefore, the mud laminae could even be exclusively composed of clay-sized material. (ii) The excrements contained more uniformly sized and smaller carbonate particles than the material of the mud flake laminae, whereas the latter often contained more complete or broken diatoms derived from planktonic as well as from benthonic species. (iii) When the mud laminae were composed of excrements, the boundary with a preceding sand lamina was sharp.

Apart from sand and mud laminae, laminae composed of complete or broken shells and snails, peat grains and pebbles and isolated peat boulders, detritus and other fragments of organic matter, and mud pebbles, whether or not arranged in laminae, were also observed.

(i) Shell and snail laminae were mainly restricted to intertidal flat deposits. They were found in present-day or former gully and creek floors, in storm-tide deposits or as pedogenetic accumulations resulting from the activities of *Arenicola maritima* (see Section 1.7). Shell and snail laminae were often more than 10 mm thick. Individual shells and snails embedded on plane surfaces were also found.

(ii) Peat grains usually formed thin laminae, which resembled the laminae of type 3 given in Figure 52. They were found in the intertidal flats and some natural levees. Laminae composed of detritus, including fine peat fragments, were found in the intertidal flat deposit as well as in the salt marshes, especially in the basins. They were up to 8 mm thick. In salt marshes, detritus and peat grain laminae were also sometimes storm-tide deposits. The storm-tide laminae indicated in Table 14 were composed of sand.

(iii) Larger parts of peat in the form of abraded pebbles and isolated boulders some 200 mm long were not exceptional. The peat pebbles were usually slightly flattened and sometimes occurred in laminae as shown in type 3 of Figure 52. The peat boulders were isolated phenomena, present in former creek floor deposits and on and in natural levees. This peat was derived from the Holland Peat and the Lower Peat present 3-6 m below the surface and exposed in the tidal channels of the Oosterschelde (see Section 1.1.2 and Figure 2). Only the smallest

mud pebbles were arranged in laminae. They measured up to 5 cm in diameter and were found in the upper 10 cm of a sand bar that had been buried under a mud deposit.

(iv) The mud pebbles were derived from eroded mud deposits in the salt marshes. After erosion, large blocks were fragmented, abraded and embedded in coarse sands.

(v) The coarse versus finer (c/f) related distribution in the laminae. The fine fraction comprising the mud laminae not derived from excrements had a type of a porphyric c/f related distribution (STOOPS & JONGERIUS, 1975). A normal porphyric c/f related distribution has a dense groundmass of fine material (clay-sized) in which the coarser particles (2-30  $\mu\text{m}$ ) are embedded. In this marine sediment the groundmass of finer material has an 'open' initial structure. As a result of compression the groundmass becomes denser and as a consequence the content of coarser particles increases (see Section 3.3). After ripening, the bulk densities of clay-rich soils increased by 2-3 times; this is due to compaction of the clay-sized part. Excrements did not show changes in their internal fabric because they had already been compressed by the animal. The freshly deposited sand laminae had a monic c/f related distribution with a high pore space, due to large simple packing voids. With compaction, the size of these packing voids decreased.

The occurrence of fine particles (less than 30  $\mu\text{m}$ ) as bridges, coatings or loose aggregates in the coarse fraction, was mostly the result of soil-forming processes and need not be considered here.

#### 4.4.2 Pedogenetic fabrics

Pedogenetic fabrics are the result of soil-forming processes acting on the sediment. According to BREWER (1964):

Soil structure is the physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves; fabric is the element of structure which deals with arrangement.

The soil materials occurring in the intertidal zone were apedal. The coarse polygons did not have surfaces of weakness on the lower side; so they were not peds. In nearly all salt basins, weak, fine to medium crumbs were observed in the soil pits; these could not be detected in the thin sections. Nevertheless, the patterns resulting from passage features of *Hydrobia ulvae* resembled that of the crumbly structure, and therefore it is possible that the central zones of the passage features (see Section 4.3.2.1) were identical with the surfaces of weakness of the crumbly structure.

In the following Sections the phenomena caused by the pedogenetic processes are discussed at two levels. At the lower level the occurrence and abundance of individual simple or complex phenomena (caused by one process or a combination of processes, respectively) are given. The patterns formed by these phenomena are classified at the higher level. These patterns are referred to as soil fabrics\*, as they deal with the arrangements of the solid particles and voids (BREWER, 1964). The last section presents a scheme of the different soil fabrics occurring from the low intertidal flat to the highest saltings, with reference to the soil-forming processes that caused them.

##### 4.4.2.1 Occurrence and abundance of the effects of the different processes over the intertidal zone

In Sections 4.3.1 to 4.3.5 inclusive, the phenomena observed in thin section are grouped according to the processes that caused them. The phenomena may also be grouped according



to the kinds of changes, as was done by SIMONSON (1959) and by JONGERIUS (1970). A separate category, voids, has been added to the four basic kinds of changes discerned by SIMONSON (1959): see Section 4.3.5. Appendix 4 A presents the occurrence, abundance and sometimes also size of the main phenomena in the sediments in the intertidal zone from low to high, grouped in kinds of changes. In this appendix only data from the vertical thin sections taken in the profiles studied are represented. In the text data from thin sections of samples taken horizontally and from thin sections of specific phenomena are also included. In Appendix 4 A additions are not listed separately. Excrements from suspension feeders belonging to the additions are included in the phenomena where present, e.g. in passage features. Phenomena associated with voids that are still open are treated together with the voids. They mainly comprise transfers and transformations. When a void has been completely infilled, the phenomenon is listed under the transfers.

In subsequent paragraphs the distribution of the phenomena belonging to the different kinds of changes is treated in more detail. The emphasis lies on the higher parts of the intertidal zone because more stable deposits are found here which, moreover, are most closely related to the reclaimed polder soils.

#### 4.4.2.1.1 Voids and the additions, transfers and transformations related to them

In Section 4.3.3 it has already been mentioned that the pedogenetic voids are of physical or biological origin. Planar orthovoids and the voids classified as vughs are of physical origin. The channels and central void pattern in the passage features of *Hydrobia ulvae* are of biological origin. Channels of biological origin that have subsequently been completely infilled are listed under the transfers as pedotubules. Completely infilled planar orthovoids are given separately as they cannot be classified as pedotubules.

#### Voids of physical origin

##### Cracks

The occurrence of the planar orthovoids as shrinkage cracks in the intertidal flats, natural levees and high salt basins has already been mentioned in Sections 1.5 and 4.3.3. The dimensions of the polygons were too large for the size of the thin sections, so only parts of planes were present in the sections. The walls of the planar orthovoids in the intertidal flat usually had neoferrans; these were best developed near gullies and the highest parts of the slightly undulating flats. In these kinds of orthovoids cutans of soil material were found, generally only on one face. Sometimes in these inflow-cutans (see Section 4.3.3) excrements occurred that had obviously been transported with the soil material, for no disturbance of laminae was visible. If these cutans covered neoferrans the latter became quasiferrans. In the new surface other neoferrans occasionally developed. Sometimes neomangans were found in combination with neoferrans, forming compound neocutans (see Section 4.3.4). Locally neocalcitans and quascalcitans were also found in the walls of these voids. In the lower part of these planar voids angular fragments of soil cutans, with or without neoferrans and neomangans, sometimes occurred together with excrements. The planar voids were even sometimes blocked locally by these aggregates and excrements. Only one thin section from a natural levee showed part of a shrinkage crack. This crack had a distinct neoferran and occasionally a goethan. Inflow-cutans probably also occurred in these cracks, but none were found. The smaller shrinkage cracks present in high salt basins also sometimes had distinct neoferrans and occasional goethans. These neoferrans and ferrans were not visible at the surface as they occurred

deeper in the cracks. No cutans of soil material were found, and indeed it is unlikely that they would have occurred, because the soil material was probably too ripened to move plastically. However, complete infillings consisting of coarse particles did occur.

#### Vughs

The voids classified as vughs were the result of shrinkage (see Section 4.3.3). They were only present above the G horizon in the salt marshes situated at and above Mean High Tide level. They were usually irregular, partly interconnected orthovughs protruding from existing channels into the soil matrix, and were present in salt basins as well as in natural levees. These orthovughs were commonest in high salt basins, where *Spartina townsendii* did not dominate (see Map 4 B, Appendix 3). They were better developed in muddy sediments than in sandy material. Sometimes the soil material between closely crossing roots had so many orthovughs that soil aggregates were formed that were transported downwards in the voids. Orthovughs often crossed neoferrans that surrounded channels, but rarely had their own neoferrans. Probably the vughs were situated too high above the G horizon for ferric iron to accumulate. No cutans of soil material were found in the vughs, but small aggregates of soil material were occasionally present.

#### Voids of biological origin

These voids comprise the faunal and floral channels and the central voids in the passage features produced by *Hydrobia ulvae* (see Sections 4.3.2.1 and 4.3.2.2).

#### Faunal channels

Faunal channels were found in the intertidal flats, transitional zone, natural levees and in the small upper zones of higher salt basins. They were most abundant in natural levees. The diameters of faunal channels varied from about 50 micrometres to several centimetres. The variation in diameters of the faunal channels was greater in the intertidal flat, transitional zone and lower parts of the natural levees than in the higher parts of the natural levees and upper zones of the higher salt basins. There, channels less than 3 millimetres in diameter were generally found. Most faunal channels could be grouped by size in a few categories because the animals responsible for them belong to a restricted number of species. The length of the faunal channels depends on the species and the age of the animals (see Sections 1.6 and 4.3.2.1). The faunal channels in the higher and more sandy natural levees were more convoluted and branched and lacked a dominant orientation. Channels present in the upper parts of the higher salt basins were made by *Hydrobia ulvae* and had a random distribution. In recent and buried natural levee and gully-wall deposits, both horizontally and vertically oriented channels were found, whereas in the intertidal flats and transitional zones the vertical orientation dominated.

#### Associated transfers including some additions

(i) Pressure-affected zones (see Section 4.3.2.1) were found along all faunal channels. Since these zones were related not only to the unripened state of the soil material but also to the loose original packing, they were present in all granular compositions (see also Sections 4.3.2, 4.3.3 and 4.4.3).

(ii) Zoocutans were found in sandy soil material in the intertidal flats and transitional zone. The mud occurring in the zoocutans, especially the mud-zoocutans (see Section 4.3.2.1), was mostly derived from excrements from suspension feeders and therefore these zoocutans can be considered to be a special kind of addition. In thin sections zoocutans were not often found.



But zoocutans, especially mud-zoocutans, should have been common in the syphonal channels of molluscs.

(iii) Cutans of soil material resulting from physical processes were restricted to channels with large diameters and were rare. Usually these cutans had been modified by animals and were therefore classified as zoocutans; sometimes the channels had been completely infilled.

Associated transformations (see Section 4.3.4)

Neoferrans and ferrans were found associated with faunal channels. Neoferrans were much more common than ferrans. When ferrans were present, neoferrans were nearly always also found. The neoferrans were generally rather uniform in thickness and colour. Usually only one neoferran was present. Compound neomangans-neoferrans occurred around crab holes in natural levees. Neoferrans were present in zones near and just in the G horizon (see also Map 2, Appendix 3). They first appeared in the higher parts of the intertidal flats. They were also present in the transitional zone, upper parts of natural levees in the low salt marshes, deeper below the surface in the higher natural levees and finally also in the upper zones of the higher salt basins. In the latter location, most of the faunal channels of *Hydrobia ulvae* showed neoferrans. Generally, the faunal channels with largest diameters had the best developed neoferrans. The thickest neoferrans were found in sandy natural levees. In muddy soil material, the neoferrans were usually thin. Ferrans consisted of amorphous iron or were crystalline (goethans). The ferrans usually varied in thickness and were sometimes patchy. They were present in the higher parts of the intertidal flats and in small zones near the G horizon in the salt marshes, mainly in the natural levees. They seemed to be best developed in channels with large diameters in sandy soil material.

Quasicalcitans, neocalcitans and calcitans associated with faunal channels were uncommon in the intertidal zone. Several types of carbonate accumulations could occur in association with the same channel: these carbonate accumulations usually only occurred on one side of the channels.

Central voids in passage features produced by *Hydrobia ulvae* (see Section 4.3.2.1)

This central void pattern was found in muddy sediments of the salt marshes. In the low salt marsh the central void pattern was common in small natural levees, but in the salt basins it was rare. In the middle-high salt marsh this pattern occurred to a limited extent in the natural levees, but was common to abundant in the salt basins. In the high salt marsh the pattern was not very common and only occurred in the salt basins. Deeper below the surface the cross-sections of the central voids were smaller as a result of compaction (see Section 4.3.3). The occurrence of the central voids in the passage features produced by *Hydrobia ulvae* was clearly related to a specific state of ripening of the muddy sediment. If the soil material was too fluid, then passage features were formed, as in the low salt basins, but if it was too firm, then channels remained, as in the high salt basins. No additions, transfers and transformations were observed associated with this central void pattern. They only occurred in inter-sections with other voids e.g. root channels.

Floral channels

Floral channels were present upslope from and including the transitional zone (see Map 4, Appendix 3) and there they outnumbered the faunal channels. Floral channels formed more or less continuous systems of different types, sizes and lengths. In the higher parts of the intertidal flat zones with channels of the thallus fibre of macroscopic green algae occurred locally, together with floral channels made by *Zostera* spp. (see Sections 1.7 and 4.3.2.2). Channels with almost intact remains of green algae were also found in intertidal flat deposits buried under the low salt marsh.

Two different types of floral channels were distinguished; those produced by monocotyledon species and those by dicotyledon species (see Section 4.3.2.2).

(i) Monocotyledon species comprise, *inter alia*, the grasses that cover large areas of the salt basins and the highest natural levees (see Map 4, Appendix 3). The floral channels they produced had rather uniform diameters with the exception of the zone where the rhizomes occurred. They were evenly distributed and had dominant vertical orientations, where unimpeded by differences in granular composition. In the salt basins rather homogeneous muddy sediments were present whereas the highest natural levees were sandy with only very thin mud laminae (see Section 4.4.2). In both cases the rather even distribution and uniform diameters of the floral channels together with the uniform geogenetic fabric of the sediment gave the soil an undifferentiated appearance.

(ii) In the thin sections from all but the highest natural levees, a large variation in the distribution and diameters of floral channels was found. This was because (i) dicotyledon species predominated, (ii) there was a greater variety of species and hence a larger variety in root systems, and (iii) not only perennials such as *Halimione portulacoides* occurred, but also biennials such as *Aster tripolium* and annuals such as *Salicornia europea* (see Section 2.2, Map 4, Appendix 3 and Section 4.3.2.2). To add to this diversity there was a large variation in geogenetic fabrics. The natural levees were usually strongly laminated, with the different laminae varying greatly in thickness and composition (see Section 4.4.2). Irregularities in root systems, such as deflected roots generally caused by the presence of other roots, were not unusual. So here a more complex irregular pattern resulted.

In high salt basins on transitions from salt basin to natural levee transitions of the two extreme patterns discussed above were also found. Parts or whole roots (living or dead) were often present in the floral channels. In dead roots many diatoms were sometimes found and often the effects of animals' gluttony were visible.

#### Associated tranfers

Like their counterparts around faunal channels, pressure-affected zones around floral channels were found up to the highest salt marshes. The reasons for this fact are identical with those given for the faunal channels, namely high water contents and loose initial packing (see also Sections 4.3.2.1 and 4.3.2.2). In the higher salt basins the pressure-affected zones seemed to be more pronounced, probably as a result of a higher degree of ripening. The water content of these sediments is lower from the onset, and once it has been compressed and oriented, the soil material cannot be easily changed afterwards. This fact is accentuated by the high intensities of roots.

Cutans of soil material formed along roots occurred mainly in the transitional zone and low salt marsh, especially in the muddy basins. In these latter areas this feature was fairly common. When root channels had penetrated into deeper intertidal flat deposits, cutans of soil material were also sometimes found there.

#### Associated transformations (see Sections 4.3.2.2 and 4.3.4)

(i) Pyritization of roots was found in the G horizon, in muddy deposits, mainly in the salt basins but also in small natural levees. This pyritization was not restricted to the upper zone of the G horizon. Roots occurring up to 40 cm below the top of this horizon sometimes showed distinct pyritization. The highest abundances of pyritized roots were found in the low and middle-high salt basins. These pyritized roots occurred partly associated with thin pyritans but more often with neopyritans. Neopyritans were sometimes found around roots, associated with thin pyritans between the outer part of the root and the neopyritans. These pyritans and neopyritans occurred in the same places in the intertidal zone as the pyritization of roots, but were not so abundant.



(ii) Ferrans and neoferrans were also found around floral channels. Neoferrans were fairly common, but ferrans were very rare. Neoferrans were most pronounced in a zone just above the G horizon. Thus in the low salt marsh they were restricted to the natural levees. In the middle-high salt marsh they occurred in the upper centimetres of the salt basins and deeper in the natural levees. In the high salt marsh they were found in the upper zone of the salt basins and deeper in natural levees (for the position of the G horizon see also Map 2, Appendix 3). Generally, neoferrans around floral channels were best developed in the sandy soil material that formed the natural levees.

In the salt basins of the middle-high and high salt marsh very red neoferrans were also present around manganized root remains. Manganized root remains and embedded manganized organic remains were only found in the upper layers in these salt basins where an oxidizing environment occurred. Neomangans were never found solely, but always in combination with neoferrans. These compound neocutans were present next to shrinkage cracks of large polygons in the high intertidal flat and in channels and chambers made by the shore crab in creek and gully walls. The rare neoferrans due to oxidation of pyritans/neopyritans occurring in the upper parts of middle-high and high salt-marsh deposits were also very red. As a result of these red colours, the ferric accumulations in the higher salt basins were very conspicuous.

In Section 4.3.4 the occurrence of carbonate accumulations associated with voids has already been given.

#### 4.4.2.1.2 Transfers

In this study all visible changes in the original arrangements of the solid components in the pedon due to soil-forming processes are reckoned to be transfers. So these transfers are regrouping phenomena as defined by JONGERIUS (1970). The regrouping can result in very minor changes, such as variations in original packing, or orientation of elongated particles, as well as in much larger-scale features such as translocations via voids extending over 20-40 cm depth.

Several groups of features belong to the transfers. Some of them have a more or less distinct tubular form: pedotubules and passage features. The difference between the two groups is the presence of a relatively sharp external boundary in the first case and a gradual transition towards the undisturbed soil matrix in the second case. Other transfers are: infilled planar orthovoids, (rare) infilled vughs and sepic-like fabrics. The pressure-affected zones, zoocutans and soil cutans due to physical processes have already been discussed in Section 4.4.2.1.1 together with the voids they are associated with.

Regrouping phenomena may result from one single process, for example passage features, but may also have a complex genesis, as for example an infilled faunal channel with a mud-zoocutan.

#### Passage features (see Section 4.3.2.1)

Passage features were present in most of the intertidal zones except for the higher parts of the more sandy natural levees. They were abundant in the intertidal flat, transitional zone and lower salt basins. They decreased markedly with increasing ripening of the soil material. The transitions from passage features to channels produced by the same species, *Hydrobia ulvae*, occurring in zones with different ripening, clearly demonstrate the importance of the state of ripening of the sediment for the development of passage features. Individual passage features attained up to 10 mm in diameter, but usually the individual tracks were only a few millimetres

in cross-section. These individual tracks were only found locally in the thin sections. As each passage feature results from a single journey by an animal, usually in relation to the tides, individual tracks often cross. This produces a complex pattern of local oriented and reoriented zones in which part of an individual track is only rarely discernable. Remains of individual tracks with different diameters and the presence of several types and sizes of excrements reveal that more than one species has produced these complex patterns, especially those of the intertidal flats, transitional zone and lower parts of natural levees. In the salt basins the passage features were generally all produced by *Hydrobia ulvae*. Here *Hydrobia ulvae* seems to have burrowed into the sediment not only to avoid predators or dryness, but also in search for food. Passage features were particularly abundant in zones with many algae, or along and in root channels where high concentrations of diatoms (and probably also of bacteria) were often found. Apart from the passage features produced by *Hydrobia ulvae*, no other passage features could be ascribed to specific species with certainty. Whether the complex patterns were produced by several species or only by one, the final result is a more or less intensively bioturbated soil matrix.

The abundance of passage features does not necessarily mean that the animals producing them are more numerous than those producing faunal channels or striotubules. Faunal channels may be used more than once, and striotubules are produced by sessile species, whereas one animal producing passage features can bioturbate large parts of the soil matrix in a few days.

#### Pedotubules

These can be subdivided into striotubules, isotubules and aggotubules.

##### (i) Striotubules (see Section 4.3.2.1)

Striotubules were mainly restricted to the intertidal flat and transitional zone. They were unevenly distributed within these zones. Locally, high populations of striotubule-producing animals, such as pelecypods, caused high concentrations of striotubules. Discontinuities due to erosion and different sedimentation rates also resulted in uneven distributions. Therefore, abundance cannot be specified. Appendix 4 A shows that striotubules were also recorded in thin sections from samples taken in the salt marshes; however, these striotubules were present in buried intertidal flat and transitional zone deposits. Their diameters were up to 4 cm across. Most of the striotubules had a vertical orientation, which was sometimes slightly curved. Pressure-affected zones were often present along the striotubules. The striotubules present in thin sections were produced by (amongst others) *Mya arenaria*, *Macoma balthica* and *Cardium edule*.

##### (ii) Isotubules (see Section 4.3.3)

Pedotubules formed by wet gravitational infilling of channels were found in the intertidal flats, transitional zone and the salt marshes, with the exception of the higher natural levees. In the intertidal flats all the infilled channels were of faunal origin. In higher parts they were of floral as well as of faunal origin; in the salt marshes they were mainly of floral origin. The distribution and abundance of the pedotubules formed in this way in the intertidal flat had the same characteristics as those of the striotubules: they were locally abundant and unevenly distributed. In the salt marshes the highest frequencies were found in the low salt basins. Here many coarse root channels were infilled over long distances. This is a result of a combination of coarse, long, root channels and very unripened muddy soil material. In the upper zones of the higher salt marshes, infilled channels were not very abundant: they were restricted to the



muddy sediments. Deeper below the surface, they were more abundant. These zones generally coincided with low salt-marsh deposits.

The channels discussed here measured up to 2 cm in diameter. In the intertidal flat, transitional zone and lower part of the natural levees the infilled faunal channels were produced by species of *Vermes* and were the infilled syphonal channels of molluscs. In the basins of the salt marshes most of the infilled channels were produced by *Spartina townsendii*, for this species is most abundant here.

### (iii) Aggotubules

Aggotubules filled with excrements (see Section 4.3.2.1)

These aggotubules were present in the thin sections of the high intertidal flats and transitional zone. Nothing can be said about their abundance, as it is not known which species produced them, and they only occurred in the thin sections a few times. The diameters of the aggotubules filled with excrements measured up to 2 mm.

Aggotubules infilled with soil aggregates (see Section 4.3.3)

These aggotubules were found in the higher natural levees and in some transitions from high natural levee to salt basin. They were not very abundant and were predominantly found in sandy soil material. These aggotubules originated either as faunal or as floral channels. In thin sections, aggotubules formed from faunal channels predominated. The diameters were small and rarely larger than a few millimetres.

### Non-tubular transfers

(i) Infilling of voids other than channels (see Sections 4.3.3 and 4.4.2.1.1)

Infilled planar orthovoids were also found. An infilled planar orthovoid was only found once in a thin section from a high salt basin. This infilling consisted of coarse particles derived from storm-tide deposits. Field observations suggest that infilling of these shrinkage cracks in the high salt basins is not uncommon. Some vughs present in the highest sandy parts of the intertidal zone were filled with loose aggregates in the same way as the second type of the aggotubules. This phenomenon was rather rare.

(ii) Regrouping in the soil material (see also Section 4.3.2.2)

In the higher salt basins, where many root channels and effects of faunal activities such as channels, passage features and intergrades were present, striated fabrics were observed in the soil material. Floral and faunal activities caused pressure to be exerted on the soil material, resulting in pressure-affected zones. The higher degree of ripening and the large number of roots in the muddy soil material intensified these pressure-affected zones, producing local orientations of elongated particles of carbonates, for example in the fine fraction (less than 30  $\mu\text{m}$ ). These oriented zones resembled the sepic plasmic fabrics such as insepic, lattisepic, masepic and bimasepic recognized by BREWER (1964). These orientations also sometimes merged into the remains of organic matter, causing striated fabrics but in other cases no relation was found with organic matter. The anisotropic domains (in the sense of BREWER, 1964) with preferred orientations only rarely consisted of anisotropic clay minerals.

### 4.4.2.1.3 Transformations (see Section 4.3.4)

In this Section only the transformations in the soil matrix are discussed. Transformations due to processes related to voids have already been discussed in Section 4.4.2.1.1. The euhedral carbonate crystals were too sporadic to warrant inclusion here. In Section 4.3.4 the observations on this subject have already been discussed in detail.

(i) An important phenomenon belonging to the transformations is the presence of newly formed pyrite (neo-formation). To indicate the amount of pyrite that has been formed since deposition, the level of the pyrite that was geogenetically present was taken as reference. Neo-formation of pyrite was first seen in the transitional zone and continued up to the high salt marsh. Pyrite formation was restricted to the G horizon and to a small zone just above the G horizon where reduction and oxidation alternate. Pyrite formation is related to the presence of organic matter. As the organic matter content was found to be directly related to the clay content (see Section 3.4), pyrite formation was most evident in muddy sediment. The organic matter was usually rather randomly distributed in this sediment. In this organic matter the first indication of active pyrite formation was an increase in the number of small spherical framboidal pyrites. These spherical framboidal pyrites eventually completely filled the organic matter and were also present near organic matter. As the number of pyrite spheres increased, they also grew larger and amoeboidal pyrite and pyrite pseudomorphs were observed. This resulted in local clusters of pyrite spheres rather randomly distributed in the groundmass. In laminae nearly wholly composed of organic matter and in and near root-remains, large concentrations were sometimes present. The pyritization of root-remains has already been discussed in Section 4.4.2.1.1, which deals with floral channels.

The largest neo-formation of pyrite was found in muddy sediments in the middle-high salt marshes. In the low salt marshes high increases were also present. By contrast, in the high salt marshes pyrite was still being formed, but the quantities found were low. The greater abundance of pyrite with increasing depth in this zone mostly consisted of pyrite that had been formed when the sediment was located at about Mean High Tide level. It was not easy to identify where and when the actual neo-formation occurred. However, distinct increases in pyrite in the soil material were found extending from just above the G horizon to about 10 cm within it. By contrast, actual pyritization related to floral channels often took place deeper in the G horizon.

In sandy sediments very little pyrite had formed. In the sandy natural levees of the high salt marshes, the pyrite content decreased owing to oxidation. Perhaps the small increase in pyrite in the upper zones of the high salt basins is also due to local oxidation of pyrite, which reduces the increase at other locations in the same zone.

(ii) In the upper zones above the G horizon of the middle-high and high salt basins, manganese pseudomorphs were also present in the soil material. Around these manganese pseudomorphs, zones of ferric iron accumulations of varying thickness were present (see Section 4.3.4). Due to local oxidation in these zones, ferric iron fringes were found around pyrite present in the soil matrix. The ferric iron accumulations in the soil matrix formed only a minor part of the total ferric iron present; most was associated with voids. In the soil matrix the largest quantity was formed by the ferric iron accumulations around manganese pseudomorphs.

#### 4.4.2.1.4 Removals (see Section 4.3.4)

Removals from the soil matrix were restricted to carbonate deficiencies and a loss in salt-content. Distinct salt crystals were not observed: they were probably lost from the sample when the thin sections were being prepared, probably because of the low degree of crystallization in this frequently flooded material. In Appendix 4 A only a generalized outline of the carbonate deficiencies could be given, because the thin sections were too large to allow the characterization of the carbonate deficiencies. Table 15 shows the course of the deficiencies during continuing sedimentation more accurately. This table shows the dominant state of deficiency with depth. From this table four characteristics of decalcification are evident.



Table 15. Post-depositional changes in carbonate content of the fine and coarse material in the transitional zone and salt marshes.

	depth in cm										
	0	10	20	30	40	50	60	70	80	90	100cm
TRANSITIONAL ZONE:											
Profile no. 3, natural levee	1a				1a						
Profile no. 4, incipient salt basin	1a				1a						
LOW SALT MARSH:											
Profile no. 5, large natural levee	1a				1a			1a			
Profile no. 6, salt basin	1a				1a			1a			
Profile no. 7, small natural levee	1a				1a			1a			
Profile no. 8, salt basin	1a				1a			1a			
MIDDLE-HIGH SALT MARSH:											
Profile no. 9, small natural levee	1a	2a	3b	3b	2a	1/2a	1/2a				
Profile no. 10, salt basin	1a	2a	3b	3c	2a	2a	1/2a	1/2a			
Profile no. 11, large natural levee	1a	2a	2/3b	2/3b	2/3a	2a	1/2a				
Profile no. 12, salt basin	1a	2b	4c	3b	2a	1/2a	1/2a				
HIGH SALT MARSH:											
Profile no. 13, large natural levee	1a	1a	1a	2a	2a	1a	1a	1a			
Profile no. 14, transitional profile	1a	2b	3/4c	3c	2/3b	2a	1a	1a			
Profile no. 15, salt basin	1a	3b	4c	3c	2/3b	2a	1a	1a			
Profile no. 15b, salt basin	1a	3b	4c	4c							
Profile no. 16, buried sand-barrier	1a	3/4c	4c	4c	4b	2/3b	1a	1a			
FINE PARTICLES (< 30 μm)						COARSE PARTICLES (> 30 μm)					
1) dense calcic basic fabric (sedimentary)						a) many CaCO <sub>3</sub> grains (sedimentary)					
2) moderately calcic basic fabric						b) common CaCO <sub>3</sub> grains					
3) weak calcic basic fabric						c) few CaCO <sub>3</sub> grains					
4) sporadic calcic basic fabric											

(i) *The occurrence and degree of decalcification.* The decalcification starts in the middle-high salt marsh, increases with height and is most marked in the high salt basins. The lower parts of the intertidal zone still contain the carbonate content originally present at the time of sedimentation.

(ii) *The way in which the decalcification proceeds.* At first the fine carbonate particles in the fine fraction (less than 30 μm) decrease. Then this decrease of fine particles apparently slows

Table 16. Correlations of the different carbonate content criteria.

Field observations with HCl (10%)	Micromorphological observations <sup>1)</sup>	Chemical data % CaCO <sub>3</sub>
Calcareous	1a, 2a, (2b)	>2.5%
Slightly calcareous	(2b), 2/3b, 3b	1.6-2.5%
Non calcareous	3c, 3/4c, 4c	<1.6%

<sup>1)</sup> For explanation of micromorphological criteria see Table 15.

down because coarse grains are affected and first mostly break down into small particles. So in spite of their size, small particles were still found in zones with large deficiencies. In thin sections no distinct zones in which all the carbonate present was dissolved were found: some fine particles and a few larger carbonate grains were always observed. The deficiencies had no regular pattern; in the same lamina different deficiencies could be found often with the greatest deficiencies occurring near voids.

(iii) *The influence of the granular composition on the degree of deficiency:* the more coarse-grained the sediments, the lower the deficiency.

(iv) *The differences in depth at which the deficiencies begin.* The higher the level of the salt basins, the earlier the deficiencies occurred. The higher the level of the natural levees, the deeper the deficiencies were found. They always began above the G horizon, most usually in a zone 20-30 cm above this horizon.

The upper boundary of the zones without and with carbonate deficiencies was slightly undulating and in sediment with the same granular composition and height, was generally parallel to the surface. The transition from the zone without carbonate deficiency to a zone that was only slightly calcareous, 1a to 3b (see Table 15) took place over a thickness of 2 cm in the high, clay-rich salt basins. The lower boundary showed many tongues. Here there was a rapid transition (usually only a few millimetres) from the zone with large deficiencies to the original amount present in the sediment. Often a slight lowering of the sedimentary level remained micromorphologically visible in a rather broad zone below the strong deficiencies (see Table 15). The zone with distinct carbonate deficiencies had a lower boundary that lay above, at, or just inside the G horizon.

Map 3, Appendix 3, shows the occurrence of zones of different thicknesses that did not react with diluted HCl (10%), whereas Section 2.3.2 outlines the depth at which these zones began. A comparison of the results of field investigations, analytical data and micromorphological data is presented in Table 16.

The zones classified as calcareous in the field contained more than 2.5% CaCO<sub>3</sub>. However, micromorphological studies revealed that they could contain less calcareous material (beginning with fine particles and some coarse ones) than the amount originally in the sediment. Slightly calcareous zones had a large decrease of fine carbonate particles and a distinct decrease of coarse carbonate grains. They contained 1.6-2.5% CaCO<sub>3</sub>. The non-calcareous zones contained up to 1.6% carbonate. Low quantities of fine carbonate particles were still present, mostly derived from the fragmentation of coarser grains. The number of coarse grains decreased greatly.

From these data it is evident that (i) the decalcification of the sediment started when distinct aeration of the sediment occurred (see also Maps 2 and 3, Appendix 3), (ii) the decalcifications occurred in sediments where there were large quantities of newly-formed pyrite (see Appendix 4 and Section 4.4.2.1.3), (iii) the decalcification was greatest in clay-rich sediments that



contained most pyrite, and (iv) the degree of decalcification in the zone with deficiencies, and the topography of the lower boundary reveal that the deficiencies are related to better drainage via channels, slightly coarser-grained laminae in clay-rich materials and passage features. These data were important for the development of the hypothesis given at the end of Section 3.10. This hypothesis stated that cyclic oxidation and reduction involving iron may be one of the causes of decalcification and perhaps is the most important cause.

