LEIDSE GEOLOGISCHE MEDEDELINGEN, Deel 49, Aflevering 1, pp. 125–144, 15-3-1973

SEDIMENTOLOGY OF A LINEAR PROGRADING COASTLINE FOLLOWED BY THREE HIGH-DESTRUCTIVE DELTA-COMPLEXES (CAMBRO-ORDOVICIAN, CANTABRIAN MOUNTAINS, NW SPAIN)

BY

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ABSTRACT

In the Luna area of the Cantabrian Zone the Cambro-Ordovician Oville and Barrios Formations were studied. Five facies groups were distinguished, each consisting of one or more subfacies. Facies group I represents littoral deposits and consists of four subfacies: barrier-beach deposits, beach deposits surrounded by tidal deposits, sub-beach deposits and littoral-channel fills (rip-current channels). Facies group II represents tidal deposits, consisting of high-energy tidal-channel deposits, low-energy tidal-channel deposits, non-channel tidal deposits and highly wave-influenced tidal deposits. Fluvially influenced deposits form facies group III. Three subfacies were distinguished: fluvial-channel fills, fluvio-tidal deposits and fluvial-overbank deposits. Shelf, pro-delta and delta-slope deposits form facies group IV, four subfacies are found: pro-delta deposits, lower delta-slope deposits, upper delta-slope deposits and shelf deposits. The subfacies of this group form sequential units: delta-slope sequences, shelf sequences or combined shelf and delta-slope sequences, all of which are regressive. Facies group V represents lagoonal deposits.

The Oville Formation can be subdivided into four members, the Barrios Formation into seven members.

The Oville and Barrios Formations together consist of four large sequences. Sequence I, in which the Griotte Member of the underlying Lancara Formation is included, begins with deposits of a carbonate-clay shelf environment, followed by argillaceous mottled shelf deposits. The top of the sequence consists mainly of littoral deposits. The sequence represents a linear prograding coastline. Sequence II consists of a lower part formed by pro-delta and delta-slope deposits and an upper part formed by tidal delta-top deposits. It represents a high-destructive tide-dominated delta. Part of the area was not influenced by the delta, here a tide-controlled prograding coastline existed. Sequence III begins with a thin transgressive sandstone sheet, which is followed in part of the area by tidal-delta deposits. After the transgression a regressive sequence was formed: tidal-delta deposits, littoral deposits (barrier-bar complex), tidal-flat deposits and fluvial or fluvio-tidal deposits. In part of the area the latter two are absent. The sequence represents a high-destructive wave- and tide-controlled delta, which was bordered on both sides by a coastal plain, consisting of beach ridges. Sequence III was followed by a period of subaerial exposure. Sequence IV begins in some sections with lagoonal deposits, which are overlain by barrier-bar deposits. Fluvial channels are locally found in the top of the sequence. Sequence IV possesses only small lateral continuity and is absent or extremely thin in the larger part of the area. Sequence IV represents a high-destructive wave-dominated delta, bordered on both sides by emerged areas of non-deposition.

INTRODUCTION

Geological setting

The Cantabrian Mountains belong to the Iberian Hercynian orogenetic belt. On the basis of differences in stratigraphy, tectonic structures, igneous characteristics and grade of metamorphism this orogenetic belt was divided into zones by several authors (Lotze & Sdzuy, 1961; Matte, 1968; Parga, 1970; Bard et al., 1971). The area studied, the Luna area, is part of the Cantabrian Zone and is situated near the southwestern border of this zone close to the Precambrian Narcea Anticlinorium, which forms the boundary between the abovementioned zone and the West Asturian-Leonese Zone (Fig. 1).

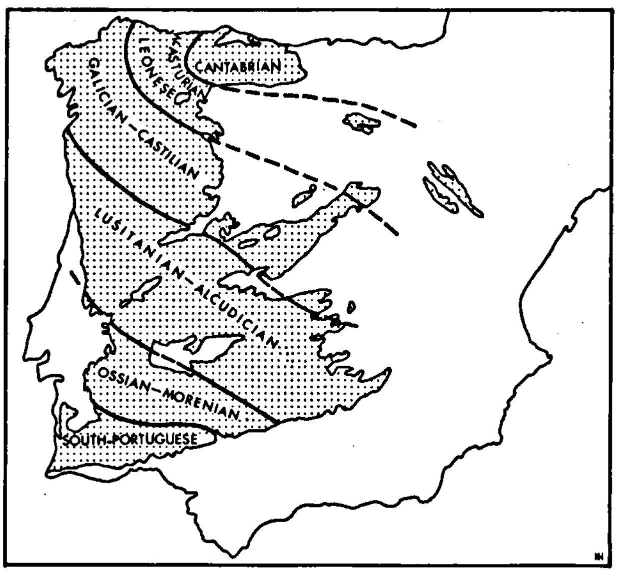

Fig. 1. Zonation of the Paleozoic (Hercynian) core of the Iberian Peninsula (after Parga, 1970).

Stratigraphy

In the area selected the Oville and the overlying Barrios Formations were studied. These formations belong to the Lower Paleozoic Luna Group (Brouwer, 1964), which consists of five siliciclastic and one carbonate formation. The siliciclastic Herreria Formation discordantly overlies previously folded Precambrian rocks. The Lanca-

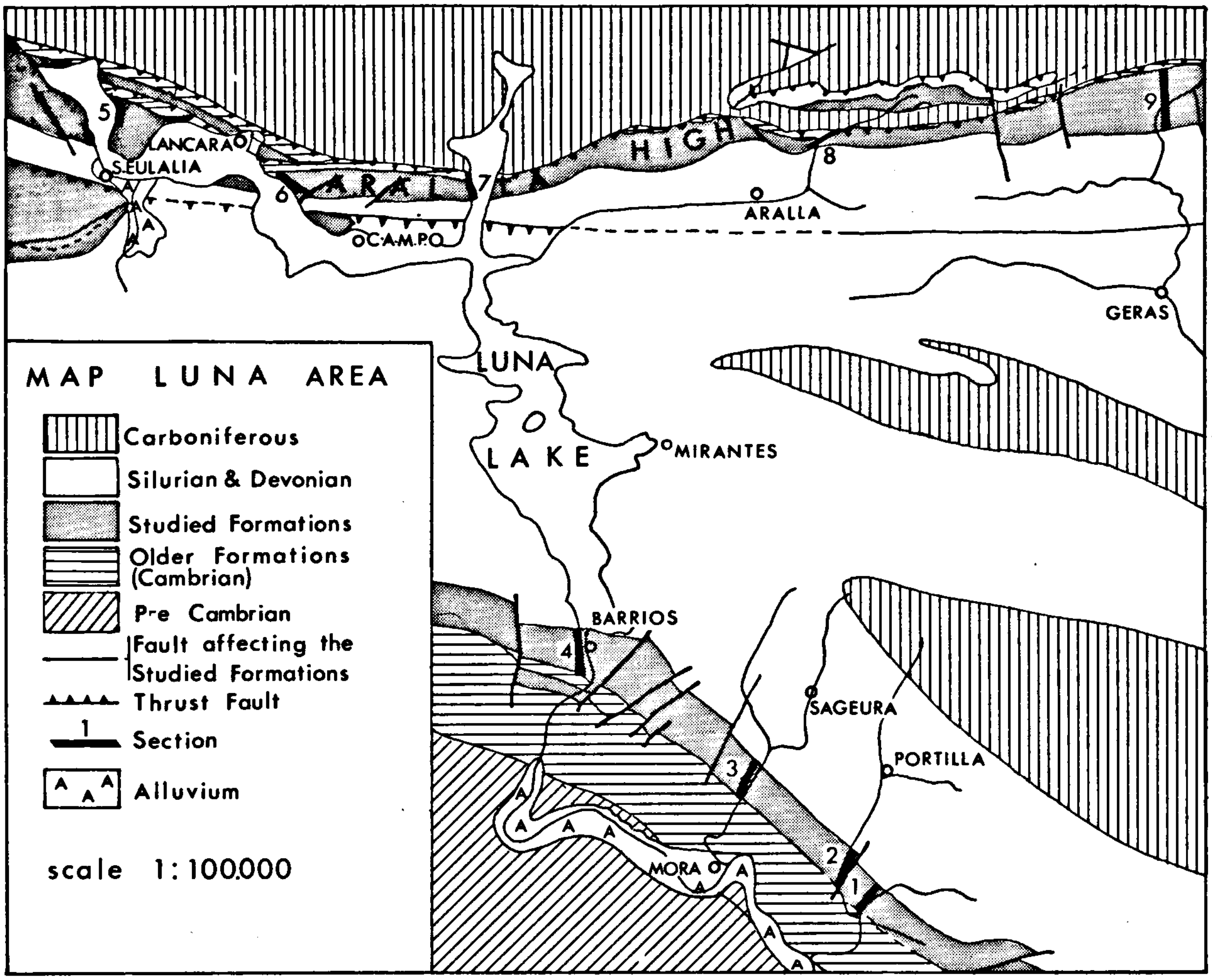

Fig. 2. Map of the Luna area showing location of sections.

ra Formation gradually overlies the Herreria Formation and consists of three members (van der Meer Mohr, 1969): the Dolomite Member, the Limestone Member and the Griotte Member. A disconformity is found between the Limestone and Griotte Members. The latter forms the logical base of the succession studied and is therefore included in the present paper. The Lancara Formation was studied by van der Meer Mohr (1969) and his results and conclusions are used. The Oville Formation gradually succeeds the Lancara Formation and consists of sandstone-shale alternations. The Barrios Formation is very sandy, gradually overlying the Oville Formation. The two uppermost formations of the Luna Group are separated from the Barrios Formation by a large hiatus. The main part of the succession studied is non-fossiliferous, only the Griotte Member of the Lancara Formation and the lowermost part of the Oville Formation containing fossils, which indicate a Middle Cambrian age (Lotze & Sdzuy, 1961). The Barrios Formation is overlain by the Formigoso Formation, which was dated by means of graptolites found at the base, indicating Llandovery (Silurian) age (Comte, 1959). Lithological correlations with the Barrios Formation of Asturias, which is overlain by the Luarca Formation of Llanvirn and Llandeillan age, suggest that the top of the Barrios Formation is not younger than Arenig (Poll, 1963; van den Bosch, 1969). This means a large hiatus between the Barrios and the Formigoso Formations, comprising most of the Ordovician.

Sedimentary petrography

The sedimentary petrography of the formations studied was described in an earlier paper (Gietelink, 1972) and only the main facts will be summarized. The bulk of the sediment consists of sandstones, argillaceous sandstones, mudstones, silty shales and argillaceous siltstones. Pure shales are rare.

The majority of the grains (generally over 90 %) are quartz grains, minor quantities of microcline (and a few plagioclases), composite quartz rock fragments, volcanic rock fragments, argillaceous rock fragments and micas (mainly muscovite); heavy minerals and glauconite occur as well. The matrix clay minerals are mainly altered into illite, in a few instances authigenetic muscovite or chlorite are found in small quantities. Quartz cement is generally found in thin sections. Other authigenetic minerals, which are of minor importance, are muscovite, iron oxides and hydroxides, anatase, apatite, calcite and barite.

Using the classification system by Travis (1970), most sandstones should be classified as siliceous quartz sandstones (arenites and wackes).

Subdivision of the formations into members
Up to the present study no attempt was made to distinguish members in the formations studied. At an early stage of the study the need arose to distinguish and describe lithological facies groups and subfacies in these groups with a view to a better examination of the succession. At a later stage larger lithological units (members) were distinguished, each of which consists of a characteristic combination of the various subfacies.

FACIES GROUPS

Introduction
The various facies groups and subfacies in these groups are distinguished and described on the basis of those lithological characteristics and sedimentary structures which are of genetic importance. These characteristics are used to assign the various subfacies to different sedimentary environments. The grouping together of several subfacies into a facies group implies a genetic relationship. The boundaries between subfacies are in many cases arbitrary, because they are often gradual.

