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SYMPOSIUM: SEDIMENTOLOGY OF RECENT AND OLD SEDIMENTS

MINOR STRUCTURES OF SOME RECENT LITTORAL AND NERITIC SEDIMENTS

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CONTENTS

I. INTRODUCTION

In this paper a brief summary will be given of the data that have come to the author's attention with regard to the character and origin of minor structures in recent terrigenous sediments, deposited in shallow marine environment. With minor structures those features are meant which are visible in (preferably vertical) sections of e.g. 2 x 3 inches. In general only those structures will be mentioned which appear to be of widespread occurrence and which may be expected in any fossil sediment that has been formed under similar conditions as those of the investigated environments of the present day. The restriction of this study to terrigenous sediments implies that deposits which are essentially composed of carbonate material will be left out of consideration. It will be noted that there seem to be as yet only very few areas where detailed observations on sedimentary structures and their distribution have been made. This aspect of geology has long been neglected and much work has still to be done before the origin and environmental significance of most of the structures or distributions of structures found in fossil sedimentary rocks can be fully understood.

The amount of information which can be obtained about the structures of recent sediments depends on the manner in which the samples are collected and prepared for investigation. If core samples are used, it should be made sure that the sedimentary structures have not been disturbed during the coring process itself. Experience shows e.g. that a piston coring apparatus often gives poor results when used in coarse sands, partly because the suction exerted by the piston tends to produce differential movements of the sand grains and the interstitial water.

As to the manner of preparation of the samples, it appears that practically all structural properties in sediment cores can be made visible by applying one or more of the following methods.

(1) Structures in moist or water-saturated sands which are marked by the distribution of finely divided, dark coloured iron sulphides, may be revealed by simply slicing through the core samples with the aid of a thin ($^1/_3$ mm) steel wire.

(2) Small differences in texture of successive layers or laminae etc. can be made visible by making lacquer peels from dried core sections (obtained with the above mentioned thin steel wire) in the manner described by Voigt (1949)[2]. The method is based on the circumstance that the depth of penetration of the lacquer and hence the thickness of the peel varies with the permeability of the material, which in its turn depends on the texture. It

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[2] The method used in the Koninklijke Shell Laboratory at Delft will be described by Kruit.

works best in sediments that are rich in sand and silt.

(3) For more fine grained material one may make use of metal trays which are pressed into the sediment. The tray samples are partially dried on a heating plate and then scraped clean with a razor blade or a sharp knife. The degree to which the samples must be dried depends on the composition of the sediment (less in sandy, more in clayey material). The method is described by van Straaten (1954b).

(4) The finest details of the structure can be examined in thin sections of artificially indurated sediment samples.

By not applying these, or other adequate preparation techniques some sedimentary structures may easily escape observation. It may seem somewhat exaggerated to pay so much attention to structures which are hardly visible at all when the sediment is examined in a more direct way. However, it must be stressed that precisely such fine details of the structure may provide indispensable criteria for understanding the manner of formation of the sediments. Moreover, one of the most important scopes of the study of primary sedimentary structures is its application to fossil rocks and it is a striking fact that many structures in lithified rocks, which are based on relatively small differences in texture or composition of the detrital material, are nevertheless conspicuous, because they were accentuated by variations in the degree of cementation or other diagenetic changes.

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II. DEPOSITS FORMED IN TIDAL FLAT ENVIRONMENT

Environment

Sedimentary environments where a large part of the bottom is alternately covered and uncovered by the tides are called tidal flat areas. They are found in basins on the landward side of coastal barriers, in estuaries, and, exceptionally also along the open sea. Tidal flat areas formed in the shelter of coastal barriers are found all over the earth, notably as parts of coastal plains. Examples are the Wadden Sea along the North Sea coasts of Holland, Germany and Denmark, the tidal flat areas on the coast of Norfolk (England), the basin of Arcachon (France) and the so-called lagoon of Venice (Italy)[3]. Estuaries with tidal flats, though usually of smaller dimensions are even more numerous than tidal flat areas behind coastal barriers. They are found both in coastal plains, e.g. in the southwestern part of the Netherlands, and along rocky coasts. Tidal flat areas along the open sea shore are known from Louisiana, Surinam and a few other countries.

Three sub-environments can usually be distinguished in tidal flat areas: the salt marshes, lying above the level of mean high tide and inundated only during spring tides or storm surges, the tidal flats proper, between the lines of mean high and mean low tide, and the tidal channels below the low tide level.

The salt marshes are covered by a vegetation of halophytes, which may start to grow already a little before the bottom has silted up to high tide level. The marshes are normally dissected by meandering and sometimes anastomosing marsh creeks, which are bordered by narrow natural levees. Behind these raised banks the surface slopes downward into "marsh basins". In some of these basins as well as in many parts of abandoned creeks so-called salt pans (Steers, 1953), are found, in which standing water is left after inundation of the marshes. Such pans are often free of vegetation owing to the relatively high salinities which may develop during evaporation of the water. Along their seaward side the marshes either pass gradually into the forelying tidal flats, or they are cut off by vertical bluffs. In the latter case there is often a zone of maximum elevations along the marsh edge, which is genetically partly a natural levee, partly a beach ridge. Salt marshes are also found along coasts where the range of the astronomical tides is very small or even negligible, but where appreciable wind tides occur, e.g. in the Rhône delta. In such areas there may be relatively few creeks and in consequence little relief of natural levees and marsh basins.

The tidal flats are often completely or almost completely devoid of large plants (some algae excepted). Examples are the Dutch and German Wadden Sea, the Wash Bay in England, etc. In other areas, such as the basin of Arcachon, there is at least locally, a close cover of *Zostera* or other intertidal plants. The relief of the flats is mostly very small, except for occasional mussel beds, but on their lower parts there may be numerous incisions of gullies, debouching into the tidal channels. Where the flats are

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[3] The tidal range at Venice is larger than in most other parts of the Adriatic or Mediterranean seas, viz. of the order of 80 cm. The area behind the barrier islands is a typical tidal flat area since by far the greater part of the bottom is alternately covered and uncovered by the tides.

narrow these gullies sometimes extend upstream into the higher parts of the flats or even (as creeks) into the salt marshes.

The difference between vegetation covered salt marshes and more or less bare tidal flats is not confined to the areas in temperate and subtropical regions like those studied by the present writer. It is also found in many tropical regions, where the salt marsh vegetation may consist largely of mangroves, e.g. in the estuaries of French Guinea (Francis Boeuf et Romanovsky, 1950).

The channels between the tidal flats, which are scoured out or kept open by the strong tidal currents, are often quite deep. The greatest depths, sometimes several dozens of meters, are found in the tidal inlets. The bottom of the channels has in many cases a relief of transverse megaripples (van Straaten, 1950, 1953a).

Lithology

Vertical sections through formations deposited in tidal flat environments show usually a distinct zonation (e.g. van Straaten, 1954b) which corresponds to differences in composition (and structure) found at the surface in the various sub-environments mentioned above. The most normal zonation is as follows:

(4) a thin series of relatively clayey marsh deposits;

(3) a thin series of relatively sandy deposits of high tidal flats;

(2) a thin series of relatively clayey deposits of low tidal flats, sometimes with thin shell beds;

(1) a thick series of relatively sandy channel floor deposits, often with shell beds and clay pebble beds.

The fact that the channel floor deposits are mostly very sandy is the result of the force of the tidal currents. Exceptions are found in some abandoned channels, or in channels close to the inner shores, where the currents are less effective in winnowing out the bottom material and where the sediments tend to be richer in mud.

The more clayey composition observed on the low parts of the tidal flats is due to the diminished effect of the tidal currents, combined with a high average rate of sedimentation during the stages when sedimentation takes place (see below, in the section on the structures).

On the higher parts of the flats where sedimentation is more continuous, and where the rates of deposition are much lower, a relatively sandy composition is found. The scarcity of finer materials is in this case largely due to wave action. [4] Close to the high tide line the sediment is again in many cases somewhat richer in clay.

A sharp increase in the average clay content is met with when passing to the salt marsh environment. During the inundations of these areas by the sea a great part of the finer materials suspended in the water, is trapped by the marsh plants.

Structures

The various structures found in the Dutch and German Wadden Sea area have been described in a great number of papers, e.g. by Haentzschel (1936, 1939/1955), Reineck (1956, 1958), Schaefer (1956), van Straaten (1954b), to name only a few.

The *marsh sediments* are usually characterized by a wavy, nodular lamination, caused by deposition of sediment on uneven, dry, plant covered surfaces. The lamination is preserved as the result of the absence or scarcity of a burrowing fauna. The marine fauna, encountered in the tidal flat sediments, cannot live in the marshes because the inundations by salt water are too infrequent and because the sediment is mostly too dry in consequence of the normal position of the ground water level below the surface. Burrowing land animals such as earth worms and mole rats, on the other hand, do not invade the area so long as it is still inundated occasionally by sea water and the bottom contains an appreciable amount of salt. The only disturbances of the typical marsh laminations are caused by the roots of halophyte plants. However, these disturbances are normally much less important than those caused by animals.

It may be remarked in passing that the sediments of river built levees show sometimes the same kind of wavy, nodular lamination. This is not surprizing since the circumstances of deposition are very similar. A difference is that these laminations are usually less well preserved owing to the work of burrowing land animals which may be quite abundant in this environment.

