SEDIMENTOLOGY AND PETROGRAPHY OF THE MARADA FORMATION (MIOCENE), ~~SIRTE BASIN~~, LIBYA

By

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ABSTRACT

The Marada Formation, Middle Miocene, Libya, is a transgressive succession of interbedded limestone and shale, which changes southwards and at the base of the sequence into sands, calcareous sandstone, and shale of fluviatile and fluvio-marine origin. The aim of this thesis was to attempt a resolution of the controversy over the interpretation of the limestone and shale facies which were previously argued by Selley (1966) and Doust (1968).

Sedimentological analysis, based on detailed local sections of closely spaced vertical facies profiles, revealed that the limestones were deposited under open marine (wackestone) barrier bars and beaches (grainstone), tidal inlet and delta (sandy grainstone), and tidal flat (dolomitic mudstone) conditions. Periodic influxes of terrigenous sediments have produced shale in the lagoons behind barriers, and formed submarine delta marls in the open marine environment. Isopach facies maps and regional facies cross-sections provide the bases for interpretation that the distribution and growth of the facies was controlled by climatic conditions, the rise of the sea level, and Pre-Marada topography.

Petrographic studies provide detailed evidence of the origin and diagenesis of the limestones. Algal boring, decay,

and skeletal grain-size reduction by burrowing organisms played an important role in providing some of the fine grained carbonate detritus in the wackestones. Coralline red algal mats aided sediment trapping under subtidal conditions.

Porous grainstones were cemented by an early intergranular acicular cement, followed by a secondary calcite cement of bladed habit. Cementation was locally interrupted by intergranular geopetal sedimentation. Regionally bored surfaces in the wackestone, and encrustation of the grainstone bodies by corals, coralline algae and oysters indicate syndepositional cementation. Some bodies exhibit evidence of supratidal beach rock diagenesis (dolomitization of intergranular cement), and subaerial exposure (solution cavities, dissolved oyster shell beds, etc.).

Dolomitization of intertidal and supratidal sediments resulted from evaporation of sea water and percolation of magnesium rich brines at the sediment interface. During the regression of the Marada sea, sabkha conditions produced evaporite minerals (gypsum pseudomorphs). Solution of evaporites by meteoric water produced dolomite collapse breccias, and induced dedolomitization of the fine grained matrix and clasts of the breccia.

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"The various deposits of the same facies areas and similarly the sum of rocks of different facies areas are formed beside each other in space, though in cross-section we see them lying on top of each other. As with biotopes, it is a basic statement of far-reaching significance that only those facies and facies areas can be superimposed primarily which can be observed beside each other at the present time."

Johannes Walther (1860-1937)

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CHAPTER 1

INTRODUCTION

1.1 Geographic Location (Plate 1-1, 1-2)

The Marada Formation is exposed in an area about 11,000 sq.km. around Marada Oasis ($19^{o}15'$ x $29^{o}10'$), which lies 120 Km south of Mersa el Brega oil terminal (Plate 1.1). Several oil fields are located in and around the Marada area; these are Zelten, Raguba, Lahib, Zuggut, Jebel and Waha oil fields, and others.

The Miocene rocks of the Marada Formation are lying horizontally on the Oligocene Greir Bu Huscise Formation, which is exposed in a north-south escarpment to the west of the area (Plate 1.2). The Marada Formation is exposed along a step-like scarp of plateaus and mesas, about 150 metres high. All of the topographic features are flat topped. The Marada Formation is well exposed and beds show no indication of structural deformation. Beds appear gently inclined northward following the original regional dip (Selley, 1966; Doust, 1968). These scarps are cut by wadis and washouts. At the base of Dor Marada-Dor Zuggut escarpment, evaporation pans and sabkhas are developed. During occasional flash floods, water and sediments accumulate in the sabkhas. Springs and water pools are also found whenever the water table comes close to the surface.