#### 4.4.3 Classification of the soil fabrics of the thin sections

During upward growth, successions and combinations of processes take place. The effects of these processes occurred on different scales, had different abundances and distributions and were to some extent related to specific granular compositions. These combined effects gave the soil material characteristic appearances. The resulting patterns visible in thin sections can be classified into four groups, which in turn can be divided into subgroups, types and subtypes. The first three levels of this classification concern the pedogenetic elements, whereas differentiation on the last level is based on geogenetic considerations.

(i) The groups are characterized by a specific combination of processes, resulting in characteristic patterns of phenomena and their abundance. These processes are (a) biological processes (phenomena caused by the fauna: passage features, striotubules, channels; those caused by the flora: channels) and (b) physical processes (phenomena: formation of shrinkage cracks and the results of wet and dry gravitational transport of soil material in voids, which are cutans and complete infillings).

(ii) The distinction into subgroups is based on absence or presence of ferrans and neoferrans. Quasiferrans have not been mentioned separately, for they only occurred occasionally and usually resulted from the downward transport of wet soil material. Cutanic and sub-cutanic features composed of carbonate, pyrite and manganese, are not included in the classification.

(iii) The 'types' are differentiated according to the abundance of a specific phenomenon. On this level a number of transitions are distinguished; these are termed 'varieties'.

(iv) At the lowest level of the classification, the geogenetic fabrics in which the types occurred are represented. Geogenetic fabrics are important because they form an essential part of the soil fabric. Moreover the types, occurrence and abundance of pedogenetic phenomena show changes with differences in granular composition and lamination.

Table 17 gives the classifications of the soil patterns. This classification is based on large thin sections (8 cm x 15 cm). The characteristic patterns always covered at least 90% (and sometimes over 95%) of the classified area of the thin section.

Phenomena previously recorded but not mentioned as important criteria in this classification have been mentioned in the explanatory text and may be added as subsidiary phenomena after the soil fabric has been classified.

##### Group 1

Characterization:

*biological processes*, phenomena and abundance:

*fauna* - many passage features, striotubules and channels made by several faunal species;

*physical processes*, phenomena and abundance:

*shrinkage* - common planar orthovoids

*downward transport of wet soil material in voids* - few to common complete infillings and cutans.

Table 17. Classification of soil fabrics present in thin sections from the intertidal zone.

GROUP 1: biological processes: fauna - many passage features, striotubules and channels, made by several faunal species				
physical processes : shrinkage - common planar orthovoids				
wet downward transport of soil material in voids - few to common complete infillings and cutans				
subgroup 1: without neoferrans and/or ferrans	: type 1	: with cracks	subtype 1: laminated bedding, sandy*	subtype 2: laminated bedding, sandy with mud pebbles
			subtype 3: laminated bedding, muddy	subtype 4: homogeneous bedding, sandy
			subtype 5: homogeneous bedding, muddy	
	: variety	: dominating characteristics of type 1, with few root-channels	subtype : same subtypes as type 1	
subgroup 1: without neoferrans and/or ferrans	: type 2	: without cracks	subtype 1: laminated bedding, sandy	subtype 2: laminated bedding, sandy with mud pebbles
			subtype 3: laminated bedding, muddy	subtype 4: homogeneous bedding, sandy
			subtype 5: homogeneous bedding, muddy	
	: variety	: dominating characteristics of type 2, with few root-channels	subtype : same subtypes as type 2	
subgroup 2: with neoferrans and/or ferrans	: type 1	: with cracks	subtype 1: laminated bedding, sandy	subtype 2: laminated bedding, sandy with mud pebbles
			subtype 3: laminated bedding, muddy	subtype 4: homogeneous bedding, sandy
			subtype 5: homogeneous bedding, muddy	
	: variety	: dominating characteristics of type 1, with few root-channels	subtype : same subtypes as type 1	
subgroup 2: with neoferrans and/or ferrans	: type 2	: without cracks	subtype 1: laminated bedding, sandy	subtype 2: laminated bedding, sandy with mud pebbles
			subtype 3: laminated bedding, muddy	subtype 4: homogeneous bedding, sandy
			subtype 5: homogeneous bedding, muddy	
	: variety	: dominating characteristics of type 2, with few root-channels	subtype : same subtypes as type 2	
GROUP 2: biological processes: fauna - many passage features and few central voids, mainly of <i>Hydrobia ulvae</i>				
flora - few, rather coarse channels				
physical processes : wet downward transport of soil material in voids - common complete infillings in channels and few cutans, present over long vertical trajectories				
subgroup 2: without neoferrans and/or ferrans	: type 1	: mainly <i>H. ulvae</i> activities	subtype 1: homogeneous bedding, muddy	
	: type 2	: central concept of the subgroup	subtype 1: homogeneous bedding, muddy	
	: variety	: dominating characteristics of type 2 in sediment, with properties of group 1	subtype 1: laminated bedding, muddy	subtype 2: homogeneous bedding, muddy



GROUP 3: biological processes: fauna - few to common passage features, partly with central voids, and some channels of *H. ulvae* and other species  
 flora - common channels  
 physical processes : wet downward transport of soil material in voids - few cutans and few to common complete infillings over short distances

subgroup 1: without neoferrans and/or ferrans : type 1 : central concept of the subgroup  
 subtype 1: laminated bedding, without domination of sand or mud laminae  
 subtype 2: laminated bedding, muddy  
 subtype 3: homogeneous bedding, muddy  
 : variety : dominating characteristics of type 1 in sediment, with properties of group 1  
 subtype : same subtypes as type 1

subgroup 2: with neoferrans and/or ferrans : type 1 : central concept of the subgroup  
 subtype 1: laminated bedding, sandy  
 subtype 2: laminated bedding, without domination of sand or mud laminae  
 subtype 3: laminated bedding, muddy  
 subtype 4: homogeneous bedding, muddy

GROUP 4: biological processes: fauna - common channels and passage features, mostly with central voids. Channels are usually dominant  
 flora - many channels  
 physical processes : shrinkage - few vughs  
 wet/dry downward transport of soil material in voids - few local cutans and complete infillings

subgroup 1: with neoferrans and/or ferrans, partly proceeding into the soil material : type 1 : central concept of the subgroup  
 subtype 1: laminated bedding, sandy  
 subtype 2: laminated bedding, without domination of sand or mud laminae  
 subtype 3: laminated bedding, muddy  
 subtype 4: homogeneous bedding, muddy

subgroup 2: yellow red-brown and ferruginous colouring in the material, with rare neoferrans and/or ferrans : type 1 : central concept of the subgroup  
 subtype 1: laminated bedding, sandy  
 subtype 2: laminated bedding, without domination of sand or mud laminae  
 subtype 3: laminated bedding, muddy  
 subtype 4: homogeneous bedding, muddy

sandy\*: in sandy laminae vesicles may be present.

each of these may be subdivided into two types i.e. one without and one with vertical planar orthovoids. In all types a variety that also contains some floral channels is discernable.

The original geogenetic fabric of this group was often considerably changed by passage features. The passage features were usually the most abundant phenomena due to faunal activity. A varying quantity of pedotubules, striotubules and infilled faunal channels formed the second important group of phenomena. A few faunal channels were also present. The pedotubules and the faunal channels were rather randomly distributed with mainly vertical orientations. In this basic pattern large vertical cracks were sometimes present eventually associated with neoferrans, ferrans and cutans of soil material. Carbonate accumulations in the form of quasicutans, neocutans and cutans, and manganese accumulations as neo-mangans were also found. There were no removals in the soil matrix.

## Group 2

Characterization:

*biological processes*, phenomena and abundance:

*fauna* - many passage features and few central voids, mainly produced by *Hydrobia ulvae*

*flora* - few rather coarse channels;

*physical processes*, phenomena and abundance:

*downward transport of wet soil material in voids* - common complete infillings in channels and few cutans, present over long vertical trajects.

Only one subgroup is discerned, i.e. one without neoferrans and ferrans. There are two types. In the first type the passage features of *Hydrobia ulvae* dominate the fabric. The second type is equivalent to the central concept of this group. One variety has been discerned. In this variety the phenomena of group 2 dominate but characteristics of group 1 also occur.

In usually homogeneous, muddy sediments in which sandy stormtide laminae occasionally occurred many passage features formed by *Hydrobia* were found. These animals had disturbed large parts of the original deposits, giving the muddy soil material a cloudy appearance. In the upper centimetres a few central voids were also found in the passage features. Some of the passage features extended over long vertical distances and locally had relatively distinct external boundaries. These passage features were associated with floral channels which often showed infilling of soil material. Other phenomena due to faunal activity were rarely found, such as an infilled channel or passage features due to juvenile shore crabs (*Carcinus maenas*). The few rather coarse floral channels, nearly all of *Spartina townsendii*, had approximately the same diameters and had mainly vertical orientations. Floral channels were generally infilled with soil material over long vertical trajects. In root remnants and organic matter embedded in the groundmass, framboidal pyrite was found, generally occurring in small spheres less than 25  $\mu\text{m}$  in diameter. There were no carbonate deficiencies in these soil fabrics.

## Group 3

Characterization:

*biological processes*, phenomena and abundance:

*fauna* - few to common passage features, partly with central voids, and some channels produced by *Hydrobia ulvae* and other species

*flora* - common channels;

*physical processes*, phenomena and abundance:

*downward transport of wet soil material in voids* - few cutans and few to common complete infillings over short distances.



There are two subgroups, one without and one with neoferrans and ferrans. Each of these subgroups has only one type in which the phenomena of the central concept of the subgroups are found. The type of subgroup 1 has a variety in which phenomena of group 1 occur.

In this group floral channels dominated. The type of subgroup 1 was characterized by (i) common fine to medium floral channels, with rather uniform sizes and an even distribution, (ii) few to common passage features, partly with central voids and faunal channels, not all made by *Hydrobia ulvae*. They were generally the same size or smaller than most of the floral channels, and (iii) in the channels local infillings of soil material, more often complete infillings than cutans, were found. The pedogenetic phenomena in subgroup 1 all were rather alike in size and distribution. In the soil matrices of this subgroup large quantities of newly formed pyrite were found. The framboidal pyrite spheres attained up to 180  $\mu\text{m}$  in diameter. Pyrite formation was common in root remnants. In some of the fabrics of this subgroup, small strongly decalcified horizontal zones were found.

Some of the pedogenetic phenomena in the second subgroup showed variations in size and distribution, related to different geogenetic fabrics.

– In thinly laminated sandy sediments the floral channels were fine and rather evenly distributed whereas the phenomena due to faunal activity were almost entirely restricted to small winding channels made by unidentified species. Some infilling of soil material due to downward transport of wet material was found locally in the channels.

– In the other laminated beddings of this subgroup, the dominant size of the floral channels was medium to coarse. Channels were the main phenomena due to faunal activity, but passage features also occurred. The sizes of the faunal channels were fine and medium. The fine channels were mostly identical with those from the previous subgroup, but some channels of *Hydrobia ulvae* also occurred. The rather important group of medium-sized channels was probably produced by species of the Vermes, perhaps *Nereis* spp. The faunal channels, especially the largest ones, generally had better developed neoferrans than floral channels. Ferrans were rare. In the channels some infilling of soil material due to downward transport of wet material was locally found.

– The homogeneous muddy sediments had common fine, medium and coarse channels, nearly all (except for some of the fine ones) produced by plants. The medium and coarse channels were mostly produced by *Spartina townsendii*. The effects of faunal activity were mainly restricted to passage features of *Hydrobia ulvae*. Downward transport of wet material was most accentuated in this subtype and was mainly found associated with the coarser floral channels.

In the first mentioned subtype of subgroup 2, the one developed in thinly laminated sandy sediment, neither neo-formation of pyrite nor carbonate deficiencies were found. In the other subtypes newly formed pyrite was present, though usually not in large amounts and less than 50  $\mu\text{m}$  in diameter. Carbonate deficiencies in the form of strongly decalcified small zones occurred, but were rare.

#### Group 4

Characterization:

*biological processes*, phenomena and abundance:

*fauna* - common channels and passage features, mostly with central voids. Channels are usually dominant

*flora* - many channels;

*physical processes*, phenomena and abundance:

*shrinkage* - few vughs

*downward transport of wet/dry soil material in voids* - few local cutans and local complete infillings.

Two subgroups were distinguished. In the first subgroup the accumulations of ferric iron were no longer restricted to distinct neoferrans and ferrans, but diffuse continuations of red-brown colours extended into the soil matrix, especially in muddier parts. In the second subgroup the ferric iron accumulations were found in the soil matrix, and were not so strongly coloured as in the previously described subgroups with iron accumulations. Neoferrans or ferrans were rare. Each of the subgroups had one type.

In this group many of the pedogenetic phenomena showed variation in size and distribution, related to different geogenetic fabrics. This variation was larger than in subgroup 2 of the previous group. Of the phenomena due to biological processes, floral channels dominated. In sandy laminated beddings, many fine, uniformly sized roots were usually present. The common faunal channels were fine and winding. In sediments where neither sand nor mud predominated, floral channels were fine to medium in size. Some faunal channels had larger diameters. They were fine to medium, less winding, and could be followed in thin section over longer distances than the faunal channels of the previous subtype. In muddy sediments fine, medium and coarse floral channels were present. Here fewer faunal channels, usually fine, were found. A few passage features of *Hydrobia ulvae* and transitions to channels were present too. The effects of pressure exerted by roots and fauna were present on a large scale, accentuated by the large numbers of channels.

In all subtypes there were few vughs due to shrinkage. They were most pronounced and largest in muddy sediment. In muddy sediments small planar orthovoids, due to shrinkage, were also found. In voids some downward transport of soil material in limited quantities sometimes occurred locally. In sandier sediments dry transport of mineral grains and small aggregates took place; in muddy sediments transport of both wet and dry soil material occurred.

All these phenomena were identical in both subgroups. In the first subgroup the neoferrans and ferrans were mainly associated with the channels. In the muddy sediments of subgroup 1, ferric iron accumulations were also found in the soil matrix around manganese pseudomorphs. In contrast with the first subgroup, the ferruginous colours in the second subgroup occurred dominantly in the soil and were relatively faintly developed. In sandy sediments the red-brown colouring in the matrix was less well pronounced than in muddy sediments.

In the sandy laminated beddings of both subgroups no pyrite was formed and no carbonate deficiencies found. The laminated beddings where neither sand or mud dominated, had neoformations of pyrite, but these were rare and comprised small amounts. The same holds for carbonate deficiencies. In muddy sediments only small amounts of newly formed pyrite were found, although pyritized roots occurred. By contrast, the carbonate deficiency was sometimes very impressive, especially in subgroup 1 where large parts of the thin sections were sometimes almost completely decalcified.

In Table 18 the thin sections taken in the intertidal zone and arranged into zonations and locations, are classified according to the above system. When all the thin sections classified into the same group, subgroup, type and subtype are arranged according to zonation and location, they can be interpreted as follows:

#### Group 1

Group 1 comprises all the thin sections of samples taken in the intertidal flat and some of the deepest samples from higher profiles. The presence of neoferrans and ferrans is associated



Table 18. Soil fabrics of the thin sections taken in the intertidal zone.

Zone, location and depth in cm of the thin sections		Group	Subgroup	Type	Subtype
Low intertidal flat	profile no. 1: 0- 15	1	1	2	1
	5- 20	1	2	1	1
High intertidal flat	profile no. 2: 0- 15	1	2	2	3
	: 4- 19	1	2	1	3
	near profile no. 2: 0- 15	1	2	1	1
Transitional zone	n.l. profile no. 3: 0- 15	3	2/1	1/1	3/2
	21- 36	3	2	1	3
	40- 55	1	1	var.2	1
	i.s.b. profile no. 4: 0- 15	1	1	var.2	5
	15- 30	1	1	var.2	5
Low salt marsh	n.l. profile no. 5: 0- 15	3	2	1	4
	24- 39	3	2	1	3
	45- 60	1	2	var.2	3
	68- 83	1	1	var.2	1
	s.b. profile no. 6: 0- 15	2	1	1	1
	0- 15*	3	2	1	4
	15- 30	2	1	2	1
	30- 45	3	1	var.1	3
	n.l. profile no. 7: 0- 15	3	2	1	4
	18- 33	3	1	1	2
	45- 60	3	1	1	3
	s.b. profile no. 8: 0- 15	2	1	2	1
	0- 15*	3	2	1	4
	15- 30	2	1	2	1
	33- 48	2	1	var.2	2
	52- 67	1	1	var.2	3
	Middle-high salt marsh	n.l. profile no. 9: 0- 15	4	1	1
23- 38		3	2	1	4
44- 59		3	1	1	3
62- 77		3	1	1	3
s.b. profile no.10: 0- 15		4/3	1/2	1/1	4/4
22- 37		3	2	1	4
39- 54		3	2	1	3
n.l. profile no.11: 0- 15		4	2	1	2
17- 32		4	2	1	2
39- 54		3	2	1	3
75- 90		2	1	var.2	1
s.b. profile no.12: 0- 15		4	2/1	1	4
17- 32		3	1	1	4
38- 53		3	1	1	3
68- 83		3	1	1	3
High salt marsh		n.l. profile no.13: 0- 15	4	2	1
	15- 30	4	2	1	1
	33- 48	4	2	1	2
	55- 70	4	2	1	2
	75- 90	3	2	1	1
	92-107	3	2	1	1
	124-140	1	1	2	1
	tr. profile no.14: 0- 15	4	2/1	1	2
	38- 53	3	2	1	3
	54- 69	3	2	1	3
	69- 84	3	1	1	2
	90-105	1	1	var.2	1
	s.b. profile no.15: 0- 15	4	1	1	4
	15- 30	4/3	1/1	1/1	4/3
	55- 70	2	1	2	1
	90-105	1	1	var.2	1
	profile no.15b: 0- 15	2/4	1/1	1/1	1/4
	15- 30	4	1	1	4
	b.s.b. profile no.16: 0- 15	4	1	1	4
	15- 30	4	1	1	3
40- 55	1	1	var.2	2	
56- 71	1	1	var.2	2	

i. = incipient  
s.b. = salt basin  
n.l. = natural levee  
tr. = transition n.l. to s.b.  
b.s.b. = buried sand barrier  
var. = variety  
\* = sample taken one year later

with the better drained parts of the intertidal flat, i.e. the higher unvegetated parts and the zones along gullies. Thus the subgroups are related to separate parts of the intertidal flat. Both types distinguished occur in the same locations. This is because of the dimensions of the large polygons present in the intertidal zone. Sometimes a planar orthovoid is included, sometimes not.

Thin sections belonging to group 1, which are derived from the deepest parts of the higher-situated sample sites, represent buried intertidal flat deposits. Thus after being covered with younger sediments the original characteristics of the intertidal flat deposits remain. In this buried intertidal flat deposit sometimes a few roots of the vegetation growing on the younger sediments penetrate and add a new feature. These roots may be of *Spartina townsendii* or of *Aster tripolium*. These intertidal flat deposits are represented in the varieties.

#### Group 2

This group represents thin sections of samples taken in the salt basins of the low marsh and some deeper samples from sites in higher-situated salt marshes. These sediments were not aerated and so only one subgroup is found (see also Map 2 A, B, Appendix 3). This subgroup has two types. The first type, in which *Hydrobia ulvae* activities predominate, is present in parts of the unvegetated low salt basins, such as salt pans, and in the first centimetres of rather fresh sediment where the leafy sprouts from the rhizomes have not yet penetrated. The second type, which is more frequent, occurs in the vegetated low salt basins, where the vegetation mainly consists of *Spartina townsendii*. Both types have only one, identical, subtype: a homogeneous muddy bedding. The observed variety of the second type has the characteristics of this type but in the soil fabric properties of group 1 are also present, increasing with depth.

The conclusion must be drawn that this group represents a soil fabric that can be formed directly upon intertidal flat deposits. Thus the varieties of group 2 represent transitions which already mainly have the characteristics of group 2. This is confirmed by the presence of soil material with a soil fabric of group 2 above soil material with a soil fabric classified as group 1 in two successive thin sections of deeper samples taken in a high salt basin (Profile no. 15). After covering with younger sediments, the soil fabric of these materials remains unchanged, and thus the deeper samples from sites in higher-situated salt marshes are classified in the same category as more recent ones.

#### Group 3

In group 3 a clear distinction between both subgroups can be made. Both have only one type which is identical with the central concept of the subgroups.

(i) The phenomena of subgroup 1 of group 3 are characteristic for recently buried low salt-marsh deposits. The subtypes 'laminated bedding without domination of sand or mud' and 'muddy' are found associated with natural levees; the subtype 'muddy homogeneous beddings' is present in the salt basins. In the salt basins these muddy homogeneous beddings may occur next to or on deposits with a soil fabric belonging to group 2. The occurrence of a variety in which some properties of group 1 are present reveals that sediment with a soil fabric of this subtype can be developed on intertidal flat deposits. Deposits with characteristics of subgroup 1 of group 3 may occur in rather thick layers.

(ii) Soil material having phenomena from subgroup 2 of group 3 is found on soil material with characteristics of subgroup 1 of group 3 and of group 2. As in the type from the previous subgroup, there are more subtypes. These subtypes have a more distinctive character than the subtypes of the previous groups, as the size and distribution of the phenomena change more with the geogenetic fabrics.

The subtypes with a sandy laminated bedding or a laminated bedding without domination of sand or mud are associated with natural levees; i.e. the high parts of large natural levees in



the low salt marsh, the natural levees of the middle-high salt marsh and some small natural levees in the high salt marsh. The muddy beddings, whether laminated or homogeneous, can be found in the upper parts of small natural levees but they are more common in the salt basins of the middle-high salt marsh.

The transition of subgroup 1 to subgroup 2 of group 3 can take place within a few centimetres as a result of the aeration of the soil. As both subgroups have soil fabrics with an identical central concept, the occurrence of aeration determines the subgroup. As in the previous groups, sediment with the characteristics of group 3 can be found buried under younger sediments. This only occurs in the high salt marshes.

#### Group 4

The occurrence of both subgroups of group 4 is largely restricted to the high salt marshes. Sediment with characteristics of subgroup 1 of this group is generally found on sediment with properties of group 3, subgroup 2, and sediment with characteristics of subgroup 2 is found upon material classified as subgroup 1 of this group.

In sandy soil material the transition from subgroup 2 of group 3 to subgroup 2 of group 4 is generally rather direct with only rarely a distinct zone with characteristics from subgroup 1 of group 4. By contrast, in muddy soil material, subgroup 1 of group 4 is important: it can also be found in the middle-high salt-marsh deposits, namely in the high natural levees, and sometimes in the first centimetres of the highest salt basins. Subgroup 2 of this group is restricted to the highest part of the high salt marsh; in the high natural levees and upper centimetres of the highest salt basins. In this group the separate subtypes of the subgroups show the largest differentiation.

From this distribution of the soil fabrics over the intertidal zone several conclusions can be drawn.

- (i) During upward growth several clearly distinguishable soil patterns develop.
- (ii) The different groups of soil patterns correlate strongly with the zonation used in the intertidal zone.
- (iii) In the higher zonations in spite of their larger differentiation (see also Map 1-4, Appendix 3) the soil fabric remains characterized by a specific combination of phenomena. These phenomena however show more variation in size and distribution with changes in granular composition.
- (iv) Subsequent covering with younger sediment preserves the characteristics acquired from a specific zonation. This means that in a profile in the high salt marsh, preserved fabrics of the middle-high and low salt marsh and intertidal flat can be recognized.

These conclusions indicate that the level at which a sediment is deposited in relation to the tides determines the soil fabric. At different levels the sediment acquires other characteristic phenomena. Thus the different soil fabrics are not related to differences in age of the sediment, or to changes occurring after they have been covered with younger sediments.

#### 4.4.4 Outline of soil development during upward growth in the intertidal zone

In Section 4.4.2 the occurrence and abundance of the phenomena distinguished over the intertidal zone were discussed. The combined effects of the individual phenomena resulting in the different soil fabrics visible in thin sections were treated in Section 4.4.3. An outline of the results of both sections is given in Table 19. This table again shows the distinct succession in occurrence and intensity of the pedological features from low water level to highest saltings in the recent deposits and the correlation with the groups and subgroups of the classification.

Differences in geogenetic fabrics are not indicated in this table. The higher the level of deposition, the larger the differences in granular composition become (see Section 1.3). Granular composition strongly influences the occurrence of certain processes and the appearance of phenomena. Examples are: (i) the negligible formation of pyrite in sandy soil materials compared with muddy ones, (ii) the lack of carbonate deficiencies in sandy soil material, (iii) in the salt marshes, the predominance of faunal channels in sandy soil material and of passage features in muddy material and (iv) the presence of certain species of plants and animals on and in certain soil materials, resulting in different sizes, shapes and distributions of faunal and floral phenomena in the sediment.

Table 19. Correlation between the occurrence of the characteristic phenomena and the groups and subgroups of fabrics in the intertidal zone.

Phenomena in recent deposits	Intertidal flat			Salt marshes			
	low	high	transition	low	middle-high	high	
Voids	- planar orthovoids	▨	-	-	-	-	▨
	- vughs						▨
	- faunal channels	▨	▨	▨	▨	▨	▨
	- central voids in passage features	-	-	-	-	▨	-
	- floral channels			-	▨	▨	▨
Transfers	- passage features	▨	▨	▨	▨	▨	-
	- striotubules	▨	▨	▨	▨	▨	-
	- wet downward transport of soil material in channels	▨	▨	▨	▨	▨	-
	- dry downward transport of soil material in channels					▨	▨
	- infilled planar orthovoids						▨
Transformations	- carbonate accumulations	▨					
	- pyrite neo-formation		-	-	-	-	▨
	- ferric iron accumulations		▨	▨	▨	▨	▨
Removals	- carbonate deficiencies					-	▨
Classification, recent deposits							
Group 1, both subgroups	▨						
Group 2, one subgroup			▨				
Group 3, subgroup 1			▨				
subgroup 2					▨		
Group 4, subgroup 1						▨	
subgroup 2						▨	
- = rare, but present      ▨ = general occurrence      ▨ = maximal development							



In conclusion, soil development changes upslope from low water level to the highest saltings and the ultimate soil fabric in a certain zone is related to the geogenetic fabric.

Not only is the geogenesis of the intertidal zone determined by the dynamics of the tide; the pedogenesis of this zone is also determined by the tide to a large extent. As one moves upslope in the intertidal zone, the flooding frequency and duration of the tides diminish and consequently the possibilities for aeration and evaporation in the sediment increase. Evaporation influences the moisture content of the sediment, which in turn influences the consistency and type of transport of soil material in voids. Cracks and the irregular vughs in the high salt marshes both due to shrinkage are another result of evaporation. The chemical processes that were distinguished in the thin sections resulted largely from evaporation and aeration. Many chemical processes were restricted to a zone just above and in the top of the G horizon. Pyrite formation, which occurred mainly in muddy sediment, took place just above and in the top of this horizon. The accumulation of ferric iron was mostly found just above this horizon. The carbonate deficiencies in the muddy sediments were also associated with the zone just above and in the top of the G horizon. Thus most of the physical and chemical processes are related to the dynamics of the tide. In this case weather factors such as temperature, wind and rain play an important role.

Biological processes occurred over the whole intertidal zone. However, the distribution of the faunal and floral species over the intertidal zone correlated with specific environments, generally related to flooding frequency and duration, and granular composition of the sediment. It is difficult to evaluate fully the importance of the processes distinguished, because they were mostly micromorphographically assessed. The importance of the processes can be estimated on the percentage of the area occupied by a feature in a large thin section (8 cm x 15 cm). Because of the constraints imposed by the size of the thin sections, large and unevenly distributed phenomena could not be adequately represented, and so the values obtained must be regarded as approximate only. Given these limitations the following general trend of the soil development in the intertidal zone can be given.

In Figure 53 the characteristic phenomena of the processes are shown schematically for each zone. For the salt marshes two examples are presented to show the phenomena at each end of the range of granular compositions. Up to the low salt marsh the current velocities are too high to give a distinct differentiation in granular composition. So for this zone only one example is given. Fabrics of soil materials with granular compositions between both extremes given in Figure 53 showed transitions from these fabrics. In the classification these transitions are represented as different subtypes. In the zones distinguished only the soil development that takes place in recent sediment is dealt with. In Figure 53 the patterns of the different zones from low water level to high salt marsh are given from bottom to top, so idealized successions of the soil fabrics present in high salt marsh profiles can also be seen. The transitions in granular composition that occurred along the surface within a zone also appeared vertically in the profile as sedimentation increased. In the classification these vertical transitions are presented as varieties. However, these transitions took place over short distances, usually less than 20 cm. The granular composition may change in a vertical direction too, producing successions of transitions within the different zones. These cases occurred, for example, when new creeks were formed or when a creek changed course (see Figure 20). Generally the thickness of the deposits in the different zones decreased with increasing height.

#### *Intertidal flat and part of the transitional zone*

In the intertidal flat and large parts of the transitional zone chemical processes were of minor importance. Biological processes (mostly restricted to faunal activities) and physical

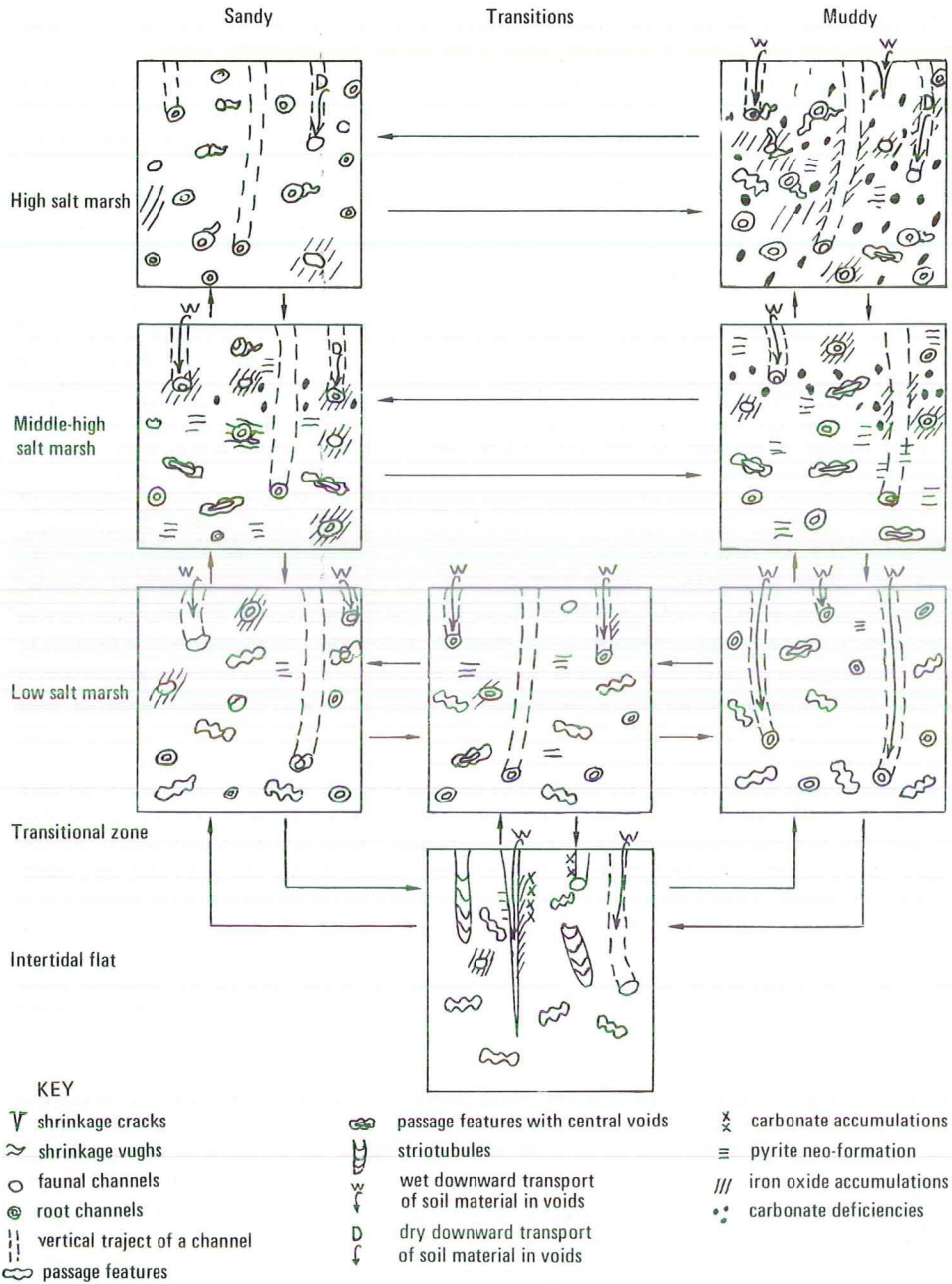


Fig. 53. Schematic representation of the characteristic phenomena of soil-forming processes in the different subzones of the intertidal zone.



processes dominated and their effects on the geogenetic fabric were generally large. Voids were formed by faunal activity as well as by physical processes. Whole parts of the original fabric were homogenized as a result of the formation of passage features. Striotubules were present in varying distributions and sizes. Many of the voids had been subsequently infilled. Voids that had not yet been infilled sometimes had accumulations of carbonates, manganese and ferric iron in the soil matrix near and along voids.

These soil fabrics, all belonging to group 1 of the classification, were found in the soil units indicated as 4/5, 0; 4/5, 0<sub>1</sub>; 4,1 and the part of 2,1 that had no cover of phanerogams (see the soil map, Appendix 3). In the soil units 2,1 and 1,2 fabrics belonging to the varieties of group 1 were found.