Not all salt marsh sediments show the above mentioned laminations. They are best developed where the deposits contain a certain amount of sand or silt, i.e. close to the seaward edge of the marshes and along creeks. In most cases there is a gradation from relatively sandy clays at the bottom of the sections to more silty and pure clays at the top. The lamination is then most

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[4] Of course there are many exceptions to this general rule. In some cases the opposite situation is even observed, with relatively sandy sediments on the low parts of the flats and more muddy deposits on the higher parts.

marked in the lower parts. Upwards it may become very indistinct, especially where the material is deposited in marsh basins, at an appreciable distance landward from the edge of the marshes, where the velocity of sedimentation is low. It is possible that in these cases the lack of distinct laminations is largely due to the influence of plant roots, which of course varies inversely with the rate of deposition.

A further exception to the occurrence of the typical marsh laminations is found in the sediments of salt pans. Here a primary structure with more even, continuous laminae is formed. In many cases, however, this lamination is disturbed by a fauna of burrowing animals which develops during periods when the pans are filled with sea water. Another complication of the structure of salt pan deposits is due to mud cracks which are formed after evaporation of the water.

Finally, it must be mentioned that marshes which have become silted up to such a height that they are inundated by the sea only at very rare occasions, can become inhabited by burrowing land animals. The activity of the latter may then result in the disturbance of any depositional structures that were present in the upper layers of the marsh sediments.

The deposits formed in marsh creeks have a composition which ranges from pure sands to more or less sandy and silty clays. They show a great variety of structures, such as current ripple laminations, burrows and marsh laminations.

The type of lamination found on the vegetation-less *tidal flats* is different from that of the salt marsh sediments. The laminae are usually comparatively smooth and even, or they may show a relief and internal structure due to wave and current ripples. They lack the wavy, nodular character of marsh laminae. They are, moreover less continuous and may wedge out over distances of only a few feet.

The tidal flat laminations are often quite undisturbed by benthonic organisms. In other cases they are full of burrows[5]. The influence of benthonic life upon the sediment structures is most pronounced where deposition is relatively slow and continuous, as on the higher parts of most tidal flats. There, all traces of lamination may become obliterated.[6] On the lower parts of the flats, along the channels, the influence of the burrowing animals is usually much smaller. The minor gullies as well as the larger tidal channels are shifting their courses most of the time and the sediment in these areas is alternately eroded and (comparatively rapidly) redeposited. With each redeposition a fresh, undisturbed lamination is produced (see van Straaten, 1954b).

A consequence of the above mentioned situation is that there is no relation at all between the abundance of special features like ripple marks and tracks and trails of animals as observed on the surface of the tidal flats and their abundance in the "fossil" state. Although wave ripples of various kinds are often the dominant markings on the surface of the flats, the greater part of them is formed in places where the rate of vertical deposition is very low and where the only structures preserved in the sediment are those produced by burrowing animals. Much better conditions for the preservation of ripple marks are present on the low parts of the tidal flats, close to the tidal channels, but here current ripples often dominate (cf. van Straaten, 1954a)[7].

The *channel floor deposits* have in general the same types of lamination as those found on the low parts of tidal flats, with the difference that burrowing animals have still less influence upon the structures, that current ripple structures are much more abundant and that wave ripple structures are absent, except sometimes very close below the low tide level. Shell beds and clay pebble beds show commonly an imbricated position of shells and clay pebbles.

Channel sediments have often directional properties, owing to the preferred orientation of the crests of current ripple marks at right angles to the channel banks, at least in the deeper parts of the channels. Along the sides an oblique position of the crests is frequently observed, which is caused by the decrease in current velocities from the centre towards the banks. The crests then point obliquely downstream. Where waves in the channel water break against the banks, there may be wave-current-ripple marks (van Straaten, 1951), the crests of which are parallel to the direction of the currents.

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[5] A detailed investigation of the disturbances of sediment laminations caused by various burrowing organisms was made by Schaefer (1956). It may be concluded from his data that many different animals may produce the same kind of disturbance. In most cases it is therefore impossible to refer the burrows to a definite species or even to a definite genus.

[6] A secondary stratification of shell beds alternating with sand layers without many shells can be produced by the burrowing activity of the worm *Arenicola* (van Straaten, 1952, 1954b, 1956).

[7] This may explain how McKee (1957) could not demonstrate the presence of ripple structures in the sediments of parts of the Cholla Bay tidal flat area (Mexico), where, at the time of his observations the surface was closely covered by wave ripple marks (wrongly interpreted by him as due to „sheet flood").

In all cases of asymmetrical subaqueous ripple marks there is transport of sand in the direction of the steeper sides of the ripples. The laminations are parallel to these steeper sides. Apart from ordinary, small ripple marks one often finds transverse megaripples, with distances between successive crests of more than one meter. They are especially frequent in channels where either the ebb or the flood currents predominate. Studies of the directions of such megaripples were made by Huelsemann (1955) and van Straaten (1953a).

In general, the directions of inclination of megaripple laminations must show a fan-like arrangement around the tidal inlets, the laminae dipping partly away from the inlets and partly in the opposite direction. In the remaining parts of tidal flat areas a more random orientation must be present, in accordance with the general channel pattern (see e.g. the map of the Dutch Wadden Sea in the Waddensymposium, 1950).

A similar distribution of sedimentary structures as that found in the various environments of the Wadden Sea was encountered by the writer in a number of other areas: the estuaries in the southwestern parts of the Netherlands, the estuary of the Somme and the basin of Arcachon in France, the Hamford water estuary near Harwich, the tidal flat area on the Norfolk coast, the Wash Bay and the Dee river estuary near Liverpool in England, the lagoon of Venice in Italy, and, to a lesser extent the estuaries at Rabat and Mehdia in Morocco.

In the Moroccan estuaries most of the investigated flats showed a predominance of burrowing structures over the whole section, from the marsh edge to the low tide line: Hence, the influence of burrowing structures on the sediment structure has, at these places, been of more importance than the influence of shifting channels and gullies. This may be partly due to a relatively constant position of these water courses.

Many burrows in the sediments of these estuaries are produced by a crab, *Uca Tangeri.* This animal, which does not live in the tidal flat areas of temperate regions, builds small, volcano-shaped mounds around a central, vertical shaft which penetrates into the original sediment surface. The crab is found at all parts of the flats, but is especially abundant near the high tide line. Similar crab-made structures are of widespread occurrence in other subtropical and in tropical tidal flat areas, e.g. in French Guinea (Francis Boeuf et Romanovsky, 1950), in South China (Krejci Graf, 1935) and in Indonesia (Verwey, 1930).

Another difference between tidal flats in temperate and in tropical areas is the abundance of mud cracks. In temperate areas fully developed, "complete" mud crack systems in which the polygons are entirely separated from one another by the fissures (Shrock, 1948), are practically limited to the salt marsh environment and to the highest parts of the tidal flats. A few incomplete mud cracks are occasionally encountered on steep banks of gullies and channels which may become dry during low tides when the water table sinks at these places below the surface. In tropical areas the solar radiation is so much stronger that complete mud cracks can also be formed on lower parts of the tidal flats.

III. DEPOSITS OF COASTAL LAGOONS

Environment

The term coastal lagoon is used in this paper for comparatively shallow bodies of standing or almost standing water, situated in a coastal plain or delta environment. They may have an open connection with the sea (inlet or pass), but in some cases they are completely separated from it by a beach barrier or spit. Lagoon waters have a wide range in salt content, varying from only slightly brackish to supersaline. They receive salt water from the sea, either via the inlets or by waves breaking over the barrier, or by temporary elevations of the sea level during storms, or by underground percolation. Fresh water may be supplied continuously by rivers debouching into the lagoon, or intermittently during flood stages, when river water flows over the natural levees, or simply by rains.

Lagoon floors are usually very flat, but in tidal lagoons deep channels can be present, especially in and near the inlets. The water level in many lagoons varies as the result of river floods, astronomical or wind tides in the sea and owing to the alternation of dry and wet periods. Some lagoons are partially or wholly dry for great lengths of time.

Lithology

With regard to the composition of the lagoonal deposits, distinction must be made between the actual lagoon floor sediments and the sediments that are deposited on the beaches or banks of lagoons by breaking waves, as well as those formed in the areas behind the lagoon shores during exceptionally high water stages.

The deposits of the lagoon beaches are normally very sandy. Locally they are moreover extremely rich in shells. The lagoon marsh sediments are on the other hand mostly very clayey.

Their sand content may decrease from fairly high in the immediate vicinity of the lagoon shores to almost nil already at small distances inland from these shores.

The lagoon floor deposits show a great variation in lithology. It ranges from coarse sands, e.g. close to the enclosing barrier along the open sea, via fine sands, silty sands, mixtures of sand, silt and clay, to silty clays and almost pure clays. In some examples the bulk of the material is composed of silt. Shells are admixed to the sediment in varying amounts. They may be concentrated by wave action in separate layers.

Structures

Much information is available about the structures of the bottom material in some lagoons of the Texas coast, viz. Aransas Bay, Mesquite Bay and San Antonio Bay, which were investigated by Moore, Scruton and Shepard (Shepard and Moore, 1955; Moore and Scruton, 1957). A large number of cores taken from the floor of these lagoons showed the following distribution of structures: "regular" (undisturbed, parallel) laminations in and near the Guadalupe delta in the innermost part of San Antonio Bay, mottled structures in the main part of the lagoons and homogeneous "structures" in the deepest parts. The mottling is mainly caused by the burrowing activity of benthonic animals. The homogeneity of the deposits in the deepest parts is also supposed to be due to burrowing organisms, which in these cases resulted in the complete mixing of the various grain size fractions.