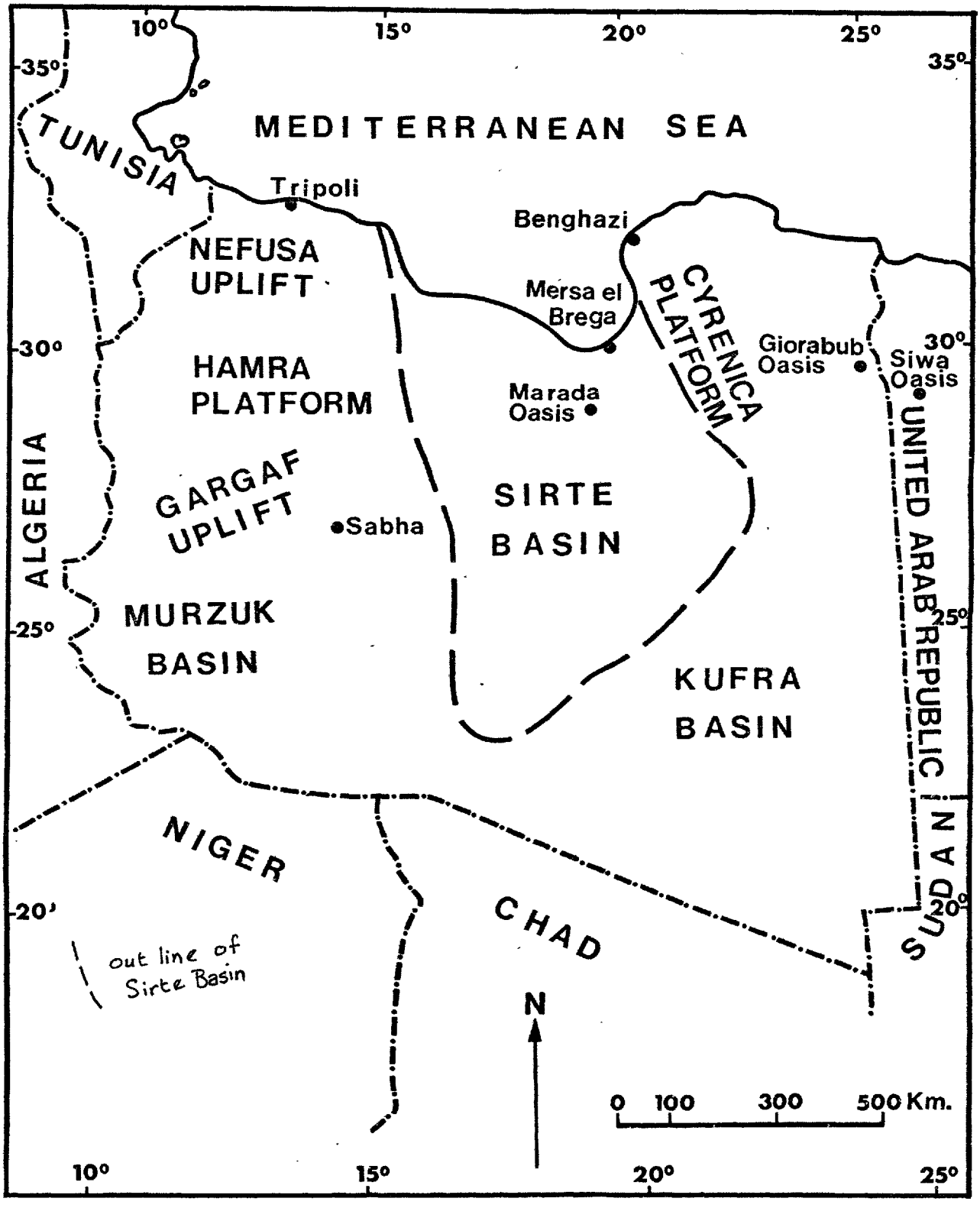


Plate 1-1 MAP OF THE LIBYAN ARAB REPUBLIC

19°
19°30′
20°
N
29°
28°30′
M8
M7
GARET GEHENNEN
GARET-EL-LUBEN
GARET
MARADA OASIS
RAGUBA AREA
M1
DOR MARADA AREA
M4
M3
M2
Oilfields
D5 4 3 2 1
DOR ZUGGUT AREA
D7
6
D9
D10
D8
M6
JABEL AUF
M5
Camp
Oilfield
JABEL-EL-RAGUBA
GARET-EL-CRA
C1 C9 C3
C8
Zelten Oilfields Camp
C2
C4
C5
C7
C6
CENTRAL JABELS AREA
J4
J5
J6
J1
J7
Ora Oilfield
JABEL ZELTEN AREA (Oilfield)
J8
J3
J2
Camp
Escarpment
Paved Roads
Dirt Roads
0 10 20 30 40 50Km.