Facies group I – littoral deposits
Subfacies Ia, barrier-beach deposits (Fig. 6). – 1. Description. We always find a close vertical relation between subfacies Ia and Ic. Subfacies Ia is generally underlain and overlain by subfacies Ic. Locally subfacies Ia is underlain by lagoonal deposits or overlain by tidal or fluvial deposits. Channels belonging to subfacies Id were occasionally cut into subfacies Ia.

The sediment consists of 95 % or more of very well sorted sandstones, which generally contain less than 5 % of matrix. Between different beds the grain size varies from fine to (very) coarse sand and the grains are rounded to well-rounded. The sandstones partly contain glauconite grains. Locally (less than 5 % of the sediment) finer-grained sediments are intercalated. The thicknesses of the sandstone beds range from 10–20 cm to over 5 m, those of lithological units, which as a whole belong to subfacies Ia, range from 2 m to about 35 m.

The most typical sedimentary structure of these sediments are parallel laminations, accompanied by heavy mineral concentrations and primary-current lineations, which are found in most sandstone beds. Large-scale low-angle planar cross-stratification is a common feature. Wave-ripple laminations, wave ripples, morphologically resembling those of recent beaches, and micro wave ripples (mm high) occur locally. Channelling beds with

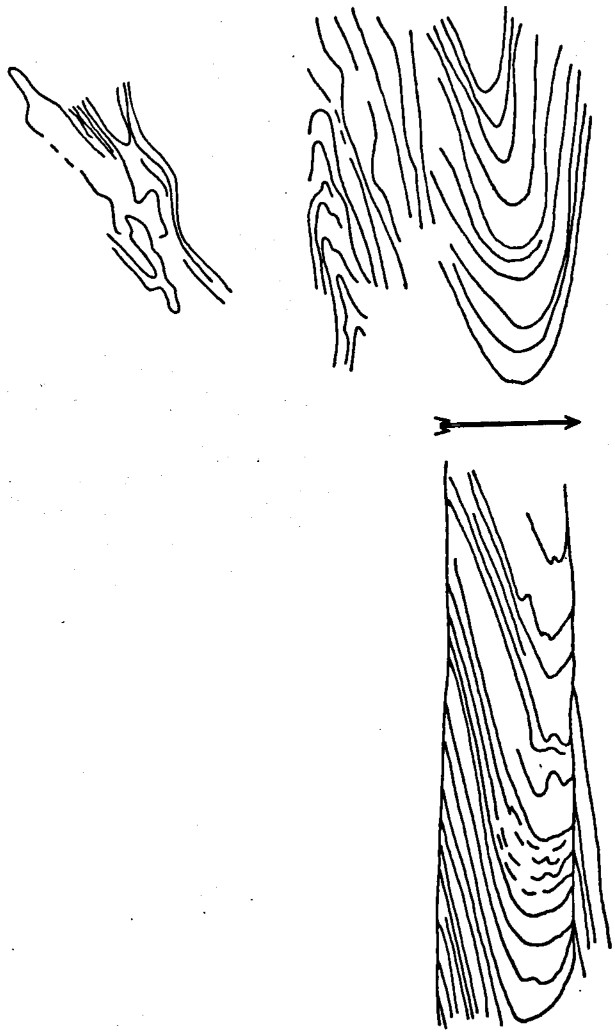

Fig. 3. Quicksand structures (arrow indicates top).

large and small-scale moderate to high-angle trough and tabular cross-stratification form only a minor constituent. Large-scale inclined laminations are found, which are tangential to a non-erosional bottom and have micaceous silty bottomsets. Current ripples occasionally occur in the more channelling parts. Some beds show convolute laminations (Fig. 3). Large-scale loadcasts (up to 1.5 m in diameter and 0.5 m in depth) are frequent in part of the sediments. The majority of these loadcasts were formed by foundering of sand into sand (Fig. 4). Sandstones underlying a bedding plane with such loadcasts are in general homogeneous. Upper surfaces of sandstone beds are often covered with small depressions (a few mm in diameter) which are surrounded by a low wall (1 mm high). The uppermost parts of these sandstone beds are homogeneous (Fig. 5). Subfacies Ia is almost entirely non-life, bioturbate structures occurring only occasionally.

2. Interpretation. The most typical sedimentary structure of subfacies Ia are the parallel laminations with heavy mineral concentrations and primary-current linea-

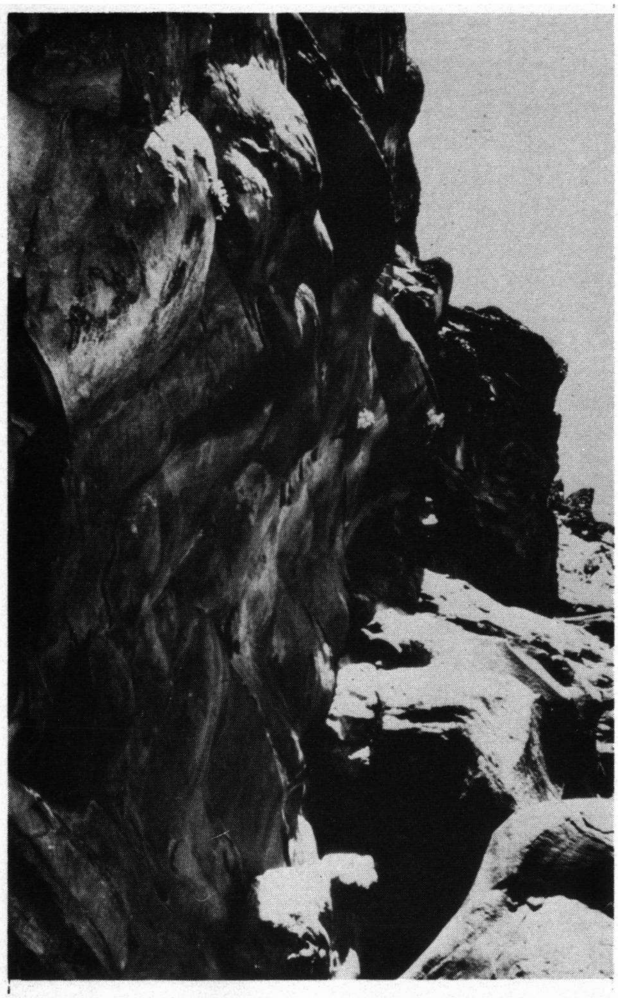

Fig. 4. Photo of bedding plane with large-scale loadcasts of sand into sand. The bedding plane is vertical and the photo is taken in a vertical sense.

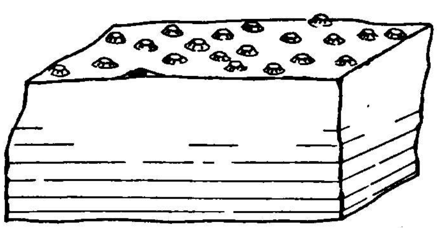

Fig. 5. Soft beach sand, bubble-sand structures. Upper part sandstone bed structureless.

tions. It is generally accepted that these structures were formed on beaches by swash and backwash activity. There are several other indications of subaerial exposure or very thin water cover. Micro wave ripples are recently known to form in quiet water only a few cm in depth, when the wind blows gently over the water surface. Small depressions found on top of homogeneous sandstone beds are described by Hoyt & Henry (1964) from recent soft beach sands as bubble-sand structures. From this evidence we may conclude that subfacies Ia represents beach deposits.

Large-scale low-angle planar cross-stratification is typical of the upper-foreshore or swash zone (Thompson, 1937; Zenkovich, 1967; Andrews & van der Lingen, 1969; Clifton et al., 1971). Convolute laminations on beaches can be formed in several ways: by sliding down of oversteepened berms (Soliman, 1964; Panin, 1967), by higher mobility of sand, on account of entrapped air (Panin, 1967) or by quicksand movement (Selley & Shearman, 1962; Selley, 1964; Shearman, 1964). Convolute laminations of the first and the second type, together with a more irregular type of bedding, are to be expected in sediments of the backshore (Thompson, 1937; Soliman, 1964; Panin, 1967). Quicksand structures, on the other hand, are more likely in water-saturated sediments, as are the probably related loadcasts of sand into sand. Both phenomena occur in or near beds with a more channelling character showing moderate to high-angle cross-stratifications. These structures were probably formed on the lower foreshore or breaker zone (Thompson, 1937; Zenkovich, 1967; Clifton et al., 1971). Current ripples are also indicative of lower-foreshore conditions. The large-scale tangentially inclined laminations with fine-grained bottomsets are also a sedimentary structure of this sub-environment. They probably represent longshore bars that moved shorewards over the fine-grained deposits of the protected beach troughs, which lay on their shoreward side (McKee, 1957).

Concluding we may say that subfacies Ia represents the beach itself (backshore, upper and lower foreshore).

Subfacies Ia is always found in close vertical relation with subfacies Ic, that, as will presently be outlined, represents a sub-beach environment dominated by longshore currents. This implies that the sediments of subfacies Ia were deposited on beaches that formed true

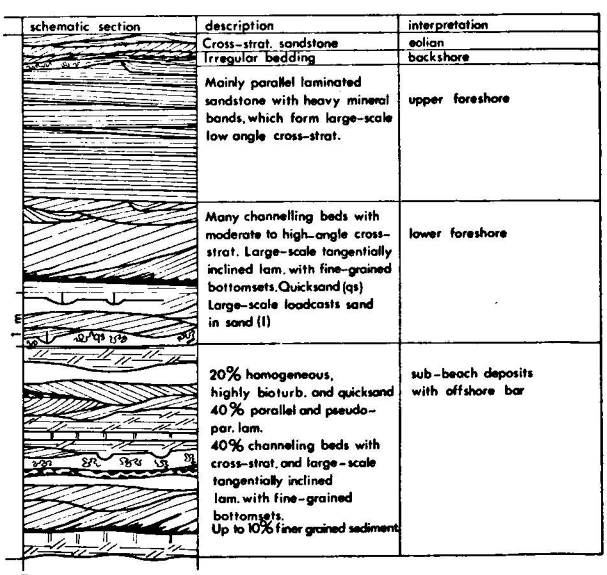

Fig. 6. Subfacies Ia and Ic, littoral deposits.

barriers between the open sea and the areas on their landward side.

Subfacies Ib, beach deposits (Fig. 10). – 1. Description. Its close relation with tidal deposits (facies group II) is typical of this subfacies. Subfacies Ib is always intercalated in tidal deposits.

The sediments are similar to those of subfacies Ia. Fine-grained intercalations are more frequent (up to 10 %) and are probably of tidal origin, showing as they do sedimentary structures similar to those described in facies group II. The thicknesses of the sandstone beds (5 cm to 2 m) as well as those of lithological units, which as a whole belong to subfacies Ib (1 m to 15 m), are smaller than those of subfacies Ia.

The sedimentary structures are essentially the same as those of subfacies Ia, and only the differences will be mentioned. Channelling beds with moderate to high-angle cross-stratification and current ripples are in general more frequent. Bioturbation is somewhat higher, though the subfacies is still in general non-life. Large-scale loadcasts of sand into sand occur only occasionally.

2. Interpretation. The similarity of lithology and sedimentary structures between subfacies Ia en Ib permits of the analogous conclusion that subfacies Ib also represents a beach environment. The main difference between the two subfacies lies in their stratigraphic relations to other deposits. Subfacies Ib is always found in relatively thin and isolated units, which are entirely surrounded by tidal deposits. The beaches under consideration probably lay on shoals in the entries of estuaries. Similar Recent shoals are described from the German North Sea coast (Dörjes et al., 1970). Part of the beaches were possibly small beaches surrounding or lying upon tidal flats (salt marshes did not occur, because land plants did not yet exist).