Exactly the same type of mottled structure due to the abundance of small burrows, as found in the Texas bays, was observed by the present writer in the sediments of the flat-bottomed central parts of Barataria Bay, Louisiana. Hardly any traces of lamination were left in this material. A core taken in deeper water (6.50 meters) close to the main inlet (Barataria Pass) and cores from the tidal channel directly north of Grand Isle were composed of undisturbed laminations of sand and clay. Many of the sand laminae in the core from the northern approach to Barataria Pass had a detailed structure of current ripple laminae, formed by the tidal currents. The character of these laminated deposits was completely similar to that of the channel floor sediment from the Dutch Wadden Sea.

A predominance of burrowing structures is also present in lagoon deposits in the Rhône delta (France). Minor disturbances due to roots of waterplants were also observed. Several cores from the large Etang de Vaccarès, situated in the centre of the delta, show a stratification of thin beds of sand and washed mollusc shells alternating with thicker beds of clayey material with only scattered shells and in which the finer laminations are mostly completely disturbed by bottom animals.[8]

Alternations of well preserved laminations and layers with burrowing structures were found in a small submerged delta on the lagoon side of the inlet to the Etang de Gloria (Rhône delta). These alternations are probably caused by strong variations in the rate of sedimentation or by successive stages of erosion and deposition, just like on the low parts of the flats in tidal flat areas.

Not all lagoons are characterized by sediments with dominantly mottled structures. Exceptions are formed e.g. by the deposits in the area of the former Zuiderzee in the Netherlands. The recent history of sedimentation in this area, especially in the drained northeastern part, has been investigated in great detail by Wiggers (1955). For the post-Roman period three main stages of deposition can be distinguished: the Lake Flevo (later called Lake Almere) stage, lasting till approximately the year 1600, the Zuiderzee-stage, from circa 1600 till 1932, the year when the whole area was closed off from the sea by the "Afsluitdijk", and the IJssel-lake stage, starting in 1932. The Flevo Lake was only slightly brackish, with chlorinities of less than 0.3 % (as established by microfauna and microflora research, see Middelhoek en Wiggers, 1953). During the Zuiderzee-stage the chlorinities were a little higher, viz. up to 0.6 % in the Northeastpolder area. In the subsequent IJssel Lake they decreased rather suddenly to values below 0.02 %.

It is admitted that the Lake Flevo can hardly be called a lagoon. Yet, some attention will be paid to its sediments, since their structures may help to explain the structures of some other, truly lagoonal deposits. The Flevo sediments, which have probably been mainly supplied by the IJssel distributary, debouching into the lake, are very rich in silt. The relation between fine silt (2-16 μ) and clay ($< 2\ \mu$) content is

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[8] When investigating the structures of lagoon floor deposits, it should be carefully examined whether the sediments are really of lagoonal origin. Great parts of the smaller coastal lagoons in the Rhône delta are characterized by non-deposition and some parts even by (wave) erosion. Here older (often fluvial) deposits crop out on the lagoon floor. Yet, in these instances, the uppermost layer, of about an inch thickness, has then often acquired the properties of the lagoonal facies (abundance of burrowing structures, admixture of the remains of brackish water invertebrates and plants etc.).

roughly 2 to 1. In tidal flat and marsh sediments in the Netherlands this relation is generally close to 1 to 2. The Zuiderzee deposits are relatively richer in clay but still do not reach the ratios that are found in sediments deposited from more normal sea water. It is assumed that the relatively low clay contents are caused by the weak effect of flocculation in these brackish waters. Most of the clay supplied by the IJssel must have been kept in suspension by the turbulence of the water and carried off to other environments.

The structures of the sediments in the eastern Zuiderzee area were investigated by the present writer at some 12 places. The Flevo Lake deposits appear to be characterized by very fine, parallel laminations and abundant, equally fine cross laminations. There are only few burrowing structures. The relative scarcity of burrows can not be due to (continuous) rapid deposition. The annual rate of sedimentation for a particular subdivision of the Flevo Lake deposits was tentatively estimated by Wiggers as 0.4 to 0.5 mm. Even if other parts of the formation had rates of deposition of a hundred times as great, i.e. 5 cm/year, there would be ample time for an ordinary bottom fauna to disturb all laminations. The most likely explanation is perhaps that both scarcity of a burrowing bottom fauna and constant reworking of the sediments by wave action are responsible. A bottom fauna of macro-invertebrates could have been scarce not only because of the peculiar fresh to brackish composition of the water, but also as a result of the extreme mobility of the dominantly silty bottom material (cf. Hjulstroem, 1935), which could be stirred up as soon as wave action reached down to the (shallow) lagoon floor. Another factor of importance may have been the relative scarcity of waterplants, which tend to protect the bottom deposits from erosion and reworking by the waves.

The above interpretation could also be applied to the laminated zone around the Guadalupe delta in San Antonio Bay. This zone is very narrow and occupies a far smaller area than the lake Flevo deposits, but it seems significant that it is precisely in this area that the salinities of the water are very low and that the bottom material is especially rich in silt. Shepard and Rusnak (1957) ascribe the occurrence of relatively undisturbed laminations in this area to the scarcity of bottom animals as a result of the low salinities and to the high rate of sedimentation. The present author wonders whether the last factor is not of subordinate importance. In an earlier paper Shepard (1952) states that the outline of the Guadalupe delta has changed very little since 1875, which may indicate that the rate of deposition in these parts is only moderate.

Normal lagoonal conditions existed in the Zuiderzee area during the Zuiderzee stage itself (ca. 1600-1932). The sediments of this stage show similar fine, parallel laminations and cross-laminations as those of the Flevo deposits, but, as far as they were investigated, they seem to be on the average distinctly richer in burrowing structures. This can be easily understood as the result of the higher salinities of the water, which permitted the development of a benthos fauna of greater importance (cf. Redeke et al., 1922). The fact that this fauna did not disturb the laminations more completely may have been caused by the composition of the sediment which was still comparatively rich in silt and poor in clay so that it could easily be reworked by the waves.

Another lagoon environment where the laminations of the bottom deposits are little disturbed by burrows is the Laguna Madre (Texas), investigated by Shepard and Rusnak (1957). The scarcity of burrowing animals is explained in this case as the consequence of the very high salinities of the lagoon water, which are often as much as 5,0 % and may locally exceed 10 % (cf. Hedgpeth, 1953; Ladd, Hedgpeth and Post, 1957; Emery and Stevenson, 1957).

IV. BEACH DEPOSITS

Environment

Beaches can be defined as the comparatively narrow zones along the coast, which lie above the low water mark and which are mainly shaped or at least strongly influenced by wave action. They are formed along the shores of seas, bays, lagoons, lakes and in tidal flat areas, e.g. at the base of marsh bluffs. Some beaches, especially small ones, such as those along minor lakes have an almost uniform slope from the upper limit of wave action to the low water line. Most beaches, however, show a relief of benches of outcropping rocks, or of berms, ridges and swales, the ridges with transverse rip current channels, etc. On sandy beaches a distinction can usually be made between a foreshore part and a backshore part. The foreshore lies below the swash limit of ordinary high tides, the backshore lies above this limit.

Lithology

Owing to the winnowing effect of the waves most beach deposits are composed of relatively coarse material, such as sand, shells and pebbles. Where pebbles are present, they are often accumulated in a ridge or in ridges on the highest parts of the beach. This concentration is due to the circumstance that the upward thrust effected by the swash and the breaking waves is mostly stronger than the transporting power of the backwash. The difference between the effects of swash and backwash causes also frequently a concentration of heavy minerals on the upper parts of the beaches.

Structures

A very detailed study on the structures of beach sands on the coast of California was published by Thompson (1937). Other investigations were made by Doeglas (1955) on the Dutch coast, by McKee (1957) in California, Mexico and Texas, by van Straaten in the Netherlands (1954b) and in the Rhône delta (this paper) and by several others.

It appears that the distribution of structures depends on the type of beach. Where the foreshore shows a pronounced relief of ridges and swales, cross laminations with landward dipping foreset laminae may be found (Doeglas, 1955), due to the landward migration of the ridges. These foreset laminae rest on sands with finer, more irregular cross laminations, deposited in the swales. The crests of the ripples in the swales which account for the cross laminations are often at right angles to the trend of the beach, viz. when they are formed by currents following the direction of the swales. In other cases one finds asymmetric wave ripples in the swales, with crests that are parallel to the beach (cf. van Straaten, 1953b).

On beaches that have a more uniform slope, the dominating type of minor structure on the upper foreshore consists in remarkably even, parallel laminations, mostly gently inclined towards the sea, the inclination being approximately the same as that of the surface (cf. Martens, 1939/1959). The even character of the laminae is due to the effect of swash and backwash, which generally tend to produce very smooth surfaces on the sand, especially when the beach has a marked seaward slope. Where ripples are formed on such surfaces, e.g. rhomboid ripples or regressive sandwaves (van Straaten, 1953a, 1953b) they are in many cases extremely flat.

The average thickness of the parallel laminae on the beaches investigated by Thompson is given as approximately 7½ mm. A somewhat smaller value (4 to 5 mm) was found in lacquer peels of beach sand cores from the Rhône delta, possibly as the result of the different method of observation. The successive laminae are composed of well sorted sand of different textures (see also Emery and Stevenson, 1950, and Schalk, 1938). The differences in grain size composition are sometimes only very small. In such cases they may be nevertheless conspicuous owing to different contents of dark coloured heavy mineral grains. The laminations are formed by periodical variation in the ratio between the transporting and sorting effects of swash and backwash. These periods are often fairly long. Thompson found that one single lamina may correspond to many hours of wave action.