PLATE 1-2.

LOCATION MAP OF MARADA AREA

1.2 Regional Stratigraphy of the Miocene

Rocks of Middle Miocene age are found in Tunisia, Libya and Egypt. In general this was a time of renewed transgression along the north-eastern coast of the Mediterranean (Barr and Walker, 1973). In Libya, the Miocene was also a time of transgression following the brief emergence at the end of the Oligocene. The junction between the Oligocene and the Middle Miocene appears to be erosional. Locally, fossilized tree trunks mark the pre-Miocene land surface at the margin of Sirte Basin (Selley, 1966). The Oligocene-Miocene boundary may have been uninterrupted in the deeper parts of the basin (Barr and Walker, 1973). The Sirte Basin consists of differentially subsiding horsts and grabens. In the deeper and rapidly subsiding troughs shale reaches great thickness, whilst in the shallower horsts block, shallow water carbonate facies, including coralline deposits, usually prevail (Berggren, 1969).

In northeastern Libya, deposits of shallow water carbonates containing the diagnostic foraminifer Boralis melo cover most of the Cyrenaica platform. These limestones which are assigned to the Regima formation in Libya, extend across the western desert of Egypt as Marmarica limestone. Southeast of the Cyrenaica platform along the Libyan-Egyptian border, these limestones are assigned to the Al-Jaghbub Formation in Libya.

Billini (1969) recorded a thickness of 115 metres for the Al-Jaghbub Formation in its type area (near Al-Jaghbub oasis); similar thickness is reported for the Middle Miocene rocks across the border in the Siwa depression, western desert of Egypt (Gindy and El-Askary, 1969). These authors suggested that the Middle Miocene rocks in this area belong to the Marmarica and Moghra Formations; the latter formation was previously thought to be of Lower Miocene age (Said, 1962). They also indicated that the Middle Miocene in this area are exposed in a major geomorphic arc of the Jaghbub-Siwa-Qattara depressions of the northwestern desert; they also claim that these depressions are a result of post-Middle Miocene tectonics which were followed by water erosion.

The Upper Miocene was a time of regression in Libya and Egypt. Continental deposits of Pliocene and Quaternary age are found covering a large area extending from Al-Jaghbub to a point north of Qasr-as-Sahabi, northeast of the Marada area (Barr and Walker, 1973). The Upper Miocene is also absent in the western desert of Egypt (Gindy and El-Askary, 1969); Said (in Billini, 1969, p. 181) stated that the marine carbonates of the Pliocene age unconformably overlies the Middle Miocene Marmarica limestone.

1.3 Previous Work

The scientific expedition to El-Kufra in 1931, led by Professor Desio, passed through the Marada area. Desio (1935) gave the name Marada series to the succession of Dor Marada. Desio's type section of Garet el Mazzala, near Marada Oasis, is about 80 metres thick and comprises mainly shales interbedded with sands and limestones; he recorded fauna of marine invertebrates and fish. Colley (1963) summarized the regional geological framework of Libya; he indicated that Cyrenaica platform is characterized by shelf limestones, sandy limestones and marls, and that the Sirte Basin is characterized by a rapid landward transition from basal shales into a mixed carbonate and clastic fluviomarine facies.

In 1959 Professor W.D. Gill examined the Marada area and recommended it as an ideal area for sedimentological research. In 1963 Dr. R.C. Selley commenced a series of visits to study the sedimentological history of the area (Selley, 1966, 1967, 1969). Table 1.1 summarizes his findings.

Selley (1971) suggested that the position of the Marada estuarine channels is controlled by syndepositional subsidence along NNE trending synclinal axes, which were formed as a result of negative movement along the pre-Miocene Palaeohighs (Selley, 1973, p. 130); he also claimed that the carbonate calcarenites were deposited on an east-west trending

Facies	Lithology	Supposed Environment
1. Detrital limestones	Bioclastic calcarenites, rare calcirudites, and calcilutites.	Off-shore bars and barrier beaches
2. Laminated shales	Calcareous shales and calcilutites and oyster reefs	Lagoonal
3. Interlaminated shales and sandstone	Shales and silts; rare fine sands.	Intertidal
4. Cross-bedded sands and shales	Coarse sands silts and shales	Fluviatile
5. Calcareous sandstone channels	Coarse calcareous sandstones and sandy limestones	Estuarine channels

TABLE 1.1 Summary of the Marada Sedimentary Facies as recognised by Selley (1966, 1969).

anticline passing through the Central Jebel area (Selley, 1971); furthermore, he suggested that the folding took place before the deposition of the Middle Miocene rocks.