Subfacies Ic, sub-beach deposits (Fig. 6).– 1. Description. As was mentioned before, subfacies Ia and Ic are closely related. Downward and upward gradual passages to tidal and shelf deposits are frequent. Channels belonging to subfacies Id are seen to have been cut into sediments of subfacies Ic.

The sediments consist of well-sorted to moderately-sorted sandstones, which have matrix percentages varying from less than 10 % to about 25–30 %. Grain size varies from very fine to coarse sand and the grains are rounded to well-rounded. Most of the sandstones contain glauconite grains. Intercalations of finer-grained sediments may constitute up to 10 % of the sediment and are often of tidal origin, as may be deduced from the similarity of their sedimentary structures to those of facies group II. The thicknesses of the sandstone beds range from 10 cm to 3 m, those of the larger lithological units belonging to subfacies Ic range from 1–2 m to about 30 m.

The sandstone beds are generally channelling, but are continuous over distances which are large in relation to their thickness. In good exposures the channel trends are often seen to be at right angles with the general direction of sediment transport in the section considered. Channels are up to 5 m in width and seldom deeper than 75 cm. Another sedimentary structure typical of this subfacies is pseudo-parallel lamination. Pseudo-parallel laminations are not truly parallel, though they appear to be at first sight. A closer look reveals frequent small-scale cross-laminations besides the parallel lamination (Fig. 7). The internal structures of the sandstone beds can be grouped into three types, the first and the second of which are about equally important and are found in 80 % of the beds:

a. Large and small-scale planar, tabular and trough cross-stratifications with angles of 8–25 degrees. Large-scale inclined laminations, which are tangential to a non-erosive bottom and have micaceous silty bottomsets, occur locally. Small and large-scale current ripples are frequent.

b. Parallel and pseudo-parallel laminations, the latter being far more frequent. Wave-ripple laminations occur in this type.

c. The main part of this type is homogeneous and without structure. Highly bioturbated sandstone beds and beds with quicksand structures are included in this type.

Large-scale loadcasts of sand into sand as well as of sand into finer-grained sediments are found. Bioturbation is

Fig. 7. Röntgen photo taken from a sample of a more irregularly bedded part in a pseudo-parallel laminated sandstone bed (scale approx. 1:1).

far more frequent in subfacies Ic than it is in the previous subfacies.

2. Interpretation. Pseudo-parallel lamination can be explained by the constant formation and subsequent erosion of wave ripples. The small-scale cross-laminations are remnants of wave ripples. The equal importance of wave-generated beds and current-generated beds proves that waves and currents exerted equal influence on the sediment. About 20 % of the beds are homogeneous. Two possible mechanisms might be responsible: quicksand movement or bioturbation. As both are found, it is likely that both mechanisms formed homogeneous sandstone beds. Upward gradual passages to beach deposits and downward gradual passages to tidal and shelf deposits, together with the above-mentioned characteristics, suggest deposition in a zone offshore from the beach sensu stricto, the so-called sub-beach (Werner, 1963; Reineck, 1967). Higher percentages of matrix and relatively smaller grain sizes of the sandstones in comparison with the beach deposits are in good agreement with a sub-beach origin (Davies et al., 1971). Very clear information on the environment of deposition is to be found in the channel trends normal to the overall direction of sediment transport in the section considered. The only currents to flow parallel to the coast in a marine littoral environment are longshore currents. Offshore bars are to be expected in such an environment (van Straaten, 1959; McKee & Sterrett, 1961; Zenkovich, 1967). A large sand supply causes progradation of the offshore bar by deposition of gently seaward dipping laminae on the seaward side of the bar (McKee & Sterrett, 1961). Exposures not being sufficiently large, bars of this kind could not be detected. On the contrary, limited sand supply results in shoreward growth of the bar with steep shoreward dipping strata (McKee & Sterrett, 1961). Such bars are probably represented by the large-scale inclined laminations. As this sedimentary structure is found only locally, we may conclude that sand supply was usually fairly large.

Concluding we may say that subfacies Ic may represent sub-beach deposits. Deposition took place in an environment where sediment was constantly deposited and eroded by waves and longshore currents.

Subfacies Id, littoral-channel fills (Fig. 8). – 1. Description. These channel fills are always intercalated in littoral deposits. In a good exposure a channel is seen to be at least 30 m wide and 4 m deep. The trend of the channel is parallel to the general direction of sediment transport in the section considered.

The channels are mainly filled with sandstones which have matrix percentages of less than 10 %. Grain size is generally somewhat higher in the bottom of the fill than it is in the sediments just below. The sediments contain glauconite grains. The thicknesses of the sandstone beds decrease in upward direction from 1.5 m to 10 cm.

The sandstone beds show pronounced channelling and are generally discontinuous. Most beds display large and small-scale moderate to high-angle trough cross-stratification. Cross-stratification measurements show a unimodal distribution pattern. The ideal channel fill shows a sequence of sedimentary structures indicating decreasing current velocities (parallel lamination, large-scale and small-scale trough cross-stratification). Wave-generated beds may locally occur in the top of the fill.

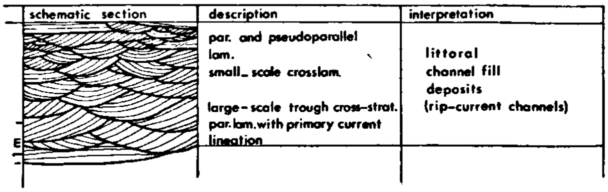

Fig. 8. Subfacies Id, littoral channel-fill deposits.

2. Interpretation. Channels belonging to subfacies Id were always cut into littoral deposits; this means that they were eroded by currents in the littoral environment. Such unidirectional currents normal to the shoreline could be interpreted as rip currents (Shepard et al., 1941; Zenkovich, 1967). The sizes of the channels (rip currents are known to be up to 40 m wide) and the waning character of the currents as is to be seen from the sedimentary structures, are in agreement with a rip current origin.

Additional remarks. – Eolian deposits are not detected with certainty, because of the absence of sections in which a good three-dimensional picture can be obtained, and are therefore not included in the description as a subfacies. Eolian deposits might well have existed on top of the beach deposits of the formations studied.

Facies group II – tidal deposits

The subfacies in this group are all very closely related to each other, and all kinds of transitions exist between them.

De Raaf & Boersma (1971) give a list of diagnostic features for tidal deposits. In diminishing order of importance these are:

a. Herring-bone structures.
b. The coexistence of sandy successions showing large-scale structures with sandstone-shale alternations showing small-scale structures indicating hydrodynamic conditions being highly variable in space and time.
c. With the exception of channel deposits, which as a whole show fining upwards, no clear sequential regularity is found. This is in contrast to fluvial (fining upwards) and deltaic deposits (coarsening upwards).
d. Discontinuity planes, often covered with some argillaceous sediment, are regularly found. This feature indicates repeatedly interrupted progradation of the mega-ripple followed by reactivation of sedimentation.
e. Flaser and lenticular bedding are very common in tidal deposits, but can also be found in other environments with highly fluctuating hydrodynamic conditions. When found in close relation with the above-mentioned characteristics, flaser and lenticular bedding are an indica-

tion of tidal conditions during deposition.
f. Bioturbation independent of lithology appears to be typical of tidal deposits.

Subfacies IIa, high-energy tidal-channel and tidal-inlet deposits (Fig. 10). – 1. Description. Channels belonging to this subfacies were usually cut into the other subfacies of facies group II. But channels cut into littoral deposits are also found. In both cases the channel fills grade upwards into sediments of the same facies group as the sediments below the channel fills. Incisions of up to 4 m can be measured in the field, but deeper ones most probably exist as well.

The channel fills consist of 75–90 % of sandstones, the remainder is formed by mudstones, silty shales and argillaceous siltstones. The sandstones are poorly to well sorted, have matrix percentages varying from less than 10 % to nearly 50 % and generally contain glauconite grains. The grain size of the sandstones varies from very fine to coarse sand and the grains are subangular to rounded. The thicknesses of the sandstone beds range from a few cm to 1.5 m, those of the sandy channel deposits range from about 1 m to over 10 m.

The sandstone beds are strongly channelling and all beds are discontinuous. The channel fills are generally fining upwards, but are always complex with frequently renewed erosion, and shaly layers are often found low in the channel fills. Fining upwards is seen in the size of sedimentary structures, passing from large-scale trough cross-stratification via small-scale trough and tabular cross-lamination to flaser bedding, as well as in grain size. The upper parts of channel fills in many cases belong to subfacies IIb. In most channel fills herring-bone structures are found. The measurements of cross-stratifications give a bimodal distribution pattern, though in nearly all cases one of the two directions is clearly dominant. Large and small-scale current ripples are frequent. The mega-foresets often show discontinuity planes and fan up locally in the manner described by de Raaf & Boersma (1971) (Fig. 9). Many channel fills contain large quantities of clay pebbles and clay flakes, which are not concentrated in the base of the fill but are scattered over the channel fill. Loadcasts are generally found at the interfaces of sandstones and the underlying finer-grained intercalations. Bioturbation is usually restricted to the finer-grained intercalations, but nowhere are high degrees of bioturbation found.

2. Interpretation. Comparison of the sedimentary structures of these sediments with those of the list by de Raaf & Boersma (1971) clearly shows that the sediments of this subfacies are tidal deposits. The sandy character of the sediments and the dominance of large-scale structures indicate deposition under high-energy conditions. The channels grouped in this subfacies represent large tidal channels. The fact that some of them are found intercalated in littoral deposits indicates that part of them represent tidal inlets.

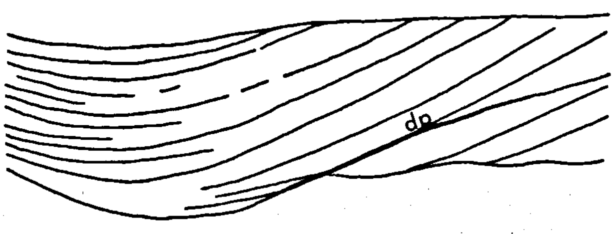

Fig. 9. Discontinuity plane (dp) and fanning up in tidal deposits.

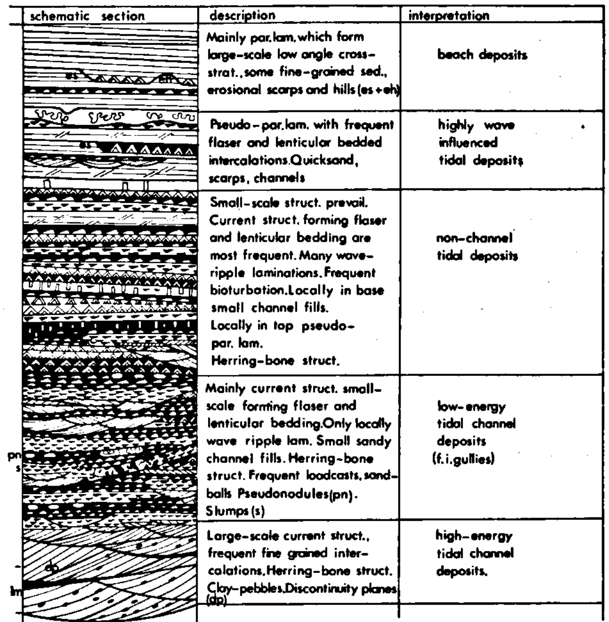

Fig. 10. Subfacies IIa, b, c and d, and Ib, tidal channel and tidal non-channel deposits and thin beach deposits surrounded by tidal deposits.

Subfacies IIb, low-energy tidal-channel deposits (Fig. 10). – 1. Description. Sediments belonging to this subfacies are found either as channel fills or forming the upper parts of channel fills as described in subfacies IIa. Subfacies IIb is always intercalated in the other subfacies of facies group II. The depth of incision of the channels is hard to determine, but incisions of over 2 m have been measured.