In larger sections through the beach sand on the upper foreshore it is frequently seen that the separate laminae wedge out laterally or that they are cut off by unconformities. According to Thompson the lateral extension of the laminae is nearly always considerably greater in sections parallel to the trend of the beach than in normal sections. The surfaces which truncate the laminations are themselves in most cases also very even, and make usually only small angles with these older laminations.

No direct observations were made by Thompson on the structures of the sediments of the lower foreshore. Here his method of studying fresh sections in situ failed in consequence of the water saturated condition of the sand, which caused the sections to cave in as soon as they were made. By applying the lacquer peel method to core samples from beaches of the Rhône delta it was found that similar laminations occur on the lower parts of the beach.

The sands of the backshore may also show the smooth, parallel laminations. In addition, various ripple structures, both of subaqueous and of aeolian origin are found. Some coarse cross-bedding is often present as the result of the formation of low sand dunes.

Structures due to the entrapment of air in beach sand have been described by several authors, a.o. Baudoin (1951a, 1951b), Emery (1945), Johnson (1938), Kindle (1936) and Palmer (1928). They originate when dry beach sand is covered by the sea, e.g. during a rising tide, and the pores in the top layer become filled with water. This top layer may then become impermeable for the air which is pushed up from below by the simultaneously rising ground water. The structures produced by this mechanism occur on all parts of beaches. Emery (1945) distinguishes between the following types: sand domes (dome shaped uplifts of the top layer of sand over a "laccolith" of air), cavernous sand (in which the entrapped air has become concentrated in large numbers of closely spaced, more or less ellipsoidal bubbles) and sand holes (vertical tubes through which the air has escaped to the surface). If these structures are preserved at all in fossil beach sediments (which themselves are already exceptions in the geological column) they must be extremely rare. Yet, it does not seem completely impossible in cases where the beach sand is cemented soon after the structures have been formed. Sand holes could also be preserved in the fossil state if they are filled with fine material deposited from the water after the outflow of air has come to an end.

Examples of folded structures in beach sands have been mentioned from California (Thompson) and from Japan (Mii, 1956). A similar case was observed by Stewart (1956) in the exposed sands of the tidal delta at the entrance of a lagoon on the coast of Mexico. Both Mii and Stewart suppose that the contortions are the result of pressure of entrapped air.

Analyses of the orientation of (elongate) sand grains on beaches along the coasts of Texas, Louisiana, North Carolina and California have been made by Curray (1956). They show a preferred orientation of the grains with their long axes parallel to the direction of currents or waves. Where the sand is chiefly deposited by waves moving at right angles to the beach, the dominant orientation of the grains is therefore also normal to the strike of the beach. In wind blown sands these orientations are parallel to the direction of the wind.

The situation is different for pebbles on beaches. It follows from the investigations by Cailleux (1934, 1938) that wave action tends to direct pebbles with their long axes parallel to the beach. Where pebbles are accumulated in great quantities they show moreover imbricated positions, with seaward dips of their medium axes. Isolated mollusc shells which lie in their most stable position, with the convex side up, are again most frequently oriented with their longest dimensions normal to the beach.

V. SUBMARINE DEPOSITS OF COASTAL BARRIERS

Environment

While practically all coasts have beaches, with or without beach deposits (see the definition of beaches in the preceding section), one finds barriers only in areas of active coastal deposition. A barrier is an accumulation of sand which starts in relatively deep water and continues till above the water line (cf. the terminology of Shepard, 1952). The emerging part of a barrier is the barrier beach.

A barrier originates by wave action of various kinds. It may develop from a submerged "offshore bar", formed by the breaking of waves in shallowing water. In other cases a barrier is built in immediate contact with the original coast. Barriers may also be formed without the influence of breaking waves, viz. by beach drift. When a barrier becomes high enough for the sand to dry out the surface, wind action, mostly helped by vegetation may build up the barrier to still greater heights.

The submarine slope of many barriers shows normally a relief of more or less parallel ridges and troughs. In most cases they are approximately parallel to the shore, but locally they stand at an angle to it. The width of the ridges decreases generally towards shallower water. They are primarily the product of wave action, although in seas with strong tides their shapes may be influenced by currents.

The base of the barriers is often marked by a distinct knick in the bottom profile, the submarine part of the barrier sloping more steeply than the forelying shelf. The depth of this knick depends chiefly on the dimensions of the waves. In many cases it lies at a depth of 10 to 20 meters.

A barrier shoreline can be in the process of prograding or of retreating, or it can be stationary, depending on whether the supply of sand is larger or smaller than, or equal to the removal of sand. One may distinguish, for the sake of convenience, between supply and removal of sand in longshore directions (by the various mechanisms of beach drifting and longshore drifting) and in directions transverse to the shore, from and towards deeper water. Transport transverse to the shore takes place from the land, under influence of rivers and winds, or from the sea floor, under influence of the direct and indirect effects of wave action (asymmetric oscillatory motion of water particles along the bottom, rip currents and undertow). The relative effects of these mechanisms of transport depend on a great many factors: position of river mouths, discharge of rivers, direction and strength of winds, waves, swell and currents, the configuration of the shoreline, the slope of the sea floor in front of the coast etc.

When a shoreline retreats, erosion may soon take away the bulk of the barrier sands, both on its submarine parts and on the beaches. Older coastal plain sediments of various origin crop out over large parts of such eroded areas or are covered only by a thin veneer of marine sand. There usually remains some sort of accumulation of sand on the highest parts of the beach, which is taken along as the shoreline shifts inland.

Lithology

It was mentioned already that most of the submarine barrier deposits are composed of sand. In addition to this they contain varying amounts of shells and other skeletal remains of marine organisms. At some places, notably along rocky coasts or in their vicinity one finds considerable quantities of gravel or even large pebbles. Towards the lower parts of the barriers clayey material becomes an ever more important part of the sediment.

Structures

Sands of the submarine slopes of the barriers of the Central Texas coast have been studied by Moore and Scruton (1957) who classify them as homogeneous deposits. The homogeneity would be caused by a complete mixing of all sand grains by violent wave action. Between the homogeneous barrier sands and the mottled sediments of the open shelf (see later) a transition zone with "irregular layers" was found.

No such general homogeneity was found by the present author in gravity corer samples of the submarine barrier sands along the coast of the Rhône delta. The latter are formed under conditions that can hardly be very different from those along the Texas coast. Yet, they show in most cases distinct, approximately horizontal laminations with occasional cross laminations and, notably in deeper water, some burrowing structures. The author wonders whether the structures in most of the Texas cores have been disturbed by the coring process itself (see introduction). Moreover it could be possible that the preparation techniques applied by Moore and Scruton failed to show those structures which were actually present in their cores.

As to the effect of waves on sediment structures, it seems unlikely that they could result in a homogenization of thick layers of sand. Even in cores from the breaker zone along the beaches of the Rhône delta distinct laminations were observed. Furthermore it follows from the investigations by Inman (1957) that the sea floor immediately in front of the shores of Southern California is richly covered by wave ripple marks. It is most probable that such ripple marks occur also in shallow water along other sea beaches. And where ripple marks are normally present some structures must surely be formed in the bottom sediments.

Although the submarine barrier sands are usually inhabited by appreciable numbers of benthonic animals, their influence upon the sediment structure is small, bceause of the almost continuous reworking of the bottom material by the waves, and, to a smaller degree, also by currents. This reworking must be strongest on the upper parts of the slope. On the lower parts, which are influenced by wave action only during exceptionally heavy storms or periods of very strong swell, the effect of burrowing animals must become more important. In fact, such a lower zone with distinct burrowing features was found by Moore and Scruton along the Texas coast (their transition zone with irregular laminations). The same situation occurs along the coasts of the Rhône delta. In the latter area it was found that this zone extends higher upward in bays that are protected from strong waves, than along the open sea coasts.

VI. SUBMARINE DELTAIC DEPOSITS

Environment

Fisk et al. (1954) introduced some new terms for the various environments of the Mississippi river delta. Some of these terms are also used by Shepard (1956) and by Scruton (1955), although partly in different ways. Shepard distinguishes between the following submarine zones:

(1) The "delta front platform", the shallow area immediately in front of the subaerial part of the delta, which has an average width of at least a few kilometers. It includes the interdistributary bays, which are left open between the advancing natural levees of adjacent distributary channels.

(2) Beyond the platform the "pro-delta slope" is found, which may be compared to the foresets slope of the more simple, lacustrine deltas studied by Gulliver. This slope has a varying width and continues to depths that vary according to the relief of the forelying sea floor.

(3) At the base of the slope the "open shelf with recent delta influence" begins. It corresponds more or less to the environment of Gulliver's bottom set beds.

(4) In addition a few other zones are distinguished by Shepard, such as the areas of reworked older delta deposits and old shelf areas.

A similar subdivision of the submarine deltaic area in delta front platform, pro-delta slope and open shelf with recent delta influence can be made in the cases of the Essequibo and Orinoco rivers (cf. Nota, 1958). The configuration of these deltas, especially of their subaerial parts, is different, however. They are not of the birdfoot type and consequently lack typical interdistributary bays.

Yet another type of morphology is shown by the Rhône delta, see Russell (1942), Kruit (1955), Razavet (1956) and Razavet et Kruit (1957). Here a delta platform is almost entirely missing. A small platform of some 4 km^2 in front of the mouth of the Grand Rhône distributary and the south-western part of the Golfe de Fos are the only areas which could be regarded as equivalents of parts of the Mississippi delta platform. Among each other these two areas of the Rhône delta show strong environmental differences. The first named platform is exposed to waves of the open sea and is built foreward by the most active distributary of the Rhône. Its surface deposits are mainly composed of coarse sand. The other area lies in the shelter of a long spit and receives chiefly muddy sediments from various sources. Apart from these two areas the whole coast of the Rhône delta is made up of almost uninterrupted sand beaches, thrown up by the waves. The dissimilarity between the Rhône delta and the Mississippi delta is due to the different relations between the effects of wave action and of sediment supply by the rivers. The latter is relatively of much greater importance in the Mississippi delta.