#### *Remaining part of the transitional zone and low salt marsh*

In these zones biological and physical processes dominated. As well as faunal activities, the influence of the vegetation was also important. Chemical processes remained less important. The geogenetic fabric was usually strongly influenced by pedogenetic development.

Three different soil fabrics were important in these zones: a muddy one with a very high water content (classification group 2); a muddy one with a lower water content and often slightly sandier (classification group 3, subgroup 1) and a sandy soil fabric (classification group 3, subgroup 1 and 2). In all the soil fabrics voids had been formed, mainly by biological processes. Floral channels dominated. Large parts of the geogenetic fabric, mostly in the first mentioned soil fabric were homogenized by the occurrence of passage features. Downward movement of wet soil material in voids had occurred on a large scale. In the first mentioned soil fabric it continued over long distances. Transformations were restricted to formations of small amounts of framboidal pyrite as small spheres and pyritization of organic fragments, and the formation of some neoferrans and ferrans. Pyrite formation was found in muddy sediments, especially in the second soil fabric; neoferrans and ferrans were mainly restricted to the sandy soil fabric. These three soil fabrics may represent a sequence from wet salt basin to natural levee. But varying successions also occurred vertically in the sediment. Soil fabrics 1 and 2 sometimes alternated, and soil fabric 3 could be present on top of soil fabric 2.

These soil fabrics correlated with the following soil units of the soil map:

*Muddy soil fabric*, classification group 2: soil units 1,3 and a part of the associations 1/2,3 and 1/2,8. The variety of type 2 of this group was also found in parts of the transitional zone with a soil unit 1,2. This soil fabric was found in the most unripened parts of the salt basins or in incipient salt basins.

*Muddy soil fabric with a lower water content and often slightly sandier*, classification group 3, subgroup 1: soil units 2,3; 2,2 and parts of the associations 1/2,3 and 1/2,8, not all occurring in natural levees.

*Sandy soil fabric*, classification group 3, subgroup 1 and 2: soil units 4,1; 3,1; 2,1 and 3,2. The unit 2,2 occurring in small natural levees also had a soil fabric belonging to group 3, subgroup 2. Subgroup 2 of group 3 was found when the soil units were on natural levees, otherwise subgroup 1 was found.

#### *Middle-high salt marsh*

In the middle-high salt marsh biological and chemical processes dominated. The importance of physical processes was slightly reduced. The geogenetic fabric became less homogenized because passage features became less common. More voids were present, mainly

as a result of an increase in the formation of faunal channels, and because there were central voids in the passage features. In the soil matrix the constituent particles could be oriented and compacted, largely due to pressure exerted by roots. Both wet and dry downward movement of soil material had occurred in voids, the first type to a lesser degree than in the previous zones. Dry downward movement of soil material was restricted to the sandy soil fabrics. Pyrite neo-formation reached maximal values. Many framboidal pyrite spheres with much larger diameters than in the previous zones were found. Pyritization of larger fragments of organic matter was common. Pyritans were present too. Neoferrans and ferrans were common. Carbonate deficiencies were found in small zones in muddy soil material.

Several soil fabrics were distinguished (see Section 4.4.3) ranging from sandy laminated sediment to homogeneous muddy sediment. In the sandy laminated sediment a distinct increase of faunal channels was found at the expense of passage features. The floral channels varied in diameter and distribution. In voids downward movement of dry soil material had sometimes taken place. Distinct neoferrans and ferrans were present. Large increases in pyrite quantities were rare, carbonate deficiencies were also rare. In homogeneous muddy sediments, passage features still dominated as a result of faunal activity. However, these passage features sometimes had many central voids. The floral channels were rather wide, and had uniform diameters and distributions. In the soil matrix, distinct zones with orientation and compaction of the constituents were found. Wet downward movement of soil material had taken place over short distances to a minor degree. Pyrite formation showed maximal values. Neoferrans and ferrans were present, but were not as well developed as in the sandy soil fabrics. Carbonate deficiencies over small zones were common. In this case the soil fabrics formed a sequence from salt basin (muddy homogeneous variant) to natural levee (laminated sandy variant). Thus the transitional soil fabrics were found between the real salt basins and large natural levees or in smaller natural levees.

These soil fabrics correlated with the following soil units of the soil map:

*Homogeneous muddy sediment*, classification group 3, subgroup 2 and group 4, subgroup 1. Soil units 1/2,8 (partly), 2,8 and 3,8 belong to this soil fabric. The lowest largest parts of the salt basins with soil units 1/2,8 and 2,8 had fabrics of group 3, subgroup 2. On the fringes of the basins and on some local higher parts in soil unit 2,8 the soil fabric of group 4, subgroup 1 was found, sometimes only in the upper few centimetres. In the small natural levees, soil unit 3,8, the soil fabric belonged to group 4, subgroup 1.

*Laminated sandy sediment*, classification group 4, subgroup 1. Soil unit 4,1 belongs to this soil fabric. These fabrics were restricted to the highest natural levees of this zone. In the smaller natural levees and transitions from high natural levees to salt basins with soil unit 3,2 the fabric generally belonged to group 4, subgroup 1.

### *High salt marsh*

In the high salt marshes biological, physical and chemical processes were important. The geogenetic fabrics became less homogenized. More voids were present because of an increase in shrinkage voids and in faunal and floral channels. Distinct orientations and compactions in the soil matrix were found, mainly caused by pressure exerted by roots.

In this zone several soil fabrics were also distinguished, ranging from sandy laminated sediments to homogeneous muddy ones. Passage features remained an essential characteristic of the faunal activity in muddy homogeneous sediments. They were not observed in the sandy soil fabrics. Wet and dry downward movement of soil material had taken place to a minor extent; both types in the muddy soil fabrics, dry transport only in the sandy ones. Pyrite neo-formation still occurred in the muddy sediments, but the amounts were small. In the muddy



soil fabrics, redbrown colouring occurred in the soil matrix; this was locally related to some neoferrans and ferrans. These colours were less pronounced than in the previous zones, except when present around manganese pseudomorphs and rare oxidizing pyrite. In the sandy soil materials, red-brown colouring was rare and neoferrans and ferrans were absent. These decreases in ferruginous colours were due to the greater distance above the G horizon. In the muddy sediments there were large carbonate deficiencies over broad zones, but no carbonate deficiencies were found in sandy soil fabrics. In this case too the soil fabrics formed a sequence from salt basin to natural levee. The sandy laminated soil fabric only occurred in the largest natural levees. Transitional soil fabrics occurred in broad zones from the salt basins to the natural levee. The homogeneous muddy soil fabric was found in the salt basins.

These soil fabrics correlated with the following soil units of the soil map:

*Homogeneous muddy sediment*, classification group 4, subgroup 1. Soil units 2,8 and 3,8 belong to this group. They were found in the salt basins.

*Laminated sandy sediment*, classification group 4, subgroup 2. Soil unit 5,00 and large parts of 4,1 belong to this group. This soil fabric was only found in the highest natural levees, where the recent sediment was deposited too high above the G horizon to be influenced by redox reactions. A minor part of the laminated sandy sediment with soil unit 4,1 had a soil fabric belonging to group 4, subgroup 1. These sediments occurred in smaller natural levees.

Soil unit 3,2 occurring between real salt basins and high natural levees or as small natural levees had a soil fabric of group 4, subgroup 1. Soil unit 3,2 on the buried sand barrier also had this soil fabric. Soil unit 2,2 on the same buried sand barrier generally had a soil fabric belonging to group 3, subgroup 2, as did soil unit 2,2 which was not on the buried sand barrier.

#### 4.5 PEDOGENETIC FABRICS IN SOME SOILS ON THE LANDWARD SIDE OF THE DIKE

The selection of the soils in the polders has already been discussed in Section 2.6; the analytical data were presented in Chapter 3. The soils selected in the polders were sufficiently representative to enable a good comparison to be made with the development of soils in the present-day intertidal zone. The marine origin of the soil material in the polders was not only evident from the presence of marine diatoms, shells and snails still in original position, but also by pedological features that were identical with those in the present-day intertidal zone.

In the following sections the unchanged and recognizable features of soil development in the present-day intertidal zone will be discussed first; next the changes that are taking place or have taken place in these soils after reclamation are given. A survey of the micro-morphological data on these subjects is given in Appendix 4 B.

##### 4.5.1 Recognizable phenomena of soil development in the intertidal zone

In this Section the phenomena have first been grouped according to the processes they belong to, as was done in Sections 4.3.2, 4.3.3 and 4.3.4. Then, the phenomena preserved in the soil fabrics have been used to correlate the soil fabrics with the subzones and locations that can be distinguished in the present-day intertidal zone.

#### 4.5.1.1 Recognizable inherited phenomena resulting from biological processes

##### *Faunal channels*

Preserved channels made by the fauna of the intertidal zone were recognizable by their morphology, associated phenomena and location. Pressure-affected zones with compactions, orientations of elongated particles and upward and downward deflections of laminae were still visible. Zoocutans, such as mud-zoocutans, sometimes with distinctively shaped excrements were found quite often. Once, part of an overlapping compound zoocutan was found. Neoferrans and ferrans were still visible, and so were infilled faunal channels. Some of the channels and associated phenomena had been disturbed, mainly by pressure and shrinkage that had taken place after embankment. New types of infilling were found. These aspects are dealt with in Section 4.5.2.

##### *Faunal pedotubules*

Channels completely filled with excrements, as described in Section 4.3.2.1, were often found. One of these filled channels was followed for several centimetres. Striotubules were often present. In vertical thin sections the most common type, A, and a cross-section of type C (see Figure 33) were observed. In horizontal thin sections all the cross-sections given in Figure 33 were observed. Some of the striotubules could be identified as those made by *Scrobicularia plana*, for shells of this animal were found in their original position. The cross-section given in Figure 54 was most probably also produced by this species. In this case the channels of the syphons were unchanged and had not been infilled 260 years after embankment. Pressure-affected zones associated with striotubules were still visible. Strio-

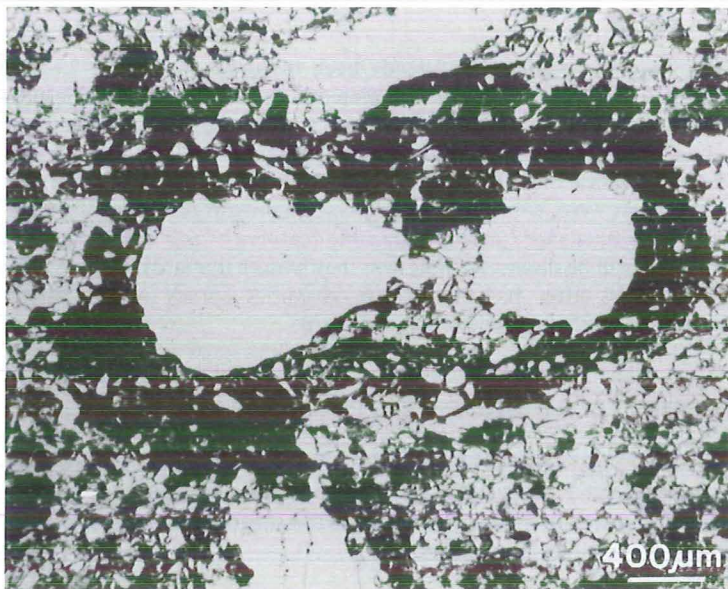


Fig. 54. Syphon channels of a pelecypod with neoferrans; ca. 260 years after reclamation (cross-section a of type A, Fig. 33).



tubules rarely showed postreclamation changes, because they were completely composed of soil material. Channels filled with excrements sometimes had local deformations due to compression, but it was impossible to say whether this compression had occurred before or after reclamation.

### *Passage features*

Passage features were still visible in the thin sections. The most significant phenomena were the embedded excrements produced as the animal moved through the sediment. These excrements retained their original compositions, and shapes, though they had slightly diminished in size. The already faint passage tracks of the animals became even more difficult to detect. In laminated sediment the typical disturbances of the lamination remained visible; in homogeneous muddy sediment they disappeared almost completely. Passage features made by *Hydrobia ulvae* in homogeneous muddy sediment could only rarely be identified from the original passage track. Usually the passage features were only identifiable by means of associated phenomena such as disturbances in floral channels, fragmented neoferrans embedded in the track (see Figure 39) and disturbance of storm-tide laminae. Only rarely was a fossil snail

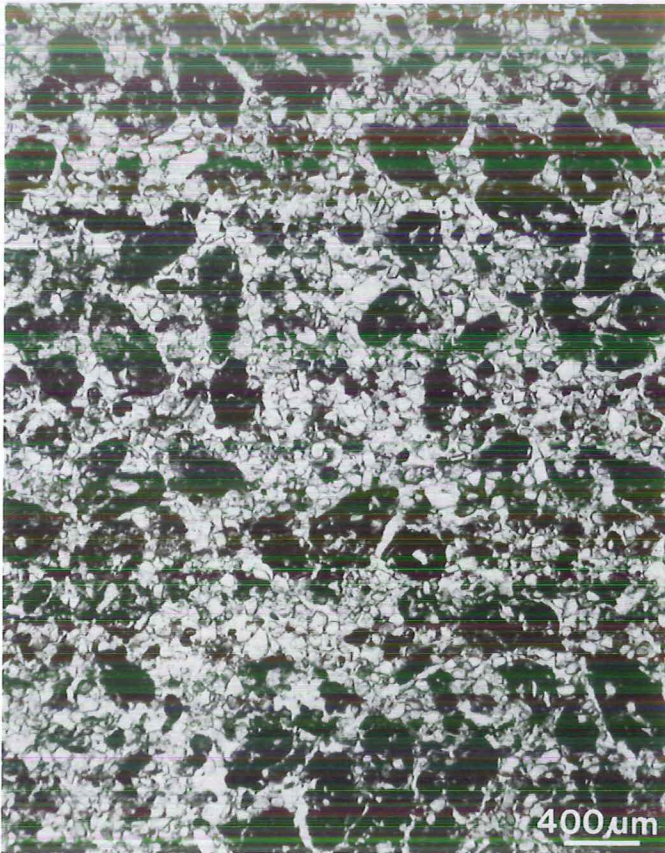


Fig. 55. Complex pattern due to crossing of many passage features; ca. 120 years after reclamation.

present. Many clay domains were found in homogeneous muddy sediment after reclamation; these obscured the original tracks. In Section 4.5.2 this aspect is discussed in more detail. The complex patterns resulting from the crossings of many passage features made by different species, which caused a remarkable homogenization and the addition of many excrements of different kinds, were still found almost unchanged (see Figure 55).

From these morphological data it is evident that all the types of faunal activity distinguished in the present-day intertidal zone can still be found in reclaimed soils. These phenomena were not only observed in soil material from the profiles selected in the Bathpolders but also in the soil profile chosen in the Rippolder, which was embanked in 1713.

#### *Floral channels*

Channels made by the former vegetation were abundant. Most of the floral channels were empty: there seemed to be far more empty channels in reclaimed soils than in present-day intertidal zone soils. In the floral channels in the thin sections from the present-day intertidal zone, the roots that had produced the channels had been preserved by slow humification under anaerobic conditions long after they had ceased to function. These roots had disappeared from the polder soils and were not found in thin sections. Floral channels could be determined not only by their morphology, position and dendritic systems but also by associated phenomena. Sometimes pressure-affected zones and downward deflection of the laminae were observed. The presence of framboidal pyrite provided an important clue: these pyrite spheres or pseudomorphs had formed in decaying roots and pyrite formation had continued in cutans in the floral channels and neocutans in the soil matrix. The channels associated with pyrites must have been of floral origin because pyrite is rarely formed in faunal channels. In the polder soils a new type of pyrite occurrence was also frequently found: this was the complete infilling usually of small channels with pyrite spheres. These pyrite-sphere tubules probably result from the accumulation of pyrite spheres, derived from decomposed pyritized roots, in deeper parts of the former channel systems. This pyrite must have moved downward from its place of origin by gravitational forces. Concentrations of pyrite spheres were often observed in infilled channels: these too must have been derived from decomposed pyritized root remnants, and this indicates that the channels were originally made by the flora. Much of the pyrite had begun to oxidize. This aspect is dealt with further in Section 4.5.2. Floral channels were sometimes partly but rarely completely, infilled after reclamation. Post-reclamation infilling had different characteristics from pre-reclamation infillings. Some of the channels had been deformed and disturbed by post-reclamation pressure and shrinkage.

#### *4.5.1.2 Recognizable inherited phenomena resulting from physical processes*

##### *Shrinkage cracks*

The large polygon shrinkage cracks of the intertidal flat, with or without neoferrans were still present. The smaller polygon patterns of the high salt basins were not found because the upper parts of the sediment had been radically changed by human activities, such as levelling of the surface and ploughing. Undamaged shrinkage cracks may have been preserved in natural levees, but none were observed in the few reclaimed soils studied. The large polygon shrinkage cracks were locally filled with coarse particles; this infilling probably occurred before reclamation.



In former salt basins, large irregular vughs caused by small shrinkage cracks originating from large root channels were observed. However, it is doubtful whether these irregular vughs, identical with the ones described in Section 4.3.3, resulted solely from pre-reclamation processes. Other phenomena present in the same soil fabric gave these soil materials the characteristics of former low and middle-high salt basins. In the present-day intertidal zone these vughs were predominantly found in the high salt basins. After reclamation, due to increased ripening, the development of these irregular vughs was more pronounced so that they were formed deeper below the surface. Mineral aggregates were found locally in these irregular vughs.

### *Compaction*

There was much more evidence of compaction in the thin sections of the reclaimed soils than in those of the intertidal zone. The results of the bulk densities discussed in Section 3.5 indicate this increased compaction. As the phenomena due to compaction mainly result from processes occurring after embankment, they will be discussed in Section 4.5.2.

### *Downward transport of soil material in voids*

The phenomena resulting from the downward movement of wet soil material in voids, as described in Section 4.3.3, were still present. Infillings produced by this process in rather homogeneous mixtures were easily recognizable as such, regardless of whether the infillings were composed of coarse or fine particles, or of combinations of material resulting from more than one inflow. Post-reclamation infillings had different characteristics, with the exception of the dry gravitational infilling already observed at a small scale before reclamation.

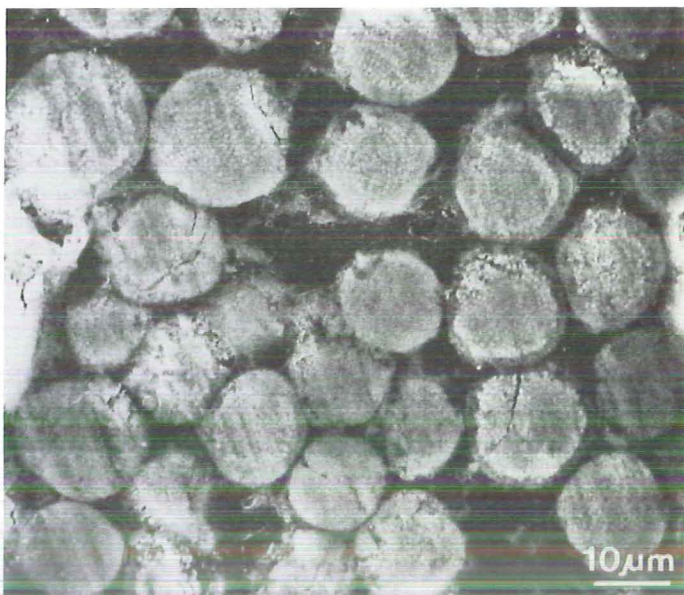
Infilled channels were sometimes deformed, mainly by pressure exerted locally. This deformation could occur either before or after reclamation. Compaction of the sediment sometimes accentuated the infilling and sometimes slightly obscured it (see Section 4.5.2).

#### *4.5.1.3 Recognizable inherited phenomena resulting from chemical processes*

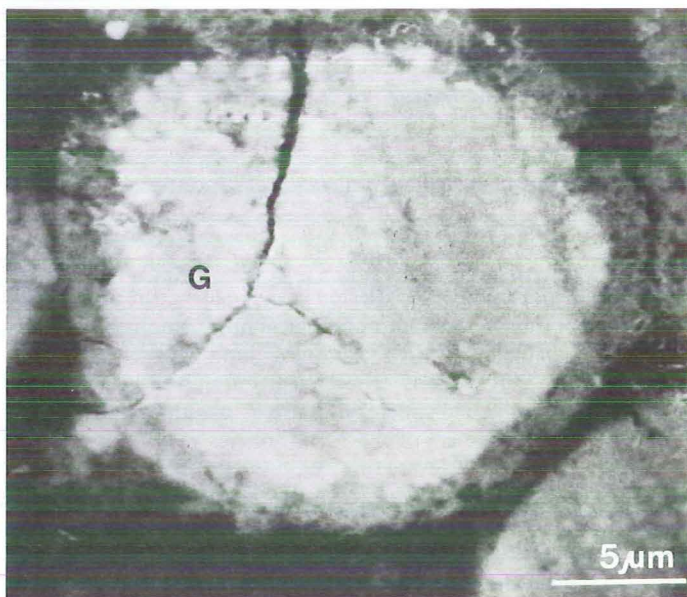
### *Pyrite*

In the thin sections of soil material from the profiles selected in the polders, the presence of pyrite could be proved conclusively not only by micromorphological observations but also by the results of energy-dispersive X-ray analysis (EDXRA) in combination with scanning electron microscopy (SEM) on parts of the thin sections. These results are given in Figure 56. Framboidal pyrite not only occurred as individual spheres but also as pseudomorphs in peat fragments and former root remains. The diameters of the pyrite spheres varied between approximately 15 and 150  $\mu\text{m}$ . Smaller pyrite spheres were rare. With the exception of the tubules filled with pyrite spheres discussed earlier, pyrite was generally present in the same locations as before reclamation. Most of the pyrite was found associated with former root channels and root remains and with larger fragments of organic matter, such as peat. In the soil matrix some individual spheres were occasionally found. Most of the pyrite present had started to oxidize, a process which is discussed in Section 4.5.2.

The presence of pyrite in environments that are thought to have long been aerated indicates that once formed, pyrite can be fairly stable, even if it is present far above the permanently reduced horizon.



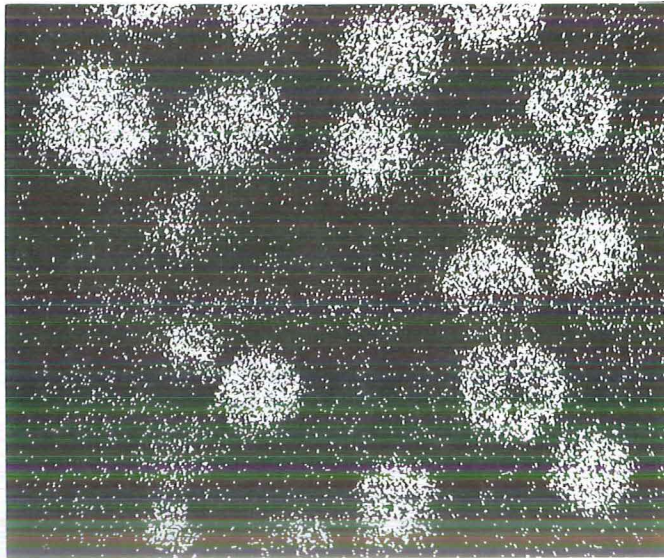
A. Secondary electron image of a cluster of oxidizing pyrite spheres.



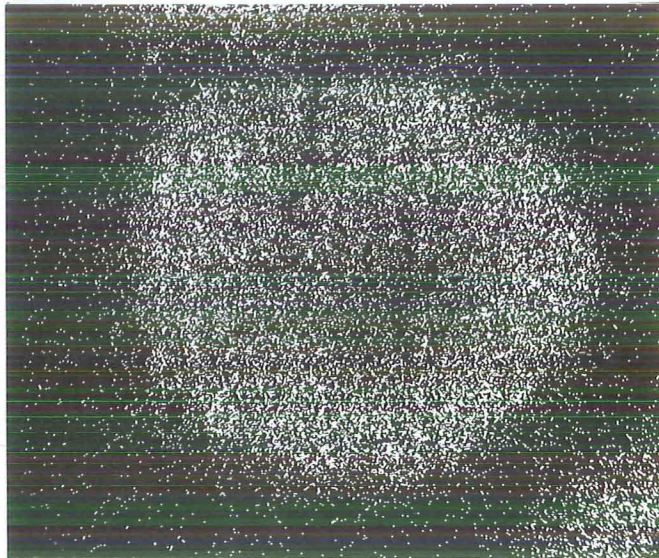
B. Secondary electron image of one oxidizing pyrite sphere.

Fig. 56. SEM-EDXRA analyses of oxidizing pyrite in polder soils.





C. X-ray image of the element S in the cluster.

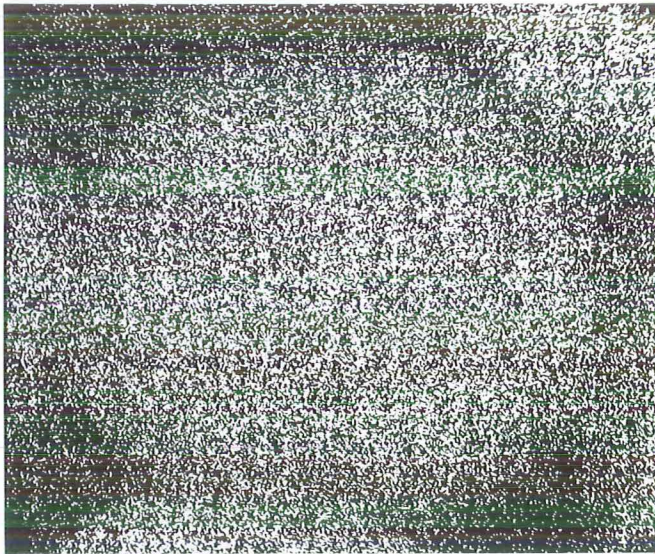


D. X-ray image of the element S in the single sphere.

Fig. 56. *Continued.*



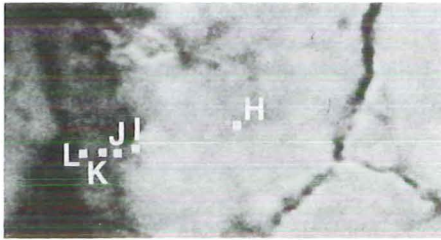
E. X-ray image of the element Fe in the cluster.



F. X-ray image of the element Fe in the single sphere.

Fig. 56. *Continued.*





G. Location of the point analyses.

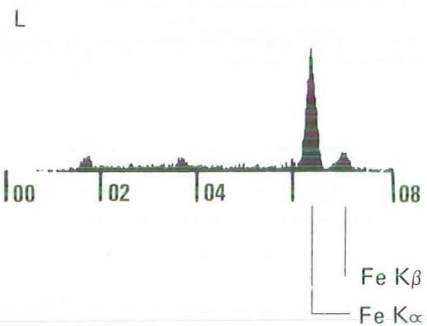
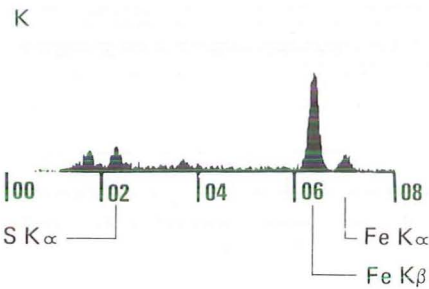
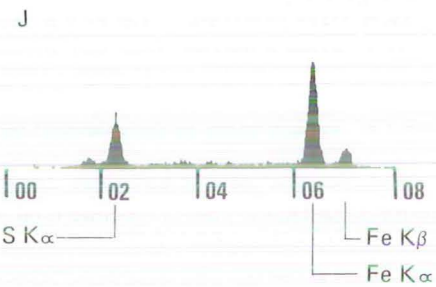
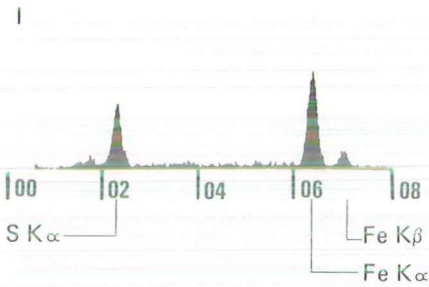
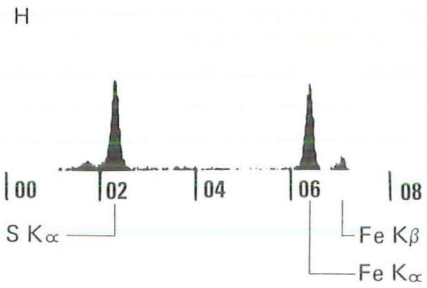


Fig. 56. *Continued.*

### Carbonate

Accumulations of fine carbonate particles such as quasicalcitans, neocalcitans and calcitans were observed in the polder soils. They occurred in soil fabrics very similar to those in the present-day intertidal zone. In the polder soils they were found associated with channels. In thin sections with similar soil fabrics, several examples were found of snails infilled with fine

carbonate particles, and of some excrements in which all clay-sized material had apparently been replaced by carbonate.

Distinct carbonate deficiencies were not observed in the polder soils. All these soils were still rich in carbonate. In some mud laminae small carbonate particles had disappeared.

#### *Ferric iron*

Quasiferrans, neoferrans and ferrans were observed until deep in the subsoil. They were found in the same places in the post-reclamation soils as in the pre-reclamation soils. In the higher parts of the clay-rich sediments of the polder soils there were more accumulations of ferric iron than in comparable locations in unreclaimed soils. The increase in presence of ferric iron, due to oxidation of pyrite, is discussed further in Section 4.5.2. Sometimes the quasiferrans, neoferrans and ferrans had been broken by the compaction of the soil material (see also Figure 58).

Most of the ferric iron accumulations present in the polder soils were probably derived from former soil development. They had no relation with the present G horizon.

#### *4.5.1.4 Classification of the inherited parts of the soil fabrics*

From the data given in the previous three sections it is evident that many of the phenomena distinguished in the present-day intertidal zone survive long after the land has been embanked and used for agriculture. In fact so many phenomena of soil development in the intertidal zone were preserved that the zones where these fabrics originated could be determined from the thin sections.

#### *Recognizable parts of the soil fabrics in the different former subzones*

All the pedological phenomena resulting from processes acting in the intertidal flat were recognizable. All types of faunal activity occurred: passage features made by several species; striotubules and channels, some with a neoferran or a small ferran, some with zoocutans and some completely filled with excrements. A pattern of coarse polygon cracks was observed and some downward transport of wet soil material in voids had taken place. Even concentrations of fine carbonate particles were present in quasicalcitans, neocalcitans and calcitans. The positions and distribution of these phenomena in the thin sections and the type of sediment were still identical with those of the present-day intertidal flat deposits. Only very minor changes due to post-embankment soil development were present in these soil fabrics.

Several times a transitional zone was recognizable. It was characterized by a soil fabric for intertidal flat deposits, in which channels without neoferrans also occurred. These channels were probably all made by plants: the presence of some spheroidal pyrites as infilling or embedded in an infilling of soil material strengthen this hypothesis.

Low salt-marsh deposits could be classified not only according to their sequence of superimposition on the intertidal flat deposits and by their higher clay content, but also because of the presence of floral channels (often infilled with formerly wet soil material) and newly-formed pyrite from the pre-reclamation phase associated with floral channels and occasionally occurring in peat fragments. Two variants were recognized. In the sandy variant faunal channels, some with neoferrans, and passage features were found. In the muddy variant, some pas-



sage features and a few *Hydrobia ulvae* snails were recognized. Although the soil fabric in these deposits had been altered to some extent by post-reclamation processes, this did not hinder interpretation.

Middle-high salt-marsh deposits were also recognizable, but with more difficulty than the previous sediments because changes in soil development had blurred much of the original phenomena. Floral channels with or without pyritized remains were clearly visible, as were large amounts of newly-formed pyrite from the pre-reclamation phase and some channels (mainly floral channels) that had been infilled by downward movement of wet soil material. In the muddy variants, dislocations and deformations resulting from passage features were also discernable. Several *Hydrobia ulvae* snails were present; also some clearly recognizable original neoferrans and ferrans. In the more sandy variants, as well as floral channels some passage features and faunal channels were also observed, many with neoferrans and/or ferrans. More ferric iron accumulations were present in these soil materials than in the pre-reclamation phase. After embankment much of the pyrite starts to oxidize. This ferric iron can be distinguished from pre-reclamation ferric iron accumulations by its location, its internal structure and the occurrence of unoxidized parts (see also Section 4.5.2).

The geogenetic and pedogenetic soil fabrics from the higher intertidal zone had been so disturbed by human activities that they were unrecognizable. Only a few inherited fragments of former neoferrans and ferrans and some pyrite accumulations survived. Deposits from the high salt marshes need not necessarily be present in a polder, for sometimes parts of an intertidal zone are reclaimed before they have reached high salt-marsh levels. The Bathpolders were reclaimed before the deposits had reached high salt-marsh levels. This may be why the soils in the Bathpolders lack carbonate deficiencies.

#### 4.5.2 Phenomena due to soil development after embankment

In addition to the changes due to direct human activities which caused drastic mechanical disturbances of the original fabrics, significant pedogenetic changes were also found. Some of these changes are given in Appendix 4 B. These significant changes will be discussed in succession below.