The percentage of sandstone beds in the total thickness of a channel fill is very variable (30–70 %). The sandstones are poorly to well sorted, have matrix percentages varying from 15–50 % and normally contain glauconite grains. The maximum grain size seldom exceeds medium sand and the grains are subangular to rounded. The remainder of the sediment consists of mudstones, silty shales and argillaceous siltstones. The thicknesses of the sandstone beds range from a few mm to 80 cm, those of the channel deposits from 0.5 m to about 5 m.

The majority of the sediment shows small-scale current laminations, that form flaser and lenticular bedding (Reineck & Wunderlich, 1968). Sandy successions of up to 1 m in thickness, showing large and small-scale moderate to high-angle trough and tabular cross-stratifications, are frequently intercalated. In the large as well as in the small-scale structures herring-bone structures are found. Large quantities of clay pebbles and clay flakes are frequently found. In the tops of the fills we often find wave-ripples. Loadcasts are very frequent in these sediments. Besides loadcasts more evolved forms such as loadcasts with lateral movement and sand-balls also occur. Even small slump levels are locally present. The intensity of bioturbation is generally low. The degree of bioturbation nowhere exceeds (2) on Reineck's (1963) scale of destratification (some 25 % destratified sediment).

2. Interpretation. The sedimentary structures found in this subfacies are indicative of a tidal origin of the deposits (compare list by de Raaf & Boersma). The structures are mainly small-scale, indicating deposition under relatively low-energy conditions. Subfacies IIb often gradually overlies deposits of high-energy tidal origin (subfacies IIa), in which case the subfacies represents the low-energy upper part of the fill of a large tidal channel. Subfacies IIb is also found as a channel fill itself. In this case it represents the (smaller) low-energy tidal channels as, e.g. gullies (van Straaten, 1954; Reineck, 1967). The slump levels were probably formed on small paleo-slopes (channel and gully flanks) as a result of water-saturated sediment sliding down due to its own weight. Wunderlich (1966) described similar sedimentary structures from the Devonian Nellenköpfchen Schichten (Koblenz, W. Germany), which he interpreted as tidal deposits.

Subfacies IIc, non-channel tidal deposits (Fig. 10). – 1. Description. Generally this subfacies is intercalated in the other subfacies of facies group II, but locally it is underlain by sub-beach, delta-slope or shelf deposits or it is overlain by sub-beach, fluvio-tidal or fluvial deposits.

The sandstone percentages of the sediment range from 25 % to 75 %. The sandstones have the same characteristics as those of subfacies IIb. The sandstone beds range in thickness from less than 1 mm to 50 cm. Lithological units, which as a whole belong to subfacies IIc, vary in thickness from less than 1 m to about 30 m.

Most of the sediment again shows small-scale current cross-laminations, which form flaser and lenticular bedding. Large-scale current structures are infrequent and both often show herring-bone structures. Current ripples occur on top of many sandstone beds. Clay pebbles and clay flakes are locally abundant. 5–50 % of the sediment shows parallel, pseudo-parallel or wave-ripple lamination. Parallel laminations of argillaceous sandstones with thin argillaceous laminae intercalated locally are frequently found. This kind of parallel lamination is not accompanied by primary current lineation. It closely resembles similar laminations described by Reineck (1967) and de Raaf & Boersma (1971). Loadcasts, with or without lateral movement, and sand-balls occur frequently. Bioturbation is very variable and ranges from 0 % to 100 % of destratified sediment (in the sense of Reineck, 1963). The degree of bioturbation is independent of lithology. Locally thick (up to several m), completely homogenized mudstones are intercalated in the flaser and lenticular bedded sediments. Bioturbation shows a large variety in forms.

2. Interpretation. The main part of the sediment shows tidal sedimentary structures (compare list by de Raaf & Boersma), but wave-generated structures are found as well. The structures are generally small-scale and the quantity of argillaceous admixture is high. This means deposition in a low-energy environment. Independent of lithology, the sediment is locally highly bioturbated, while other parts hardly show any bioturbate structures. This means that large variations existed in the rate of deposition. The above-described characteristics are very common in the sediments of tidal areas outside the channels, as described from Recent (van Straaten, 1954; Reineck, 1967; Dörjes et al., 1970) as well as from ancient (de Raaf & Boersma, 1971; Wunderlich, 1966) tidal deposits. The parallel laminations of argillaceous sandstones with thin intercalated argillaceous laminae are problematic and no satisfactory explanation of their formation can as yet be given (Reineck, 1967; de Raaf & Boersma, 1971).

Subfacies IId, strongly wave-influenced tidal deposits (Fig. 10). – 1. Description. Upward and downward gradual passages into subfacies IIc, into sub-beach and into beach deposits are particularly frequent.

About 60–90 % of the sediment is formed by sandstones, which show moderate to good sorting and have matrix percentages ranging from 10 % to 40 %. They generally contain glauconite grains. The maximum grain size seldom exceeds medium sand and the grains are subangular to (well) rounded. The thicknesses of the sandstone beds range from 1 mm to 80 cm, those of lithological units belonging entirely to subfacies IId range from 0.5 m to over 5 m.

The sedimentary structures shown are essentially the same as those of subfacies IIc, only the ratios are different. When undisturbed, 50–90 % of the sediment shows parallel, pseudo-parallel or wave-ripple lamination. The remainder of the sediment shows flaser and lenticular bedding. Bioturbation is often intense, some 10–30 % of the sediment shows destratification of 75–100 %. Clay pebbles are only sporadically found.

2. Interpretation. The frequency of wave-generated structures indicates high wave influence on the sediment. The frequently observed vertical gradations into littoral deposits suggest a position laterally adjacent to littoral deposits. Possible areas of origin are the transitional zones between the sub-beach or beach (subfacies Ib) and the tidal offshore zone or shoals in tidal areas, which were only weakly influenced by currents when being submerged by the flooding tide.

Additional remarks. – So far we have only mentioned tidal deposition without subdividing the depositional environment any further. Tidal deposition occurs on tidal flats, in estuaries, on tidal deltas associated with tidal inlets and in shelf seas. On tidal flats and estuaries extensive research has been carried out. On tidal deltas associated with tidal inlets and tidal shelf seas, on the contrary, little information is as yet available. In the present paper differentiation in the tidal environment can only be made where the vertical relations to other facies groups can be well established.

Facies group III – fluvial and fluvio-tidal deposits
Subfacies IIIa, fluvial-channel deposits (Fig. 11). – 1. Description. The channels were eroded into tidal or littoral deposits. These channels are gradually overlain by subfacies IIIc or by a discontinuity surface. The depth of incision of the channel is not measurable, but is presumed to be considerable (up to 30 m) on account of the great thickness of some channel-fill deposits.

The channel fills consist mainly of well-sorted sandstones, which usually contain less than 10 % of matrix. Grain size ranges from fine to (very) coarse sand and the grains are subangular to rounded. Intercalations of finer-grained sediments are only found locally in the uppermost parts of the fills. None of the sandstone beds contain glauconite grains. The thicknesses of the sandstone beds range from a few cm to 2.5 m, those of the channel-fill sequences from 4.5 m to 30 m.

The sandstone beds show pronounced channelling and most beds are discontinuous. Most channel fills show a fining upwards of the grain size, combined with a succession of sedimentary structures indicating decreasing current velocities. The following ideal sequence is found: in the lowermost part of the fill we find parallel lamination with primary current lineation. These are followed by large-scale trough cross-stratifications, grading upwards into small-scale trough and tabular cross-stratifications or locally even into sandstone-shale alternations with small-scale structures. Measurements of cross-stratifications give a unimodal distribution pattern for the sediments of the channel fill considered. Large clay pebbles and flakes (up to 10 cm long) occur in one instance near the bottom of the fill.

2. Interpretation. The size of the channels, the fact that they were eroded into tidal and beach deposits, the unimodality of cross-stratification measurements, the absence of glauconite grains and the discontinuities in sedimentation often found on top of the fills, together suggest a fluvial origin of the deposits. The sedimentary structures and the fining upwards can be compared with those of Recent and ancient fluvial channel deposits (Allen 1964, 1965c).

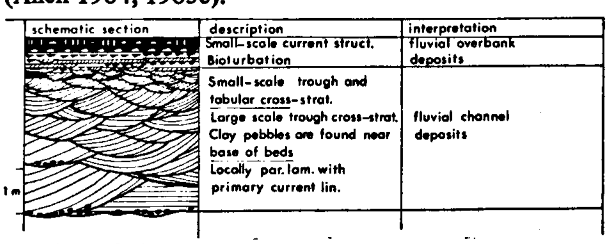

Fig. 11. Subfacies IIIa and IIIc, fluvial deposits.

Subfacies IIIb, fluvio-tidal deposits (Fig. 12). – 1. Description. This subfacies always gradually overlies tidal deposits and is in turn always overlain by a discontinuity surface.

Poorly to well-sorted sandstones constitute 50–80 % of the sediment. The sandstones have matrix percentages varying from 10–50 %. Quartz grains are subangular to rounded, and the grain size never exceeds that of coarse sand. The remainder of the sediment consists of silty shales, mudstones and argillaceous siltstones. Glauconite grains are absent. A number of tuff beds are found in these sediments. Some of these beds have a reddish colour and consist entirely of volcanic material, while others are a mixture of volcanic material and the usual sediment, having a grey colour. The thicknesses of the sandstone beds range from about 1 mm to 1.5 m, those of lithological units belonging entirely to subfacies IIIb range from 6 m to 17 m.

On the basis of sedimentary structures and lithology three types of deposits are distinguished:

a. Small sandy channel fills (up to 1 m in thickness), which show small and large-scale generally high-angle trough cross-stratification.

b. Large-scale (up to 1.5 m) inclined beddings occurring in sandstone beds with non-erosional bases. The megasets occur solitarily as well as in groups of up to four superimposed sets. The dip directions are remarkably constant in the section considered.

c. The majority of the sediments show flaser and lenticular bedding. In this type parallel and wave-ripple laminations are found. Current and wave ripples, loadcasts and locally strong bioturbation are frequently observed in these sediments. Measurements of cross-stratifications do not show any bipolarity. Herring-bone structures are not found.

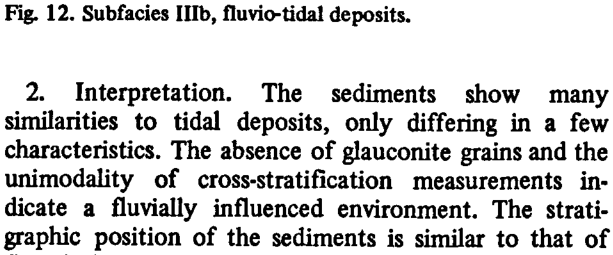

Fig. 12. Subfacies IIIb, fluvio-tidal deposits.

2. Interpretation. The sediments show many similarities to tidal deposits, only differing in a few characteristics. The absence of glauconite grains and the unimodality of cross-stratification measurements indicate a fluvially influenced environment. The stratigraphic position of the sediments is similar to that of fluvial channels, they also overlie tidal deposits and are also overlain by a discontinuity surface. The environment in which the sedimentary structures named are most likely to form is the fluvio-tidal environment. This environment is found in the area of the river mouths or estuaries where no real flood currents exist, but where

the water is stagnant during each high tide (Terwindt et al., 1963). Such hydrodynamic conditions will result in deposition of flaser and lenticular bedded sediments, the sandy ripples being formed during ebb-tide, the finer-grained layers during the stagnant period at high tide. The large-scale inclined beddings are best explained as large flat sand bars, which migrated downstream with every ebb-tide. Subaerial exposure occasionally occurred, as is demonstrated by the reddish tuff beds. These beds must have been deposited subaerially, because deposition under water cover would have resulted in reworking of the volcanic material and mixing with the fluvially supplied sediments.