The submarine topography of the deltas varies also widely from case to case. The part of the Mississippi delta which protrudes into the Gulf of Mexico is surrounded by a more or less continuous pro-delta zone, where active deposition takes place. In the case of the Essequibo and Orinoco deltas the pro-delta environment, characterized by active sedimentation, extends even far beyond the sub-aerial parts of the deltas themselves and forms a continuous, though rather narrow belt from the Essequibo river mouths to the Orinoco mouths.[9]

In sharp contrast to the above examples there is only a small portion of the sea floor in front of the Rhône delta which can be regarded as "active" pro-delta slope environment. This area lies south of the mouth of the Grand Rhône distributary and is marked by a distinct seaward bulge of the bottom contours. There are a few more of these bulges on the sea bottom. However, they have been formed in earlier stages, by deposition off distributaries that are now abandoned. Their upper parts have been removed by wave erosion. It is true that deposition continues on their lower parts, situated below wave base, but this deposition is much slower. These areas, as well as the other parts of the sea floor south of the Rhône delta belong now to the "normal open shelf" where the influence of deltaic sedimentation is of secondary importance for the submarine topography.

Lithology

The submarine deltaic deposits can be divided into two main classes. The first one comprises all those sediments of direct fluvial origin, which contain no, or only quite subordinate amounts of marine organic remains. In this paper they will be referred to as fluviomarine deposits. The second group is formed by more normal neritic sediments, in which an essential, though often small part is composed of the skeletal remains of marine animals such as foraminifera, echinoderms and molluscs.

The fluviomarine facies is mainly found on the pro-delta slopes. In the Mississippi delta it seems to be encountered also in the interdistributary bays and other delta platform environments. The sediments of the (centre of) the Fos bay east of the Rhône delta, which has a slightly different origin and which is considerably deeper than the Mississippi delta bays, do not show this facies, but rather that of the normal open shelf deposits (see the section on bay sediments).

The fluviomarine deposits are usually characterized by a distinct gradation from a relatively sandy or silty composition directly in front of the distributary mouths to more pure clays offshore. Scruton (1955) distinguishes in the Mississippi delta between delta front silts and sands, pro-delta silty clays and offshore clays. The latter contain locally already a certain amount of shells of marine organisms (cf. also Parker, 1956) and sand or other material, transported by currents from outside sources. Nota (1958) found a similar gradation from silty clays to pure clays in the Western Guiana shelf area.

The fluviomarine series deposited off the Grand Rhône mouth are on the whole much sandier in composition. They contain in their proximal parts abundant layers and laminae of sand and silty sand. Both these coarse grained layers and the intercalated layers of finer material decrease in thickness towards deeper water. The decrease in thickness is accompanied by a diminishing of the maximum and average grain sizes of the sand.

Structures

Structures of recent submarine deltaic deposits

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[9] Further westward the submarine morphology is strongly influenced by the tectonic relief. In the Serpents Mouth, south of Trinidad and in the Bocas del Dragon area, between Trinidad and the Paria peninsula, zones of non-deposition and of active scour are found. In the Gulf of Paria itself and on the shelf north of the Bocas del Dragon there is again deposition of muds supplied by the rivers of the western Guiana Shield.

have been investigated by Johnston (Fraser river delta, British Columbia), Fisk et al., Moore, Scruton and Shepard (Mississippi river delta), Koldewijn (Paria-Trinidad area), Nota (Western Guiana Shelf) and van Straaten (Rhône delta).

Proximal fluviomarine deposits. It appears that the foreset beds of all studied deltas have typically laminated structures, at least on the upper parts of the foresets slope. The delta platform deposits of the Mississippi delta are also laminated, according to Moore and Scruton (1957). Those in the Gulf of Fos (Rhône delta) show a predominance of burrowing structures. The lower limit to which distinct laminations are found on the foresets slopes varies somewhat in the different deltas (in relation to the angle of the slopes, the current velocities of the rivers, and the average composition of the supplied sedimentary material). The maximum depth for the eastern Mississippi delta is approximately 40 m. In the fluviomarine sediments of the Fraser delta (Johnston, 1922) and of the Rhône delta they occur down to depths of 60 m and more.

The laminae consist of sand (relatively close to the delta front platform), silt, clay, and various mixtures of these size classes. Grading of the grain sizes in individual lamine is occasionally present, but does not form a characteristic feature of these sediments. The laminae are usually nicely parallel and even, but sometimes small load casts are formed by the subsidence of sand into the underlying mud. In the Rhône delta area such load casts were only exceptionally observed. In the Mississippi delta deposits they seem to be more common.

The sand found in the foreset beds is deposited by settling from the turbid river water, flowing out in a thin sheet over the denser sea water. Yet, cross laminations are not infrequently seen in the sand laminae. In some cases they may be due to tidal currents, e.g. in the Fraser river delta, or to wave action, e.g. on parts of the foreset slope of the Orinoco delta. But along the Rhône delta there are no tidal currents, and a large portion of the cross laminations are formed below wave base. In a paper by vanStraaten (1959) it is argued that they are possibly due to slow turbidity currents, running down the slope, which do not transport the sand over any great distance, but which are of sufficient strength to ripple the sand. Swift turbidity currents would carry the sand much further downslope. In that case considerable differences should be observed between the grain sizes of the bottom sand and those of the sand that is suspended in the surface water at the same places. No such large discrepancies in grain sizes were found.

With regard to the lateral continuity of the laminations Moore and Scruton (1957) state, that in the delta platform deposits of the Mississippi delta relatively thick layers and sets of laminae in cores from closely spaced core holes can usually be correlated, but that individual laminae often wedge out over distances of less than a few meters. On the pro-delta slope the continuity is even smaller. Separate laminae could rarely be traced between samples taken with bident corers at distances of only a few feet.

On the other hand, a series of 14 cores, taken from the mouth of the Grand Rhône southward, shows laminations that can be correlated over a distance of about 2 kilometers, from a water depth of only 4½ meters to a depth of 70 meters (see van Straaten, 1959).

It is hard to explain the very small continuity of the laminae in the foreset deposits of the Mississippi delta. Scruton (1955) supposes that many of the laminations are due to reworking of the sediment by wave action. It is known, of course, that in shallow water relatively coarse grained laminae can be formed by unmixing of sand-silt-clay mixtures under the influence of wave turbulence. However, this explanation is less likely for laminae that are formed in deeper water. Moreover, it seems improbable that the unmixing by the waves could be localized to areas of only a few square feet.

The laminations in the foreset beds of the Rhône delta are apparently the result of variations in the river discharge. It is seen that during river floods coarse grained suspended material is transported in much greater quantities and notably further seaward than during stages of low water. Obviously, these variations in supply of sediment to the foresets must result in relatively continuous laminations of alternately coarser and finer material. Although the data need still some confirmation, it seems that as a matter of fact a direct correlation can be made between these laminations and the succession of high and low water stages of the Rhône river in the last few years (van Straaten, 1959).

The fact that the laminations in the more proximal parts of the fluviomarine deposits are in general so well preserved is due to the small effect of burrowing organisms in this environment. It has been mentioned already that skeletal remains of marine organisms are very rare or altogether absent in the fluviomarine sediments. Grab samples from the proximal fluviomarine deposits off the Grand Rhône do not contain any skeletal material at all. Only a few derived mollusc shells were encountered in cores from the upper part of the foreset slope.

Yet, the environment is not quite azoic. Many grab samples contained fairly large numbers of polychaete worms, living in the mud. Gautier (1957), who collected drag samples in the Rhône delta area to study the marine benthic biocoenoses mentions the occurrence in these same sediments of other invertebrates without hard parts, viz. some *cnidaria*, holothurians and crustaceans. It is not surprizing, therefore, that one does find occasionally a few burrowing structures. Only very rarely are these burrows vertical. Most of them are horizontally directed polychaete burrows. The latter are of the same type as those found in the distal fluviomarine sediments (see below). They are mainly confined to laminae or layers of clayey composition, and, in consequence of their preferred orientation parallel to the bedding plane, they do not disturb the laminations very strongly.

Distal fluviomarine deposits. No laminations were found in the cores taken at depths of (80), 90, and 100 meters in the foreset environment off the mouth of the Grand Rhône. These deposits are composed of relatively pure clay. They correspond to the offshore clays of Scruton in the Mississippi delta area, which are described by him as homogeneous, and to the unlaminated bottom set clays of the Fraser delta, sampled by Johnston at depths of 130 and 170 meters.

Though the offshore clays of the Rhône delta are unlaminated and though they appear homogeneous when examined in moist core samples, they have nevertheless very typical structures. Samples which have dried out to a certain extent and which are then scraped off with a sharp knife show, in vertical sections a pseudo-conglomeratic structure of small particles of relatively dark coloured clay lying embedded in a matrix of somewhat lighter coloured, more silty clay. In horizontal sections most of these particles appear to be elongate. In many cases they are distinctly worm shaped, their shorter diameters seldom exceeding more than a few millimeters while their longer diameters may be as much as several centimeters. They have, moreover, frequently a typically segmented outline. The indentations between the segments dissect sometimes the dark coloured "worms" completely, so that they resemble strings of beads. The matrix around them is either more or less homogeneous, or it shows distinct concentric zonations. There can be little doubt that these dark coloured clay elements are produced by the polychaete worms which were observed in horizontal positions in the mud of many grab samples. It seems most likely that the dark material represents clay that has passed through the intestines of these worms. The term castings might therefore perhaps be more appropriate.