(i) After reclamation the packing of the soil material changed; i.e. the original very loose organization of the solid particles became more compact. Coarse particles had more points of contact; this reduced the pore spaces. The fine fraction (less than 30  $\mu\text{m}$ ) contained more particles of 2-30  $\mu\text{m}$  per surface unit than before reclamation due to compaction of the clay-sized part. Mixtures of fine and coarse fractions all had porphyric c/f related distributions in which the coarse grains either touched each other or had distances between them ranging up to more than several times their diameter. This compaction could result in changes in initial composition being accentuated or becoming less pronounced. Thus, many of the isotubules that had been formed by downward transport of wet soil material in channels became more conspicuous after reclamation. These changes in the volume occupied by the solid particles also had consequences for the voids. The soil material near voids sometimes showed fractures, with relative displacement of the material between the fractures (see Figure 58). Sometimes fragments had become detached and could be found in voids as infillings of soil aggregates. When the walls were broken, matrix material was sometimes locally pressed into the voids, filling them partly or completely. When neoferrans were present these phenomena were more pronounced, probably because they were more resistant to compression. These phenomena were mainly found in sandy soil material. Voids were also partly or completely compressed: this

There are two subgroups, i.e. one without and one with neoferrans and ferrans. In turn, phenomenon was more common in muddy soil material.

Apart from the voids, the compaction did not result in larger internal transfers or homogenizations. The sedimentary lamination and pedological phenomena retained their pre-reclamation characteristics.

(ii) In muddy soil material, large irregular vughs resulting from the coalescence of shrinkage cracks formed from existing channels (see also Section 4.3.3) were present. In the middle-high salt-basin deposits in the polders they had mostly been destroyed by agricultural practices. In the former low salt-basin deposits, large irregular vughs identical to those in the present-day high salt-basin deposits were found. These large irregular vughs must therefore have been formed after embankment as a result of ripening processes.

(iii) Pyrite was still present in the polder soils studied. In this environment pyrite was not stable and series of transitions from distinct black pyrite spheres to dark red-brown, more or less adhesive mottles in the soil matrix, and transitions from neopyritans and pyritans to neoferrans and ferrans were found. Figure 56 illustrates the oxidation of pyrite. At first the individual spheres become brownish at the edges; this zone enlarges, sometimes the individual spheres fragment, and finally red-brown more or less adhesive nodules remain. The higher the clay content of the soil material, the more adhesive and irregular the redbrown nodules became. In the latter case the red-brown colours continued in the clay-sized soil material. More details were obtained using sub-microscopical techniques: as long as the individual microaggregates were visible in the individual pyrite spheres, sulphur was present in the spheres. In spheres where individual microaggregates were no longer visible, iron was present. The individual spheres were often cracked. The cracks studied did not allow more oxidation to occur in the spheres: the oxidation was always restricted to the outer zone. The circular sections without microaggregates visible in the SEM photographs were most probably sections through the oxidized zones of the pyrite spheres, or smaller completely oxidized spheres. The SEM photographs also revealed that the individual spheres were not necessarily perfectly round. Spheres that touched each other, were flattened at the zones of contact.

In Section 4.5.1 it was noted that greater amounts of pyrite were observed than were initially present in the sediment. The increases in pyrite occurred in deposits of former low and middle-high salt basins. In all the former intertidal zone deposits phenomena resulting from the oxidation of pyrite were present. Nearer the surface the oxidation was more advanced, most pronounced in clay-rich former salt basins. But in all cases unoxidized pyrite could be found. Oxidized pyrite had more pronounced red colours, was mainly found embedded in soil material and often showed vestiges of a previous spheroidal shape. These phenomena enabled inherited quasiferrans, neoferrans and ferrans to be distinguished from oxidized pyrite forms.

One specific pattern produced by oxidizing pyrite must be mentioned. In part of a biogenetic lamina composed of ellipsoidal excrements of fine particles, the individual shapes were lined with small oxidizing pyrite spheres which gave the soil fabric locally a honeycombed appearance. In this case, even after embankment and compaction of the sediment, the biogenetic origin of the lamina was apparent.

(iv) In the present-day intertidal zone two types of ferrans were distinguished: an amorphous type and a goethitic type. In the reclaimed soils almost all the ferrans were goethitic. As approximately the same number of ferrans was present, it is presumed that the amorphous ferrans had been transformed to the crystalline type which is goethitic.

(v) Because the coarse prisms were usually larger than the thin sections only a few ped faces formed after embankment were observed (see also Appendix 1, soil descriptions). None of these ped faces had neoferrans or ferrans.



(vi) In the polder soils studied new floral channel systems were visible. The number of these channels decreased rapidly until about 80 cm below the soil surface. New root channels were only rarely found below one metre depth. The channels were mostly empty, did not have pressure-affected zones and had no quasiferrans, neoferrans or ferrans. In the upper 25 to 35 cm no continuous systems of floral channels were found, because of ploughing. Just below the Ap horizon these new systems had caused considerable disturbance in the inherited fabrics. Roots had partly followed new routes, thereby crossing old channels and following ped surfaces, but had also followed old channels. When these new roots crossed old channels, small mineral aggregates were separated. These mineral aggregates, which were often parts of neoferrans, occasionally filled channels.

(vii) Distinct evidences of a terrestrial fauna were not observed. In the Ap horizon small and winding parts of channels which had probably been made by animals rather than roots, were found. Worm activities could not be proved to be present. Below the Ap horizon no homogenizations or other possible changes due to terrestrial fauna could be identified with certainty. Thus it is assumed that terrestrial fauna does not play an important role in these soils.

(viii) In the muddy laminae, distinct clay domains that were not present before reclamation were found. This phenomenon was also present in the smaller mud laminae of former intertidal flat deposits. Initially the clay domains were oriented in the direction of the lamination (see Figure 57), but where the original lamination had been disturbed i.e. by passage features, voids and infillings, the orientation differed. These differently oriented clay domains gave clay-rich soil material sepic fabrics, which differed essentially from the sepic-like fabrics found in the former high salt basins. There, due to local pressure, the elongated particles in the fine fraction, mainly carbonates, were oriented in various directions. In and near the Ap horizon of the polder soils the sepic fabrics had been accentuated as result of stress due to human activities such as ploughing.

As this phenomenon was absent from the present-day intertidal zone, it must be assumed that after embankment the initial composition of the mud flakes changed, causing the clay

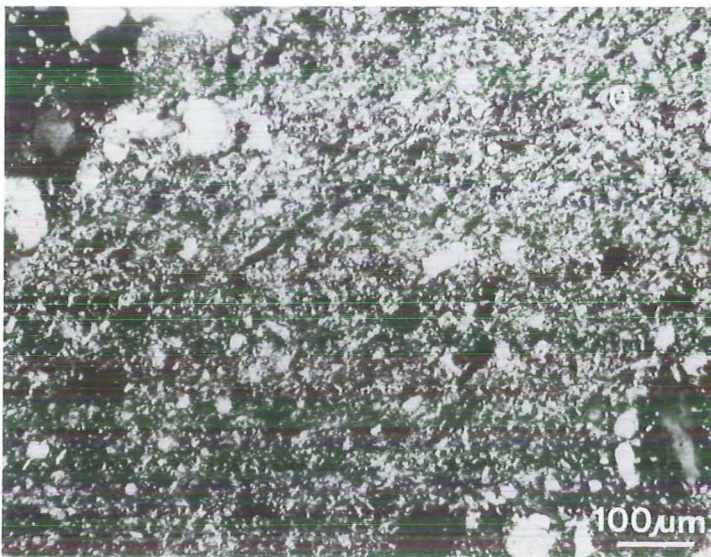


Fig. 57. Clay domains oriented parallel to the geogenetic lamination. They occur in clay-rich laminae after reclamation.

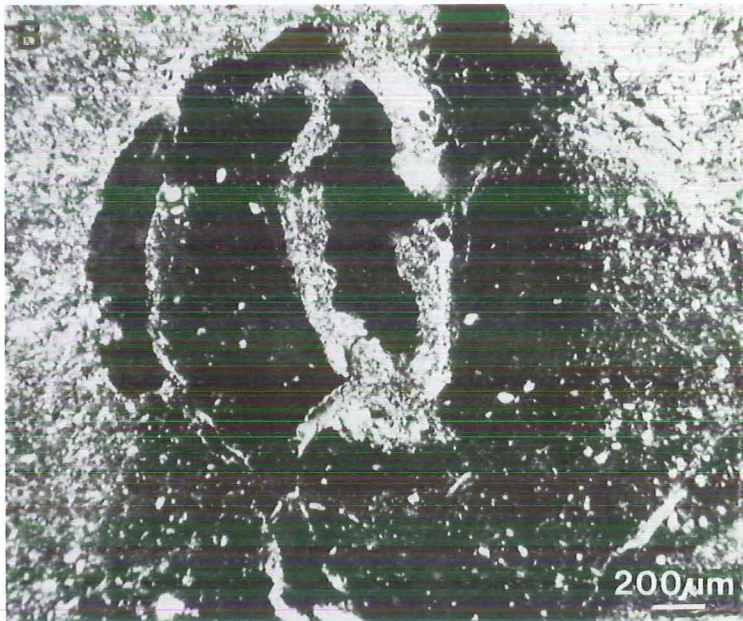
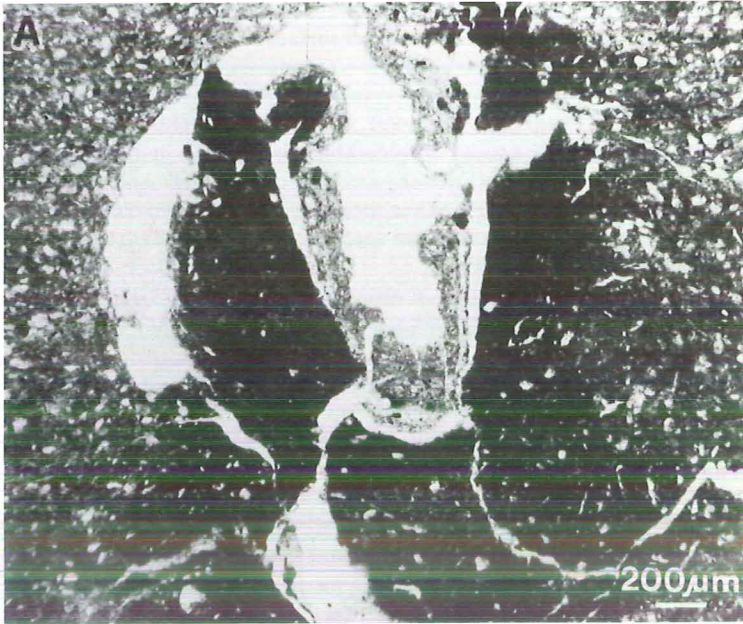
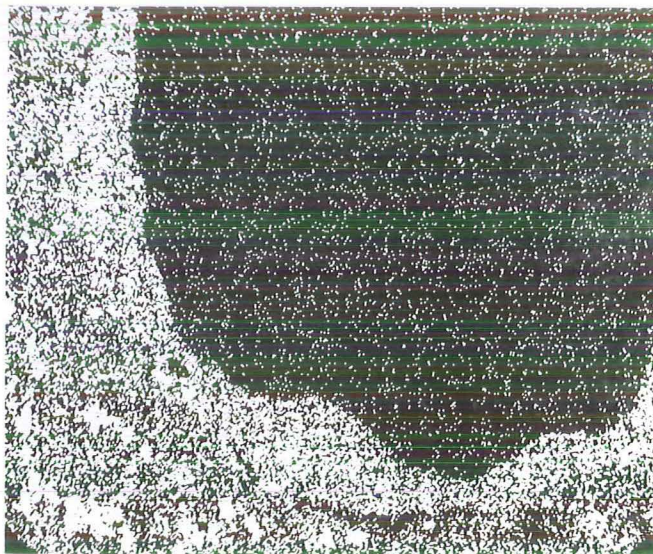


Fig. 58. Compound clayey cutan in a channel with neoferran from the pre-reclamation phase. The fractures and displacements of the neoferran are probably due to compaction of the sediment. A. Normal transmitted light. B. Crossed nicols.



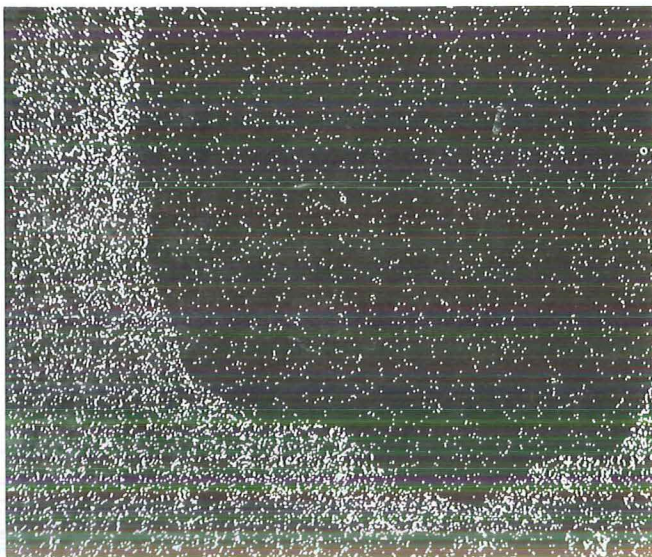


A. General view of the argillan.

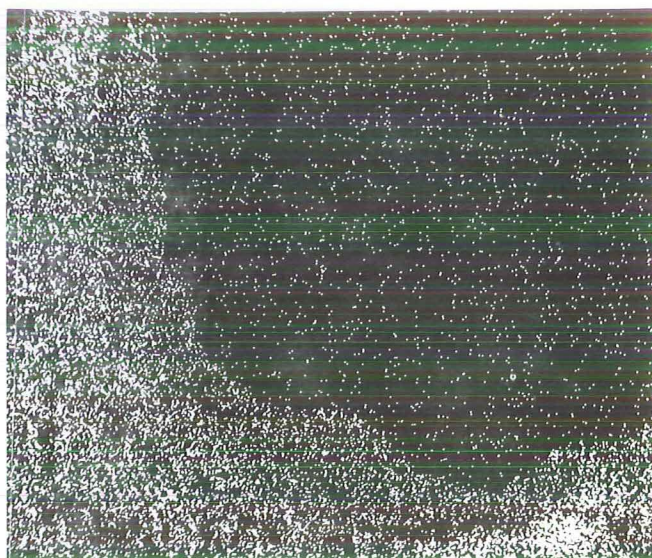


B. X-ray image of the element Si.

Fig. 59. SEM-EDXRA analyses of an argillan in a polder soil.



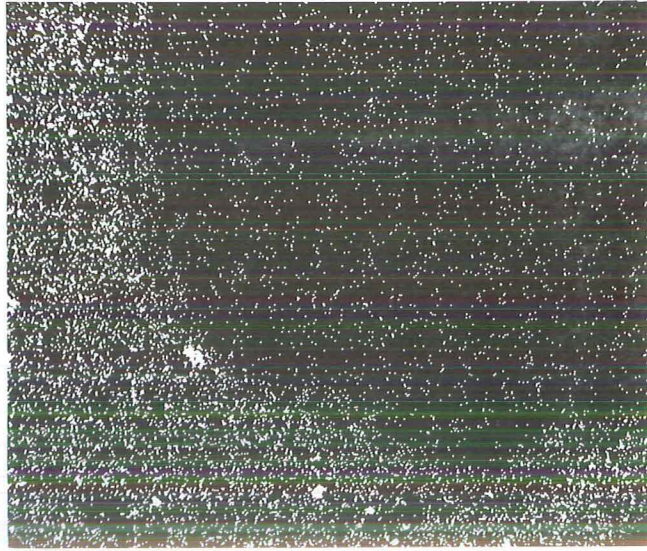
C. X-ray image of the element Al.



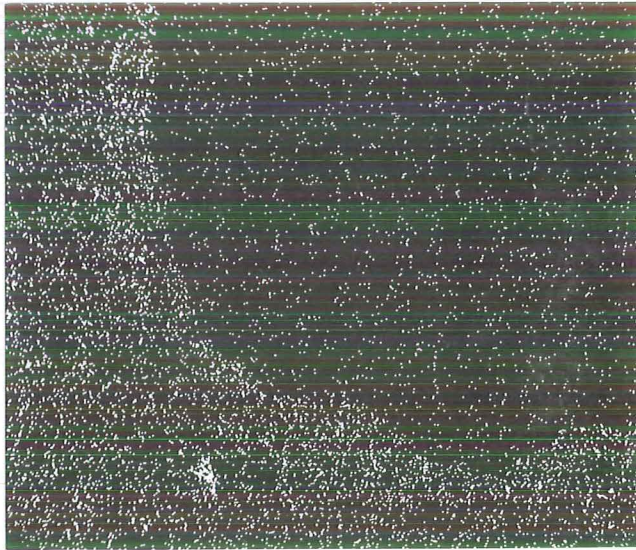
D. X-ray image of the element Fe.

Fig. 59. *Continued.*





E. X-ray image of the element Ca.



F. X-ray image of the element K.

Fig. 59. *Continued.*

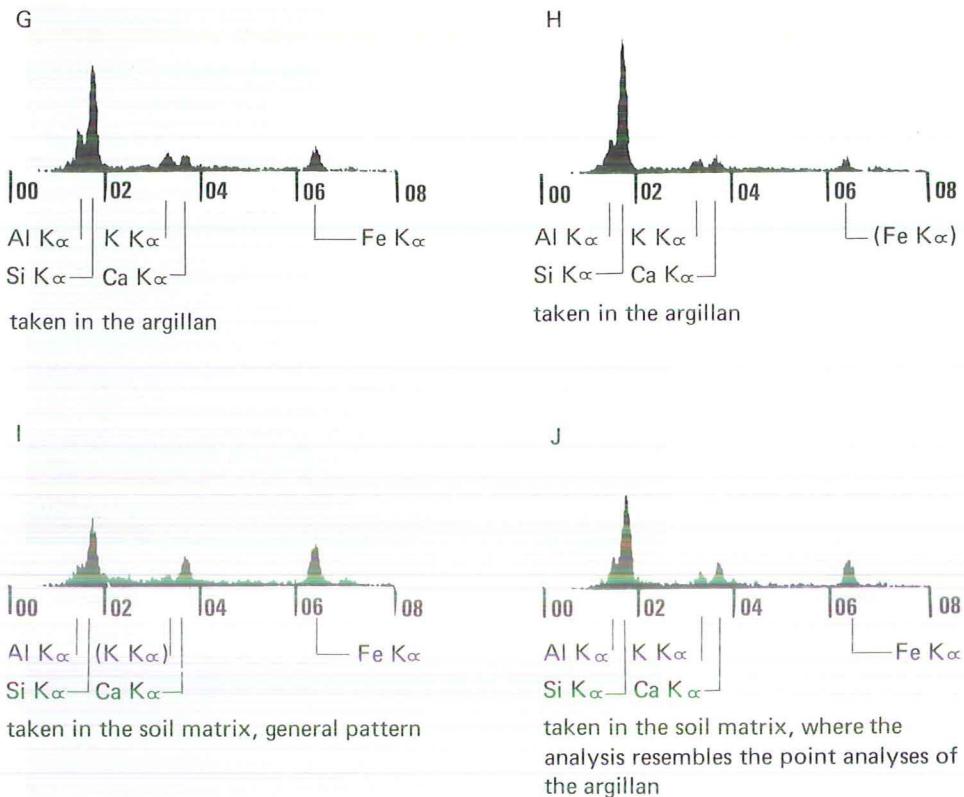


Fig. 59. *Continued.* G.-J. Point analyses in the argillan and adjacent soil matrix.

domains to become visible or to be formed. Evidence that changes in the original composition of mud flakes occur after embankment has already been given in Section 3.4. The relation between clay content and the organic matter content changes after embankment because the amounts of organic matter are much reduced.

(ix) In all the types of voids present (old and new channels, irregular vughs) and on ped faces, recent infilling was generally found. Contrary to the wet gravitational infilling of the pre-reclamation phase in which the voids were generally completely infilled in one or at most a few phases, here many thin laminae were generally found forming compound cutans. The laminae were largely composed of clay, containing minor quantities of organic matter, iron, carbonates, etc. Sometimes a lamina composed of coarse particles was included, but pure argillans also occurred. In clay-rich sediments these compound clayey cutans could be very well developed and were up to about 5 mm thick. The deeper below the surface, the more clayey these compound cutans could be. They were observed up to 120 cm depth. In sandier soil material these compound cutans were also observed, but they were very thin and usually only occurred in patches. These more or less pure argillans were common in clay-rich sediments. Figure 58 shows an example of such a compound cutan in an old channel with neoferran. One argillan was studied using submicroscopical techniques. The results are given in Figure 59.



Several facts are noteworthy. The cutan, micromorphologically determined as an argillan, was largely composed of Si and Al, some K, Ca and Fe. The point analyses revealed distinct Al and Si peaks ascribable to the presence of clay minerals. The composition of the cutan was not identical with most of the clay-sized material of the matrix: (i) in the matrix the Al and Si peaks of the point analyses were less well pronounced and (ii) the cutan contained relatively less Ca and Fe and more K than the clay-sized material in the matrix. Occasionally spots in the matrix were analysed whose composition resembled that of the cutan.

The results of these micromorphological investigations suggest that the following changes take place. After embankment the original composition of the mud flakes changes, for example by the decrease in salt content and organic matter content. This causes destruction of the flake fabric in the mud laminae, which may result in the clay minerals forming clay domains *in situ* in the mud laminae (see item viii). In addition to the formation of clay domains, clay minerals from the former mud flakes can also become mobile and be transported over certain distances, resulting, for example, in argillans.

Infilling of mineral aggregates and coarse grains that could not have been formed before reclamation were also found. These infillings were mainly due to shrinkage, the formation of new systems of floral channels and the effects of human activities.

A new type of infilling, tubules formed by infilling with pyrite spheres, was observed. These tubules have already been discussed in Section 4.5.1.3.

The pedogenetic phenomena discussed above, observed only in the reclaimed soils, cause changes in the original soil fabrics. The fewest new phenomena were found in the former intertidal flat deposits. Most changes occurred in the clay-rich former salt-basin deposits.

## SUMMARY

The intertidal zone in the area studied in detail was divided into 6 subzones: the low intertidal flat, high intertidal flat, transitional zone, low salt marsh, middle-high salt marsh and high salt marsh. These subzones represent the successive stages of landscape development in the intertidal zone with continuing sedimentation from tidal currents. In these subzones 16 locations were selected, to represent the typical soils in each subzone. The typical soils within the subzones were found on natural levee deposits that bordered the creeks and basin deposits between the creeks. Natural levees were first encountered in the transitional zone and attained their maximum development in the high salt marsh. Therefore, pairs of soils (one in the natural levee deposit and one in the salt basin deposit) were chosen in each subzone upslope from, and including the transitional zone. The soil profiles at these 16 locations were described and sampled.

Five soils were selected in the polders, and described and sampled in the same way as was done in the intertidal zone.

The results can be summarized as follows:

### *1. Original sediment*

The sediment in the intertidal zone was mostly distinctly laminated. Upslope the deposited material became finer grained and the clay content increased. Clay-rich material, the mud laminae, were micromorphologically composed of fine grains of 2-30  $\mu\text{m}$  in diameter that were embedded in a clay-sized groundmass. The mud laminae were rich in carbonate and contained many fragments of organic matter. The clay-mineralogical composition of the mud was reasonably constant. In the sediment a fixed ratio between the organic matter content and the clay content was found, regardless whether vegetation was present. Sand laminae contained many carbonate grains, shell and snail fragments and whole shells and snails. Grains of organic origin, such as peat grains, were also present in these laminae. The sediment had a high water content and was loosely packed. The initial water content of the sediment increased concomitantly with the clay content and content of organic matter. As a result of the high water contents and loose packing, clay-rich sediment in particular had weak consistencies.

### *2. Changes in the original sediment caused by soil-forming processes in the intertidal zone*

*Faunal activity.* Three groups of changes were distinguished: channels, pedotubules, and passage features. Channels were produced by animals that remained in one place for longer periods, mainly worms. They were found in the intertidal flat, natural levees, and sometimes in high salt basins. Along the walls of these channels several types of cutans formed by the animals could be present. Two types of pedotubules were observed. In the first type the channels were completely filled with distinctively shaped excrements. The second type comprised striotubules: tubular zones filled with concave layers of soil material. The first type was probably produced by worms and the second type mainly by sessile molluscs. Both types only occurred in the intertidal flat and bare parts of the transitional zone. The third group, passage features, has not previously been distinguished in the literature. Passage features were composed of soil material, had a tubular external form, consisted of a single tube and had no distinct external boundary. The tubular zones were recognizable by differences in packing, dis-



turbance of the lamination, orientation of elongated particles along the long axis of the tube and the presence of excrements also oriented in the length direction of the tube. Passage features resulted from the single passage of mobile animals in wet unconsolidated soil material. The movements of these animals were mainly related to the tides; with high tides the animals were found at the surface; with ebb tide they retreated into the sediment. Passage features often occurred in large numbers crossing each other in all directions, producing a complex pattern in the soil material. Sometimes the original fabric of the sediment was hardly recognizable. Several animals, such as worms, molluscs and some crustaceans, caused passage features. This was deduced from the diversity of excrements present in the passage features. Passage features were abundant in the intertidal flats and the basins of the salt marshes, and occurred in lower quantities in small natural levees. The passage features in the basins were solely produced by the gastropod *Hydrobia ulvae*. In the basins, transitions of passage features to channels were found, together with a few channels produced by *Hydrobia ulvae*.

*Influence of the vegetation.* Parts of the stems and roots produced channel systems in the soil. These channels were important because they allowed physical and chemical processes to take place: the presence of roots and parts of the stems could also play a role. In the salt-marsh deposits no A1 horizon was formed. This was partly a result of the impeded decomposition of plant-remains below the surface and partly due to the removal by tidal currents of plant-remains above the surface. The plant-remains in the tidal currents were fragmented and partly deposited as detritus or incorporated in mud flakes and deposited in the intertidal zone.

Small channels caused by vegetation were also found in the intertidal flat deposits. They were formed by macroscopic green algae that were fastened to the sediment by thallus fibres.

*Formation of the shrinkage cracks.* The shrinkage cracks observed were individual cracks or formed polygon patterns. Individual cracks were found in steep creek walls. Polygon patterns were present in the intertidal zone on a large scale. The polygon patterns found in high salt basins were less abundant. The former polygons had large diameters, up to 100 cm, the latter had small diameters, less than 20 cm. A special type of shrinkage void was observed in the superficial layers of the basins of the high salt marsh: there small cracks were formed from existing channels that could proceed to other channels, resulting in irregular voids (vughs).

*Transport of soil material in voids.* Transported soil material in voids occurred as cutans and as complete infillings. The transported material was generally derived from the surface. Cutans were found along channel walls and cracks, mainly in the high intertidal flat, transitional zone and low salt marsh. Complete infillings also occurred in channels and cracks in the same zones as the cutans. In these zones either the surface of the sediment was mobile, as in the intertidal flat where transport along the surface occurs in ripples, or the water content of the sediment was so high that this material could easily flow into voids that were open to the surface.

*Pyrite neo-formations.* The pyrite was composed of small micro-aggregates: framboidal pyrite. This pyrite occurred in the form of (i) spheres, (ii) spheres with protuberances (amoeboidal pyrite), and (iii) pseudomorphs in root remains, peat fragments and detritus grains. Pyrite spheres were the most common. Clusters of pyrite spheres were mainly observed near organic matter in clay-rich sediment. In this material pyrite was formed under reducing conditions. The largest accumulations were found in the basins of the low and middle-high salt marshes.

*Neo-formations of carbonate.* Two types of neo-formations were observed: (i) single idiomorphic carbonate crystals with a rhombohedral-like habit present within the soil matrix and

(ii) accumulations consisting of fine carbonate particles near and adjoining voids and along the walls of the voids. The first type occurred mainly in the intertidal flats and high parts of natural levees; the second type was restricted to the intertidal flat. Local evaporation caused the carbonate neo-formations to precipitate from an oversaturated solution.

*Decalcification.* At a shallow depth from the surface, zones with low carbonate contents occurred in the middle-high and high salt marshes. The smallest quantities of carbonates in these zones were found just above the G horizon. The carbonate deficiencies were the largest in clay-rich sediment. This means that the deficiencies were most marked in the salt basins. Here the lowest pH values were measured and the base saturation was below 100%. In thin sections the decalcification was shown by disappearance of fine carbonate particles, fragmentation of coarse carbonate grains and disappearance of these fragments. The deficiencies had no regular pattern; in the same lamina different deficiencies could be found. The decalcification probably mainly resulted from cyclic oxidation of iron and depended on the possibilities for internal drainage within the sediment.

*Iron and manganese accumulations.* Ferrans and neoferrans occurred where aeration was possible. The ferrans were composed of amorphous iron, or were crystalline (goethans). Iron accumulations were found in the intertidal flat, natural levees and basins of the middle-high and high salt marshes. Manganese accumulations were observed combined with iron accumulations as compound neocutans along cracks and channels in the intertidal flat and natural levees.

Manganese accumulations were found in organic material such as root fragments and peat grains embedded in the soil material of the basins of the middle-high and high salt marshes. They only occurred above the G horizon. Around these manganese accumulations, zones with iron accumulations could be present.

The above mentioned changes due to soil-forming processes can be classified into four categories: (i) additions such as excrements produced by suspension feeders, which are deposited in the sediment by the animal, (ii) removals of compounds from the soil, such as carbonate, (iii) transfers of material within the soil, such as passage features and infilling of voids and (iv) transformations, to which the formation of pyrite belongs.

The character of the soil development depends on the interaction, the intensity and succession of each of these four categories of soilforming processes. The results can either be clearly differentiated soil horizons or homogenization of the soil (SIMONSON, 1959; HOLE, 1961).

### 3. *Classification and model of soil development in the intertidal zone*

In the succession from low intertidal flat to high salt marsh the above mentioned processes occurred in different interactions, successions and intensities. They formed characteristic patterns visible in thin sections. These patterns were classified in four groups, that were further divided in subgroups, types and subtypes. In the first three levels pedogenetic elements were used as criteria, in the last level, geogenetic elements were used as criteria. The classification in groups is based on (i) the occurrence of voids of biological and physical origin and (ii) the presence in the soil material of several transfers of biological as well as of physical origin. The absence or presence of ferrans and neoferrans formed the criterion for the differentiation into subgroups. Types were determined by the relative dominance of one of the phenomena characterizing the group. At the level the granular composition and the lamination of the sediment were included as differentiating criteria. After the classification had been drawn up, it



was used to classify the patterns that had been found. From this, the following conclusions were drawn (i) certain combinations of phenomena were characteristic for specific phases in the deposition and (ii) after being overlain with younger sediment in which other patterns develop, the original patterns remained clearly recognizable. This means that in a profile in the high salt marsh, deposits from the middle-high salt marsh phase, the low salt marsh phase and older phases were clearly recognizable. (iii) In the natural levee and salt-marsh deposits different soil developments took place, between which transitions occurred.

#### *4. Phenomena produced by soil-forming processes in the intertidal zone deposits, recognizable in the polder soils*

All the groups of faunal activity distinguished: channels, pedotubules and passage features, were present in the thin sections. Parts of channel systems formed by the former vegetation were also found. Of the shrinkage cracks distinguished in the pre-reclamation phase, only the coarse polygon pattern of the intertidal flats was recognized. Voids infilled with soil material from the surface were still observed, as infilling that occurred since reclamation had other characteristics. In the thin sections of the polder soils pyrite was still present, mainly as spheres. These occurred in locations comparable with the pre-reclamation phase. Calcitans, neocalcitans and quascalcitans were also observed. Distinct zones with carbonate deficiencies did not occur. Ferrans and neoferrans were common, occurring in identical locations to those in unembanked areas.

The large number of inherited phenomena enabled the patterns present in thin sections to be classified according to the same system developed for the intertidal zone deposits. The patterns in the oldest deposits of the intertidal zone were the best preserved. The patterns in the former middle-high salt-marsh deposits, especially the basins, were only partly recognizable.

#### *5. Changes caused by soil-forming processes after reclamation*

After reclamation the packing of the soil material became more compact and as a result the volume decreased. Thus, sandy material increased in bulk density by 20-25% and clay-rich material increased in bulk density by 2-3 times its former weight. Decreases in volume caused compression of voids, especially in clay-rich material.

The pattern of irregular voids (vughs) present in the basins of the high salt marsh was widespread in the former low salt-marsh deposits. This probably resulted from the high original water contents of these deposits.

After reclamation a prismatic structure developed in clay-rich soil material. Neoferrans or ferrans were never found on or adjoining the faces of the prismatic peds.

The ferrans all had a crystalline structure. This suggests that all amorphous ferrans were transformed into goethans.

The pyrite was completely oxidized or had ferruginous margins. Brown spheres, sometimes fragmented remained in sandy soil material after oxidation. In clay-rich soil material, irregular brown mottles were formed around clusters of pyrite continuing into the matrix, in which parts of unoxidized pyrite were often still present.

Channel systems produced by the vegetation since reclamation were present. In the Ap horizon only remnants occurred. Below the Ap horizon many new channels were recognized; these sometimes crossed old channels. Sometimes a root followed a part of an old channel. Where former channels were crossed by newer ones, small aggregates that had worked loose near the intersection occurred deeper in the former channel systems.

Distinct evidence of the activities of a terrestrial fauna was not observed, therefore it seems that in the polder soils studied the fauna does not play an important role in soil formation.

In the former mud deposits, oriented clay domains were visible, which when undisturbed after deposition had an orientation parallel to the lamination. After disturbance the clay domains were oriented perpendicularly to the direction of pressure.