Subfacies IIIc, fluvial-overbank deposits (Fig. 11). – 1. Description. This subfacies is only found in section 9, where it gradually overlies fluvial-channel deposits and is in turn erosionally overlain by fluvial-channel deposits.

The sediment consists of 60 % of very fine to medium grained sandstones and 40 % of silty shales, argillaceous siltstones and mudstones. The sandstones are poorly to well sorted and do not contain glauconite grains. The sediment locally has a reddish colour. The thicknesses of the sandstone beds range from about 1 mm to 20 cm. The unit belonging to this subfacies is 3.5 m thick.

The sediment frequently shows current cross-laminations of a unidirectional type. The small-scale current-ripple laminations sometimes form flaser and lenticular bedding. Bioturbation of the sediment is a common feature, though the degree of bioturbation is nowhere high.

2. Interpretation. The stratigraphic position between fluvial-channel deposits suggests deposition in an environment laterally adjacent to fluvial channels. The fine-grained lithology and the mainly small-scale unidirectional structures indicate an environment of low energy. The foregoing observations lead to the conclusion that subfacies IIIc probably represents fluvial overbank deposits. The sediments were probably deposited near the fluvial channel, where relatively high current velocities were still reached during floodings, sufficiently high to transport medium sand.

Facies group IV – pro-delta, delta-slope and shelf deposits.

Subfacies IVa, pro-delta and shelf deposits. – 1. Description. This subfacies consists mainly of mottled mudstones, silty shales and argillaceous siltstones. Shales and sandstones form only minor constituents of the sediment.

Sandy burrows up to several cm in diameter are found. Very small-scale current-ripple laminations occur locally. The majority of the sediments have a mottled appearance.

2. Interpretation. The fine-grained character and the mottled appearance of the sediments, together with their stratigraphic positions, suggest a pro-delta or shelf environment of deposition. Subfacies IVa is found in three different ways.

a. Subfacies IVa is found gradually underlying deposits, which will be interpreted as delta-slope deposits (subfacies IVb and IVc). The deposits belonging to subfacies IVa are relatively thin. In this case the subfacies should be interpreted as pro-delta deposits.

b. In the same stratigraphic position we also find relatively thick subfacies IVa. In this case the upper part of the subfacies will represent pro-delta deposits, while the lower part represents shelf deposits.

c. Subfacies IVa is also found underlain by nodular limestones and overlain by littoral deposits. The top of a unit belonging to the subfacies shows rapid coarsening upwards, sandstones becoming the most important component. The stratigraphic position between nodular limestones (shelf environment, van der Meer Mohr, 1969) and littoral deposits indicates a shelf environment of deposition.

Subfacies IVb, lower delta-slope deposits. – 1. Description. The same lithological components as described in subfacies IVa are found, the ratios are, however, different. The sandstone percentages vary from 10–75% and in general increase in upward direction. The sandstones have matrix percentages of over 20 %. The grains are subangular to rounded and the maximum grain size does not exceed 300 μ (medium sand). Part of the sediment contains glauconite grains. The beds observed in the field are a few cm to 15 cm thick. They are composed of several mm-thick sandy and shaly layers. The bedding partings are produced by shaly layers, but not all shaly layers bring about bedding partings. The individual sandstone layers range in thickness from less than 1 mm to a few cm.

The most characteristic sedimentary structure is parallel bedding; channelling beds are not found. The majority of the sandy layers show small-scale current-ripple laminations. Small-scale loadcasts and sand-balls are frequent. Slump levels are found locally in these sediments. Wave ripples and wave-ripple laminations are occasionally met with in the upper parts of lithological units belonging to subfacies IVb. The sediment is locally completely homogenized by bioturbate activity. The intensity of bioturbation decreases in upward direction.

2. Interpretation. The following features are of genetic importance:

a. Parallel bedding and the absence of channels indicate rather continuous sedimentation.

b. Sandstone percentage of the sediment increases in upward direction, while intensity of bioturbation decreases, which indicates a gradual increase in the rate of deposition.

c. Wave-generated beds occur only locally in the upper parts.

d. Slump levels indicate a paleo-slope.

e. Frequency of loadcasts and sand-balls indicates rapid deposition.

f. The fact that some shaly layers form bedding partings, while others fail to do so, suggests that some of the clayey layers were already compacted to some extent before deposition of the next bed. This means that periods of rapid deposition alternated with periods of a lower rate of deposition. This cyclicity was probably due to diversions of the courses of the supplying currents.

On the basis of the above-mentioned characteristics, and in comparison with Recent examples (Allen, 1965a; Moore, 1966; Fischer et al., 1969; Morgan, 1970), we may interpret subfacies IVb as delta-slope deposits. Wave-generated beds only occurring locally, we may conclude that deposition mainly took place below wave base on the lower part of the delta slope.

Subfacies IVc, upper delta-slope deposits. – 1. Description. Sandstones constitute 75–90 % of the sediment, the percentage increases in upward direction. The wave-generated beds often have matrix percentages lower than 10 %, the others are more argillaceous and contain up to 30 % of matrix. The grains are subangular to rounded and the maximum grain size does not exceed 400 μ (medium sand). The sediment partly contains glauconite grains. The thicknesses of the sandstone beds normally range from a few cm to 10 cm, but a few thicker beds (up to 40 cm and wave-generated) occur as well.

The same sedimentary structures are found as those of subfacies IVb. Bioturbation decreases even further and is locally absent. Parallel, pseudo-parallel and wave-ripple laminations are frequent. These structures increase in frequency in upward direction. In the uppermost parts of units belonging to subfacies IVc a number of channelling sandstone beds are found with high-angle cross-stratifications.

2. Interpretation. The analogy of the sedimentary structures of this subfacies with those of subfacies IVb permits of the conclusion that subfacies IVc also represents delta-slope deposits. The frequency of wave-generated beds, the fact that subfacies IVc always overlies subfacies IVb and the occurrence of channelling beds in the uppermost parts of subfacies IVc indicate that the sediments were deposited above wave base on the upper part of the delta slope.

Sequential units. – In contrast to the other facies groups, in which the subfacies do not show regularities in the manner in which they succeed each other, the subfacies of the facies group do show such regularities. Three types of sequential units can be distinguished:

a. Type A (Fig. 13). These units consist of thin pro-delta deposits, which are overlain by thick delta-slope deposits. Sequential units of this type may be up to 120 m thick. They gradually coarsen upwards and are regressive, representing prograding deltas or delta lobes. As the delta-slope deposits are always overlain by tidal deposits with a broad transitional zone in between, it is reasonable to suppose that the delta-top sediments are tidal deposits. This has an important consequence for the hydrodynamic conditions prevailing above the delta slope. Fresh river waters were already mixed with salt sea water on the delta top. Tidal currents brought the

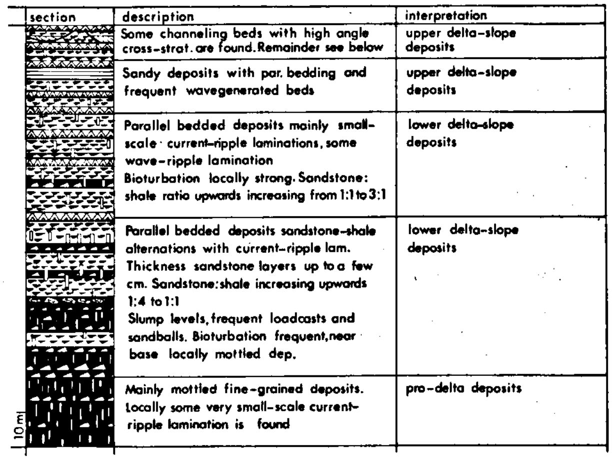

Fig. 13. Subfacies IVb, c and d, sequential unit A, delta-slope deposits.

sediment out to sea, forming tidal deltas from the tidal inlets outwards. In front of estuaries tidal currents are known to be strong down to great depths (Allen, 1965a).

b. Type B. These units are essentially the same as those of type A, with the exception of the base. In the lowermost part we find thick mottled deposits. These sequential units are thinner than those of type A (up to 100 m). They also represent prograding deltas or delta lobes. But relatively thick shelf and pro-delta deposits were laid down before the arrival of the delta itself.

c. Type C (Fig. 14). These units are considerably thinner than those of the other two groups (up to 35 m). They consist entirely of shelf deposits, which rapidly coarsen upwards in the uppermost parts of the units. Units of this type represent prograding linear coastlines.

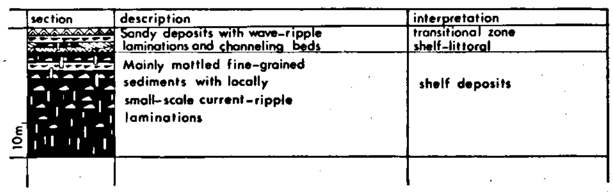

Fig. 14. Subfacies IV a, sequential unit C, shelf deposits.

Facies group V – lagoonal deposits

1. Description. In this facies group mudstones are brought together which cannot be classified in any of the other groups. These mudstones are always closely related to barrier-beach deposits. The mudstone successions range in thickness from a few m to 23 m.

The entire sediment is composed of mudstones, which have a low sand content. The quartz grains are subangular and the grain size never exceeds that of very fine sand. The sediments do not contain glauconite grains.

All the mudstones show bioturbate structures, only in a few cases are current-ripple laminations preserved.

2. Interpretation. The fine-grained character of the sediment and the high degree of bioturbation indicate a low-energy environment with a low rate of deposition.

The absence of glauconite grains indicates an environment protected from the open sea. The close relation to barrier-beach deposits suggests a laterally adjacent environment. Lagoonal deposits meet these conditions best.

DESCRIPTION OF THE SECTIONS (Fig. 15)

Lancara Formation

Griotte Member (van der Meer Mohr, 1969). – The member consists of red argillaceous nodular limestones and shales. These sediments contain glauconite, especially near the basal contact with the underlying Limestone Member. The shale content gradually increases from bottom to top. The nodular limestones are very fossiliferous: many Trilobites, Brachiopods and Carpoids are found.

Oville Formation

Member A. – This member consists entirely of shelf deposits. In the coarse-grained upper part flaser and lenticular bedding is locally found (section 7). Fragments of Trilobites, which frequently occur in this member, have generally been swept together into fossiliferous sandy beds.