The influence of these organisms upon the sediment structures decreases from the base of the foresets upwards. The cores from 100, 90 and 80 m water depth show this kind of burrows or castings practically over their whole length. In the cores from 70 and 60 m depth there is an alternation of thick layers with "clay worms" and thin sand or silt laminae without such structures. In the cores from 50, 40 and 30 m water depth they are limited to only a few clay layers, the remainder of the cores showing normal laminations, and in the material from depths of less than 30 m no "clay worms" were observed at all. The offshore clay with horizontal worm structures interfingers apparently with the more silty and sandy deposits of shallower water, the intercalations with the "clay worms" forming continuous layers that extend from deep water upward along the slope.

VII. NORMAL OPEN SHELF DEPOSITS

Environment

Shelves are the submarine terraces which border most continents and many islands and which slope more or less gradually downwards to a depth of some 200 meters or less, where they are cut off by relatively steep surfaces leading down to oceanic depths.

The surface of the shelves is often very flat, but in some cases the features of a drowned land topography are clearly recognizable. There are also shelf areas, e.g. the southern North Sea (van Veen, 1936) that show a relief of numerous, more or less parallel, subaqueously formed sand ridges. The present shape of these ridges is strongly influenced by tidal currents. It is possible that their original formation was not only due to tidal currents, but that wave action also played a part.

Other relief features, viz. what looks like old nearshore bars and wave truncated terraces that have been drowned below wave base, are described by van Straaten (1959) from the Rhône delta shelf. Submerged terraces are also described by Nota (1958) (Western Guiana shelf) and by Emery (1958) (Southern California shelves).

At the outer edge of some shelves in regions of warm climates, e.g. in the Gulf of Mexico and East of Trinidad a number of isolated prominences are found. They are drowned reefs, on which there is in some cases a small amount of biohermal aftergrowth (Koldewijn, 1958; Ludwick and Walton, 1957; Nota, 1958).

The part of the shelf that extends from the base of the coastal barriers and the seaward limit of the fluviomarine deposits to the outer edge will be called the "open shelf".

Lithology

On many shelves the following zonation of bottom deposits is observed:

(1) relatively coarse grained, recent deposits near the coast, grading into

(2) fine grained recent material further offshore, followed by

(3) a zone of mixture of recent fine grained and older, coarse grained deposits, which in its turn may pass into

(4) a zone of more pure, coarse grained, older material. In some cases an

(5) outermost zone with calcareous sediments is present close to the edge of the shelf.

Where detailed sedimentological investigations have been made, it appears that the older, coarse grained material has been deposited in times when sea level stood considerably lower than at present, viz. in the Pleistocene and in the early Holocene. Nota (1958) considers some of these "shelf sands" on the Western Guiana shelf as drowned littoral or coastal plain deposits, on account of their grain size distributions. As to the drowned sands of the Rhône delta shelf, it seems probable that at least a part of them has been formed in nearshore water at a depth of some 10 to 20 meters, on account of the enclosed mollusc shells. Sediments with typically nearshore "fluviomarine" laminations were encountered at or closely below the surface on the outer parts of the western Guiana and Paria Trinidad shelves (Nota, 1958; Koldewijn, 1958).

It follows from the presence of these older deposits at or close to the surface that the rate of recent sedimentation in the outer shelf areas is practically zero. This absence of deposition is not due to lack of available material, as is shown by various observations on the distribution of suspended matter. Hence, the prohibiting factor must be turbulence in the water.

Koldewijn and Nota suppose that in some cases the concentration of the energy of tidal currents on the shelf edge may be at least partly responsible. In other places permanent, non-tidal marine currents could be one of the causes or the main cause of the turbulence. Thus Nota believes that the North Equatorial current plays an important part in establishing non-depositional conditions on the Guiana shelf in a broad zone from the shelf edge landward.

Where small amounts of recent clay are deposited on the shelf, it may become encorporated within the mass of the older sediments by the activity of burrowing animals. In such cases a gradation may be produced from relatively pure, recent clays at the top, via sandy clays, to clayey sands at some depth below the surface.

Structures

The minor sedimentary structures found in the recent deposits of the open shelves are mostly strongly influenced by the bottom fauna. Moore and Scruton (1957) distinguish in the shelf area off the central Texas coast between 4 zones with different types of structure. Together they correspond to the first and second of the lithological zones mentioned above. The innermost zone corresponds to the sandy, submarine barrier deposits of the present paper, dealt with above. The second zone lies roughly between the 12 and 16 m contours and is characterized by irregular layers of sandy and muddy material. It forms the transition between the barrier and the "open shelf" environments. The third zone, with sediments that are still more clayey, extends to depths that increase from circa 36 m in the western part of the investigated area to approximately 70 m in the eastern part. The structures are predominantly of the mottled type. The fourth zone, with the finest sediment (silty clays, see Shepard and Moore, 1955 a) shows, according to Moore and Scruton only "homogeneous structures". The transitions between the successive zones are of course quite gradational. No data are given on the sedimentary structures on the outermost parts of the shelf.

The disappearance of the irregular layers from the second zone towards deeper water is ascribed to the decreasing intensity of reworking of the sediments by waves and the relative increase of the effect of burrowing organisms. The transition from the zone of mottled structures to that of the homogeneous sediments is explained as the result of the decreasing quantities and final disappearance of sand. It must be concluded from this interpretation that Moore and Scruton do not apply the term homogeneous in its strictest sense. The circumstance that no sand is present in the sediment does not necessarily imply that the structures must be homogeneous. So long as the clays contain appreciable amounts of silt, organic matter etc., there may be all kinds of structure due to the special distribution of these admixtures. And even when a sediment consists exclusively of elements of one grain size, a definite structure may be present, e.g. a parallel orientation of clay mineral flakes in pure clays.

Mottled and (apparently) homogeneous

Fig. 1 — *Salt marsh.* Sample from marsh cliff at Zoutkamp (Dutch Wadden Sea), 62-69 cm below top of cliff. Laminae of sand and silty clay, penetrated by thin plant rootlets. Tray sample, vertical section, scale 1 : 1.

Fig. 2 — *Tidal flat, not influenced by migration of ebb gullies.* Comparatively muddy sand, from inner (southwestern) part of Lauwerszee (Dutch Wadden Sea), 1-8 cm below surface. Tray sample, vertical section, scale 1 : 1.

Fig. 3 — *Tidal flat, strongly influenced by migration of gullies and channels.* Sample from flats near Wilhelmshaven (German Wadden Sea). Alternation of mud and sand laminae. From Haentzschel (1936). Vertical section, scale 1 : 1.

Fig. 4 — *Tidal channel.* Comparatively muddy sample from centre of Lauwerszee (Dutch Wadden Sea), 38-45 cm below surface. Depth of channel circa 6½ metres below mean low tide level. Alternation of mud and sand laminae, the latter with minor structure due to tidal currents. Tray sample, vertical section, scale 1 : 1.

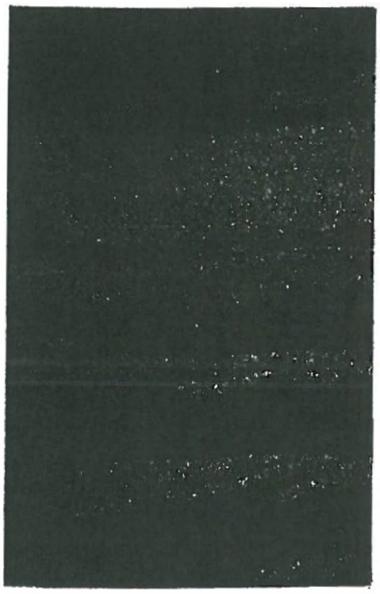
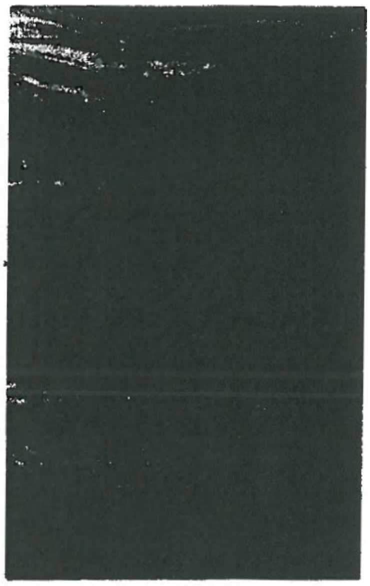


Fig. 5 — *Fresh to brackish lagoon.* Sample from deposits of former Lake Flevo (Netherlands, Noordoostpolder J 104), 58-65 cm below surface. Finely laminated sediment, dominantly composed of silt (2-50 μ). Most of the dark coloured particles are peat detritus. Tray sample, vertical section, scale 1 : 1.

Fig. 6 — *Brackish lagoon.* Sample from sediments of former Zuiderzee (Netherlands, Noordoostpolder, N 14/15). Example of laminated material (mostly silt and clay) without burrowing structures. Undisturbed laminations of this kind are less frequent in the Zuiderzee deposits than structures which show at least a moderate influence of burrowing animals. Tray sample, vertical section, scale 1 : 1.