In all voids, whether former or recent, cutans occurred that were composed of material derived from the former mud laminae, usually the finest part. These cutans were composed of many thin laminae with a slightly changing composition and a high content of oriented clay. Pure argillans also occurred and were not rare in clay-rich soil material.

From the above-mentioned data it is evident that in intertidal zone deposits many specific processes occur, producing phenomena that remain visible long after the land has been reclaimed and the processes themselves have ceased.



## SAMENVATTING

Langs de Nederlandse kust wordt op verschillende plaatsen door getijstromen sediment afgezet. Een deel hiervan bevindt zich boven gemiddeld laagwater en wordt aangeduid met namen als platen, wadden, slikken, kwelders en schorren. In een marien getijdengebied, zoals de Oosterschelde in Zeeland, waar de ontwikkeling van de afzettingen boven gemiddeld laagwater op natuurlijke wijze verloopt, is een representatief gebied uitgezocht waarin de gehele opeenvolging van laag naar hoog vertegenwoordigd is. In dit gebied is nagegaan welke veranderingen onder invloed van bodemvormende processen optreden na afzetting van het sediment, waar deze voorkomen en hoe de houdbaarheid van de ontstane veranderingen is.

Van het geselecteerde gebied werden de volgende kaarten gemaakt: een bodemkaart en twee afgeleide kaarten, een aëratie-dieptenkaart, een ontkalkingskaart, een vegetatiekaart. Verder is de opeenvolging van laag naar hoog ingedeeld in 6 zones nl.: lage slik, hoge slik (het onbegroeide gedeelte), overgangszone (open begroeiing), lage schor, middelhoge schor en hoge schor (bedekt met een aaneengesloten vegetatie). Aan de hand van de kaarten zijn in elke zone representatieve plaatsen bepaald voor verder onderzoek, waarbij rekening is gehouden met de interne differentiatie van de zones. Deze differentiatie wordt voornamelijk bepaald door de kreeksystemen waarlangs zandiger oeverwallen voorkomen met daartussen kleirijkere kommen. De ontwikkeling van oeverwallen begint in de overgangszone en heeft zijn maximale ontwikkeling in het hoge schor. In totaal is op zestien plaatsen de profielopbouw beschreven en zijn monsters genomen. Het accent van het onderzoek ligt op de micromorfologische bestudering van slijpplaten van ongestoorde bodemmonsters. Daarnaast zijn ook monsters voor fysische en chemische bepalingen genomen. Deze dienen voor een nadere karakterisering van de geselecteerde bodems en zijn nodig bij de interpretatie van waargenomen verschijnselen in slijpplaten.

Behalve in het buitendijkse gebied zijn in enkele polders ook nog vijf bodemprofielen bemonsterd. Voor de selectie van deze profielen was hun overeenkomst met de bemonsterde profielen in het hoge schor bepalend. Evenals in het buitendijkse gebied is de profielopbouw beschreven en zijn dezelfde soorten monsters genomen. Hierdoor is het mogelijk een indruk te krijgen van de houdbaarheid van verschillende verschijnselen na de bedijking en is aan te geven welke wijzigingen na de bedijking opgetreden zijn.

De resultaten van het onderzoek kunnen als volgt worden samengevat:

### *1. Het oorspronkelijke sediment*

Het afgezette sediment is meestal duidelijk gelaagd. Met toenemende hoogte wordt het zand fijnkorreliger en neemt het gehalte aan kleirijk materiaal toe. Het kleirijk materiaal bevindt zich in sliblagen en bestaat micromorfologisch uit korrels kleiner dan  $30\ \mu\text{m}$ , die ingebed zijn in een massa die fijner is dan  $2\ \mu\text{m}$ . De sliblagen zijn kalkrijk en bevatten veel fragmenten van organisch materiaal. De kleimineralogische samenstelling varieert niet in het buitendijkse gebied. In het sediment wordt een vaste verhouding tussen het kleigehalte en het gehalte aan organische stof aangetroffen die onafhankelijk is van de aanwezigheid van vegetatie. In de zandlagen komen veel carbonaatkorrels voor, evenals schelpfragmenten en schelpen. Ook bevat dit materiaal korrels die van organische oorsprong zijn zoals veen.

Het sediment heeft een hoog watergehalte en een losse pakking. Het watergehalte bij afzetting neemt toe met het kleigehalte en het gehalte aan organische stof. Door het hoge water-

gehalte en de losse pakking heeft vooral kleirijk materiaal een lage stevigheidsgraad, hetgeen in het veld duidelijk te merken is.

## 2. *Veranderingen in het oorspronkelijke sediment door buitendijks plaatsvindende bodemvormende processen*

*Dierlijke activiteit.* Drie groepen veranderingen zijn onderscheiden, namelijk: gangen, pedotubulen en passagesporen. Gangen worden gemaakt door dieren die zich geruime tijd bij één plaats ophouden; dit zijn voornamelijk wormen. Zij komen voor op het slik, in de oeverwallen en soms in de hoge kommen. Langs de wanden van de gangen worden verschillende typen huidjes aangetroffen die door de dieren zelf zijn gevormd. Er werden twee typen pedotubulen waargenomen, namelijk één waarin de gangen compleet zijn opgevuld met excrementen, en de zogenaamde striotubulen, met concave lagen gevulde gangachtige zones (BREWER, 1964). Het eerste type wordt waarschijnlijk door wormen veroorzaakt, het tweede type voornamelijk door plaatsgebonden schelpdieren. Beide typen komen alleen in de slikken en de onbegroeide delen van de overgangszone voor. De derde groep, passagesporen, vormt een nieuw onderscheiden groep van dierlijke verschijnselen. Het zijn diffuus begrensde gangachtige zones, die herkenbaar zijn aan veranderingen in de pakking, verstoring en afbuiging van de gelaagdheid, de aanwezigheid van excrementen die in de lengterichting van het verschijnsel georiënteerd zijn, evenals andere langgerekte elementen in het verstoorde sediment. Deze sporen worden gevormd door mobiele, niet aan de plaats gebonden dieren. Na passage van deze dieren vloeit het slappe, waterrijke sediment terug en blijft een diffuus begrensde verstoring van het oorspronkelijk sediment over. De verplaatsingen van deze dieren in het sediment zijn voornamelijk getij-gebonden. Bij vloed bevinden zij zich aan het oppervlak en bij eb in het sediment. Door deze relatie met het getij komen de passagesporen in grote getale voor, kriskras door elkaar. Van de oorspronkelijke afzettingsgelaagdheid is vaak weinig meer te zien. Een grote groep van verschillende dieren veroorzaakt deze passagesporen. Dit is af te leiden uit de diversiteit van de aanwezige excrementen. Hiertoe behoren wormen, slakken, schaaldieren en misschien juvenile schelpdieren. Passagesporen komen in grote getale voor in de slikken en de kommen van het schor, in mindere mate in de smalle oeverwallen. De passagesporen in de kommen worden vrijwel alleen veroorzaakt door het wadslakje *Hydrobia ulvae*. In de kommen komen overgangen voor van passagesporen naar diergangen.

*Invloed van de vegetatie.* De wortels en stengeldelen die zich onder de grond bevinden hebben gangenstelsels aangelegd. Deze zijn van groot belang voor een aantal fysische en chemische processen, die gedeeltelijk ook door de aanwezigheid van de wortels en stengeldelen zelf worden bepaald. In de schorgronden wordt geen A1-horizont gevormd. Dit wordt gedeeltelijk veroorzaakt door de slechte omzetting van het ondergronds aanwezige deel van de vegetatie. Anderzijds worden de plantenresten boven de grond afgevoerd met de getijstromen. Deze resten worden gefragmenteerd en weer gedeeltelijk als detritus of ingebouwd in slibvlokken afgezet op de buitendijkse gebieden. In de slikken komen lokaal ook smalle gangen voor die door vegetatie veroorzaakt zijn. Zij ontstaan doordat een van de macroscopische groenwiersoorten zich vasthecht in het sediment door middel van thallustraden.

*Vorming van krimpscheuren.* De krimpscheuren kunnen individueel voorkomen of polygonen vormen. Enkelvoudige scheuren zijn aanwezig in steile kreekwanden. Polygoonpatronen worden op grote schaal aangetroffen op het slik. Van meer beperkte omvang zijn de polygoonpatronen in de hoge kommen. De eerstgenoemde polygonen hebben een diameter die tot 100 cm kan reiken, terwijl die van de laatstgenoemde minder dan 20 cm is. Een apart scheu-



renpatroon wordt aangetroffen in de bovenste lagen van de kommen van voornamelijk het hoge schor. Hier zijn vanuit de bestaande holten krimpscheuren gevormd, die kunnen doorlopen tot nabijgelegen gangen waardoor grillig gevormde holten kunnen ontstaan.

*Verplaatsing van bodemmateriaal in holten.* Verplaatst bodemmateriaal komt voor in de vorm van huidjes en als complete opvullingen. Het verplaatste materiaal is meestal afkomstig van het oppervlak. Huidjes komen voor langs de wanden van gangen en scheuren van voornamelijk het hoge slik, de overgangszone en het lage schor. De complete opvullingen komen in dezelfde typen holten voor en in dezelfde zones als de huidjes. In deze zones is òf het oppervlak van het sediment mobiel, zoals op het slik waar transport in ribbels langs het oppervlak plaatsvindt, òf het sediment is erg waterrijk, waardoor het in openingen aan het oppervlak naar binnen kan vloeien.

*Pyriet.* Het aanwezige pyriet is opgebouwd uit kleine microaggregaatjes, het zogenaamde framboïdale pyriet. Dit komt voor in de vorm van gladde bolletjes, bolletjes met uitsteeksels (de amoeboïdale pyriet), en pseudomorf in wortelresten, veenfragmenten en detrituskorrels. De gladde bolletjes komen het meeste voor. Clusters van pyrietbolletjes worden voornamelijk aangetroffen bij of in organisch materiaal in kleirijk sediment. In dit materiaal wordt pyriet gevormd onder reducerende omstandigheden. De grootste pyrietaccumulaties komen voor in de kommen van het lage en middelhoge schor.

*Carbonaat-nieuwvormingen.* Er werden twee typen nieuwvormingen waargenomen, namelijk solitaire op rhomboëders gelijkende kristallen, en accumulaties van fijne deeltjes bij of in holten. Het eerste type komt voornamelijk voor in de slikken en hoge delen van oeverwallen; het tweede type is beperkt tot de slikken.

*Ontkalking.* In het middelhoge en hoge schor komen op enige afstand van de oppervlakte zones met een laag carbonaatgehalte voor. De meest ontkalkte zone ligt net boven de G-horizont. Deze kalkarme zones zijn het duidelijkst ontwikkeld in het kleirijk sediment van de kommen. In deze zones komen de laagste pH-waarden voor en is de basenverzadiging minder dan 100%. Micromorfologisch begint de ontkalking met het verdwijnen van de fijnste deeltjes op plaatsen waar drainage mogelijk is, dat wil zeggen bij wortelgangen, passagesporen en iets grovere laagjes van het afgezette materiaal. Deze ontkalking is waarschijnlijk voornamelijk het gevolg van herhaalde oxydatie en reductie van ijzer en van de mogelijkheid van afvoer in het sediment.

*IJzer- en mangaanaccumulaties.* Waar aëratie is opgetreden, komen ijzerhuidjes en ijzeraccumulaties voor in het materiaal dat de holten begrenst. De huidjes kunnen zowel amorf als kristallijn zijn. In het laatste geval bestaan ze uit goethiet. IJzeraccumulaties komen voor in de slikken, de oeverwallen en de kommen van het middelhoge schor. Mangaanaccumulaties komen voor in combinatie met ijzeraccumulaties langs scheuren en gangen in het slik en de oeverwallen. In het bodemmateriaal van de kommen van het middelhoge en hoge schor komen mangaanaccumulaties voor in organisch materiaal zoals wortelresten en veenfragmenten. Rondom deze mangaanaccumulaties kunnen ijzerrijke zones voorkomen.

Bovenstaande bodemvormende processen kunnen in vier categorieën worden ingedeeld, namelijk (1) toevoeging, zoals excrementen van dieren die slib filteren uit het vloedwater en dit

## GLOSSARY

- addition:** Addition to a soil body (SIMONSON, 1959).
- aggrotubule:** A pedotubule composed of coarse and fine materials that occur essentially as recognizable aggregates within which there is no directional arrangement with regard to the external form (Adapted from BREWER & SLEEMAN, 1963; BAL, 1973; STOOPS and JONGERIUS, 1975).
- amoeboidal pyrite:** Pyrite that is spherical in cross-section, with protuberances. The protuberances are usually smaller pyrite spheres that are linked to the main sphere by short stems. (Amoeba: a single-celled animalcule perpetually changing shape by protruding portions of its body. Source: *Oxford Illustrated Dictionary*, 1975).
- apedal soil material:** The soil material does not consist of peds (BREWER, 1964).
- bio-geogenetic laminae or beds:** Geogenetic laminae or beds composed of material of biogenic origin e.g. shells, bones, excrements, peat fragments, plant remains.
- creeks:** Water courses occurring in salt marshes and transitional zones. In cross-section the dimensions of the width and depth are about equal. Creeks are bordered by natural levees (raised banks).
- cutan:** A modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or *in situ* modification of the plasma; cutans can be composed of any of the component substances of the soil material (BREWER, 1960).
- floral channels:** Floral channels are channels produced by the part of the vegetation present below the surface. Not only roots but also underground parts of stems, e.g. rhizomes and associated leafy sprouts, produce these channels.
- gullies:** Water courses occurring in the intertidal flats. In cross-section they are asymmetrical with one steep wall and are much wider than deep. Gullies do not have natural levees (raised banks).
- inflow cutan:** A cutan formed by the inflow of a liquid soil/water mass into voids. Inflow cutans may consist of fine or coarse particles, and mixtures.
- intertidal flat:** The intertidal flat constitutes the lowest part of the intertidal zone. It is a bare and slightly undulating flat that is dissected by a few gullies.
- intertidal zone:** Area situated between low tide and high tide levels. The intertidal zone comprises sediments deposited during the rise and fall of tides. Intertidal flats and marshes form the two principle landscapes that can be distinguished in this area.
- manganese pseudomorph:** A pseudomorph of manganese after organic material such as peat fragments, root remains, detritus grains, etc.
- material, fine and coarse:** The lowest fabric units were classified according to the principle of fine and coarse grains proposed by STOOP & JONGERIUS (1975). The boundary between fine and coarse materials has been fixed at 30  $\mu\text{m}$  in this study.  
Note: This concept, rather than the plasma and skeleton grains concept of BREWER & SLEEMAN (1960), has been used in all the definitions given in this glossary.
- matrix:** The material within the simplest (primary) peds, or composing apedal soil materials, in which the pedological features occur; it consists of fine and coarse material, and voids that do not occur in pedological features other than plasma separations (BREWER, 1964).
- mud:** A slimy, and sticky or slippery mixture of water and finely divided particles (silt size or smaller) or solid or earthy material, with a consistency varying from that of a semifluid to that of a soft and plastic sediment (GARY, M., R. MCAFEE JR. & C. L. WOLF, EDS., 1973).
- mud-zoocutan:** A zoocutan composed of mud. In most cases the mud is derived from excrements.
- neocutan:** A pedological feature that occurs within the matrix but immediately adjoining and related to the natural surfaces in the soil material (BREWER, 1964).
- neopyritan:** A neocutan composed of pyrite.
- overlapping compound zoocutan:** Compound (*sensu* BREWER) zoocutans composed of organic, sedimentary or soil materials, which overlap each other and mostly have restricted dimensions.
- passage feature:** A pedological feature consisting of soil materials that has a tubular form and no distinct



external boundary. It is the result of the single passage of an animal through wet and unconsolidated soil material. Passage features can be distinguished from the surrounding material by: differences in packing, disturbance of laminae, the presence of excrements and elongated particles oriented along the long axis of the tube. Individual passage features may cross each other and may be present in such large quantities that they occupy most of a horizon.

**ped:** An individual natural soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognizable as natural voids or by the occurrence of cutans (SLEEMAN, 1963).

**pedological feature:** Recognizable units within a soil material which are distinguishable from the enclosing material for any reason, such as origin, differences in concentration of some fraction of the clay-sized material, or differences in arrangement of the constituents (BREWER & SLEEMAN, 1960).

**pedotubule:** A pedological feature consisting of soil material which has a tubular external form as a single tube or as a branching system of tubes; its external boundaries are relatively sharp (BREWER & SLEEMAN, 1963).

**pressure-affected zone (biogenetic):** A pedological feature of biogene origin, induced by pressure exerted on a channel wall. In the pressure-affected zone adjoining the channel wall the following phenomena can be distinguished: an increase in compaction; a change in orientation *vis à vis* the undisturbed material e.g. deflection of elongated particles and laminae, etc.

**pseudomorph:** A term used in micromorphology (in particular in the Soviet Union) to indicate the product of organic or mineral substitution by other substances with conservation of primary form (JONGERIUS & RUTHERFORD, Eds., 1978).

**pyritan:** A cutan composed of pyrite.

**pyrite pseudomorph:** A pseudomorph of pyrite after organic material such as peat fragments, root remains, detritus grains, etc.

**regrouping phenomena:** All changes in the mutual arrangement of solid components in the pedon, caused by natural processes or by human activity, in so far that at least as concerns the mineral components, they are not a consequence of enrichment from outside the pedon or of transformations *in situ* (JONGERIUS, 1970).

**removal:** Losses from a soil body (SIMONSON, 1959).

**salt marsh:** The salt marsh constitutes the highest part of a marine intertidal zone and is covered with a dense vegetation. Three landscape elements can be distinguished: creeks, natural levees and basins.

**soil material:** Soil material is the unit of study; it is that unit in which the characteristics being studied are relatively constant, and it will vary in size with the kind and extent of development of those characteristics (BREWER, 1964).

**striotubule:** A pedotubule composed of fine and coarse materials that are not organized into recognizable aggregates but exhibit a basic fabric with a directional arrangement related to the external form. The directional arrangement is semi-ellipsoidal with the walls of the pedotubule approximately tangential to the semi-ellipsoid (BREWER & SLEEMAN, 1963).

**transfer:** Translocation within a soil body (SIMONSON, 1959).

**transformation:** Transformation of material within a soil body (SIMONSON, 1959).

**vesicles:** Smoothed regular voids (BREWER, 1964).

**vughs:** Relatively large voids, other than packing voids, usually irregular and not normally interconnected with other voids of comparable size (BREWER, 1964).

**zoocutan:** A simple or compound (*sensu* BREWER) cutan in channels holes, chambres, etc. directly resulting from the activity of an animal. The cutan may consist of mineral and/or organic material. This material may be produced by the animal itself, or be derived from sedimentary or soil materials, or from other sources.

## REFERENCES

- Acarla, A., 1951. Gedetailleerde overzichtskartering van de Bathpolders. Stibokarapport nr. 268.
- Allen, J.R.L., 1970. Physical processes of sedimentation. Earth Science Series No. 1. London (G. Allen & Unwin).
- Bal, L., 1973. Micromorphological Analysis of Soils. Ph. D. thesis. Soils Department of the State University Utrecht, The Netherlands.
- Beefink, W.G., 1965. De zoutvegetatie van ZW-Nederland beschouwd in Europees verband. Meded. Landbouwhogeschool, Wageningen, 65 (1): 1-167.
- Berner, R.A., 1971. Principles of Chemical Sedimentology. Mc Graw-Hill, New York.
- Bisdom, E.B.A., S. Henstra, A. Jongerius & F. Thiel, 1975. Energy-dispersive X-ray analysis on thin sections and unimpregnated soil material. Neth. J.Agr.Sci. 23 (2): 113-125.
- Bisdom, E.B.A., S. Henstra, E.M. Hornsveld, A. Jongerius & A. C. Letsch, 1976. Wavelength and energy-dispersive X-ray microanalysis with EMA and SEM-EDXRA on thin sections of soils. Neth.J.Agr.Sci. 24 (4): 209-222.
- Black, C.A. (Ed.), 1965. Methods of Soil Analysis Part 1. Agronomy series 9, Am. Soc.Agron., Madison.
- Brewer, R., 1960. Cutans: their definition, recognition, and classification. J.Soil Sci. 11: 280-292.
- Brewer, R., 1964. Fabric and mineral analysis of soils. John Wiley & Sons, New York.
- Brewer, R. & J.R. Sleeman, 1960. Soil structure and fabric: their definition and description. J.Soil Sci. 11: 172-185.
- Brewer, R. and J.R. Sleeman, 1963. Pedotubules: their definition, classification and interpretation. J.Soil Sci. 14: 156-166.
- Brinkman, R., 1970. Ferrolysis; a hydromorphic soilforming process. Geoderma 3: 199-206.
- Brown, G., 1961. The X-ray identification and crystal structures of clay minerals. Mineral Society, London.
- Buol, S.W., F.D. Hole & R.J. McCracken, 1973. Soil Genesis and Classification. The Iowa State Univ.Press.Ames, Iowa.
- Coulson, J., C.T. Carr, L. Hutchinson & D. Eagle (Eds.), 1975. The Oxford illustrated dictionary. Oxford University, Oxford.
- De Bakker, H. & J. Schelling, 1966. Systeem van bodemclassificatie voor Nederland. De hogere niveaus. Pudoc, Wageningen.
- De Glopper, R.J., 1967. Over de bodemgesteldheid van het waddengebied. With summary: The soils of the Wadden Area. Van Zee tot Land No. 43. Tjeenk Willink, Zwolle.
- De Glopper, R.J., 1973. Subsidence after drainage of the deposits of the former Zuyder Zee and in the brackish and marine forelands in The Netherlands. Van Zee tot Land, No. 50, Staatsuitgeverij, Den Haag.
- De Groot, A.J., 1963. Mangaantoeestand van Nederlandse en Duitse holocene sedimenten in verband met slibtransport en bodemgenese. Pudoc, Wageningen.
- Dibbits, H.A.M.C., B. Verhoeven, D. Bakker *et al.*, 1957. De bedijking, ontginning en verpachting van de Braakman. Van Zee tot Land No. 19. Tjeenk Willink, Zwolle.
- Doeksen, J. & J. van der Drift (Eds.), 1963. Soil Organisms. Proceedings of the colloquium on soil fauna, soil microflora and their relationships. North-Holland Publishing Company, Amsterdam.
- Doeksen, J. & G. Minderman, 1963. Typical soil structures as the result of the activities of mudworms. In: Doeksen, J. and J. van der Drift, 134-137.
- Drinkwaard, A.C., 1957. The quality of oysters in relation to environmental conditions in the Oosterschelde in 1957. Anns Biol., Copenh. 14, 217-223.
- Drinkwaard, A.C., 1958. The quality of oysters in relation to environmental conditions in the Oosterschelde in 1958. Anns Biol., Copenh. 15, 224-233.
- Drinkwaard, A.C., 1959. The quality of oysters in relation to environmental conditions in the Oosterschelde in 1959. Anns Biol., Copenh. 16, 225-261.
- Drost, H. (Ed.), 1973. Acid sulphate soils. Proceedings of an International Symposium, Wageningen. ILRI, Vol. 1 en 2, No. 18. Wageningen.



- Esau, K., 1960. Anatomy of seed plants. John Wiley and Sons, London.
- F.A.O., 1966. Guidelines for soil profile description. Rome.
- F.A.O.-UNESCO, 1974. Soil map of the world 1:5 000 000. Vol. I, Legend. Unesco-Paris.
- Garrels, R.M. & C.L. Christ, 1965. Solutions, Minerals and Equilibria. Harper and Row, New York.
- Gary, M., R. McAfee Jr., C.L. Wolf (Eds.), 1973. Glossary of geology. American Geological Institute, Washington D.C.
- Hageman, B.P., 1969. Development of the western part of the Netherlands during the Holocene. *Geologie en Mijnbouw*. Vol. 48 (4): 373-388.
- Heukels, H. & S.J. van Oostroom, 1973. Flora van Nederland. Wolters-Noordhoff N.V., Groningen.
- Hofstee, J., 1966. A. Analysemethoden voor grond, gewas, water en bodemvocht in gebruik bij het Bodemkundig Laboratorium van de Rijksdienst voor de IJsselmeerpolders. Kampen.
- Hofstee, J., 19. B. Toelichting op de analysemethoden voor grond, gewas, water en bodemvocht in gebruik bij het Bodemkundig Laboratorium van de Rijksdienst voor de IJsselmeerpolders. Kampen.
- Hole, F.D., 1961. A classification of pedoturbation and some other processes and factors of soil formation in relation to isotropism and anisotropism. *Soil Sci.*, 91: 375-377.
- Holme, N.A., 1949. The fauna of sand and mud banks near the mouth of the Exe estuary. *J.mar.biol. Ass. U.K.*, 28: 189-237.
- Jackson, M.L., 1969. Soil chemical analyses. Advanced course, 5th printing. Publ. by the author. Depth of soil science, Univ. of Wisconsin.
- Jelgersma, S., 1961. Holocene sea level changes in the Netherlands. *Meded. Geol. Stichting (C)* 6 (7): 1-100.
- Jongerijs, A. (Ed.), 1964. Soil micromorphology. Preceedings of the second international working-meeting on soil micromorphology, Arnhem. Elsevier, Amsterdam.
- Jongerijs, A., 1970. Some morphological aspects of regrouping phenomena in dutch soils. *Geoderma* 4: 311-331.
- Jongerijs, A. & G. Heintzberger, 1975. Methods in soil micromorphology. A technique for the preparation of large thin sections. Soil Survey Paper, no. 10, Netherlands Soil Survey Institute, Wageningen, 48 p.
- Jongerijs, A. & G.K. Rutherford, 1978. A glossary of soil micromorphological terms. Pudoc, Wageningen.
- King, C.A.M., 1972. Beaches and Coasts. Arnold, London.
- Kohl, F. (Ed.), 1971. Kartieranleitung. Anleitung und Richtlinien zur Herstellung der Bodenkarte 1: 25000, bearbeitet von der Arbeitsgemeinschaft Bodenkunde. Hannover.
- Koninklijk Nederlands Meteorologisch Instituut, 1972. Klimaatatlas van Nederland. Staatsuitgeverij, Den Haag.
- Kubišna, W.L., 1938. Micropedology. Collegiate Press, Inc., Ames, Iowa.
- Miedema, R., A.G. Jongmans & S. Slager, 1974. Micromorphological observations on pyrite and its oxidations products in four Holocene alluvial soils in the Netherlands. In: Rutherford, G.K. (Ed.): Soil microscopy. Proceedings of the 4th international working meeting on soil micromorphology. Limestone Press, Kingston, Ontario, 772-794.
- Mulders, M.A., 1969. The arid soils of the Balikh Basin (Syria). Ph. D. Thesis, Soil Department of the State University Utrecht, Utrecht.
- Munsell Soil Color Charts, 1954. Munsell Color Company, Inc., Baltimore.
- Nienhuis, P.H., 1969. Enkele opmerkingen over het geslacht *Enteromorpha* Link op de schorren en slikken van ZW-Nederland. *Gorteria* 4, no. 10: 178-183.
- Nienhuis, P.H., 1970. The benthic algal communities of flats and salt marshes in the Grevelingen, a sea-arm in the South-Western Netherlands. *Netherlands Journal of Sea Research* 5 (1): 20-49.
- Pannekoek, A.J. (Ed.), 1973. Algemene Geologie. Tjeenk Willink, Groningen.
- Pons, L.J., 1964. A quantitative microscopical method of pyrite determination in soils. In: Soil micromorphology. A. Jongerijs (Ed.). Proceedings of the second international working-meeting on soil micromorphology, Arnhem, The Netherlands. Elsevier, Amsterdam 401-409.
- Pons, L.J., 1965. De Zeekleigronden. In: De bodem van Nederland. Stichting voor Bodemkartering, Wageningen, 23-110.
- Pons, L.J. & I.S. Zonneveld, 1965. Soil ripening and soil classification. Initial soil formation in alluvial deposits and a classification of the resulting soils. ILRI Publ. 13, Veenman, Wageningen.

- Ranwell, D.S., 1972. Ecology of salt-marshes and sand dunes. Chapman and Hall, Londen.
- Reineck, H.E., 1958. Wühlbau-Gefüge in Abhängigkeit von Sediment- Umlagerungen. *Senckenbergiana Lethaea* 39: 1-24.
- Reineck, H.E., 1970. Das Watt, Ablagerungs- und Lebensraum. Verlag von Waldemar Kramer. Frankfurt am Main, 1-142.
- Reineck, H.E. and I.B. Singh, 1973. Depositional Sedimentary Environments. Springer Verlag, Berlin.
- Richards, L.A. (Ed.), 1969. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook no. 60. Us Government Printing Office, Washington DC.
- Rickard, D.T., 1973. Sedimentary iron sulphide formation. In: Drost, 1973, Vol. I, 28-65.
- Rickard, D.T., 1975. Kinetics and mechanism of pyrite formation at low temperatures. *Am.J.Sci.* 275: 636-652.
- Rijks Geologische Dienst, 1975. Geologische overzichtskaarten van Nederland, 1:600000 (Vijf kaarten + toelichting). Haarlem.
- Rode, A.A., 1955. Soil Science (Pochvovedeniye)-(translated by A. Gourevich, 1962). Israel Prog. for Sci Trans., Jerusalem.
- Roeleveld, W., 1974. The Groningen Coastal Area. A study in Holocene geology and low-land physical geography. Ph. D. Thesis, Free University, Amsterdam.
- Rutherford, G.K. (Ed.), 1974. Soil microscopy. Proceedings of the 4th international working meeting on soil micromorphology. Limestone Press, Kingston, Ontario.
- Scheffer, F. & P. Schachtschabel, 1966, 1970. Lehrbuch der Bodenkunde. Ferdinand Enke Verlag, Stuttgart.
- Simonson, R.W., 1959. Outline of a generalized theory of soil genesis. *Soil Sci, Soc. Am. Proc.*, 23: 152-156.
- Sleeman, J.R., 1963. Cracks, peds, and their surfaces in some soils of the Riverine Plain, N.S.W. Aust. J. Soil Res. I: 91-102.
- Soil Survey Staff SCS, USDA, 1975. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. US Government Printing Office, Washington DC.
- Soil Survey Staff SCS, 1962. Soil Survey Manual. US Depth. Agriculture Handbook no. 18. US Government Printing Office, Washington DC.
- Stichting voor Bodemkartering, 1964. Bodemkaart van Nederland, schaal 1:50 000. Toelichting bij Kaartblad 43 West, Willemstad. Wageningen.
- Stichting voor Bodemkartering, 1965. Schema voor profielbeschrijving, 1:50000 kaarten. Interne publ. Stiboka, Wageningen.
- Stichting voor Bodemkartering, 1967. Bodemkaart van Nederland, schaal 1:50000. Toelichting bij de Kaartbladen 53 Sluis en 54 West Terneuzen. Wageningen.
- Stoops, G. & A. Jongerius, 1975. Proposal for a micromorphological classification of soil materials. I. A classification of the related distributions of fine and coarse particles. *Geoderma*, 13: 189-199.
- Stumm, W. & J.J. Morgan, 1970. Aquatic chemistry. John Wiley, New York.
- Strahler, A.N., 1965. Physical Geography. John Wiley and Sons, New York.
- Sweeny, R.E. & I.R. Kaplan, 1973. Pyrite framboid formation: laboratory synthesis and marine sediments. *Econ. Geology* 68: 618-634.
- Terwindt, J.H.J., 1967. Mud transport in the Dutch Delta area and along the adjacent coastline. *Neth. J. Sea Res.*, 3: 505-531.
- Van Breemen, N., 1973. Soil forming processes in acid sulphate soils. In: Drost, 1973, Vol. I. No. 18, ILRI, Wageningen.
- Van Breemen, N., 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Pudoc, Wageningen.
- Van der Plas, L. & J. van Schuylenborgh, 1970. Petrochemical calculations applied to soils, with special reference to soil formation. *Geoderma* 4, nr. 4: 375-385.
- Van der Sluijs, P., 1970. Decalcification of marine clay soils connected with decalcification during silting. *Geoderma* 4: 209-227.
- Van Rummelen, F.F.F.E., 1970. Toelichtingen bij de Geologische kaart van Nederland 1:50000, blad Schouwen-Duiveland. Rijks Geologische Dienst, Haarlem.
- Van Rummelen, F.F.F.E., 1972. Toelichtingen bij de Geologische kaart van Nederland 1:50000, blad Walcheren. Rijks Geologische Dienst, Haarlem.