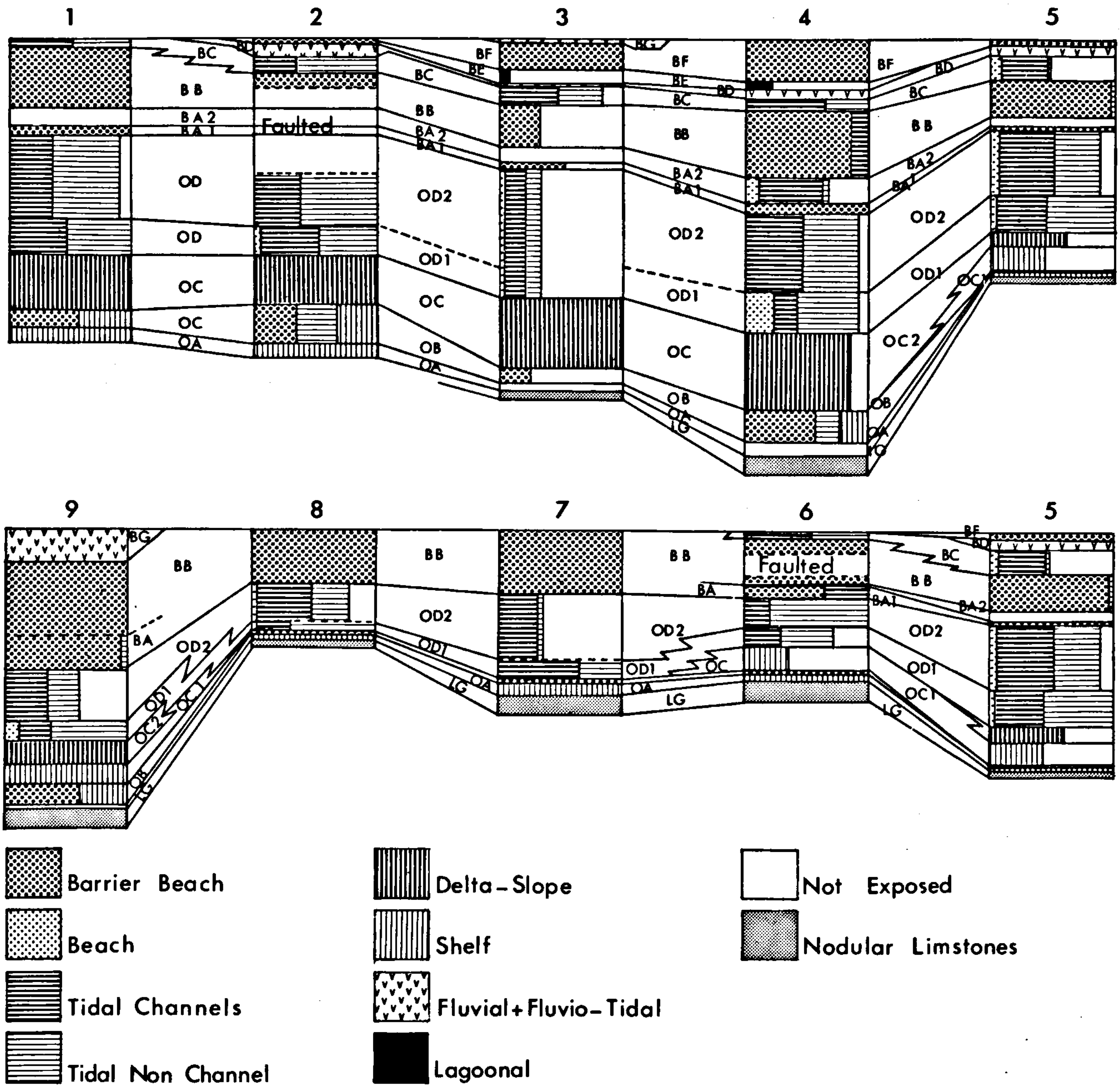

Fig. 15. Distribution of the various subfacies in the sections and correlation of the sections.
LG – Lancara Griotte Member.
O – Oville Formation.
B – Barrios Formation.

Member B. – The thin Members B of sections 5, 6, 7 and 8 consist entirely of littoral deposits, sub-beach deposits being most frequent. Members B of the other sections have a more complex composition. They consist of alternations of two or three littoral successions with one or two shelf successions. The upper part of the member in sections 2 and 4 is of tidal origin. The boundary between Members B and C is quite sharp, Member B grades into Member C within 1 or 2 m.

Member C. – This member can be subdivided into a lower and an upper part:
The lower part consists entirely of shelf and pro-delta deposits.
The upper part consists entirely of delta-slope deposits.

The transition from Member C to Member D is very gradual. A transitional zone of up to 30 m is found, in which the parallel bedding, typical of the delta-slope deposits, becomes vague and is replaced by more channelling beds with current cross-stratifications.

Member D. – Over 90 % of the member consists of tidal deposits. The remainder is formed by beach deposits (subfacies Ib). The latter are especially frequent, in most sections, in the lower part of the member. In some sections the boundary between the Oville and the Barrios Formations is rather sharp (sections 4 and 5) or even erosional (section 6), but in others (sections 8 and 9), where Member D shows a very sandy top, it is impossible to draw the boundary without subjectivity.

Barrios Formation

Member A. – This member consists of a lower littoral part and an upper mainly tidal part. The member is only distinguishable as a separate stratigraphic unit where it consists of these two parts (sections 1, 4, 5, 6). Because of the close resemblance of the lower part of Member A and Member B, these members cannot be distinguished from each other in sections 8 and 9 where probably only the lower part of Member A is present. An erosional surface is found low in lower part or at its base. As far as is visible in the field, Member A merges gradually into Member B.

Member B (Member AB in sections 7, 8 and 9). – This member is found in all sections. It generally consists entirely of littoral deposits, only in section 4 are tidal deposits intercalated. In sections 7, 8 and 9, where no differentiation is made into Members A and B, Member AB has a strongly channelling lower part, mainly consisting of sub-beach deposits. The contact between Member B and Member C is sharp or even erosional (section 4).

Member C. – This member consists entirely of tidal deposits. Member C is followed by Member D and is separated from the latter by a level of strong bioturbation. In section 2 the contact is erosional.

Member D. – In sections 3, 4 and 5 the member consists of fluvio-tidal deposits, in section 2 of fluvial channel deposits. The top of the member is in all cases slightly eroded and strongly bioturbated and overlain by a ferriferous concretionary level.

Member E. – This member is very poorly exposed, but it probably consists entirely of lagoonal deposits. The member is sharply or even erosionally (section 4) overlain by Member F.

Member F. – Member F consists entirely of littoral deposits.

Member G. – Member G is represented by fluvial deposits. In section 3 a fluvial-channel fill is found. In section 9 the member consists of three parts: the lower 37 m consist of fluvial-channel deposits, these are followed by 3.5 m of fluvial-overbank deposits. The uppermost 4.5 m are again fluvial-channel deposits.

Additional remarks. – The Barrios Formation ends in the various sections in different members, but is in all instances overlain by a ferriferous concretionary level. The top of the formation is always slightly eroded and strongly bioturbated. The formation ends in Member B in sections 7 and 8, in Member F in sections 2, 4, 5 and 6 and in Member G in sections 3 and 9. In sections 3, 4, 5 and 6 a second ferriferous concretionary level is exposed, which lies either upon Member C (section 6) or upon Member D (sections 3, 4 and 5).

Paleo-current analysis

Only Members A, B, C and D of the Barrios Formation, which, as will presently be outlined, together form a regressive sequence, supplied sufficiently numerous cross-stratification measurements to allow of conclusions. Cross-stratification data from the remainder of the succession studied suggest that the sediment dispersal pattern did not change very much during deposition of the formations studied.

Dispersal patterns in the facies groups (Fig. 16). – 1. Littoral deposits. De Vries Klein (1967) studied the dispersal patterns in several Recent environments. In beach deposits he found a bimodal dispersal pattern, with the modal classes 180 degrees apart. The littoral deposits studied show a trimodal dispersal pattern, two modal classes are opposite and the third is 90 degrees apart from these. According to de Vries Klein (1967), the two opposite modal classes represent seaward and shoreward dipping laminations and beds. The third modal class represents sedimentary structures formed by currents running parallel to the coast, i. e. longshore currents. One of the two opposite modal classes always strongly dominates the other.

2. Tidal deposits. Tidal deposits generally show a bimodal dispersal pattern, modal classes being 180 degrees apart, but on tidal flats quadrimodal patterns are also found, modal classes being 90 degrees apart (de Vries

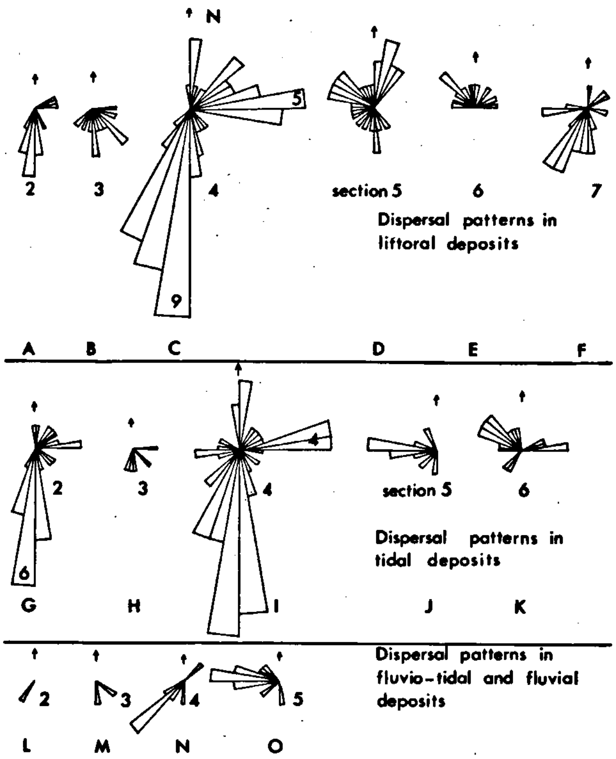

Fig. 16. Dispersal patterns in the facies groups.

Klein, 1967). One of the modal classes always dominates the others. One set of opposite modal classes, containing the largest modal class, represents the ebb- and flood-current directions. The other set represents tidal currents, which ran parallel to a local shoreline on the tidal flats.

3. Fluvial and fluvio-tidal deposits. The data are only few in number, but in general the pattern is unimodal. Divergent or even opposite inclinations are found. These are probably due to sufficiently strong flood currents, which might be expected locally in a fluvio-tidal environment.

Conclusions. – The fluvial and fluvio-tidal modal classes are always in about the same position as the largest modal classes of the tidal as well as of the littoral deposits. This implies that in the tidal deposits the ebb-current direction is dominant and that seaward dipping laminations and beds are far more frequent than shoreward dipping ones in littoral deposits. These features are indicative of a prograding coastline. From the compilation of the data above (Fig. 17), we see that this coastline was arc-shaped in a manner typical of a delta front.

ENVIRONMENTAL RECONSTRUCTION

Lancara Formation

Griotte Member. – The Lancara Formation of the studied area was described by van der Meer Mohr (1969). He stated: "It is likely that the Dolomite Member represents a sebkha-facies since it is mainly com-

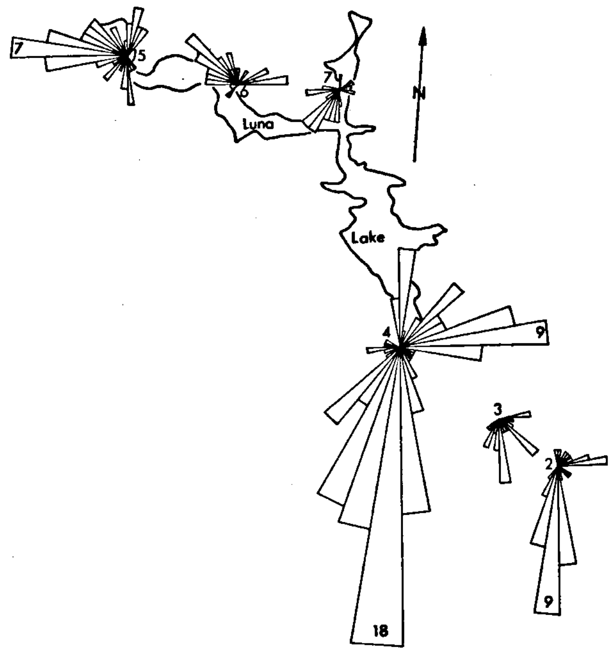

Fig. 17. Summation of the crossbedding measurements shown in Fig. 16. Note the arc shape typical of delta.

posed of finely to medium crystalline dolomites with intra-formational breccias and 'birdseye' structures. The limestones are predominantly intra-sparudites with stromatolites and oncolites. Locally the limestones have been subaerially exposed in Cambrian times, as can be concluded from karst-phenomena". The contact between the Griotte Member and the Limestone Member is sharp and even locally disconformable. The nodular limestones are of a type generally found in an open marine shelf carbonate-shale facies. From the above we may conclude that the Griotte Member lies transgressively upon the Limestone Member. The glauconitic level found at the base of the member marks the transgression. With the transgression the supply of siliciclastic material, that had stopped for a long period, was renewed and increased continuously during deposition of the Griotte Member.