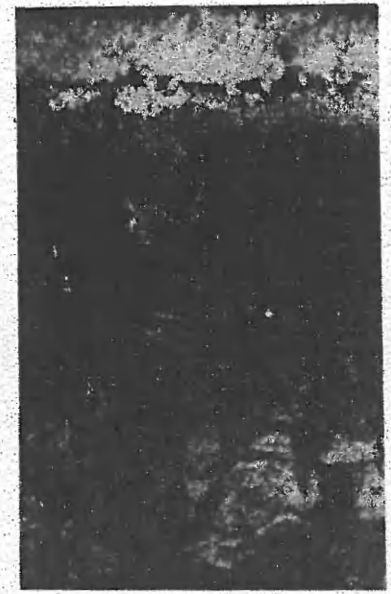


Fig. 7 — *Brackish lagoon*. Sample from eastern part of Etang de Vaccarès (Rhône delta, St. 1338 A), 8-15 cm below surface. Depth of lagoon 1¾ metres. Sandy and silty clay with burrowing structures. In centre: shell of *Cardium edule*. Tray sample, vertical section, scale 1 : 1.

Fig. 8 — *Brackish (to supersaline) lagoon*. Sample from floor of small lagoon east of Port St. Louis (Rhône delta, St. 1303 B), 0-7½ cm below surface. Sandy and silty clay, mostly of fluvial origin, covered by a thin layer of rock salt, due to temporary evaporation of lagoon water. The original lamination, remnants of which are still visible, was probably formed in a degenerating distributary channel. The burrowing structures and the intermixing of the material with shells of brackish water molluscs, ostracods and foraminifera are the result of the subsequent lagoonal conditions. Tray sample, vertical section, scale 1 : 1.

Fig. 9 — *Degenerating distributary channel*. Sample from remnant of Rhône de Pégoulier (Rhône delta, St. 1301), 23-30 cm below surface. Depth of channel: 1¾ metres. Alternation of fine clay, silt and sand laminae, with a few burrowing structures. Curving of laminae due to coring. Tray sample, vertical section, scale 1 : 1.

Fig. 10 — *Degenerating distributary channel*. Sample from deposits forming floor of small lagoon east of Port St. Louis (Rhône delta, St. 277), 98-105 cm below surface. Alternating laminae of clay, silt, fine sand and coarse sand, with a few burrowing structures and a few humified remains of plant rootlets (lower part of sample). One of the silt layers shows minor foreset laminations due to river currents. Tray sample, vertical section, scale 1 : 1.

Fig. 11 — *Delta platform*. Sample from southwestern part of Golfe de Fos (Rhône delta, St. 1201), 1-8 cm below surface. Depth of water ¼ metre. Sandy and silty clay with burrowing structures. Tray sample, vertical section, scale 1 : 1.

Fig. 12 — *Bay to open shelf (with active deposition)*. Sample from Golfe de Beauduc (Rhône delta, St. 325), 15-22 cm below surface. Depth of water 10½ metres. Silty clay with irregular layering due to influence of bottom fauna. Tray sample, vertical section, scale 1 : 1.

Fig. 13 — *Proximal fluviomarine environment.* Sample from old foreset deposits, cropping out on sea floor southwest of Faraman lighthouse (Rhône delta, St. 344), 12-19 cm below surface. Depth of water: 15 metres. Silty clay with parallel laminations. No burrowing structures. Tray sample, vertical section, scale 1 : 1.

Fig. 14 — *Distal fluviomarine environment.* Sample from recent foreset deposits, formed in front of present mouth of Grand Rhône (Rhône delta, St. 365), 23-30 cm below surface. Depth of water 90 metres. (Silty) clay with dark coloured *cross sections of structures* made by horizontally burrowing worms. Tray sample, vertical section, scale 1 : 1.

Fig. 15 — *Distal fluviomarine environment.* Sample from recent foreset deposits formed in front of mouth of Grand Rhône (Rhône delta, B 101) at depth of circa 22 metres below sea level. Silty clay with dark coloured cross sections *of structures made by horizontally* burrowing worms. Tray sample, vertical section, scale 1 : 1.

Fig. 16 — *Open shelf (with active deposition).* Sample from sea floor, southwest of Port de Bouc (Rhône delta, St. 1217) 20-27 cm below surface. Depth of water 27 metres. Silty clay with irregular layering due to influence of bottom fauna. Swarms of faecal pellets in upper left corner probably produced by *Turritella communis.* Tray sample, vertical section, scale 1 : 1.

Fig. 17 — *Open shelf (with active deposition)* Sample from sea floor, southsouthwest of Beauduc lighthouse (Rhône delta, St. 755), 18-25 cm below surface. Depth of water 50 metres. (Silty) clay with very irregular layers due to influence of bottom fauna. Tray sample, vertical section, scale 1 : 1.

Fig. 18 —*Open shelf with little or no deposition* (and without reworking of bottom material by waves and currents). Sample from sea floor, southsouthwest of Espiguette lighthouse (Rhône delta, St. 307), 8-15 cm below surface. Depth of water 40 metres. Clayey sand with homogenized structure. Tray sample, vertical section, scale 1 : 1.


Fig. 19


Fig. 20


Fig. 21


Fig. 22


Fig. 23


Fig. 24

structures are also mentioned from other shelf areas, viz. from the "open shelf with recent delta influence" seaward from the pro-delta slope of the eastern Mississippi delta (Moore and Scruton), from the northern Paria-Trinidad shelf (Koldewijn) and from the western Guiana shelf (Nota). Mottled structures are furthermore found in recent deposits of the normal open shelf off the Rhône delta. The mottling is in practically all cases due to burrows or castings of invertebrate animals, which are filled with material of a slightly different composition from that of the surrounding matrix.

The relatively pure offshore clays of the open shelf off the Rhône delta show often swarms of minute, dark coloured faecal pellets, that are probably produced by the most abundant macro-invertebrate in this area, the gastropod *Turritella communis.*

The strong effect of these animals on the sediment structures in the investigated shelf areas is, of course, the result of a rich fauna combined with a low rate of deposition and a lack of reworking of the bottom material by waves and currents. Since these same conditions are realized in most shelf areas of the world, it may be expected that shelf deposits in general are characterized by unlaminated, more or less distinctly mottled structures.

The above observations apply especially to shelf areas where the inorganic part of the sediment is mainly supplied to the sea by rivers and where marine currents, carrying the sedimentary material suspended in the water, distribute it over the various parts of the shelf bottom. Somewhat different circumstances are encountered in polar seas. Carsola (1954) found that a part of the sediment on the shelf north of Alaska and northwestern Canada is transported to the place of deposition by ice rafting. The ice receives its sediment load along the shores, by coastal erosion, by grounding and by streams flowing out over it from the land. Some of the sediment laden ice is original river ice that has drifted to the sea. When the ice melts the rafted material sinks to the bottom, where it is deposited together with mud that is supplied in the normal way by currents. The resulting sediment is poorly sorted and is sometimes called a marine till. Away from the Mackenzie river mouths, in the western Beaufort Sea, where the supply of fluvial material is small, unlaminated structures seem to be the rule. The absence of laminations may not only be due to the lack of sorting during transporation of the sedimentary material, but also to the effect of benthos organisms which inhabit even these arctic waters.

VIII. BAY SEDIMENTS

Several shallow marine areas exist which can not easily be classified in one of the above described environments. Most of them are comparatively small and do not make part of the normal open sea, e.g. fjords, calas, rias, bays behind spits, etc. Although the environmental conditions vary strongly from one case to another, they are taken together in this section for the sake of convenience, since in most instances little or nothing is known about the structures of their bottom deposits.

Bays behind spits. — An example is the Golfe de Fos on the eastern side of the Rhône delta. The features observed in this bay may, of course, be very different from those in other bays. The sediments in the central parts of the

Fig. 19 — *Open sea beach.* Sample from coast of Rhône delta, circa 3 km east of mouth of Grand Rhône (St. 294), 3-38 cm below surface. Top of core approximately 1 m above mean sea level. Sand with undisturbed, thin, parallel laminations. Lacquer peel, vertical section, scale 1 : 2.5.

Fig. 20 — *Submarine barrier environment.* Sample from coast of Rhône delta, halfway between mouth of Grand Rhône and spit de Beauduc (St. 351), 0-27 cm below surface. Depth of water: 1¼ metres. Sand with parallel laminations. Wet core, vertical section, scale 1 : 1.9.

Fig. 21 — *Submarine barrier environment.* Sample from Rhône delta, east of northeastern extremity of Spit de la Gracieuse (St. 395), 3-30 cm below surface. Depth of water 7½ metres. Sand with parallel laminations. Wet core, vertical section, scale 1 : 1.9.

Fig. 22 — *Submarine barrier environment.* Sample from sea floor, northwest of Beauduc lighthouse (St. 333), 1-28 cm below surface. Depth of water 13 metres. Sand with parallel laminations. Lacquer peel, vertical section, scale 1 : 1.9.

Fig. 23 — *Proximal fluviomarine environment.* Sample from old foreset deposits, cropping out on sea floor southwest of present mouth of Petit Rhône (Rhône delta, St. 317), 2-29 cm below surface. Depth of water 10½ metres. Alternation of undisturbed sand and clay laminae: the sand with minor cross laminations. Lacquer peel, vertical section, scale 1 : 1.9.

Fig. 24 — *Distal fluviomarine environment.* Sample from recent foreset deposits formed in front of present mouth of Grand Rhône (St. 372), 6-33 cm below surfase. Depth of water 40 metres. Alternation of fine sand and silty clay. Lacquer peel, vertical section, scale 1 : 1.9.

Golfe de Fos are composed of silty clays which show laminations that are usually strongly disturbed owing to the abundant bottom fauna. Though the depths are small, viz. less than 15 m, no new laminations are formed by wave action, since this part of the bay lies below the local wave base. Wave-produced laminations do occur in shallower water along the shores.