- Van Schuylenborgh, J., 1973. Sesquioxide formation and transformation. Pseudogley and Gley. Transactions of Commissions V and VI, Int. Soc. Soil Sci., Stuttgart 1971. Verlag Chemie, Weinheim, 1973: 93-103.
- Van Straaten, L.M.J.U., 1952. Biogene textures and the formation of shell beds in the Dutch Wadden Sea. Proceedings Kon. Nederl. Akademie van Wetenschappen, serie B, 55, no. 5: 500-516.
- Van Straaten, L.M.J.U., 1954. Composition and structure of recent marine sediments in the Netherlands. Leidse Geologische Mededelingen no. 19: 1-110.
- Veenstra, H.J., 1970. Quaternary North Sea Coasts. Quaternaria XII: 169-184.
- Verhoeven, B., 1962. On the calciumcarbonate content of young marine sediments, Neth.J.Agr. Sci. 10: 58-71.
- Verhoeven, B. & J. Akkerman, 1967. Buitendijkse mariene gronden, hun opbouw, bedijking en ontginning. With summary: Marine foreland, its formation, embankment and reclamation. Van Zee tot Land, no. 45. Tjeenk Willink, Zwolle.
- Wiggers, A.J., 1955. De wording van het Noordoostpoldergebied; een onderzoek naar de fysisch-geografische ontwikkeling van een sedimentair gebied. Van Zee tot Land, no. 14. Tjeenk Willink, Zwolle.
- Wolff, W.J., 1973. The estuary as a habitat. An analysis of data on the soft-bottom macrofauna of the estuarine area of the rivers Rhine, Meuse and Scheldt. Zoologische Verhandelingen no. 126, Brill, Leiden.
- Zeemansgids, 1974. Zeemansgids voor de Nederlandse kust. Chef der Hydrografie, 's-Gravenhage.
- Zonneveld, I.S., 1960. De Brabantse Biesbosch. Een studie van bodem en vegetatie van een zoetwatergetijdendelta. Meded. van de Stichting voor Bodemkartering. Bodemkundige Studies no. 4. Wageningen.
- Zuur, A. J., 1954. Bodemkunde der Nederlandse bedijkingen en droogmakerijen. Deel B. Hoofdsamenstelling en andere zgn. chemische bestanddelen van op water gewonnen gronden. Directie van R.I.J.P. en Landbouwhogeschool.
- Zuur, A. J., 1958. Bodemkunde der Nederlandse bedijkingen en droogmakerijen. Deel C. Het watergehalte, de indroging en enkele samenhangende processen. Directie van R.I.J.P.

## APPENDIX 1

### SOIL PROFILE DESCRIPTIONS AND LABORATORY DATA

#### Profile descriptions

##### Profile no. 1

U.S. Soil Taxonomy (1975): 'Typic' Psammaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Hydrozandvaaggrond

G <sub>or1</sub>	0- 2 cm	Dark yellowish brown (10YR 4/4), olive gray (5Y 4/2), in alternating laminae; sand; strong lamination; ripening 2 à 3; strongly calcareous; much evidence of faunal activity, presence of <i>Corophium</i> spp. and <i>Cardium edule</i> ; smooth abrupt boundary to:
G <sub>or2</sub>	2- 9 cm	Black (2.5GY 2/1) 60%, gray (10YR 4-5/1) 40%, gray in laminae and along voids; sand; faint lamination; some vertical cracks of a coarse polygon structure with sometimes thin ferruginous coatings; ripening 3 à 4; strongly calcareous; many effects of faunal activity; smooth abrupt boundary to:
G <sub>r1</sub>	9-25 cm	Gray (5Y 5/1) 60%, black (N2) 40%; sand; distinct lamination; ripening 4; strongly calcareous; common effects of faunal activity; clear smooth boundary to:
G <sub>r2</sub>	> 25 cm	Dark olive gray (2.5GY 4/1), between 25-30 cm depth some black (N2) spots; sand; no lamination visible; strongly calcareous; effects of faunal activity; a few embedded peat pebbles and shell fragments.

##### Profile no. 2

U.S. Soil Taxonomy (1975): 'Typic' Psammaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Hydrozandvaaggrond

G <sub>r1</sub>	0- 1 cm	Olive brown (2.5Y 4/3); sandy loam; ripening 2; strongly calcareous; common thallus fibres of green algae; many specimen of <i>Hydrobia ulvae</i> ; clear smooth boundary to:
G <sub>r2</sub>	1- 3 cm	Black (N1.5); sandy loam; ripening 1; strongly calcareous; few specimen of <i>Hydrobia ulvae</i> ; abrupt smooth boundary to:
G <sub>or1</sub>	3- 7 cm	Gray (7.5Y 4/1); sand; strong lamination; some vertical cracks of a coarse polygon structure with thin ferruginous coatings; ripening 3; strongly calcareous; clear smooth boundary to:
G <sub>or2</sub>	7-30 cm	Very dark gray (N3), dark olive gray (2.5GY 4/1) along many burrows; sand; faint lamination; some vertical cracks of a coarse polygon structure with ferruginous coatings (7.5YR 3/6); ripening 4; strongly calcareous; many tubular pores caused by worms and molluscs; clear smooth boundary to:
G <sub>r</sub>	> 30 cm	Dark gray (N4); sand; faint lamination; ripening 4 to 5; few burrows and some shells.

##### Profile no. 3

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>o</sub>	0- 4 cm	Gray (7.5Y 4/1); sandy loam; weak, very fine angular blocky; ripening 2 to 3; thin broken ferruginous coatings (5YR 3/6) along channels; strongly calcareous; abundant common fine roots and some medium ones; some specimen of <i>Hydrobia ulvae</i> ; clear, wavy boundary to:
G <sub>or1</sub>	4-15 cm	Black (N1.5) 70%, gray (7.5Y 4/1) in many distinct mottles and in zones along channels and cracks; loam; few vertical cracks; ripening 3; thin to moderately



		thick continuous ferruginous coatings (5YR 3/6) along fine and medium channels; few fine and medium pores; strongly calcareous; common fine and medium roots; clear wavy boundary to:
G <sub>or2</sub>	15-40 cm	Gray (7.5Y 4/1), dark brown (7.5YR 3/4) in many prominent mottles and in zones along channels, cracks and in sedimentary laminae; sandy loam; faint lamination; ripening 3; moderately thick continuous ferruginous coatings (7.5YR 3/4) along channels, cracks and in some sedimentary laminae; common fine and medium vertical pores; strongly calcareous; few to common fine roots; few worms, probably of the species <i>Nereis</i> ; clear smooth boundary to:
G <sub>or3</sub>	40-50 cm	Gray (7.5Y 5/1) 90%, gray (7.5Y 4/1), dark brown in distinct mottles; sand; strong lamination; ripening 3; few medium vertical channels; strongly calcareous, few fine and medium roots; presence of worms and empty shells, clear smooth boundary to:
G <sub>r</sub>	> 50 cm	Gray (10Y 5/1); sand; faint lamination; ripening 4; very few medium channels, strongly calcareous; very few roots; burrows, some worms and shell fragments.

#### Profile no. 4

U.S. Soil Taxonomy (1975): 'Typic' Psammaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>r1</sub>	0- 5 cm	Black (N2) 90%, dark olive gray (2.5GY 4/1) in the first 3 mm and along pores; sandy loam; ripening 1 to 2; few-common fine and medium, mainly vertical channels; strongly calcareous; few fine roots; <i>Hydrobia ulvae</i> specimen and few worms; abrupt, smooth boundary to:
G <sub>r2</sub>	5-16 cm	Dark gray (N3), gray (N4) in few filled channels; sandy loam; faint lamination; ripening 2; some tubular pores; strongly calcareous; some fine and medium roots; presence of worms and some molluscs; abrupt smooth boundary to:
G <sub>r3</sub>	16-34 cm	Gray (N4); sand; clear lamination; ripening 3; few medium, mainly vertical pores; strongly calcareous; rare fine roots; filled burrows; clear smooth boundary to:
G <sub>r4</sub>	> 34 cm	Gray (N5); sand; ripening 2; strongly calcareous; rare fine roots; lamina or beds composed of snails, shells of different molluscs and peat grains; filled burrows.

#### Profile no. 5

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>or1</sub>	0- 5 cm	Olive black (7.5Y 3/1) 90%; sandy loam; ripening 2 to 3; broken moderately thick ferruginous (5YR 3/6) coatings along pores and cracks; common fine and very fine tubular pores; strongly calcareous; many fine and very fine roots, few medium (taproots <i>Aster tripolium</i> ); presence of <i>Hydrobia ulvae</i> snails; clear smooth boundary to:
G <sub>or2</sub>	5-30 cm	Dark olive gray (2.5GY 3/1) 60%, greenish black (10GY 2/1) 20%; loam; faint lamination, initial fine crumbs; ripening 3; continuous, moderately thick ferruginous (5YR 3/6) coatings along pores and some semi-ped faces; few medium vertical pores; strongly calcareous; many medium and few coarse roots; presence of worms, grubs, and gastropods; abrupt, smooth boundary to:
G <sub>or3</sub>	30-68 cm	Dark olive gray (2.5GY 3/1) 90%; sand; faint lamination; ripening 3; some continuous thick ferruginous (5YR 3/6) coatings along channels; few medium vertical pores; strongly calcareous; common medium and few coarse roots, some of them are dead ones; clear smooth boundary to:
G <sub>r1</sub>	68-75 cm	Black (2.5GY 2/1); sandy loam; ripening 3; strongly calcareous; common medium roots, mostly dead ones; clear smooth boundary to:
G <sub>r2</sub>	> 75 cm	Dark olive gray (2.5GY 3/1); sand; ripening 4; strongly calcareous; some scattered peat fragments; few medium vertical dead roots; shell fragments.

*Profile no. 6*

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>or</sub>	0-30 cm	Olive black (10Y 2.5/1), black (N1.5) 20%, in mottles; loam; weak fine crumbs; some vertical cracks; ripening 1 to 2; thin ferruginous (5YR 4.5/8) coatings along some vertical cracks and pores; common fine and medium and some coarse tubular pores; strongly calcareous; 0-10 cm, common medium vertical roots, 10-30 cm, abundant (very fine), fine and medium roots; presence of worms and gastropods; clear wavy boundary to:
G <sub>r1</sub>	30-60 cm	Black (N2), olive black (10Y 3/1) along vertical root channels; sandy loam; weak fine crumbs; ripening 2; few medium and many very fine tubular randomly oriented pores; strongly calcareous; many very fine, few fine and some medium roots; clear smooth boundary to:
G <sub>r2</sub>	> 60 cm	Dark gray (N3); sand; distinct lamination; ripening 3 to 4; few very fine pores; strongly calcareous; few very fine dead roots; small shell fragments.

*Profile no. 7*

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Gorsvaaggrond

G <sub>or</sub>	0-30 cm	Very dark gray (5Y 3/1), dark reddish brown (5YR 3/6), very dark grayish brown (10YR 3/2) and black (N2) in mottles; clay loam; weak fine crumbs and some vertical cracks; ripening 3; continuous thin ferruginous coatings along vertical cracks and pores; common fine and very fine and a few medium tubular pores; strongly calcareous; many fine and very fine roots, few medium roots; presence of gastropods; clear wavy boundary to:
G <sub>r1</sub>	30-55 cm	Black (2.5GY 2/1), dark olive gray (2.5GY 3.5/1); loam; ripening 2; common very fine and some fine tubular mainly vertical pores; strongly calcareous; common fine, partly dead roots, few coarse ones; clear smooth boundary to:
G <sub>r2</sub>	55-85 cm	Dark olive gray (5GY 3/1); sandy loam; distinct lamination; ripening 3; few fine tubular pores; strongly calcareous; few fine roots, mostly dead ones; sedimentary bed of <i>Hydrobia ulvae</i> snails; clear smooth boundary to:
G <sub>r3</sub>	> 85 cm	Dark olive gray (5GY 3/1); sand; distinct lamination; ripening 4; strongly calcareous; very few dead fine roots; small snail and shell fragments.

*Profile no. 8*

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>r1</sub>	0- 1 cm	Olive black (7.5Y 3/2); silty clay loam; faint lamination; ripening 1 to 2; strongly calcareous; few medium vertical roots; many snails of <i>Hydrobia ulvae</i> , presence of a ferruginous film at the surface; abrupt, smooth boundary to:
G <sub>r2</sub>	1- 4 cm	Black (N1.5); clay loam; ripening 1 to 2; few very fine pores; strongly calcareous; many medium and fine vertical roots, inclusive some black roots; some <i>Hydrobia ulvae</i> snails; abrupt, smooth boundary to:
G <sub>r3</sub>	4-13 cm	Black (N1.5); clay loam; ripening 1 to 2; few (very) fine pores; strongly calcareous; abundant fine and medium roots; smell of H <sub>2</sub> S; clear smooth boundary to:
G <sub>r4</sub>	13-51 cm	Greenish black (5G 1.7/1); loam; ripening 2; few fine pores; strongly calcareous; many fine and medium roots; smell of H <sub>2</sub> S; clear smooth boundary to:
G <sub>r5</sub>	51-61 cm	Black (2.5GY 2/1); sandy loam; ripening 2 to 3; strongly calcareous; common fine and medium roots; clear smooth boundary to;
G <sub>r6</sub>	> 61 cm	Dark olive gray (2.5GY 3/1); sand; ripening 4; strongly calcareous; few fine dead roots; shell fragments of <i>Cardium edule</i> ; peat grains and fragments.



*Profile no. 9*

U.S. Soil Taxonomy (1975): Typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Gorsvaaggrond

G <sub>or</sub>	0-32 cm	Olive gray (5Y 4/2), dark reddish brown (5YR 3/6) 35% in mottles and along pores, cracks etc.; clay loam; weak coarse prismatic and moderate angular blocky; ripening 3; continuous thin ferruginous coatings along vertical ped faces and pores; common very fine and few medium tubular pores; first 18 cm strongly calcareous, deeper than 18 cm (very) slightly calcareous to non calcareous; many fine and very fine roots, few medium ones; some crabholes usually with ferruginous coatings; few specimen of <i>Hydrobia ulvae</i> ; clear wavy boundary to:
G <sub>r1</sub>	32-55 cm	Dark gray (5Y 4/1), olive black (10Y 3/1) 3%, in some rootchannels; silty clay loam; distinct lamination; ripening 2; common very fine tubular pores; till 40 cm depth (very) slightly calcareous to non calcareous, deeper than 40 cm calcareous to strongly calcareous; many very fine and fine mostly vertical roots; clear smooth boundary to:
G <sub>r2</sub>	> 55 cm	Dark gray (5Y 4/1); clay loam; distinct lamination; ripening 2; common very fine and fine tubular pores; (strongly) calcareous; many very fine and a few fine roots; disturbance of the lamination probably caused by faunal activity; sand at 120 cm depth.

*Profile no. 10*

U.S. Soil Taxonomy (1975): Typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>or</sub>	0- 7 cm	Olive black (7.5Y 3/2), dark reddish brown (5YR 3/6) 20%; silty clay; weak very fine angular blocky; ripening 2; thin to moderately thick continuous ferruginous coatings along ped faces, and pores; common fine and medium vertical pores; calcareous; many fine and medium roots; some specimen of <i>Hydrobia ulvae</i> ; clear wavy boundary to;
G <sub>r1</sub>	7-25 cm	Black (N1.5), dark gray (5Y 4/1) 5% along channels; silty clay; weak very fine angular blocky; ripening 2; common fine and medium pores; slightly calcareous 7-15 cm, non calcareous 15-25 cm, abundant very fine, fine and medium roots; clear smooth boundary to:
G <sub>r2</sub>	25-41 cm	Black (N1.5); clay loam; ripening 2; common fine and medium pores; very slightly calcareous; many very fine, fine and medium roots; clear smooth boundary to:
G <sub>r3</sub>	41-60 cm	Very dark gray (N3); silty clay; ripening 2; common fine and medium pores; calcareous; many fine and medium roots; clear smooth boundary to:
G <sub>r4</sub>	60-82 cm	Very dark gray (N3); clay loam; ripening 2; few to common fine and medium pores; calcareous; common fine and medium roots, partly dead ones; clear smooth boundary to:
G <sub>r5</sub>	> 82 cm	Very dark gray (N3); loam; weak lamination; ripening 2; few fine and medium pores; strongly calcareous; few fine roots; shell fragments; sand at 120 cm depth.

*Profile no. 11*

U.S. Soil Taxonomy (1975): Hydraquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Gorsvaaggrond

AC	0- 7 cm	Very dark grayish brown (2.5Y 3/2); loam; moderately very fine angular blocky; ripening 4; common fine pores; strongly calcareous; many very fine, fine and few medium roots; presence of grubs and snails; abrupt smooth boundary to:
G <sub>or1</sub>	7-38 cm	Very dark grayish brown (2.5Y 3/2) 60%, dark gray (5Y 4/1) 25% in mottles, dark reddish brown (5YR 3/6) 15% in mottles and along pores; sandy loam; weak coarse prismatic and weak very fine angular blocky; ripening 3 to 4; continuous thin to moderately thick ferruginous coatings along vertical ped faces, pores and holes; many fine and medium tubular pores; calcareous to 20 cm depth, slightly

		calcareous 20-38 cm depth; many fine and medium roots; clear smooth boundary to:
G <sub>or2</sub>	38-58 cm	Gray (7.5Y 4/1) 60%, dark grayish brown (2.5Y 4/2) 20% in mottles, dark red (2.5YR 3/6) 20% in mottles; loam; moderately coarse prismatic; ripening 3; moderately thick to thick continuous ferruginous coatings on vertical ped faces, pores and holes; many fine vertical pores; slightly calcareous 38-45 cm, calcareous deeper than 45 cm; few small spherical black/red mottles probably of manganese/iron; common fine mainly vertical roots; crabholes; wavy clear boundary to:
G <sub>r1</sub>	58-76 cm	Black (N2), dark gray (5Y 4/1) in zones along channels; loam; ripening 3; many fine and some medium vertical pores; strongly calcareous; many very fine, fine and medium roots, about 60% dead ones; thin dark gray (5Y 4/1) layer with many <i>Hydrobia ulvae</i> snails; clear smooth boundary to:
G <sub>r2</sub>	> 76 cm	Black (N2), dark gray (5Y 4/1) 15% along pores; loam; faint lamination; ripening 2 to 3; many very fine and some fine and medium vertical pores; strongly calcareous; few fine and very fine vertical roots; effects of faunal activity.

*Profile no. 12*

U.S. Soil Taxonomy (1975): typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>or</sub>	0-26 cm	Gray (7.5Y 4/1) 55%, dark brown (10YR 3/3) 40% along ped faces and pores, and dark reddish brown (5YR 3/6) 5% along ped faces and pores; silty clay loam; weak very fine angular blocky; ripening 2; deeper than 6 cm continuous moderately thick ferruginous coatings on ped faces and pores; common fine random pores; first 3 cm strongly calcareous, decreasing to non calcareous at 9 cm depth, from 9-20 cm non calcareous, deeper than 20 cm slightly calcareous; abundant very fine, fine and medium roots; first 6 cm many specimen of <i>Hydrobia ulvae</i> ; abrupt smooth boundary to:
G <sub>r1</sub>	26-37 cm	Black (N2) and olive black (10Y 3/1) along some vertical pores; clay loam; ripening 2; common fine, mainly vertical pores; calcareous; many fine and medium roots, partly black coloured; abrupt smooth boundary to:
G <sub>r2</sub>	37-49 cm	Very dark gray (N3); loam; weak lamination; ripening 2; few to common fine vertical pores; calcareous; common fine and medium vertical roots, partly dead ones; abrupt smooth boundary to:
G <sub>r3</sub>	> 49 cm	Dark gray (N4) and olive gray (2.5GY 5/1) in sandy laminae; sandy loam; strong lamination; ripening 2 to 3; few fine vertical pores; strongly calcareous; few to common fine and medium roots; sand at 82 cm depth.

*Profile no. 13*

U.S. Soil Taxonomy (1975): Typic Haplaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Vlakvaaggrond

AC	0- 5 cm	Dark grayish brown (2,5Y 4/2); sand; faint lamination; moderately very fine angular blocky; ripening 5; many very fine and fine pores; calcareous; abundant very fine and fine roots; presence of beetles; abrupt smooth boundary to:
C	5- 30 cm	Olive brown (2.5Y 4/3); sand; distinct lamination; moderate very fine angular blocky; ripening 4; many fine and very fine pores; calcareous; many fine random roots; abrupt smooth boundary to:
G <sub>o1</sub>	30- 40 cm	Dark gray (5Y 4/1) 45% in sandy laminae, olive brown (2.5Y 4/3) 45% in clay-rich laminae and dark reddish brown (2.5YR 3/3) in some clay-rich laminae and some mottles; sandy loam; faint lamination; weak medium angular blocky, sometimes medium platy; ripening 3; many fine and very fine pores; calcareous; common fine roots; clear smooth boundary to:
G <sub>o2</sub>	40- 52 cm	Dark grayish brown (2.5Y 4/2) 50%, gray (5Y 5/1) 40% in mottles and dark reddish brown (2.5YR 3/2) 10% in mottles; sandy loam; moderate medium angular



		blocky, few long vertical cracks; ripening 3; thin continuous ferruginous coatings along pores, cracks and holes; common fine and very fine pores; calcareous, few to common fine mostly vertical roots, clear smooth boundary to:
G <sub>or1</sub>	52- 74 cm	Gray (7.5Y 5/1) 50%, olive gray (5Y 4/2) 40% in mottles and dark reddish brown (2.5YR 3/2) in mottles and along pores; sand; weak medium to coarse angular blocky; ripening 3; continuous moderately thick ferruginous coatings along pores; few to common fine mostly vertical pores; calcareous; few vertical roots; clear smooth boundary to:
G <sub>or2</sub>	74-104 cm	Gray (10Y 5/1) 55%, olive gray (5Y 4/2) 30% in mottles and yellowish red (5YR 4/6) in mottles and along pores and cracks; sand; weak coarse prismatic; faint lamination; ripening 3; continuous moderate a thick ferruginous coatings along pores; few fine vertical pores; strongly calcareous; very few fine roots; abrupt smooth boundary to:
G <sub>r1</sub>	104-123 cm	Gray (10Y 4/1); sand; strong lamination; ripening 2 to 3; strongly calcareous; laminae of shell fragments; abrupt smooth boundary to:
G <sub>r2</sub>	> 123 cm	Olive black (10Y 3/1); sandy loam; faint lamination; ripening 3; shell fragments, shell doublets of <i>Mya arenaria</i> and <i>Scrobicularia plana</i> in original position and some burrows; sand at 135 cm depth.

Profile no. 14

U.S. Soil Taxonomy (1975): Typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Gorsvaaggrond

G <sub>ro1</sub>	0-14 cm	Dark gray (5Y 4/1) 50%, dark olive brown (2.5Y 3/3) 40% in mottles and red (2.5YR 4/8) 10% in mottles; loam; weak to moderate very fine to fine angular blocky; ripening 3; common fine random tubular pores; strongly calcareous to calcareous at 14 cm depth; abundant fine and few medium roots; clear smooth boundary to:
G <sub>ro2</sub>	14-23 cm	Dark olive brown (2.5Y 3/3) 55%, dark gray (5Y 4/1) 40% in mottles, and red (2.5YR 4/8) 5% in mottles; loam; moderate very fine to fine angular blocky; ripening 2 to 3; common fine random tubular pores; slightly calcareous to non calcareous; many fine and few medium roots; clear smooth boundary to:
G <sub>or1</sub>	23-41 cm	Gray (10Y 4/1), olive black (10Y 3/1), together 75%, very dark brown (10YR 3/2) 20% and red (2.5YR 4/8) 5% in mottles and along pores and ped faces; loam; ripening 2; continuous moderately thick ferruginous coatings along pores and vertical ped faces; few fine and common medium and coarse tubular pores; non calcareous to slightly calcareous; common fine and few medium roots; shell fragments; clear smooth boundary to:
G <sub>or2</sub>	41-63 cm	Dark olive gray (2.5 GY 4/1), dark reddish brown (2.5YR 3/4) in mottles but mainly along pores; loam; ripening 1 to 2; many ferruginous coatings mainly around vertical pores and afterwards infilled pores; few medium, vertical tubular pores; slightly calcareous to calcareous; many fine and medium vertical roots, also dead ones, abrupt smooth boundary to:
G <sub>r1</sub>	63-75 cm	Dark gray (N4) 70% and greenish black (10GY 2/1) 25%; sandy loam; faint lamination; ripening 2; few to common medium vertical pores; strongly calcareous; common fine vertical roots, many dead ones; shell fragments; gradual smooth boundary to:
G <sub>r2</sub>	> 75 cm	Greenish black (10GY 2/1), dark olive gray (2.5GY 4/1) 15% in mottles, along pores and infilled in pores; sandy loam; strong lamination; ripening 2 to 3; few medium vertical pores; strongly calcareous; many fine vertical roots, mostly dead ones; many shell doublets and burrows; diffuse transition to less laminated sediment; sand at 125 cm depth.

Profile no. 15

U.S. Soil Taxonomy (1975): Typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Slikvaaggrond

G <sub>or1</sub>	0- 7 cm	Very dark gray (5Y 3/1), dark brown (7.5YR 3/4) 15% in mottles, along pores and ped faces; clay loam; moderately very fine angular blocky; ripening 2; thin discontinuous ferruginous coatings along pores and ped faces; many fine random pores; strongly calcareous to calcareous; many fine and common medium roots; <i>Hydrobia ulvae</i> specimen in the first 2 cm; clear smooth boundary to:
G <sub>or2</sub>	7- 24 cm	Olive black (7.5Y 3/1), dark reddish brown (5YR 3/6) in mottles, along pores and ped faces; clay loam; moderate very fine angular blocky; ripening 2; moderately thick continuous ferruginous coatings along vertical ped faces and pores; many fine pores; slightly calcareous to non calcareous; many fine mainly vertical roots, abrupt smooth boundary to:
G <sub>r1</sub>	24- 47 cm	Olive black (10Y 3/1); loam; weak very fine angular blocky; ripening 1 to 2; common fine vertical pores; non calcareous to calcareous with depth; common fine and medium roots; clear smooth boundary to:
G <sub>r2</sub>	47- 82 cm	Dark gray (N4), black (N2) 20% in laminae and mottles; sandy loam; distinct lamination; ripening 2; few very fine and fine vertical pores; strongly calcareous; common vertical medium roots; clear smooth boundary to:
G <sub>r3</sub>	82-102 cm	Dark gray (N4), black (N2) 10% in thin laminae and some mottles; sandy loam; distinct lamination; ripening 2 to 3; few fine pores; strongly calcareous; few to common vertical fine and medium roots; clear smooth boundary to:
G <sub>r4</sub>	102-140 cm	Gray (N5); sand; weak lamination; ripening 3; very few fine pores; strongly calcareous; fine vertical roots till 135 cm depth; abrupt smooth boundary to:
G <sub>r5</sub>	> 140 cm	Gray (N5); sand; faint lamination; ripening 3; strongly calcareous; shell fragments and doublets.

Profile no. 16

U.S. Soil Taxonomy (1975): Typic Sulfaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Gorsvaaggrond

AC	0-14	Dark greenish gray (10GY 4/1) 50% and very dark reddish brown (5YR 2/3) 50% in laminae, along pores and ped faces; silty clay; moderate very fine to fine angular blocky; ripening 3; many very fine, fine and some medium random pores; calcareous to non calcareous with depth; many very fine and fine random roots; abrupt smooth boundary to:
G <sub>or</sub>	14-27 cm	Dark greenish gray (10GY 4/1), greenish gray (10GY 5/1) in sandier laminae, together 65%, dark reddish brown (2.5YR 3/4) and very dark reddish brown (5YR 2/3) along pores; loam; weak fine angular blocky; distinct lamination; ripening 3; continuous thin ferruginous coatings along pores and vertical ped faces; common fine and medium mostly vertical pores; non calcareous; many very fine and fine roots, abrupt smooth boundary to:
IICG <sub>or</sub>	27-42 cm	Greenish gray (10G 5/1) 75%, dark reddish brown (2.5YR 3/4) in mottles and along pores; sand; ripening 2 to 3; continuous moderately thick ferruginous coatings along vertical (infilled) pores; few fine vertical pores; calcareous; common fine vertical roots; shell fragments; embedded peat fragments and mud pebbles; abrupt smooth boundary to:
IIG <sub>r1</sub>	42-60 cm	Dark olive gray (2.5GY 4/1); sand; strong lamination; ripening 2 to 3; few fine vertical pores; calcareous; common fine vertical roots; shell fragments; embedded peat fragments; abrupt smooth boundary to:
IIG <sub>r2</sub>	> 60 cm	Greenish black (10GY 2/1); sand; ripening 3; calcareous; few vertical roots; shell fragments.



*Profile no. 1, Tweede Bathpolder*

U.S. Soil Taxonomy (1975): Typic Haplaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Poldervaaggrond

Ap	0- 35 cm	Dark grayish brown (2.5Y 4/2) moist; sandy loam; moderate medium crumb; slightly sticky; slightly plastic; many fine and medium tubular pores; strongly calcareous; abundant fine roots; abrupt smooth boundary to:
G <sub>o1</sub>	35- 52 cm	Grayish brown (2.5Y 5/2) moist, dark reddish brown (5YR 3/3) 20%, moist, along pores; sandy loam; moderately fine to medium angular blocky, very weak coarse prismatic; distinct lamination; non sticky, slightly plastic; moderately thick cutans, resembling argillans, on ped faces and along pores; common fine and very fine in ped tubular pores, some with ferruginous coatings; strongly calcareous; many fine roots; few to common infilled channels and chambers; shell fragments; gradual smooth boundary to:
G <sub>o2</sub>	52- 70 cm	Grayish brown (2.5Y 5/2) moist in clay-rich laminae; light gray (5Y 6/1) moist in sandy laminae; sandy loam; distinct lamination; non sticky, non plastic; continuous moderately thick ferruginous (7.5YR 4/3) coatings, mainly along common fine to medium pores; strongly calcareous; few fine roots; few infilled burrows; shell doublets; abrupt smooth boundary to:
G <sub>o3</sub>	70-100 cm	Grayish brown (2.5Y 5/2) moist, in clay-rich laminae, light gray (5Y 6/1) moist, in sandy laminae; sandy loam; strong lamination; slightly sticky, slightly plastic; many ferruginous (7.5YR 4/6) coatings along pores, and infilled pores; few to common fine, medium and coarse vertical pores; strongly calcareous; shell doublets; clear smooth boundary to:
G <sub>o4</sub>	100-125 cm	Yellowish brown (2.5Y 5/3) light gray (5Y 6/1) 10%, brown (7.5YR 4/6) and dark brown (7.5YR 4/4) in many mottles, moist; sand; weak lamination; non sticky, non plastic; few ferruginous coatings along pores, afterwards infilled pores and cracks; few fine and medium vertical pores; strongly calcareous; shell fragments; abrupt smooth boundary to:
G <sub>r</sub>	> 145 cm	Dark greenish gray (5G 3/1) moist, sand.

*Profile no. 2, Tweede Bathpolder*

U.S. Soil Taxonomy (1975): Typic Haplaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Poldervaaggrond

Ap	0- 35 cm	Dark grayish brown (2.5Y 4/2), moist; loam; moderate medium crumb and medium angular blocky; slightly sticky, slightly plastic; many fine and medium tubular random pores; strongly calcareous; evidence of faunal activity; abundant fine roots; abrupt smooth boundary to:
C	35- 70 cm	Grayish brown (2.5Y 5/2) 55%; olive gray (5Y 5/2) 20% in sandy laminae and dark brown (7.5YR 4/4) 25% in mottles and along pores, moist; clay loam; moderate medium prismatic and weak to moderate medium and coarse angular blocky; non sticky, slightly plastic; continuous thin to moderately thick cutans, resembling argillans, on ped faces and along inped pores; common very fine and fine random pores; strongly calcareous; evidence of faunal activity, some roots; abrupt smooth boundary to:
G <sub>o1</sub>	70- 83 cm	Yellowish brown (2.5Y 5/3) 60%, olive gray (5Y 5/2) 25%, brown (10YR 4/3) 15% in mottles, moist; sandy loam; distinct lamination; weak moderate prismatic; non sticky, slightly plastic; discontinuous moderately thick cutans, resembling argillans, along pores and on ped faces; common fine continuous random tubular pores; strongly calcareous, weak evidence of faunal activity; abrupt smooth boundary to:
G <sub>o2</sub>	83- 90 cm	Olive gray (5Y 5/2) 40%, yellowish brown (2.5Y 5/3) 20%, brown (10YR 4/3) 40% in mottles, moist; sandy loam; weak lamination; some vertical cracks; non sticky, non plastic; patchy thin cutans, resembling argillans, along pores and cracks; some continuous ferruginous coatings along pores and infilled pores; com-

		mon fine pores, also infilled pores; strongly calcareous; shell doublets, clear smooth boundary to:
G <sub>03</sub>	90-145 cm	Olive gray (5Y 5/2) 60%, brown (10YR 4/3) 30% and yellowish red (5YR 4/6) 10% in mottles, moist; sandy loam; non sticky, non plastic; continuous ferruginous coatings around pores and infilled channels; some fine and medium vertical pores; strongly calcareous; shell doublets and coarse shell fragments; abrupt smooth boundary to:
G <sub>r</sub>	> 145 cm	Dark greenish gray (5G 3/1) moist; sand.