Oville Formation

Member A. – The ever-increasing supply of siliciclastic material put an end to the deposition of carbonate material. The sediments of Member A were deposited in an open marine shelf environment, mainly below the reach of the waves. Only in the zone transitional to Member B are indications of wave and tidal activity found.

Member B. – The sandy parts are mainly sub-beach deposits, they have quite sharp boundaries with the intercalated shelf deposits. This probably indicates that the sandy parts represent influxes of sand into a shelf environment with mainly clayey deposition. In other words, small local transgressions and regressions succeeded each other. Similar features are shown by the sandstones of the Reynard facies of the Baggy Beds in Devon (Goldring, 1971). The shelf deposits of Member B frequently show wave-ripple laminations, they were therefore deposited in shallower water than those of Member A. As the littoral deposits of Member B are in most sections overlain by shelf or pro-delta deposits, renewed transgression must have occurred at the end of deposition of Member B. This transgression might have produced a reworking of at least part of the sediment. The thinness of the member in several sections is possibly due to reworking, in which case Member B is a transgressive sandstone body. The tidal deposits found in the uppermost parts of Member B in sections 2 and 4 possibly represent tidal-flats or they are also a result of reworking of the top of the member.

Member C. – After the transgression at the end of the deposition of Member B, shelf conditions again came into being. The filling up of this shelf sea was not uniform over the area studied.

a. In sections 1, 2, 3 and 4 a coarsening upward deltaic sequence was formed (see type A, p. 135).
b. In sections 5 and 9 shelf deposition occurred first, followed at a later stage of the filling up by a coarsening upward deltaic sequence (see type B, p. 135).
c. In section 6 only relatively thin shelf deposits are found, which are overlain by Member D (see type C, p. 135).
d. In sections 7 and 8 Member C is absent.

The above permits of several conclusions. The transgression did not affect the entire area to the same extent, the Aralla High acted as a relatively stable area. A delta complex expanded into the shelf sea. Shortly after the transgression the delta complex reached the area of sections 1, 2, 3 and 4 and only as the delta complex enlarged itself, it began to expand over the areas of sections 5 and 9. Over the Aralla High deltaic influence was never present.

Member D. – Because of the broad transitional zone between Members C and D, the sediments of Member D must represent the delta-top deposits. This means that the delta complex should be classified as a high-destructive tide-dominated delta complex (Fischer et al., 1969). Van Straaten (1960) described a hypothetical example: "The distributary mouths are usually widened and have estuarine properties. On their seaward ends one finds large shoals, which together form more or less distinct tidal deltas. Between the estuarine mouths there are often only relatively short beaches separated from each other by tidal inlets, which give access to tidal flat areas". In the lower part of Member D we find littoral deposits (subfacies Ib). The surrounding tidal deposits are in general more influenced by waves than the tidal deposits of the upper part of the member. In van Straaten's (1960) model the lower part represents the tidal deltas with the related small beaches, the upper part the estuaries and tidal flats behind the littoral zone, which gave some protection to wave attack but certainly was not a real delta front barrier-beach complex.

An indication of the presence of tidal deltas is probably given by the coarsening upward tidal sequences described below, which are found in several sections (1, 2, 3) low in Member D. These sequences are up to 16 m thick. In the ideal case they are composed as follows: they begin with highly bioturbated, very argillaceous sediments (shelf deposits), which grade upwards into argillaceous sediments with tidal as well as wave-generated structures (subfacies IIc). These in turn grade into sandier deposits, which do not show wave-generated structures (subfacies IIb). The uppermost part of the sequence is formed by sandy channelling deposits (subfacies IIa). The sequence shows clearly increasing energy of the depositing currents and shows many similarities to deltaic sequences (coarsening upwards, increasing energy of depositing currents, decreasing bioturbation). As a matter of fact, these tidal sequences are supposed to represent tidal delta deposits of a prograding tidal delta.

Member D of the Aralla High also shows a lower part with relatively high wave influence and an upper part with low wave influence. Here we may therefore also make the subdivision into tidal-delta deposits with thin beachy intercalations in the lower part and estuarine and tidal-flat deposits in the upper part.

Member D is overlain by Member A of the Barrios Formation, which, at least in the lower part, consists of littoral deposits. If the regression shown by Members C and D had continued, the tidal-flat and estuarine deposits would have been covered by fluvial deposits or have been followed by a period of non-deposition. The fact that they are overlain by littoral deposits means that the area was again transgressed.

Barrios Formation

Member A. – As the sea level rose relatively, the delta top was submerged and strongly reworked by waves, which had free access to the delta top. As the transgression continued, a transgressive sandstone body was formed (Member A, lower part). Locally an erosional surface is found in the basal part of the member. Below this surface we mainly find beach deposits and above mainly sub-beach deposits. Similar erosional surfaces are described by Fisher (1961) as the marine transgression plane. The sequence (beach deposits, erosional plane, sub-beach deposits) formed during the landward migration of a barrier bar. A large part of the barrier-beach deposits is eroded on the seaward side of the barrier bar as it migrated landwards. The barrier bars were probably formed by enlargement of part of the small beaches on the delta front as the intensity of wave attack increased (Hoyt, 1969). The littoral deposits grade upwards into tidal deposits (Member A upper part), which in general show the results of strong wave influence and are similar to those interpreted as tidal-delta deposits in the lower part of Member D of the Oville Formation. They will therefore also be interpreted as tidal-delta deposits. As these tidal-delta deposits are overlain by littoral deposits (Member B), the transgression must have died out at some time during the deposition of the upper part of Member A, and progression of the coast was renewed.

This transgression again did not affect the entire area to the same extent. In section 6 the tidal-delta deposits are very thin and in sections 7, 8 and 9 they are absent. In the latter sections the area remained entirely within the littoral zone, so that the transgression died out towards the N to NE.

Member B. – This member consists mainly of barrier-beach and sub-beach deposits, which alternate with one another. The thickness of the member is too large to be attributed to one single littoral cycle, which is about 40 m at the maximum (Potter, 1967). Member B represents the deposits of a coast that prograded by means of seaward aggradation of the beach. The sediment was supplied by longshore currents and waves through the beach and sub-beach zones and subsequently deposited in beach ridges. A similar process was described by Curray & Moore (1964) from the Costa de Nayarit (Mexico). Here aggradation occurs by submerged longshore bars being built up to the water surface during periods of low wave energy. The alternations of barrier-beach and sub-beach deposits might be explained by local transgressions and regressions, caused by variations in sand supply under conditions of constant rate of subsidence, as described from the Recent Rhône delta barrier-beach complex by Guilcher (1954). Locally tidal-channel deposits are intercalated in the littoral deposits. This means that the barrier-beach complex was locally crossed by tidal inlets.

Member C. – The tidal deposits of this member sharply or even erosionally overlie the barrier-beach complex and are in turn overlain by fluvio-tidal and fluvial deposits. Their vertical position between littoral and fluvial environments also implies a lateral transition of these tidal deposits into those of the two other environments. In other words, they represent tidal-flats and/or estuaries.

Member D. – The tidal deposits of Member C are overlain by fluvio-tidal deposits in sections 3, 4 and 5. The boundary between the two is formed by a level of strong bioturbation. This level also marks the end of the occurrence of glauconite grains in the sediment. The level was probably formed as the tidal flat area was filled up to the high water mark and little or no deposition took place. With continuing subsidence deposition was renewed and occurred in a fluvio-tidal environment. During deposition of the fluvio-tidal sediments periods of emergence occurred, as can be seen from tuff beds, which are not reworked. In section 2 the member is represented by a large fluvial channel, deeply eroded into the tidal flat and estuarine deposits of Member C. Member D is capped by a ferriferous concretionary bed, which marks a discontinuity in sedimentation. Non-deposition is also indicated by the slight erosion and strong bioturbation shown by the top of the member.

Member E. – After this period of non-deposition sedimentation was renewed, which means that the area was once more transgressed. The first deposits to form were the lagoonal deposits of Member E. They were formed behind a barrier-bar system (Member F), that was formed by an upward growth of the former delta front barrier-beach complex (Hoyt, 1969). The transgressing sea pushed this barrier-bar system landwards over the lagoonal deposits. In section 4 the marine transgression (Fisher, 1961) eroded all the beach deposits and part of the lagoonal deposits. In section 3 a few dm of beach deposits have been locally preserved at the base of Member F.

Member F. – This member is similar to Member B, we find alternations of sub-beach and barrier-beach deposits, which may be explained in a similar manner. Somewhere low in Member F the transgression died out and progradation of the coast was renewed by aggradation of new beach ridges to the existing beach. The sand for the formation of new beach ridges was supplied by waves and longshore currents from the mouths of fluvial distributaries. In sections 5 and 6 the member is very thin and directly overlies the ferriferous concretionary level. Here Member F represents a thin transgressive sandstone sheet; shortly after the transgression this area again emerged. In most sections Member F shows a slightly eroded and highly bioturbated top and is overlain by a ferriferous concretionary bed. These features indicate the long period of non-deposition between the Barrios and Formigoso Formations.

Member G. – In the sections studied two fluvial-channel fill complexes are found in the uppermost part of the Barrios Formation. They form the visible part of the fluvial distributary system, which crossed the coastal plain formed by the littoral deposits of Member F.

Sequences and their regional aspects in the area studied

Sequence I. – After the transgression at the beginning of the deposition of the Griotte Member of the Lancara Formation, shelf conditions came into being in the area studied. At a certain moment, probably during deposition of the Griotte Member, the rate of deposition became higher than that of subsidence and the shelf was partly filled up. At first carbonate deposition dominated, but with the approach of the coastline the supply of siliciclastic material increased and carbonate deposition slowly ceased. The Griotte Member and Members A and B of the Oville Formation form a regressive sequence, from shelf deposits formed below wave base, in the lower part of the sequence, to sub-beach and locally beach deposits in the uppermost part.

The prograding coastline was probably more or less linear and moved towards the S or SW. At the time of its maximum extension the coastline was situated somewhere in the area studied.

Sequence II (figs. 18, 19). – This sequence is formed by

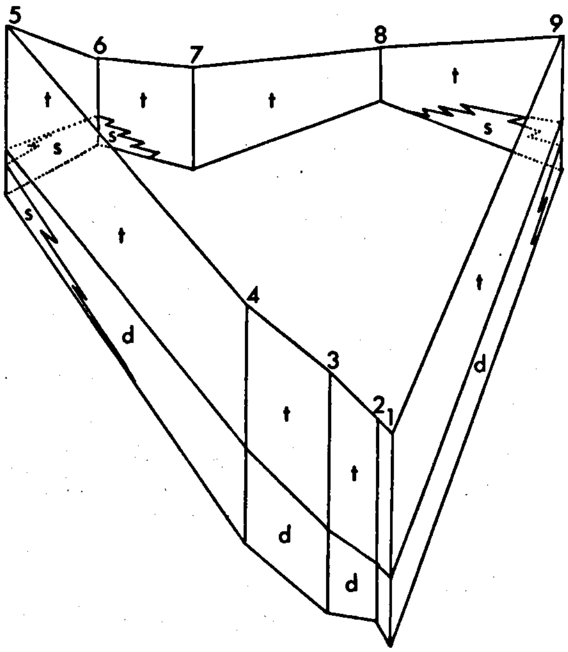

Fig. 18. Regional distribution of sequence II; t = tidal, d = delta-slope and prodelta, s = shelf.