Fjords. — Some fjords have depths of up to 1000 m or more, but many others belong mainly or completely to the neritic environment, with depths of less than approximately 200 m. Few data are available concerning the structures of fjord deposits. In some Norwegian fjords well laminated sediments were found (Muenster Stroem, 1953). The laminations may be caused by (1) seasonal changes in the supply of material owing to variations in the production of planctonic life, (2) seasonal fluctuations in the supply of terrigenous sediment, e.g. glacial varves, (3) occasional, short lived turbidity currents. The fact that these structures are preserved is mainly the result of the absence of a benthonic fauna, which can not live in the stagnant, anaerobic bottom water.

Rias. — An example of a drowned river valley system which is not directly influenced by pleistocene or present day glaciations is the Chesapeake Bay in Maryland. This bay forms a typical estuarine environment (Pritchard, 1952), in which, contrary to many other estuaries, tidal flats are of quite subordinate importance. The sediments were investigated by Ryan (1953). They are supplied by rivers flowing into the bay from the North and the West, by flood currents entering the bay from the South and by waves eroding the shores. The deposits are at many places comparatively homogeneous, but distinct laminations are also observed. The latter are caused by variations in the supply of material and by reworking of the sediment by currents (especially in the deeper parts) and waves (along the shores).

IX. SUMMARY AND CONCLUSIONS

Minor sedimentary structures (as visible in small, vertical sections of e.g. 2 x 3 inches) are described from a number of environments. The conclusions may be summarized as follows:

1. *Salt marshes* (bordering tidal flats, lagoons etc.).

Examples: Dutch, German and Danish Wadden Sea, Wash Bay, Dutch, British, French and Moroccan estuaries a.o.

Lithology: Mostly clays and silty or sandy clays.

Structures: Undulating, nodular laminations which show usually considerable lateral continuity. Uneven character of laminae owing to deposition on plant covered surfaces. Laminae often graded as a result of decreasing competency of the currents during each stage of inundation of the marshes. Because of scarcity or absence of bottom fauna little or no disturbance of laminations by burrowing. Occasional formation of mud cracks. Abundance of normally very thin plant rootlets.

2. *High parts of tidal flats* (largely undissected by gullies; in tidal flat areas behind coastal barriers and in estuaries).

Examples: See 1.

Lithology: Mostly sands with very little clay. More clayey sands, locally even sandy clays, are often found close to the marsh edges.

Structures: Few or no laminations, owing to abundance of burrowing animals in combination with relatively slow (but rather continuous) type of sedimentation. Mud cracks may be formed where the sediment is rich in clay, especially in warm climates.

3. *Low parts of tidal flats* (banks of tidal channels, in tidal flat areas behind coastal barriers and in estuaries).

Examples: See 1.

Lithology: Sands, clayey sands and sandy clays.

Structures: Laminations, due to strong variations in competency of tidal currents, often of relatively small lateral continuity. The laminae show not unfrequently a relief and internal structure due to current or wave ripples. More irregular cross laminations due to local erosion are also found. Relatively few burrows, owing to high rates of deposition (during stages when deposition takes place). Some incomplete mud cracks occasionally present. Commonly shell and clay pebble beds, with imbricated structures.

4. *Tidal channels* (in tidal flat areas behind barriers, in estuaries and in tidal lagoons).

Examples: See 1; also Barataria Pass (Louisiana).

Lithology: Mostly sands and clayey sands, locally also sandy clays; abundant shell and clay pebble beds.

Structures: Laminations owing to strong variations in competency of tidal currents. Laminae very often with relief and internal structures due to current ripples. Shell and clay pebble beds with imbricated structures.

5. *Low salinity lagoons* (receiving considerable quantities of fresh water from rivers).

Examples: Lake Flevo (Netherlands, ca. 0-1600 A.D.), Northern extremity of San Antonio Bay (Texas).

Lithology: Clayey or sandy silts and clays and sands with high silt contents.

Structures: Usually very thinly laminated structures. Laminae even, or with relief and internal structures due to wave ripples, locally also to current ripples. Influence of scarce bottom fauna on sediment minimized by frequent reworking of bottom material by waves.

6. *Normal brackish or salt water lagoons*

Examples: Zuiderzee (Netherlands) Rhône delta lagoons, Barataria Bay, Texas bays.

Lithology: Sands, clayey sands, sandy clays and clays with small or moderate contents of silt.

Structures: Mostly few or no laminations owing to abundance of burrowing animals, combined with relatively slow but continuous type of sedimentation. Effect of waves often reduced by close cover of water plants on lagoon floor. In other cases better developed laminations. Formation of mud cracks in temporarily emerging parts of lagoon bottom.

7. *Hypersaline lagoons*

Example: Laguna Madre, Texas.

Lithology: Sands, silty and clayey sands, sandy and silty clays, occasional intercalations of evaporites.

Structures: Laminations or stratifications with subordinate burrowing structures, locally penetrated by mud crack structures.

8. *Beaches*

Examples: Netherlands, Rhône delta, California and elsewhere.

Lithology: Sands, occasionally with shells and or pebbles.

Structures: Mostly relatively thin, smooth laminae, each lamina being the result of the long continued activity of swash and backwash. Occasional ripple laminations and other cross laminations or cross stratifications. Mostly only few burrows. In some cases structures of various kinds due to entrapment of air in the sand.

9. *Submerged parts of coastal barriers*

Example: Rhône delta.

Lithology: Sands, on lower parts passing into clayey sands.

Structures: Mostly parallel laminations with some ripple structures and a few burrows, the latter more frequent on the lower parts of the barriers.

10. *Sheltered parts of delta platforms* (e.g. in interdistributary bays and bays on landward side of spits).

Examples: Mississippi river delta, Rhône delta (Southwestern part of Bay of Fos).

Lithology: Clays, sandy clays and clayey sands with varying amounts of silt.

Structures: In some cases well developed laminations due to variations in supply of material by currents and to reworking of the material by waves; often with wave ripple structures. In other cases more or less complete disturbance of the laminations by burrowing animals. The degree of disturbance by burrows depends on the relative abundance of bottom fauna, the rates of sedimentation, the influence of waves and the composition of the sediment.

11. *Upper parts of delta front slope* (areas of deposition of proximal fluviomarine sediments)

Examples: Deltas of Fraser, Mississippi, Orinoco and Rhône rivers.

Lithology: Sandy and silty clays.

Structures: Well developed laminations, due to variations in supply of sediment (e.g. river floods — stages of low discharge) and to differences in settling velocity of the various size grades; occasional current ripple structures probably due to (slow) turbidity currents and, on the uppermost parts, also some wave ripple structures (Rhône delta). Possibly a few load casts. Hardly any vertical burrows, but in clayey laminae sometimes abundant horizontal burrows (Rhône delta).

12. *Lower parts of delta front slope* (areas of deposition of distal fluviomarine sediments).

Examples: See 11.

Lithology: Clays and siltry clays.

Structures: Laminations vague or absent, but abundance (in Rhône delta) of mainly horizontal worm burrows.

13. *Normal open shelf in areas of "active" deposition.*

Examples: Western Guiana shelf, Paria Trinidad area, northern and northwestern Gulf of Mexico, shelf off Rhône delta coast.

Lithology: Mostly clays and silty clays.

Structures: Laminations usually completely or almost completely disturbed by burrowing organisms, in some cases leading to comparative homogeneity of the sediment. Predominance of burrowing effect due to well developed bottom fauna and to relatively low rate of deposition. Not unfrequently abundance of faecal pellets (Rhône delta).

14. *Shelf areas with little deposition but with strong reworking of bottom material by waves and tidal currents.*

Examples: Southern North Sea Floor.

Lithology: Mainly sands.

Structures: Probably many laminations and cross laminations owing to waves and currents, but locally with strong influence of burrowing animals.

15. *Shelf areas with little or no deposition, without reworking of bottom material by wave- and (tidal) current action.*

Examples: Outer parts of Paria Trinidad, Western Guiana and Rhône delta shelves.

Lithology: Older deposits of various compositions (clays, silts, sands, gravels etc.), mixed at surface with varying amounts of recent clay material and with skeletal remains of marine organisms.
rowing organisms, in some cases leading to com-

Structures (at surface): Mottled to homogeneous.

16. *Fjords with stagnant bottom water*

Examples: Some Norwegian fjords.

Lithology: Clays and silty clays, occasionally perhaps with ice rafted pebbles.

Structures: Fine laminations owing to fluctuation in sediment supply and to differences in settling velocity of the various size grades. No burrowing structures owing to absence of bottom fauna.

It follows that the minor structures of the sediments deposited in the above environments are the result of the interaction of a large number of different factors:

(A) *Primary factors,* which tend to produce various kinds of parallel laminations or cross laminations, e.g. variations in the composition of material supplied to the place of deposition, variations in competency of currents supplying the material, differences in settling velocity of the various size grades, reworking of bottom material by (currents and) waves, relief of the surface on which the sediment is deposited etc.

(B) *Secondary factors* which tend to modify or to disturb these original structures or even prevent their initial formation. They may be distinguished into organic factors, e.g. burrowing of bottom animals in vertical and horizontal directions through the sediment, penetration of the sediment by plant rootlets, and inorganic factors like the formation of mud cracks, load casts and the modification of the structures by air heave, slumping etc.

Most of the sediments show either a predominance of laminations produced by the primary factors, or a predominance of burrowing structures. Whether the effect of these primary factors or of the burrowing prevails depends on the ecological conditions and on the rates of deposition or of reworking by waves (and/or currents).

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