*Profile no. 3, Tweede Bathpolder*

U.S. Soil Taxonomy (1975): Typic Haplaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Poldervaaggrond

Ap1	0- 5 cm	Dark grayish brown (2.5Y 4/2) moist; silty clay; medium fine crumb; non sticky, plastic; common fine pores; calcareous; evidence of faunal activity; clear smooth boundary to:
Ap2	5- 35 cm	Dark grayish brown (2.5Y 4/2) moist; silty clay; medium angular blocky, fine aggregates and structureless material; non sticky, plastic; common fine inped random pores; calcareous; evidence of faunal activity; abrupt smooth boundary to:
G <sub>01</sub>	35- 50 cm	Grayish brown (2.5Y 5/2) on ped faces, brown (7.5YR 4/3) in the peds and dark reddish brown (5YR 3/3) along pores and in some mottles, moist; silty clay; moderately medium to coarse prismatic and fine to medium angular blocky; non sticky, plastic; continuous moderately thick to thick cutans resembling argillans, on ped faces and along some pores; common fine inped pores; calcareous; few to common fine roots, mainly between ped faces; gradual smooth boundary to:
G <sub>02</sub>	50- 70 cm	Grayish brown (2.5Y 5/2) on ped faces, brown (7.5YR 4/3) in the peds and dark reddish brown (5YR 3/3) along pores, moist; clay loam; moderately to strong coarse prismatic and moderately fine and medium angular blocky; few slickensides; non sticky, plastic; some manganese mottles; continuous moderately thick and thick cutans resembling argillans, mainly on ped faces and along pores; common fine and very fine inped pores; calcareous; few fine roots; gradual smooth boundary to:
G <sub>03</sub>	70- 82 cm	Grayish brown (2.5Y 5/2), brown (7.5YR 4/3) and dark reddish brown (5YR 3/3) 50% in mottles, moist; loam; distinct lamination; thin platy with vertical cracks; slightly sticky, slightly plastic; common continuous cutans, resembling argillans, along pores and some vertical cracks; calcareous; few fine roots, mainly in vertical cracks; sharp smooth boundary to:
G <sub>04</sub>	82-108 cm	Light gray (5Y 6/1) and dark reddish brown (5YR 3/3) in mottles, moist; sandy loam; strong lamination; non sticky, non plastic; ferruginous coatings along pores and afterwards infilled pores; some discontinuous cutans, resembling argillans in vertical pores; common fine and medium vertical pores; calcareous; shell fragments and doublets; gradual smooth boundary to:
G <sub>05</sub>	108-155 cm	Brown (10YR 5/3) 80%, light gray (5Y 6/1) 10% and dark brown (7.5YR 4/4) 10% in mottles and along pores, moist; sand; weak lamination; few infilled pores with ferruginous coatings; abrupt smooth boundary to:
G <sub>r</sub>	> 155 cm	Dark gray (N4) moist; sand.

*Profile no. 4, Eerste Bathpolder*

U.S. Soil Taxonomy (1975): Fluvaquent, proposed to be Psammic (pers. comm. DE BAKKER)

Dutch classification (DE BAKKER & SCHELLING, 1966): Vlakvaaggrond

Ap	0- 30 cm	Dark grayish brown (2.5Y 4/2) moist; moderate medium crumb and fine to medium angular blocky; common fine random pores; strongly calcareous; evidence of biological activity; common fine and medium roots; abrupt wavy boundary to:
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G <sub>01</sub>	30- 40 cm	Yellowish brown (2.5Y 5/3), dark brown (7.5YR 3/4) 10% along pores and cracks, moist; loam; slightly sticky, non plastic; common fine random pores; strongly calcareous; evidence of biological activity; few fine and medium roots; abrupt smooth boundary to:
G <sub>02</sub>	40- 70 cm	Olive gray (5Y 5/2) 50%, light olive gray (5Y 6/2) 40% and dark yellowish brown (10YR 4/4) 10% along pores, moist; sand; non sticky, non plastic; strongly calcareous; few fine roots; shell fragments and some peat fragments; clear smooth boundary to:
G <sub>03</sub>	70-120 cm	Olive gray (5Y 5/2), dark yellowish brown (10YR 4/4) 25% in mottles, moist; sand; strongly calcareous; few fine roots; shell fragments, common peat fragments; abrupt smooth boundary to:
G <sub>r</sub>	> 120 cm	Dark greenish gray (5G 3/1) moist; sand.

*Profile no. 5, Rippolder*

U.S. Soil Taxonomy (1975): Typic Haplaquent

Dutch classification (DE BAKKER & SCHELLING, 1966): Poldervaaggrond

Ap	0-35 cm	Dark grayish brown (10YR 4/2) moist; clay loam; moderate medium crumb; slightly sticky, plastic; common fine random and medium vertical pores; strongly calcareous; many fine and medium roots; evidence of faunal activity; abrupt slightly wavy boundary to:
IIIG <sub>0</sub>	35- 55 cm	Pale olive (5Y 6/3) and brown (10YR 4/6) 8% in pores and infilled burrows of fossil faunal activity, moist; sand; a few fine vertical pores; calcareous; nearly no roots; shell fragments; abrupt smooth boundary to:
IIIG <sub>01</sub>	55- 63 cm	Light olive gray (5Y 6/2) and yellowish gray (2.5Y 6/1) with brown (5YR 3/6) 9% along pores and infilled burrows, moist; sand; non sticky, non plastic; new fine random and few medium vertical pores; strongly calcareous; no roots; no evidence of actual faunal activity; abrupt smooth boundary to:
IIIG <sub>02</sub>	63- 80 cm	Olive gray (5Y 5/2) and yellowish red (5YR 4/6) 9% in mottles and along pores, moist; sandy loam; distinct lamination; weak coarse prismatic; non sticky, plastic; ferruginous coatings along vertical pores; many fine and very fine pores; strongly calcareous; no presence of the actual vegetation or fauna; abrupt smooth boundary to:
IIIG <sub>03</sub>	80-125 cm	Gray (5Y 5/1) and yellowish red (5YR 4/6) 30% in mottles and along pores, moist; loam; distinct lamination; weak coarse prismatic; sticky, plastic; few to common fine and very fine pores, some medium vertical pores; strongly calcareous; shell fragments; abrupt smooth boundary to:
IIIG <sub>r</sub>	> 125 cm	Dark greenish gray (5G 3/1), moist; sandy loam; distinct lamination; sticky, slightly plastic; few vertical pores; few filled vertical burrows; strongly calcareous; shell fragments.

Laboratory data, intertidal zone soils

Profile no.	Depth in cm	% Moisture		Granulometric analysis in % of oven-dry soil in $\mu\text{m}$								% $\text{CaCO}_3$	pH		E.C. $\times 10^{-3}$	% C	% N	ppm $\text{P}_2\text{O}_5$ -Olsen	% $\text{Fe}_2\text{O}_3$ dithionite
				210-150	150-105	105-74	74-50	50-16	16-2	<2	$\text{H}_2\text{O}$		KCl						
Profile no. 1	5- 15	0.4	0.3	49.4	31.7	6.8	4.3	1.0	6.4	4.95	8.5	8.3	4.30	0.14	0.02	22	0.04		
	25- 35	0.8	0.7	41.8	29.7	11.2	9.9	1.3	5.4	6.79	8.4	8.1	5.30	0.55	0.05	26	0.07		
Profile no. 2	5- 15	0.7	0.2	9.7	32.0	25.6	25.1	2.8	4.6	7.71	8.3	8.0	5.00	0.53	0.05	28	<0.01		
	25- 35	0.8	0.6	17.5	36.6	20.9	17.8	2.1	4.4	6.98	8.3	8.0	5.00	0.62	0.04	16	<0.01		
Profile no. 3	5- 15	2.8	0.1	3.0	15.4	15.8	29.0	9.9	24.8	6.26	8.0	7.7	10.6	2.09	0.19	136	1.32		
	25- 35	1.5	0.4	22.0	25.6	14.4	19.5	4.3	13.6	3.07	8.1	7.8	6.00	1.07	0.10	63	0.65		
Profile no. 4	5- 15	1.0	0.1	5.9	28.5	29.5	26.6	3.0	6.4	7.91	8.2	7.9	5.70	0.85	0.07	18	0.07		
	25- 35	1.7	0.2	9.6	20.5	17.9	30.6	7.7	13.4	7.59	7.8	7.5	8.60	1.85	0.13	29	0.15		
Profile no. 5	5- 15	3.2	0.1	2.1	9.5	11.1	31.1	16.2	29.8	9.00	7.9	7.4	13.4	2.59	0.28	131	1.51		
	25- 35	2.7	0.1	4.1	14.2	14.6	30.4	12.4	23.9	7.75	7.9	7.6	11.4	2.15	0.22	111	1.40		
	45- 55	1.4	0.4	25.7	28.9	14.4	14.4	3.1	12.9	6.65	8.2	7.6	6.50	1.21	0.11	67	0.65		
Profile no. 6	5- 15	4.5	0.0	0.1	0.6	1.5	31.1	23.6	43.1	10.9	7.8	7.5	13.6	2.95	0.33	188	1.61		
	25- 35	2.0	0.3	0.8	9.3	11.4	29.9	17.3	31.0	6.66	7.4	7.2	13.3	2.77	0.23	37	0.33		
	45- 55	1.3	0.2	12.8	26.1	20.9	18.9	4.8	16.3	10.1	7.6	6.9	7.60	1.56	0.10	16	0.07		
Profile no. 7	5- 15	3.8	0.1	3.0	9.5	9.5	28.9	15.7	33.2	12.7	7.9	7.0	14.7	2.54	0.30	158	1.70		
	25- 35	3.0	0.1	4.4	14.6	12.4	28.9	12.3	27.2	8.05	7.7	7.4	10.0	2.97	0.26	98	1.11		
	45- 55	2.2	0.2	9.1	19.9	13.6	23.3	9.9	24.0	5.66	7.7	7.4	12.0	2.12	0.20	72	0.51		
Profile no. 8	5- 15	3.8	0.0	0.4	1.7	2.9	31.8	20.5	42.5	12.0	7.8	7.5	17.1	3.13	0.33	89	1.01		
	25- 35	3.2	0.0	0.4	2.4	5.4	30.7	22.0	39.1	11.3	7.6	7.4	13.3	3.02	0.29	58	0.89		
	45- 55	1.5	0.2	7.9	23.4	22.3	24.5	6.0	15.7	5.37	7.6	7.3	8.70	1.76	0.13	18	0.22		
Profile no. 9	5- 15	3.9	0.1	2.6	6.4	3.6	23.1	21.0	43.2	6.30	7.7	7.3	17.0	3.88	0.37	240	2.12		
	25- 35	4.1	0.2	2.4	5.9	5.9	29.2	17.6	38.5	1.60	7.4	7.0	14.7	3.54	0.34	272	3.21		
	45- 55	4.1	0.1	1.3	2.0	4.7	30.1	18.3	43.5	4.38	6.8	6.6	15.0	4.16	0.39	32	0.71		
	65- 75	2.9	0.1	2.3	11.0	13.3	30.9	12.6	29.7	5.28	7.1	6.9	12.0	3.12	0.24	21	0.37		
Profile no. 10	5- 15	5.2	0.0	0.2	0.4	0.3	21.8	26.6	50.7	2.42	7.4	7.1	20.2	4.78	0.52	302	2.45		
	25- 35	3.5	1.2	2.3	12.4	11.2	24.5	15.1	33.3	1.92	6.6	6.4	16.0	4.10	0.35	57	0.59		
	45- 55	4.1	0.1	1.0	2.6	6.0	29.1	19.0	42.2	2.34	6.6	6.4	17.0	5.69	0.41	22	0.63		
	65- 75	5.3	0.1	1.5	8.2	14.2	34.1	4.3	37.5	6.41	7.1	6.9	12.0	3.90	0.25	16	0.38		
Profile no. 11	5- 15	2.3	0.1	10.0	24.6	15.1	24.2	8.9	17.1	5.19	7.8	7.5	11.5	1.88	0.19	118	1.33		
	25- 35	2.7	0.1	4.7	17.8	14.8	26.5	11.0	25.1	3.76	7.7	7.4	12.2	2.06	0.22	92	2.24		
	45- 55	1.0	0.1	6.8	19.0	14.6	27.5	12.3	19.6	6.45	7.7	7.3	10.0	2.27	0.21	31	1.16		
	65- 75	2.6	0.1	5.3	16.2	14.6	29.5	10.8	23.4	7.56	7.5	7.2	11.1	2.97	0.22	18	0.81		
	85- 95	2.6	0.1	3.1	14.2	14.0	29.0	12.2	27.3	9.17	7.6	7.3	10.0	3.01	0.25	18	0.70		
Profile no. 12	5- 15	5.5	0.2	0.5	2.3	5.9	31.1	19.0	40.8	1.24	7.0	6.8	19.6	5.63	0.60	191	3.18		
	25- 35	3.8	0.1	0.5	4.2	6.6	39.8	11.0	37.7	2.54	7.0	6.8	15.9	4.32	0.38	30	0.97		
	45- 55	2.6	0.1	4.8	15.2	14.0	29.8	10.3	25.7	3.38	7.4	7.1	10.7	2.40	0.22	21	0.51		
	65- 75	1.7	0.1	3.2	18.9	21.4	34.0	7.5	14.8	8.09	7.9	7.6	7.5	1.39	0.11	19	0.22		
	85- 95	1.3	0.2	7.8	25.5	24.4	29.7	4.4	7.8	9.29	8.0	7.6	6.0	1.24	0.09	13	0.22		
Profile no. 13	10- 20	0.8	1.8	38.5	28.2	11.4	9.1	3.0	7.8	3.8	8.2		4.9	0.77	0.06				
	52- 74	0.7	1.2	34.9	35.8	13.3	11.4	3.5	9.8	4.7	8.0		6.8	0.54	0.05				
	74-103	0.7	1.2	32.1	29.6	14.4	11.5	2.9	8.2	5.5	8.0		14.7	0.46	0.04				
	103-123	0.6	1.5	35.7	27.8	12.8	10.4	3.0	8.7	5.1	8.2		9.4	0.46	0.03				
	135-140	0.6	1.1	33.0	29.0	12.9	11.9	3.2	8.9	7.0	8.1		8.6	0.54	0.04				
Profile no. 14	5- 15	1.4	0.5	21.0	22.8	14.6	16.9	7.1	17.0	3.3	7.8		9.8	1.54	0.15				
	25- 40	1.9	0.6	8.6	15.8	14.5	26.0	10.9	23.7	1.3	7.4		14.1	1.93	0.21				
	55- 65	1.7	0.3	13.1	16.8	13.6	22.5	10.2	23.4	2.5	7.8		12.0	2.16	0.15				
	75- 85	1.2	0.9	23.1	22.2	13.6	17.5	6.9	15.6	7.0	7.6		15.0	1.23	0.12				
	95-105	1.2	1.0	26.1	24.1	13.1	14.0	6.6	14.9	6.0	7.8		10.5	1.16	0.12				
Profile no. 15	10- 20	1.0	1.0	4.5	6.5	7.8	24.7	19.0	36.3	2.5	7.6		14.3	3.31	0.25				
	55- 70	1.3	0.5	9.2	18.7	15.1	25.1	9.6	21.8	8.7	7.7		10.7	1.77	0.16				
	90-105	0.6	1.0	31.6	27.5	12.0	11.6	4.5	11.7	7.7	8.1		7.0	0.85	0.03				
Profile no. 16	0- 14	4.2	0.4	2.0	1.5	0.9	21.1	23.1	50.9	0.71	6.8	6.5	14.9	5.04	0.62		3.25		
	14- 27	2.4	0.4	3.7	10.0	18.7	26.8	10.3	27.9	1.13	7.2	6.8	10.2	2.15	0.24		2.16		
	27- 42	0.4	4.0	54.6	21.5	4.6	5.3	1.9	8.0	4.24	8.6	8.3	3.40	0.15	0.01		0.40		
	60- 80	0.5	7.5	48.6	16.7	6.7	9.5	2.9	7.8	5.52	8.3	8.2	4.50	0.40	0.03		0.18		

x = soil material insufficient to allow analysis



me/100 g					E.S.P.	E.C. <sub>e</sub>	1 : 5 waterextract, me/100 g													Profile no.	
Exchangeable bases							C.E.C.	% Base saturation	E.C. <sub>5</sub> x 10 <sup>3</sup>	cations					anions						
Ca	Mg	K	Na	Sum						Ca	Mg	K	Na	Sum	Sum	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	NO <sub>3</sub>		
3.51	1.09	0.41	0.17	5.18	2.19	8	>100	27.6	2.40	1.13	1.32	0.41	8.69	11.6	11.3	0.20	9.39	1.74	<0.01	1	
5.80	2.52	0.75	0.52	9.59	5.71	9	>100	28.2	3.00	1.76	1.98	0.53	11.7	16.0	15.6	0.30	11.8	3.52	<0.01	1	
6.29	2.19	0.73	0.70	9.91	5.48	13	>100	31.6	3.50	1.89	2.06	0.51	13.2	17.7	17.5	0.27	13.8	3.41	<0.01	2	
6.30	2.42	0.78	0.44	9.94	4.83	9	>100	31.6	3.40	1.76	2.31	0.56	12.8	17.4	17.5	0.38	13.6	3.52	<0.01	2	
11.8	6.20	1.58	4.73	24.3	20.1	24	>100	48.0	8.10	2.31	5.23	0.78	35.6	43.9	44.9	0.77	38.8	5.30	0.3	3	
6.60	4.14	0.86	1.86	13.5	10.9	17	>100	34.8	4.80	1.02	2.50	0.47	20.8	24.8	26.8	0.51	24.0	2.28	0.03	3	
7.83	3.16	0.83	0.35	12.2	7.47	5	>100	30.0	4.30	3.28	3.23	0.63	15.7	22.8	22.9	0.35	16.1	6.47	<0.01	4	
9.66	5.22	1.25	0.88	17.0	12.8	7	>100	37.4	5.80	3.69	4.76	0.86	26.4	35.7	32.9	0.49	23.0	9.37	<0.01	4	
13.7	7.88	2.28	4.40	28.3	26.8	16	>100	52.0	10.3	3.62	6.78	1.32	46.0	57.7	58.1	0.44	49.5	8.16	0.01	5	
12.3	6.40	1.92	3.84	24.5	22.4	17	>100	46.2	8.74	2.57	5.22	1.05	37.9	46.8	47.0	0.44	40.8	5.77	0.01	5	
8.62	4.84	0.91	1.50	15.9	11.5	13	>100	34.8	4.52	1.37	2.33	0.52	18.7	22.8	22.6	0.56	19.9	2.11	0.02	5	
13.3	8.96	3.19	7.11	32.6	31.4	23	>100	53.6	11.3	2.88	6.96	1.74	52.2	63.8	65.5	0.74	56.5	8.26	0.02	6	
13.3	6.20	1.92	2.05	23.5	22.6	9	>100	54.0	10.8	5.91	9.26	1.31	45.7	62.2	61.7	0.67	49.3	11.7	0.01	6	
8.61	4.26	1.06	0.71	14.6	11.0	7	>100	35.0	5.20	3.29	4.57	0.78	20.9	29.6	29.2	0.35	21.4	7.48	0.01	6	
14.0	8.56	2.23	5.24	30.0	29.1	18	>100	x	11.6	3.89	7.31	1.33	50.6	63.2	64.7	0.47	56.4	7.77	0.03	7	
10.9	7.00	1.93	3.28	23.1	24.9	13	93	x	10.0	3.61	6.42	1.05	43.6	54.7	56.8	0.51	48.2	8.14	0.03	7	
11.0	5.84	1.76	3.03	21.6	20.0	15	>100	49.0	8.83	3.32	6.03	1.04	38.8	49.2	49.5	0.44	41.1	7.87	0.02	7	
13.8	10.3	3.12	5.89	33.1	32.6	18	>100	x	14.8	5.20	10.9	1.73	66.6	84.4	85.9	0.70	73.3	11.9	0.02	8	
15.0	9.32	2.62	3.59	30.5	29.4	12	>100	x	11.9	5.17	9.32	1.53	52.7	68.7	69.3	0.67	56.8	11.8	0.02	8	
8.88	5.21	1.20	0.88	16.2	12.8	7	>100	39.4	5.44	3.81	4.99	0.78	25.4	35.1	35.0	0.44	26.1	8.44	0.01	8	
13.4	10.7	2.07	7.92	34.1	39.9	26	86	x	13.5	4.68	9.05	1.06	59.9	74.8	78.2	0.51	69.2	8.44	0.13	9	
9.77	10.2	2.60	6.98	29.6	36.3	19	82	x	11.8	2.61	7.35	1.34	53.2	64.5	65.4	0.25	58.6	6.52	0.04	9	
13.4	10.8	3.11	5.15	32.5	35.2	15	92	52.0	14.3	7.04	11.8	1.73	55.5	76.1	80.4	1.18	61.2	18.0	0.02	10	
11.5	7.12	1.87	1.56	22.1	25.1	6	88	44.0	9.92	5.15	8.28	1.32	40.3	54.9	55.3	0.75	42.8	11.7	0.02	10	
10.9	13.5	3.30	8.91	36.6	48.9	18	75	x	17.3	4.22	14.9	1.89	80.2	101	104	0.46	93.3	9.65	0.04	10	
11.0	7.54	2.23	1.51	21.9	27.5	5	80	52.0	12.9	5.96	11.4	1.60	55.1	74.1	75.9	1.10	60.2	14.6	0.02	10	
11.6	9.39	2.92	5.13	29.0	35.2	15	82	61.0	14.4	6.26	13.0	1.87	61.1	82.3	85.5	1.04	68.1	16.3	0.03	10	
13.1	7.43	1.95	2.45	24.9	25.7	10	97	49.0	10.0	6.07	8.66	1.35	42.5	58.7	59.6	0.89	45.1	13.6	0.02	10	
9.08	6.07	1.26	2.42	18.8	20.3	12	93	62.6	7.60	2.30	4.54	0.72	33.4	41.0	42.2	0.57	37.5	4.04	0.01	11	
9.12	6.35	1.43	3.32	20.2	23.5	14	86	42.6	8.40	2.06	5.06	0.79	36.8	44.7	46.5	0.56	41.8	4.06	0.01	11	
9.97	5.73	1.50	2.34	19.5	21.1	11	92	41.2	7.00	2.27	4.47	0.78	29.6	37.1	38.5	0.46	32.1	5.80	0.02	11	
11.4	6.46	1.82	1.55	21.2	22.3	7	95	40.2	3.00	4.21	6.23	1.05	33.5	45.0	45.8	0.52	35.4	9.83	0.01	11	
11.4	6.84	1.95	2.44	22.6	23.5	10	96	39.2	7.54	3.08	5.22	1.05	32.4	41.8	42.7	0.54	33.6	8.54	0.02	11	
9.12	14.6	3.12	10.8	37.6	53.6	20	70	x	17.3	3.70	13.9	1.89	82.6	102	106	0.30	94.8	10.6	0.04	12	
10.8	10.3	2.80	4.28	28.2	32.3	13	87	57.4	13.8	5.46	11.4	1.56	57.5	76.0	80.0	0.82	65.1	14.0	0.03	12	
9.11	6.72	2.00	1.55	19.4	21.2	7	92	47.0	8.11	2.82	5.89	1.31	33.5	43.6	45.1	0.41	36.2	8.54	0.03	12	
8.26	4.02	1.28	0.65	14.2	14.8	4	96	35.6	5.12	1.53	3.00	0.78	21.0	26.4	30.8	0.41	22.0	8.46	0.02	12	
7.97	3.25	0.93	0.58	12.7	11.9	5	>100	35.0	4.64	2.53	3.16	0.80	17.6	24.0	24.4	0.37	18.3	5.69	0.02	12	
									2.8	0.54	0.79	0.31	10.4	12.0	12.6	0.65	10.3	1.68		13	
									4.2	0.92	1.74	0.36	15.3	18.3	20.7	0.44	18.5	1.78		13	
									8.8	2.30	5.22	0.66	31.7	39.8	41.8	0.33	37.9	3.56		13	
									5.6	1.74	3.43	0.75	19.6	25.5	25.9	0.29	22.5	3.14		13	
									5.4	3.12	3.35	0.71	18.5	25.7	25.2	0.24	19.5	5.49		13	
									6.6	1.37	2.92	0.60	25.3	30.2	30.8	0.66	26.5	3.48		14	
									9.6	1.76	5.86	0.78	38.7	47.1	47.4	0.38	42.0	4.98		14	
									7.8	1.50	3.85	0.82	30.9	37.1	37.7	0.65	32.5	4.55		14	
									9.6	5.67	6.90	1.11	35.7	49.4	47.3	0.51	36.4	10.4		14	
									6.6	2.38	4.24	0.86	24.1	31.6	32.4	0.63	25.6	6.21		14	
									10.6	2.50	5.39	0.91	41.6	50.4	47.5	0.93	43.8	2.73		15	
									7.2	3.96	5.58	0.94	25.8	35.3	37.7	0.63	28.4	8.64		15	
									4.0	1.99	2.36	0.60	13.1	18.1	19.0	0.31	14.6	4.13		15	
6.26	14.1	3.05	9.35	32.8	53.1	18	62	x	12.6	1.83	8.59	1.28	58.9	70.6	71.5	0.03	61.8	9.23	0.45	16	
4.25	9.31	1.90	5.44	20.9	24.5	22	85	38.2	7.20	0.76	3.06	0.64	34.8	39.3	32.9	0.02	31.3	1.28	0.31	16	
									20.4	2.06	0.34	0.68	0.23	9.13	10.4	8.11	0.04	7.20	0.87	<0.01	16
									27.2	2.82	0.62	1.53	0.46	11.3	13.9	15.6	0.04	11.3	4.29	<0.01	16

## Laboratory data, polder soils

Profile no.	Depth in cm	% Moisture		Granulometric analysis in % of oven-dry soil in $\mu\text{m}$										pH		me/100 g					% Base saturation	% C	% N	% Fe <sub>2</sub> O <sub>3</sub> dithionite		
				2000-300	300-210	210-150	150-105	105-75	75-50	50-16	16-2	<2	% CaCO <sub>3</sub>	H <sub>2</sub> O	KCl	E.C.2.5 x 10 <sup>3</sup>	Exchangeable bases								C.E.C.	
																	Ca	Mg	K	Na						Sum
Profile no. 1	0-30	1.2	0.1	0.1	0.9	23.2	30.2	15.4	8.5	3.1	18.5	6.75	8.0	7.3	0.20	11.9	0.25	0.23	<0.01	12.4	10.8	>100	0.76	0.09	0.87	
	30-45	1.3	0.1	0.1	0.2	14.7	29.7	18.9	12.7	4.4	19.2	9.03	8.0	7.4	0.28	11.4	0.28	0.28	<0.01	12.0	10.5	>100	0.45	0.05	0.87	
	45-70	0.6	0.1	0.1	0.6	24.5	32.0	21.3	9.1	1.2	11.1	6.97	8.3	7.7	0.19	6.79	0.15	0.18	<0.01	7.12	5.03	>100	0.23	0.02	0.50	
	70-100	1.0	0.0	0.0	0.1	9.0	29.1	27.5	14.0	3.5	16.8	9.87	8.1	7.5	0.20	9.85	0.35	0.28	0.09	10.6	8.13	>100	0.33	0.04	0.76	
	100-125	0.5	0.0	0.0	0.3	30.3	39.1	14.3	6.6	0.0	9.4	6.73	8.3	7.8	0.14	5.28	0.21	0.15	<0.01	5.64	3.72	>100	0.18	0.02	0.47	
Profile no. 2	0-35	1.7	0.0	0.0	0.4	13.2	21.2	16.8	15.4	9.0	24.0	6.02	7.9	7.2	0.22	14.2	0.49	0.42	0.09	15.2	14.6	>100	0.86	0.11	1.16	
	35-70	1.8	0.0	0.1	0.1	6.1	20.1	17.6	17.9	9.8	28.3	8.41	7.9	7.2	0.30	15.8	0.75	0.37	0.09	17.0	15.5	>100	0.75	0.09	1.27	
	70-83	0.6	0.0	0.0	0.2	22.4	32.8	20.6	9.5	4.4	10.1	7.98	8.3	7.6	0.17	7.04	0.35	0.15	<0.01	7.54	5.47	>100	0.28	0.03	0.47	
	83-93	0.8	0.0	0.0	0.3	24.5	35.0	18.1	8.4	0.0	12.7	9.41	8.3	7.7	0.16	5.80	0.25	0.13	<0.01	6.18	4.38	>100	0.19	0.02	0.43	
	96-120	0.7	0.1	0.0	0.1	14.3	37.1	24.2	8.8	2.0	13.4	9.17	8.2	7.7	0.19	7.05	0.61	0.18	0.09	7.93	5.70	>100	0.23	0.03	0.65	
Profile no. 3	5-35	2.9	0.2	0.1	0.1	1.9	5.8	7.3	18.3	19.3	47.0	7.73	7.9	6.9	0.28	27.8	2.12	0.95	0.18	31.1	25.3	>100	1.36	0.17	1.92	
	35-65	3.4	0.0	0.0	0.4	0.4	1.1	1.2	15.7	23.4	57.8	10.5	8.0	7.0	0.35	25.1	2.74	0.83	0.09	28.8	29.1	99	1.12	0.16	2.21	
	65-82	2.6	0.0	0.1	1.8	12.8	17.8	17.5	17.3	7.6	25.1	11.7	8.1	7.3	0.23	12.3	1.84	0.47	0.17	14.8	12.7	>100	0.59	0.07	1.21	
	82-105	1.4	0.0	0.0	0.2	3.0	9.0	9.0	16.6	16.6	44.6	9.86	8.0	7.1	0.34	19.8	2.85	0.63	0.09	23.4	22.1	>100	0.93	0.13	1.98	
	105-120	0.5	0.0	0.2	3.2	29.2	33.0	17.0	6.6	0.5	10.2	7.22	8.3	7.8	0.15	5.78	0.51	0.23	<0.01	6.57	4.37	>100	0.25	0.03	0.68	
Profile no. 4	0-30	1.4	0.1	0.1	0.9	21.8	20.0	13.1	15.9	6.3	21.8	8.31	8.1	7.3	0.22	14.2	0.31	0.55	0.09	15.2	13.3	>100	0.81	0.11	1.03	
	30-40	0.9	0.1	0.0	1.0	27.3	22.0	17.0	12.1	2.5	18.0	9.58	8.1	7.4	0.25	10.6	0.21	0.28	<0.01	11.1	8.78	>100	0.35	0.05	0.69	
	40-70	0.4	0.0	0.1	4.5	46.1	26.1	7.1	6.4	1.1	8.6	6.04	8.3	7.9	0.20											
	70-100	0.5	0.0	0.1	0.9	38.0	31.9	12.5	6.7	0.0	9.9	8.01	8.2	7.8	0.18											
Profile no. 5	0-35	1.7	0.4	5.4	17.5	11.5	4.8	4.3	18.6	9.8	27.7	10.0	8.1	7.3	0.22	17.5	0.68	0.45	0.17	18.8	15.3	>100	0.70	0.11	0.82	
	35-55	0.1	2.0	24.9	52.8	15.8	1.6	1.0	0.5	0.6	0.8	3.25	8.9	8.5	0.07	2.75	0.03	0.05	0.09	2.92	1.09	>100	0.02	0.01	0.14	
	55-63	0.4	0.4	4.3	25.7	29.2	8.0	7.1	14.7	2.5	8.1	7.71	8.5	7.9	0.13	5.02	0.10	0.10	<0.01	5.22	3.49	>100	0.06	0.01	0.36	
	63-80	0.9	0.0	0.5	7.3	18.1	11.7	16.6	25.7	4.6	15.5	12.9	8.2	7.7	0.22	9.84	0.36	0.21	0.09	10.5	7.02	>100	0.14	0.03	0.65	
	80-100	1.2	0.1	1.2	6.8	20.5	10.6	10.8	22.0	7.0	21.0	14.5	8.2	7.5	0.26	12.7	0.60	0.28	0.09	13.7	10.3	>100	0.36	0.08	0.87	



## APPENDIX 2

### ANALYTICAL METHODS AND LABORATORIES

#### 1. *Granulometric analysis*

Soil samples were dried at 40°C, and then crushed by a pestle and sieved through a 2 mm sieve. The material passing through the sieve was kept for analysis. 20 mg of it was thoroughly mixed with 10 ml of dispersion agent consisting of a solution of 44.69 g sodium-pyrophosphate and 4.24 sodium carbonate. The paste thus formed was washed out with distilled water and wet-sieved through a 50- $\mu\text{m}$  sieve into a 1000 ml cylinder which was subsequently filled with demineralized water to the 1 litre mark. Then the suspension was thoroughly stirred. The fractions 0-50, 0-16 and 0-2  $\mu\text{m}$  were separated and determined by the pipette method and the weight percentage of the fractions 2-16 and 16-50  $\mu\text{m}$  was indirectly obtained by calculation. The fractions 2000-300, 300-210, 210-150, 150-105, 105-75 and 75-50  $\mu\text{m}$  were obtained directly by sieving, drying and weighing the material remaining on the 50  $\mu\text{m}$  sieve. The weight of each fraction was corrected for moisture content and expressed as percentage of dry soil at 105°C (oven-dry).

#### 2. *pH-H<sub>2</sub>O and pH-KCl*

The soil was shaken for two hours with distilled water or 1 N KCl in a soil-water c.q. 1 N KCl mixture of 1:5. The pH was measured in the suspension.

#### 3. *% CaCO<sub>3</sub>*

The soil was shaken with 20% HCl for 1-3 hours in a 'Scheibler' apparatus and the volume of evolved CO<sub>2</sub> was measured. Results are given as % CaCO<sub>3</sub> (oven-dry soil); however MgCO<sub>3</sub> may also be present.

#### 4. *Electrical conductivity (E.C.)*

The soil was shaken with water for 2 hours in a soil/water ratio of 1:2.5. The conductivity was measured in the soil suspension. The results are expressed in mS cm<sup>-1</sup> at 25°C.

#### 5. *Exchangeable bases*

The soil was mixed with purified sand, put into percolation tubes and leached with water/96% alcohol (1:1) to remove the water-soluble salts. Subsequently the soil was percolated with 1 N NH<sub>4</sub>-acetate/96% alcohol (1:1) at pH 8.2. In the leachate Ca<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> were measured by flame-photometer and Mg<sup>2+</sup> by atomic absorption. The results are expressed in me per 100 g of oven-dry soil.