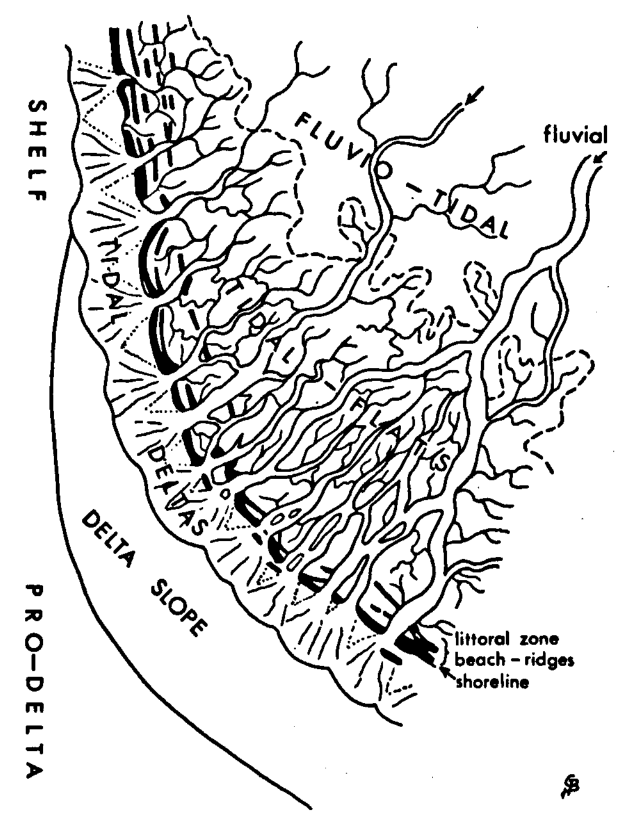

Fig. 19. Hypothetical map of the delta represented by sequence II. High-destructive tide-dominated delta.

Members C and D of the Oville Formation. After deposition of Member B the area was transgressed and part of Member B was reworked. Shelf conditions came into being in the area studied. After the transgression the rate of deposition quickly exceeded that of subsidence and the shelf sea was filled up. Three types of regressive sequences are found:

1. Deltaic sequence: thin pro-delta deposits, relatively thick delta-slope deposits, tidal-delta deposits with subordinate beach deposits, thick tidal-flat and estuarine deposits.
2. Composite sequence: The upper part of the sequence is identical to the deltaic sequence, but the lower part consists of thick very argillaceous mottled sediments.
3. Regressive linear coastline sequence: shelf deposits, which may be absent, tidal-delta deposits with subordinate beach deposits and thick tidal-flat and estuarine deposits.

A high-destructive tide-dominated delta complex (Fischer et al., 1969) expanded into a shelf sea. This delta complex was bordered on at least one side (the other is not exposed) by a regressive linear coastline with a tidal character. A Recent example of such tidal marginal areas of a delta is found on both sides of the Niger delta (Allen, 1965 a & b). The maximum depth of the shelf sea in the area studied probably ranges from 20 m (Aralla High) to over 100 m (section 4).

Sequence III (Figs. 20, 21). – The third transgression formed a transgressive sandstone sheet. The transgression progressed N to NW, in the S and SW sections the transgressive sandstone sheet is overlain by tidal-delta deposits, in the N sections the area was still in the littoral environment when the transgression died out. The thin transgressive sequence is overlain by a relatively thick regressive sequence, in which three types are distinguished:

1. Deltaic sequence: tidal-delta, littoral, tidal-flat and estuarine, fluvial or fluvio-tidal deposits, followed by a period of non-deposition. The littoral deposits were formed in a prograding delta-front barrier-beach complex, as they are described from several Recent deltas (Oomkens, 1967; Zenkovich, 1967; Fischer et al., 1969). With continuing subsidence the landward end of the barrier-beach system was lowered below sea level and tidal currents, which could enter through breaches in the barrier-beach system, formed tidal-flats on the landward side. As the delta complex progressed SW, the tidal-flat deposits were covered by fluvio-tidal and fluvial deposits. Still later the delta top emerged and was probably crossed by a few fluvial distributaries, which hardly eroded or deposited any sediment, but carried their load through the area towards the delta, further SW. The delta complex should be classified as a high-destructive wave and tide-controlled delta (Fischer et al., 1969).
2. Transitional sequence: tidal-delta, littoral and tidal-

flat deposits. This sequence was formed along the margins of the deltaic plane. The barrier-beach system was still covered by tidal-flat deposits, but emerged before the fluvial environment expanded into the area. Similar sequences, but not tidally influenced, tidal flats being replaced by lagoons, are often found in the Cretaceous of the U.S.A. (Masters, 1967; Campbell, 1971).

3. Coastal plain sequence: this sequence consists entirely of littoral deposits. It represents a prograding coastline that expanded by aggradation of new beach ridges against the older ones, forming a broad sandy coastal plain similar to those of the Costa de Nayarit (Curray & Moore, 1964) and the Tabasco Coast in Mexico (Psuty, 1965). This sequence was also followed by a period of emergence and non-deposition.

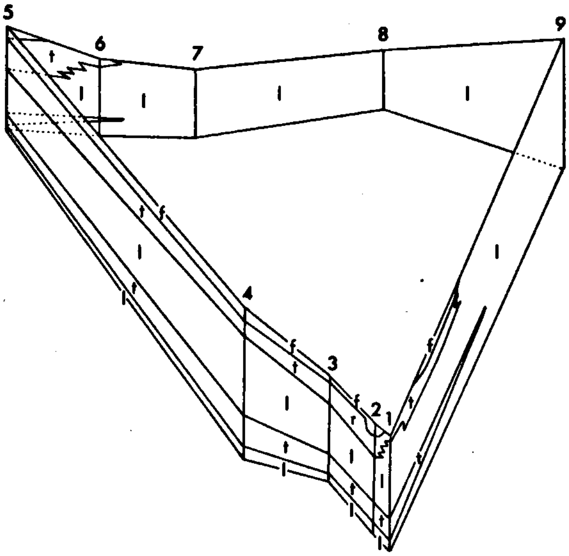

Fig. 20. Regional distribution of sequence III; l = littoral, t = tidal, f = fluvial and fluvio-tidal.

After the transgression died out, the river started building a new delta-complex into the extremely shallow sea (nowhere did the maximum depth exceed 30 m). This delta complex was of a different type (high-destructive wave- and tide-controlled) and had smaller dimensions than the underlying delta complex. The delta was bordered on both sides by a coastal plain consisting of beach ridges. The sediment was supplied by fluvial distributaries and was immediately redistributed by tidal currents over the tidal flats and estuaries. From there the bulk of the sediment was transported through the tidal inlets in the delta-front barrier-beach system to the open sea, where part was deposited in tidal deltas. But the majority of the sediment was picked up by longshore currents and waves, to be finally deposited in beach ridges. The fine-grained sediments were mainly deposited further SW, outside the area studied. The delta and the adjacent coastal plains probably prograded quickly, because the extremely shallow sea was easily filled up. The high rate of progradation is illustrated by the frequent occurrence of quicksand structures and the probably related loadcasts of sand into sand.

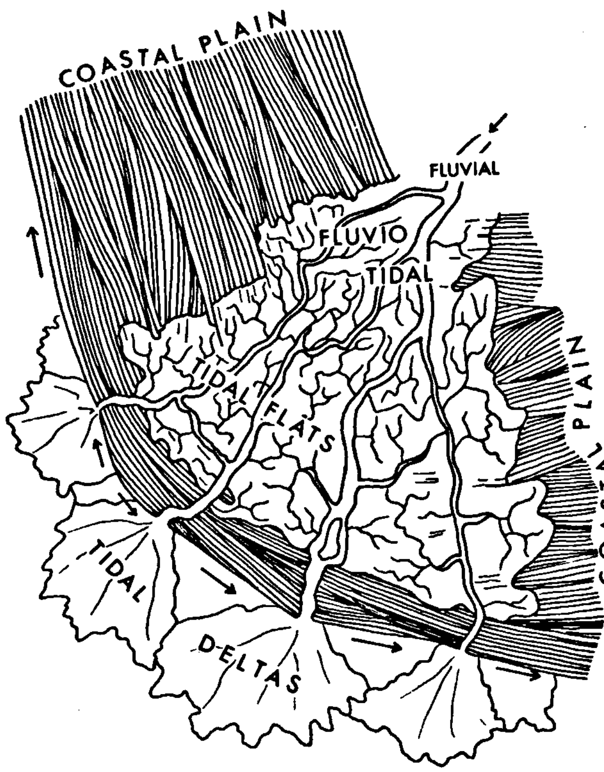

Fig. 21. Hypothetical map of delta represented by sequence III. High-destructive wave- and tide-controlled delta.

Section 9 is somewhat problematic, the barrier-beach deposits of Member B were eroded by a large fluvial channel. This fluvial channel might have eroded the tidal-flat deposits of Member C, but these might just as well never have been deposited. The fluvial channel itself is also difficult to correlate with other fluvial deposits. The channel might belong to the present delta as well as to the overlying one. We presume that the channel belongs to the youngest deposits of the Barrios Formation and that it represents one of the large fluvial distributaries of the youngest delta.

Sequence IV (Figs. 22, 23). – The fourth transgression, which was responsible for the deposition of this sequence, was of minor importance and only slightly affected the main part of the area. Only in sections 3 and 4 are relatively thick deposits found. Sections 1, 7, 8 and 9 remained emerged and in the other sections only thin transgressive sandstone sheets are found. After the transgression the entire area with the exception of the area of sections 3 and 4 quickly reemerged. In sections 3 and 4 sequence IV can be divided into a transgressive lower part (lagoonal, littoral deposits) and an upper regressive part (littoral, sometimes fluvial deposits, followed by a period of non-deposition). The transgression caused the delta-front barrier-beach system of the second delta to migrate inwards and a lagoon was formed behind it. The barrier-beach complex migrated inwards over the

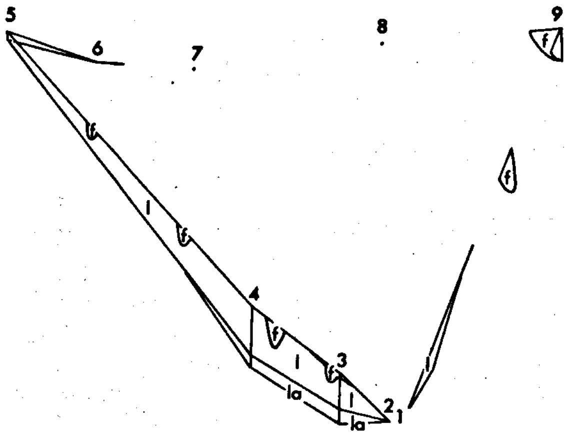

Fig. 22. Regional distribution of sequence IV; f = fluvial, l= littoral, la = lagoonal.

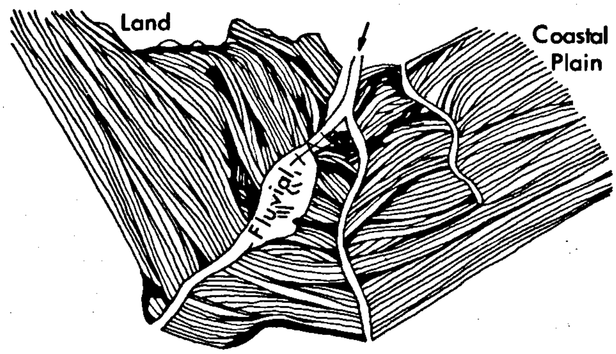

Fig. 23. Hypothetical map of delta represented by sequence IV. High-destructive wave-dominated delta.

lagoonal deposits. On its seaward side most or all of the barrier-beach deposits were eroded, sometimes even part of the lagoonal deposits. The transgression died out somewhere low in Member F and progradation of the coast was renewed by aggradation of beach ridges. As only littoral and fluvial deposits are found, the delta should be classified as a high-destructive wave-dominated delta (Fischer et al., 1969). Progradation occurred in an extremely shallow sea (not deeper than about 20 m) and was, as a consequence, rapid; quicksand structures and loadcasts of sand into sand are common occurrences.

A high-destructive wave-dominated delta of small dimensions expanded into an extremely shallow sea. The deltaic plain consisted of beach ridges, which were crossed by fluvial distributaries. On both sides of the deltaic plain areas of non-deposition, land areas, were found.

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