In 1965 Dr. H. Doust commenced a study of the Paleo-ecology of the Marada invertebrate and trace fossils. Table 1.2 summarizes his interpretation of the lithologic types of the Marada Formation (Doust, 1968, p. 189-216). Both Selley (1969) and Desio (1935) gave the rocks formation status, but Doust thought group status was suitable.

Rock type	Lithology	Environment
Limestones	Calcisiltite and calcilutite.	Marine, water depth 10-40 m.
	Calcarenites, horizontally bedded and cross-bedded.	Marine, depth down to 30 m, probably channels
	Mixed calcarenites and calcisiltites.	Open bay and lagoon. Water depth 5-40 m.
Shales	Calcareous laminated shale, sandy gypsyferous	Fully marine, bay and lagoonal.
Calca. clastic deposits	Cross-bedded calcareous sands; silts and shales; interlaminated sand silt and shale.	Intertidal, subtidal and channel deposits.
Mixed clastics & carbonates	Calcareous SS and sandy LS, calcareous silt and interlaminated shales and sandstones, calcareous SS channels	Intertidal and estuarine channels.
Unconsolidated deposits	Cross-bedded sands and silty shale.	Fluviatile.

TABLE 1.2 Summary of the Marada sedimentary facies as recognised by Doust (1968).

1.3.1 Age and Palaeoclimate

Dating of the Marada Formation by previous investigators (Desio, 1935; Selley, 1969; Doust, 1968; Savage and White, 1965; Savage and Hamilton, 1973) has been fairly consistent. The Marada Formation rests on the Grier Bu Hascise Formation which contains Nummulites intermedius fitcheli which is characteristic of the Rupelian age, Oligocene of North African sequence (Desio, 1935; Savage and Hamilton, 1973). The age estimates from the vertebrate mammals fauna found in the fluviatile sands of

Jebel Zelten have suggested early Burdigalian age (Savage and White, 1965; Savage and Hamilton, 1973). The shelly fauna found in the more marine facies of Garet el Mazzala indicated Burdigalian-Helvetian in age, whilst those in Jebel Zelten indicate earlier age of Aquitanian-Burdigalian (Desio, 1935). The limestone facies of Dor Zuggut contain Boralis melo and Boralis melo Curdica (Selley, 1966, 1969; Savage and Hamilton, 1973), the latter being characteristic of Burdigalian age in North Africa and the Middle East (Said, 1962; Barr and Walker, 1973).

After studying the palaeoecology of the invertebrate fauna of the Marada Formation, Doust (1969) envisaged climatic conditions closely related to the tropical Atlantic. Principi (1932) concluded that the Miocene climate indicated by fossil trees was tropical, and Desio (1935) stated that the climate of the Marada Formation was uniformly hot and humid, but with periods of relative drought, the characteristic climate of the Savannah. Terrestrial and aquatic vertebrates fauna associated with the fluviatile and fluviomarine facies suggest a forested belt along the river and savannah in the hinterland (Savage and Hamilton, 1973).

1.4 Aims and Methods of Approach

The aim of this thesis was to study the limestone/shale succession of the Marada Formation in order to attempt a resolution of the controversy over the interpretation of the limestone and shale facies which were investigated by Selley (1966, 1969) and Doust (1968). Tables 1.1 and 1.2 show that Doust's interpretation of the Marada terrigenous dominated facies was in general agreement with those presented by Selley (cit. op.). However, Doust (in Selley, 1969, p. 453) disagrees with Selley on the interpretation of the limestones and shales, whilst Selley interpreted all the limestones as having been formed as offshore barrier bars and beaches, Doust (1968) thought that they were deposited under a deeper marine condition and possibly ~~by~~ in channels. Also, as Selley (1969) regarded all the laminated shale facies (associated with the limestones) as of lagoonal origin, Doust suggests that these shales were deposited at least partially under marine conditions. Doust (in Selley, 1969, p. 453) reached this conclusion because; "(i) most fossils found in the limestones indicate water depth in the order of 30-40 metres, (ii) cross bedded units were rather rare (about 13% of the total), (iii) many limestones were too ill-sorted to have been lain down under high energy conditions, only 44% of the units were true calcarenites, while 56% were ill-sorted silty calcarenites or calcisiltites". Finally, he indicated that about 30% of the

shale units contain marine fauna.