#### 6. *Cation exchange capacity*

Following the treatment of the soils as given in 5., the material was percolated with 1 N Na-acetate at pH 8.2 to saturate the soil complex with sodium. The excess sodium salt was then washed out once, or if necessary, several times with 96% alcohol. Lastly the adsorbed sodium was replaced by leaching with 1 N NH<sub>4</sub>-acetate at pH 8.2. The adsorbed sodium was then determined in the leachate by flame-photometer. The results are given in me per 100 g of oven-dry soil.

#### 7. *Water-soluble salts (1:5 extract)*

The dry soil was shaken with water (soil-water ratio 1:5) for two hours and the extract obtained by filtration. In the extract the pH and conductivity were measured and subsequently HCO<sub>3</sub><sup>-</sup> was determined by titration with 0.1 N HCl; Ca<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> with the flame-photometer; Mg<sup>2+</sup> by atomic absorption; and Cl<sup>-</sup> with the 'chlor-o-counter'. The results are given in me per 100 g of oven-dry soil.

#### 8. *% C*

The soil was oxidized with potassium dichromate and sulphuric acid without application of external heat (Walkley-Black method). The amount of potassium dichromate used was determined by titration with

ferrous sulphate. According to Walkley and Black only 77% of the carbon in organic matter is oxidized. The % C gives the content of carbon present in the readily oxidizable organic matter.

#### 9. % N

The soil was oxidized with concentrated sulphuric acid and a mixture of selenium and sulphates of copper and sodium as catalysts (Kjeldahl-method). After steam distillation into boric acid, the  $\text{NH}_4$  was determined by titration with 0.01 N HCl and the results were given as % N of oven-dry soil.

#### 10. Phosphorus determination

The soil was shaken for 30 minutes with 0.5 mol.  $\text{NaHCO}_3$  in 1:20 ratio. In the extract P was determined with the molybdenum blue/ascorbic acid method. The results are given as mg  $\text{P}_2\text{O}_5$  per kg oven-dry soil.

#### 11. Dithionite-extractable iron

To 4 g of soil 2 g of  $\text{Na}_2\text{S}_2\text{O}_4$  and 130 ml 0.54 M Na-citrate were added (Holmgren-method). This mixture was shaken overnight. The  $\text{Fe}^{3+}$  was reduced and complexed by the citrate present. The  $\text{Fe}^{2+}$  formed was measured by atomic absorption spectrophotometry. The results are expressed in %  $\text{Fe}_2\text{O}_3$  of oven-dry soil.

#### 12. X-ray diffraction analysis

Material from the clay fraction (see 1.) was dried either in an oven at 40°C or freeze-dried, and if necessary ground. Random powder specimens of all samples were analysed using Philips X-ray diffraction equipment consisting of: a generator control cabinet (PW 1320/00), a stabilized generator (PW 1310/00) with wide-range goniometer (PW 1050/25), a base recorder unit (PW 1352/10) with scale combination (PW 1353/100), and a pulse height analysis combination (PW 1355/10). The experimental conditions to obtain the pen-recorded X-ray diffractograms are:

radiation: $\text{CoK}\alpha$	detector: proportional detector probe
high voltage: 35 kV	scanning speed: $1^\circ$ (2 $\theta$ ) per minute
current: 30 mA	full scale: 400 counts per second
filter: Fe	time constant: 2 seconds
divergence slit: $1^\circ$	sample holders: flat aluminium holder
receiving slit: 0.3 mm	or glass slides
scatter slit: $1^\circ$	

Additional diffraction data were obtained from a selected number of oriented specimens. Saturation with Mg, ethylene-glycol solvation, and saturation with K for heating treatments were performed according to procedures outlined by Jackson (1969).

#### 13. Elemental analysis of the clay fraction

The concentration of 9 major elements was determined with X-ray fluorescence. The analyses were done by the same basic units as described in 12. The results were recorded on paper tapes for computer analyses by means of a Tape Punch Control (PW 4206/01). To prepare the samples for analysis, 4-6 g of the air-dried sample were heated at 900°C for two hours and the loss on ignition calculated. From this sample 400 mg were taken to which LiOH and  $\text{B}_2\text{O}_3$  were added. The fusion reaction was made at 1300°C in a furnace in which the crucible (made of platinum + 3% gold) was placed. The resulting homogenized soil material was retrieved as a solid button on cooling. The sample: flux ratio is 1:10.

#### 14. Bulk density and water content

Soil samples of 100 or in a few cases 50 cc were taken in metal cylinders. The water content of these known volumes was determined by weighing before and after drying at 105°C. The water contents are given in weight percentages of oven-dry soil. The bulk densities, calculated from the known volumes and water contents, are expressed in  $\text{g cm}^{-3}$ .

#### 15. Redox potential ( $E_H$ )

Small boxes were completely filled with soil material and closed. The  $E_H$  of this material was measured



using a Pt electrode and a calomel electrode filled with a solution of KCl saturated with silver chloride, as recommended by Orion research, for measurements in concentrated solutions.

16. *Total SO<sub>4</sub>*

1 g of soil was oxidized by a mixture of HNO<sub>3</sub> and HClO<sub>4</sub> in a 1.5 : 5 ratio. After filtration the SO<sub>4</sub> was determined gravimetrically. The results are given in % SO<sub>4</sub> of oven-dry soil.

17. *Water-soluble SO<sub>4</sub>*

40 g of fresh soil material was transferred to a dialysis tube. After the addition of 50 ml distilled water the tube was placed in a bottle containing 400 ml of distilled water. The bottle was closed and rotated. After rotation the sulphate in the dialysate was determined titrimetrically according to the benzidine method. The results are given in % SO<sub>4</sub> of oven-dry soil.

18. *Total iron*

The soil was heated with Na<sub>2</sub>CO<sub>3</sub>. The residue was dissolved in HCl. Iron was precipitated by adding NH<sub>4</sub>OH, dissolved in H<sub>2</sub>SO<sub>4</sub> and reduced with hydrogen *in statu nascendi*. Ferrous iron was determined titrimetrically with KMnO<sub>4</sub>. The results are given in % Fe of oven-dry soil.

19. *pH-H<sub>2</sub>O on fresh soil material*

15 g of fresh soil were shaken with 20 ml distilled water. The next day the pH-H<sub>2</sub>O was measured in the suspension.

The analyses 1-11 were performed in the Department of Agricultural Research of the Royal Tropical Institute, Amsterdam; the analyses 12-15 at the Soil Science Institute, State University, Utrecht and 16-19 at the laboratory of the Rijksdienst voor de IJsselmeerpolders, Kampen.

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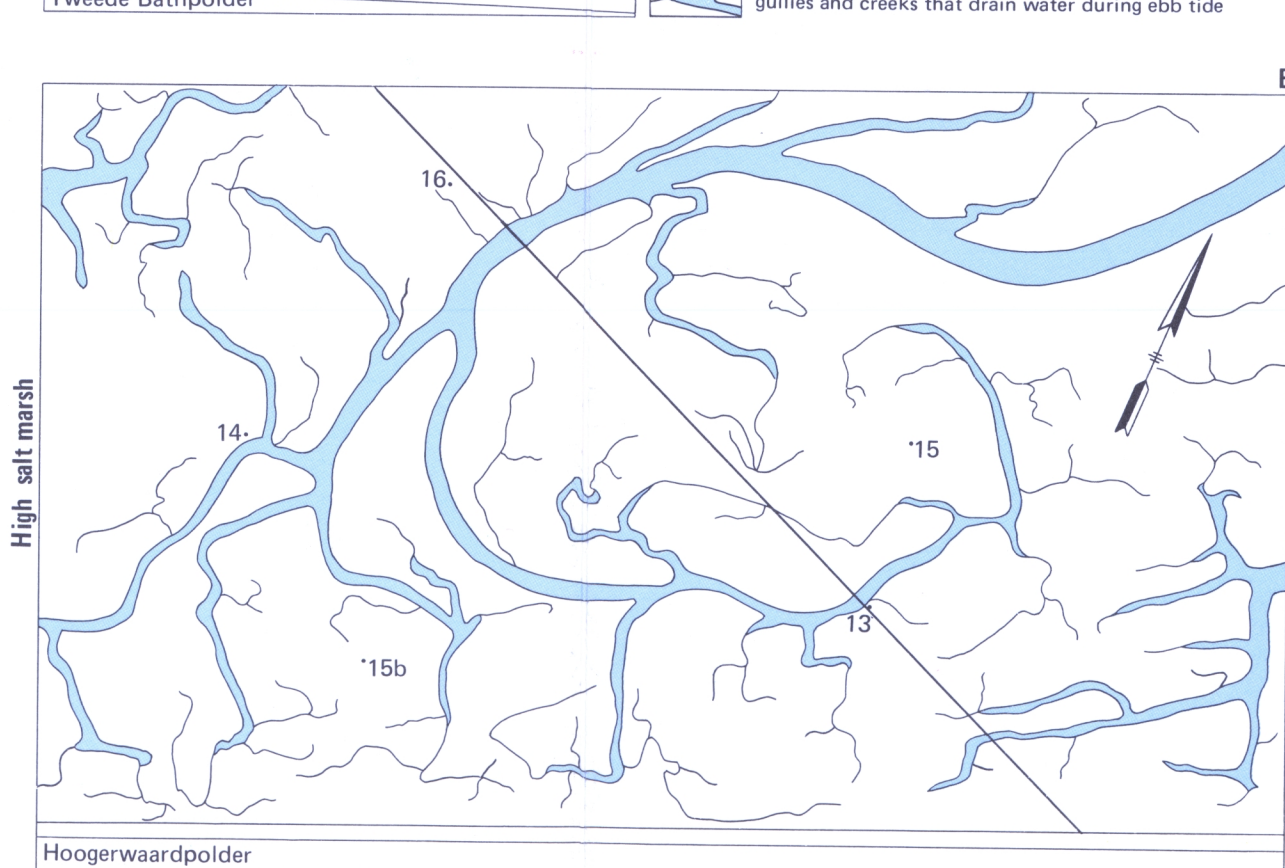
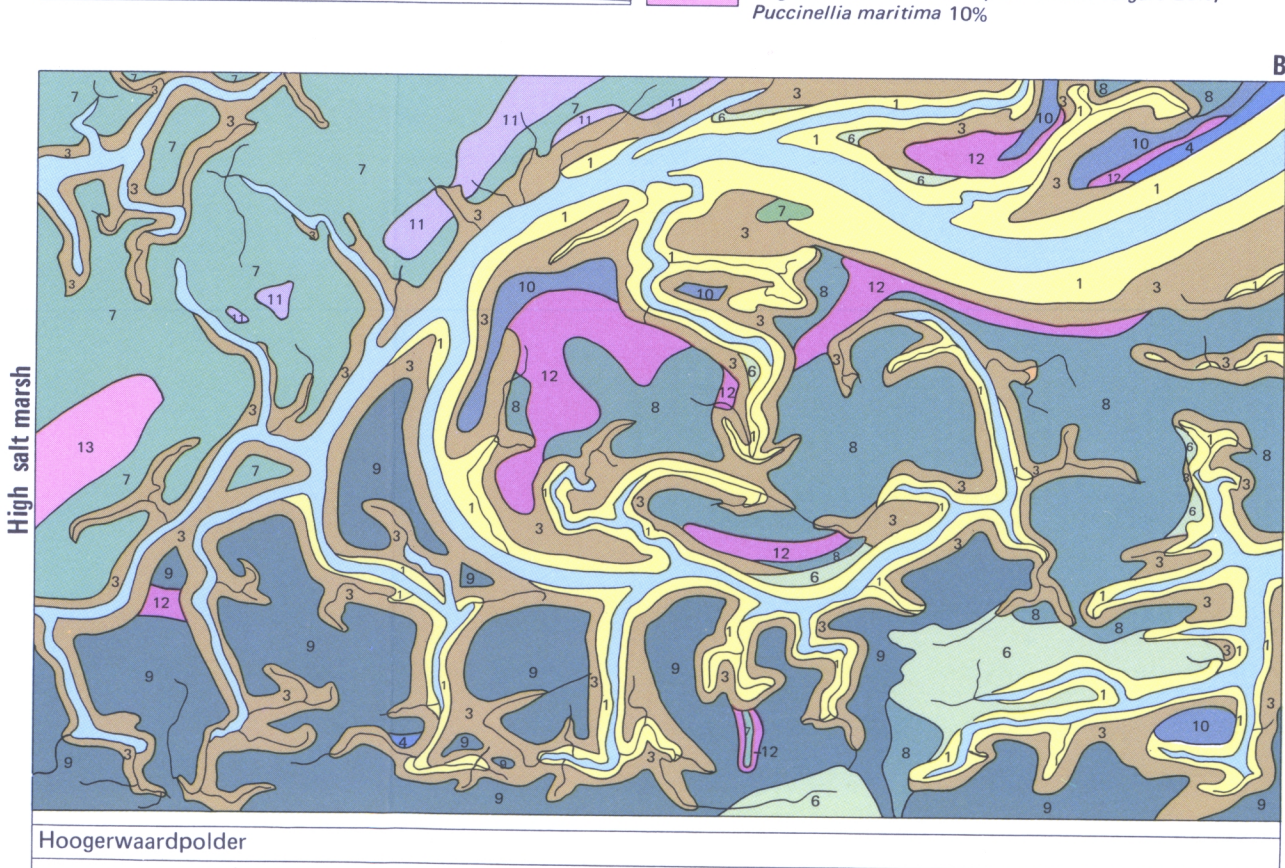
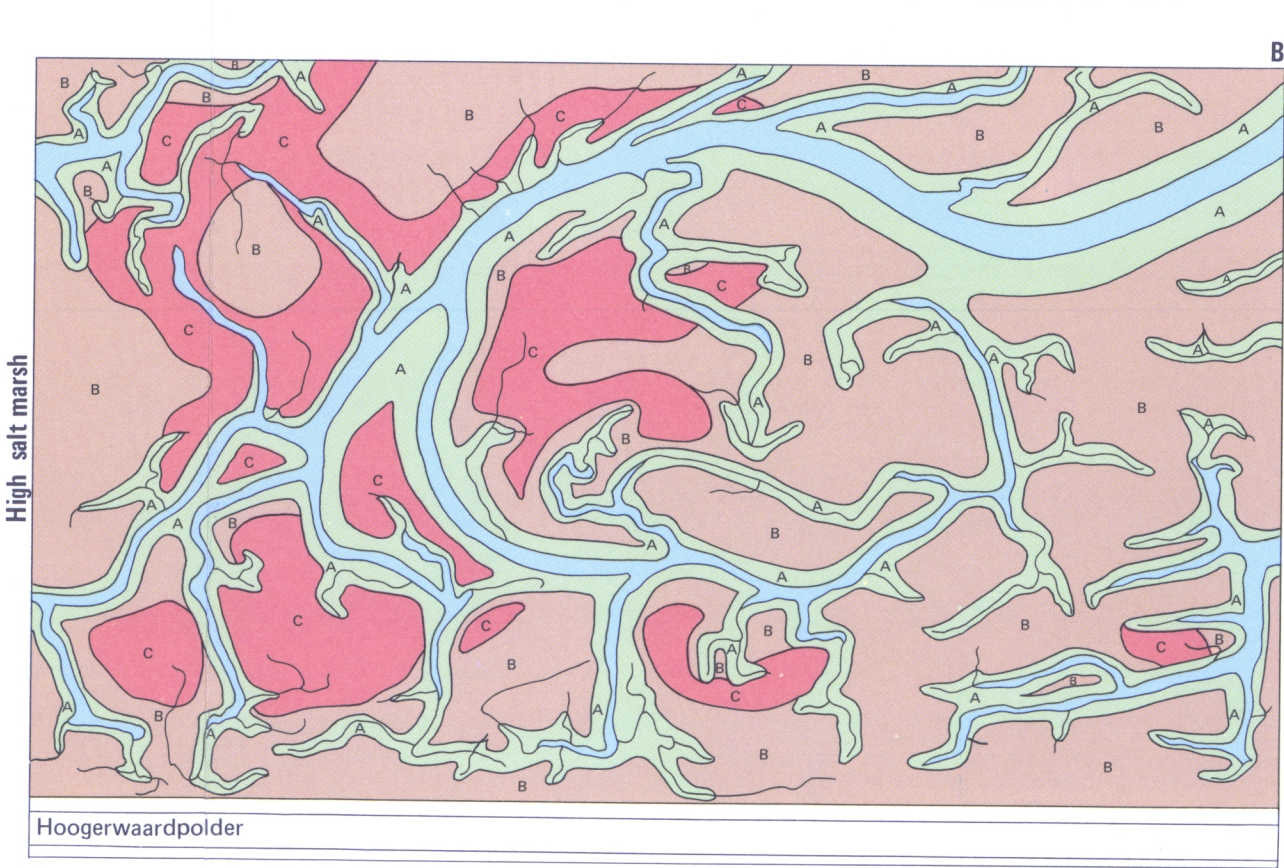
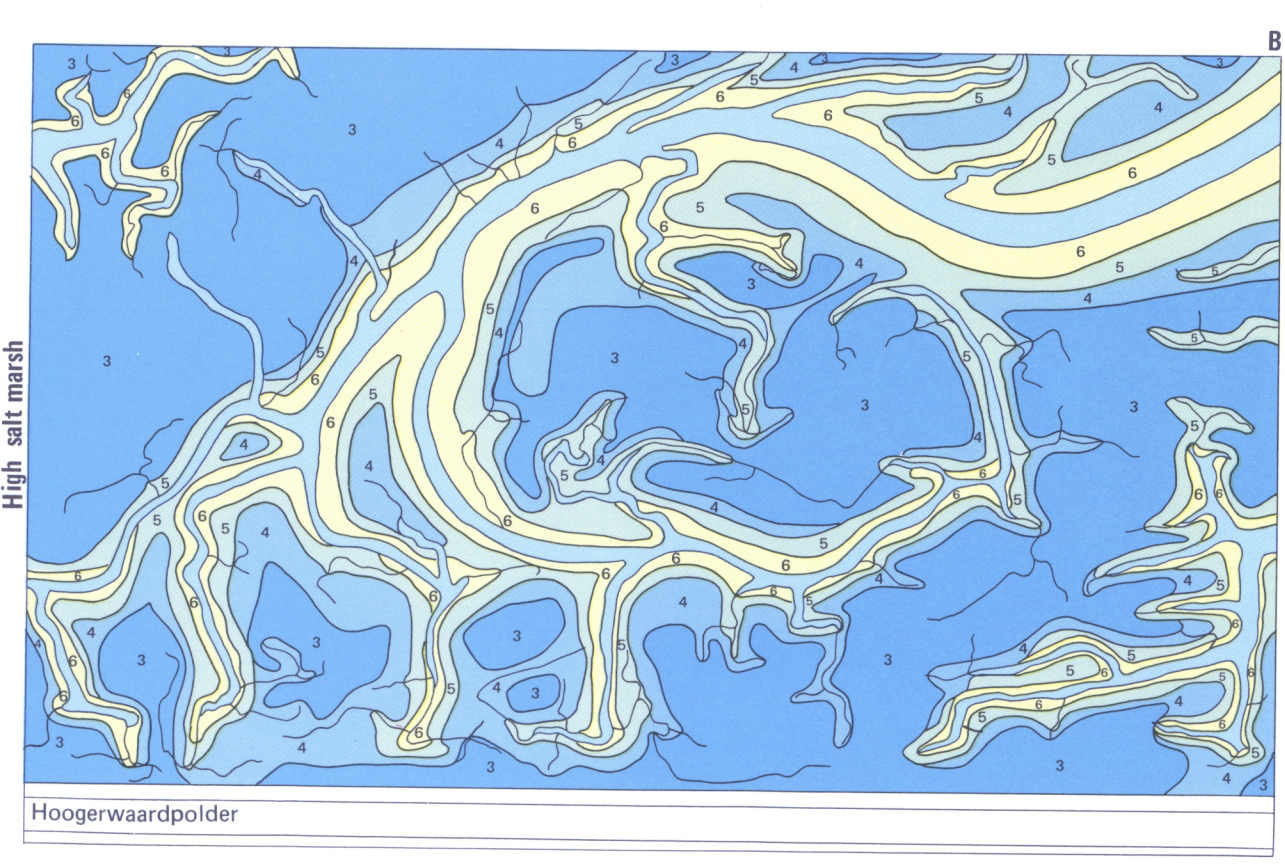
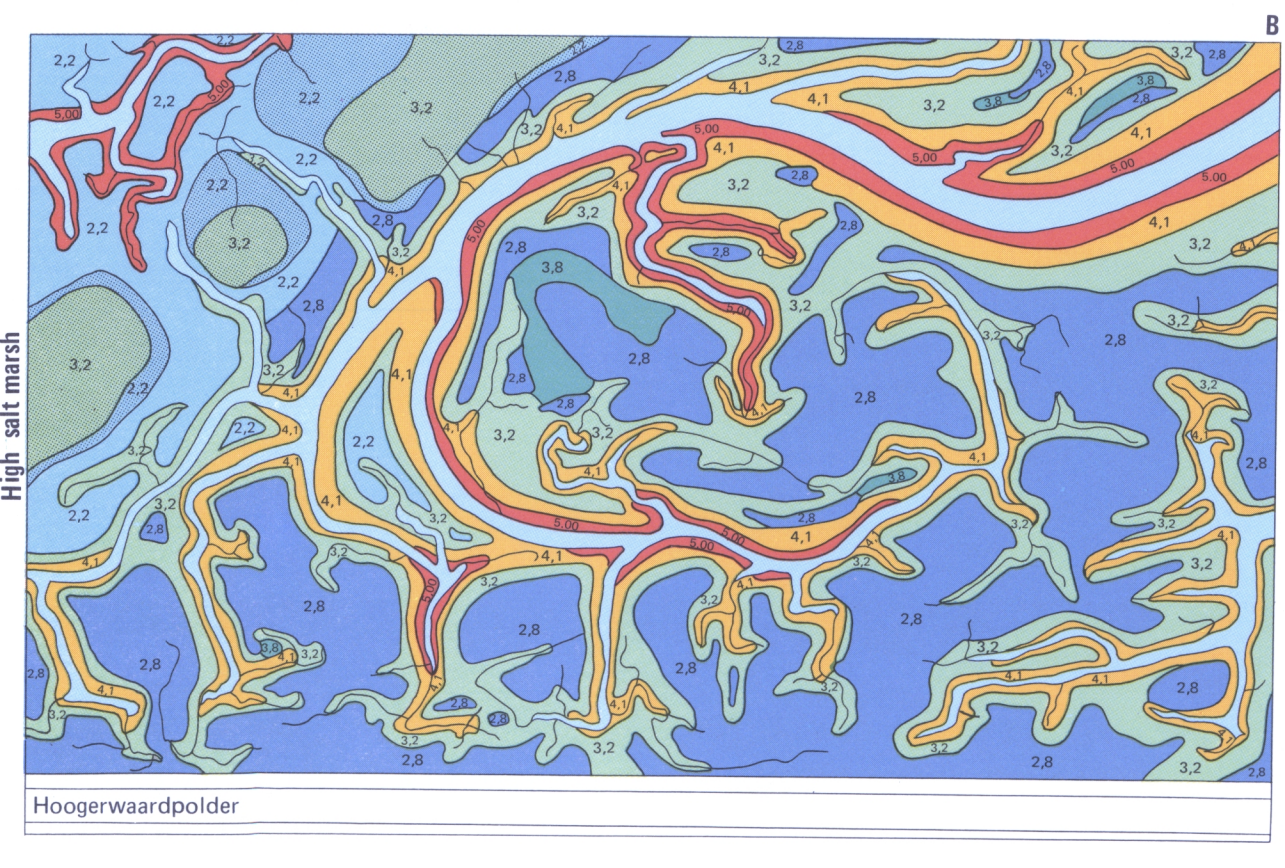
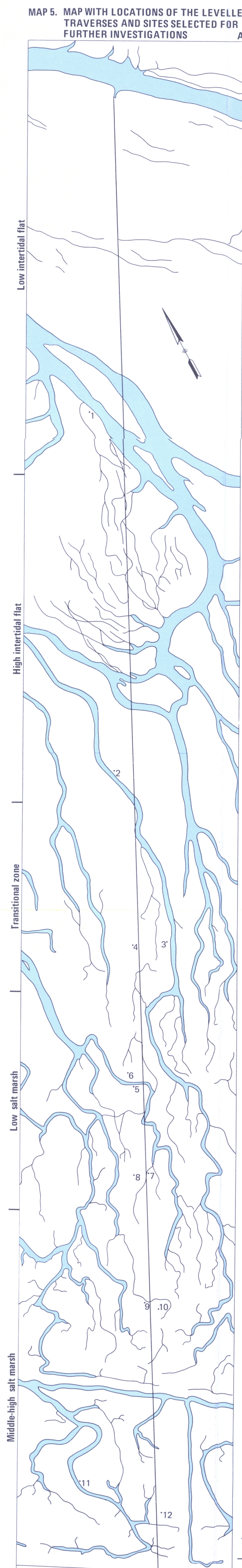
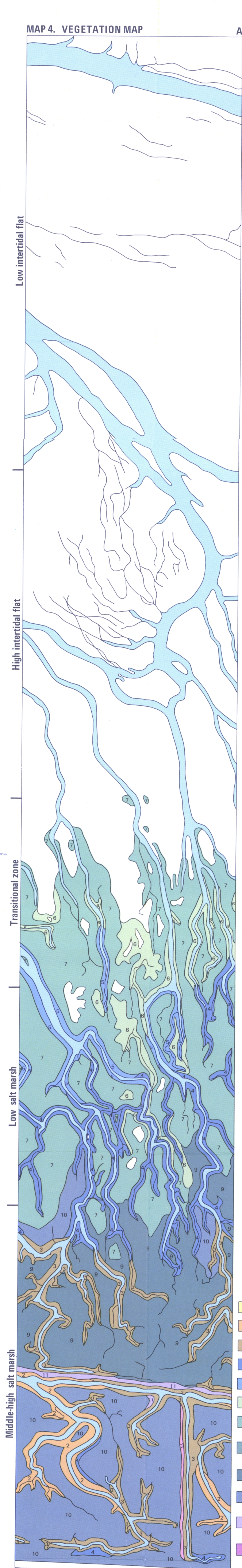
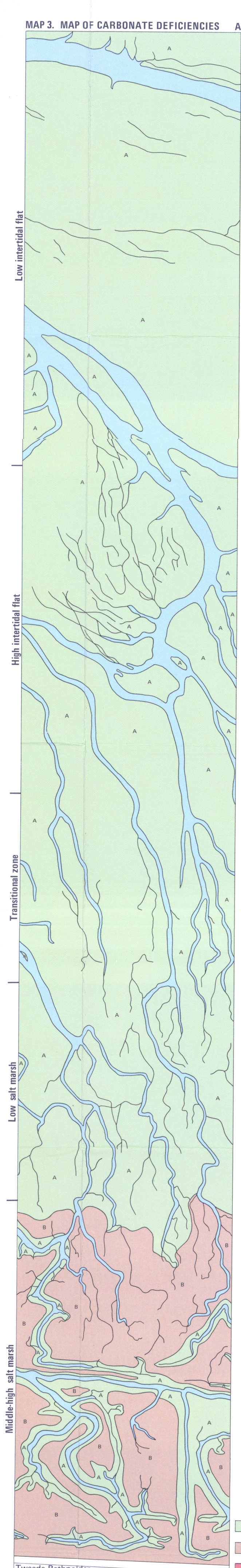
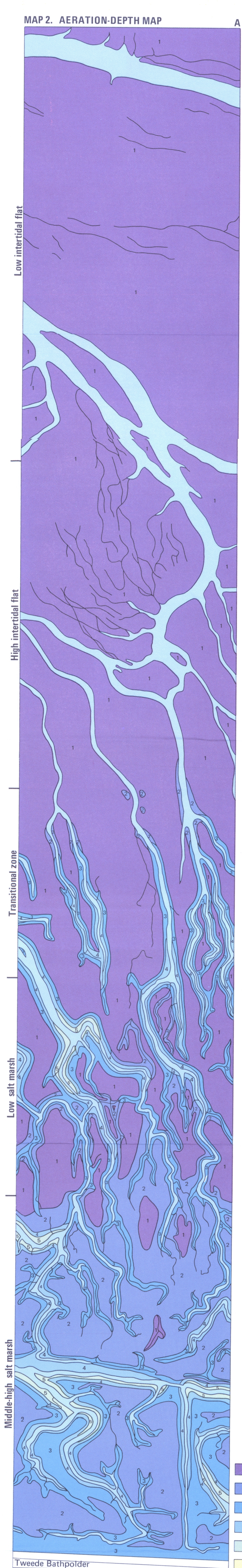
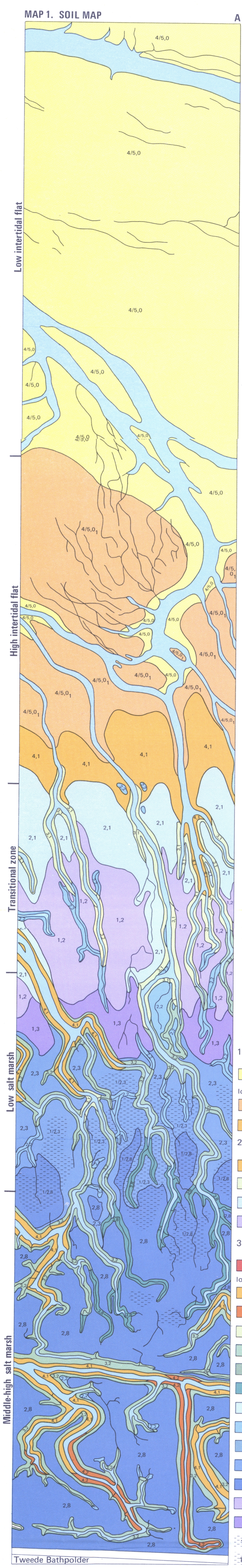
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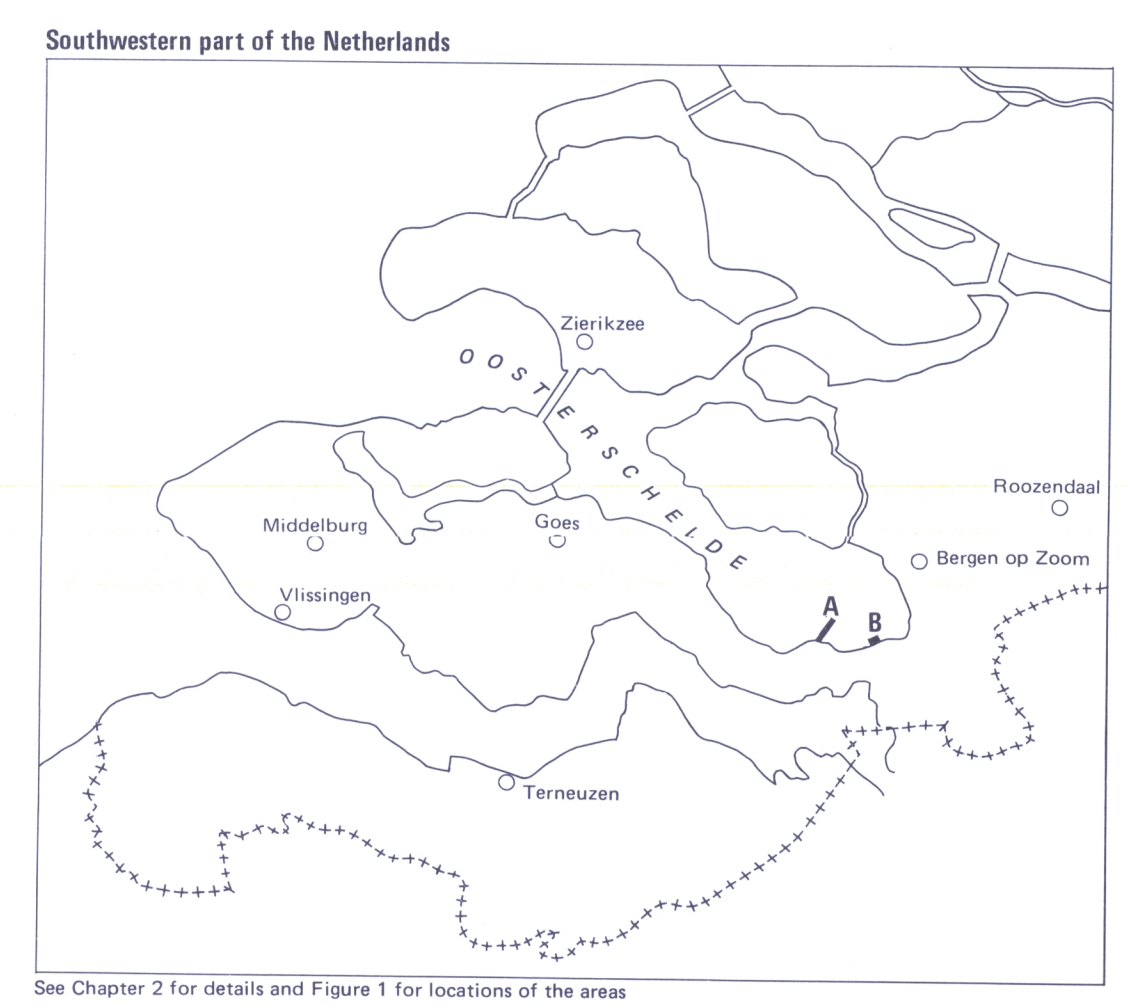








DETAILED SOIL AND VEGETATION MAPS OF THE STUDY AREA AND MAPS WITH LOCATIONS OF LEVELLED TRAVERSE AND SITES SELECTED FOR FURTHER INVESTIGATIONS



See Chapter 2 for details and Figure 1 for locations of the areas