To resolve the controversy a two-fold approach was used in the study of the limestone/shale succession of the Marada Formation; (A) Sedimentologic, and (B) Petrographic.

A) An actualistic method of interpretation based on characteristic sedimentary sequences is indicated in Walther's law of the succession of facies (Middleton, 1973). Johannes Walther (1893-1894) was the first to recognize the fact that facies and facies areas which are observed beside each other at the present time can be superimposed in a stratigraphic sequence. The law represents three important aspects in sedimentology (Middleton, 1973); (a) it represents the first definition of uniformitarianism, or as Walther called it, "ontology", (b) it is actualistic, that the vertical sequence of superimposed facies is a reflection of the sedimentary environments at the time of deposition, and (c) the law is non-reversible, so that it does not state that the vertical sequence always reproduces the horizontal sequence, but "only those facies .... can be superimposed...." which can be seen developing side by side.

Although the actualistic interpretation method has been discussed in a number of publications (e.g. Masters, 1967; Blatt et al, 1972, p. 185-214; Yapaudjian, 1972) yet its application in the field presents some problems for geologists, who consider interpretive analyses are premature. However,

construction of a regional facies cross-section based on detailed vertical facies profiles and small scale cross-sections has aided interpretation of the lateral and vertical facies relationship of the Marada Formation. Accurate interpretation of the various sedimentary facies has helped the construction of regional facies isopach maps, which have been used to interpret the factors controlling sedimentation.

B) The study of the detailed textural and diagenetic fabric of the limestones by means of petrography have aided accurate identification of the facies. The syn- and post-depositional diagenetic changes in the limestones provided a valuable information on the sedimentary and diagenetic environmental events in the history of a given lithofacies (e.g. the difference between submarine and subaerial diagenesis of the grainstone facies).

It is the author's opinion that the combined actualistic sedimentologic (Walther's law) and petrographic approach as presented in this thesis is a realistic means of studying the limestone/shale succession of the Marada Formation. This opinion may also hold true in the study of any other carbonate/clastic; carbonate/evaporite; and/or clastic sedimentary successions.

1.5 Methods of Study

Sections of the Marada Strata were measured by 1.5 metre Jacob's staff and Abney level; for the purpose of this study stratigraphic sections were measured, and sampled with special emphasis on the limestones. These sections are (Plate 1.2):

In Dor Zuggut area: ten sections are measured, their number starting with the letter D (e.g. D1, D2, D3, ... etc.).

In Dor Marada area; four sections are measured and are numbered M1, M2. M3, M4.

Area west of Dor Marada and Central Jebels; four sections are measured and numbered M5, M6, M7, M8.

Central Jebels area; nine sections numbered C1 to C9.

Jebel Zelten area; eight sections numbered J1 to J8.

The sedimentological details of these sections are illustrated in enclosures nos. 1, 2, 3.

The study of the depositional facies generally proceeded with section measurements, but some type localities were revisited for detailed studies. Environments of deposition were determined first in areas where the relations were reasonably clear. In this study, multiple criteria have been

used for the recognition of environments (Potter, 1967; Selley, 1973). These criteria include sedimentary structures, lithology, geometric relationship of rock units, character of biological content and trace fossils (using Doust, 1968), and apparent diagenetic features; or other criteria were noted and evaluated with respect to criteria in the literature. As field studies progressed, several categories of depositional facies and sub-facies were established, tested and modified when necessary, and retested until a satisfactory and reasonably consistent scheme of facies and broad facies associations of the strata was established.

Well exposed facies type sections were thoroughly examined, and detailed closely spaced (50 to 100 metres apart) subsections were measured in order to obtain a clear picture of the various facies relationships. Samples were collected wherever there is any apparent change in the sedimentary or diagenetic festures of the rocks.

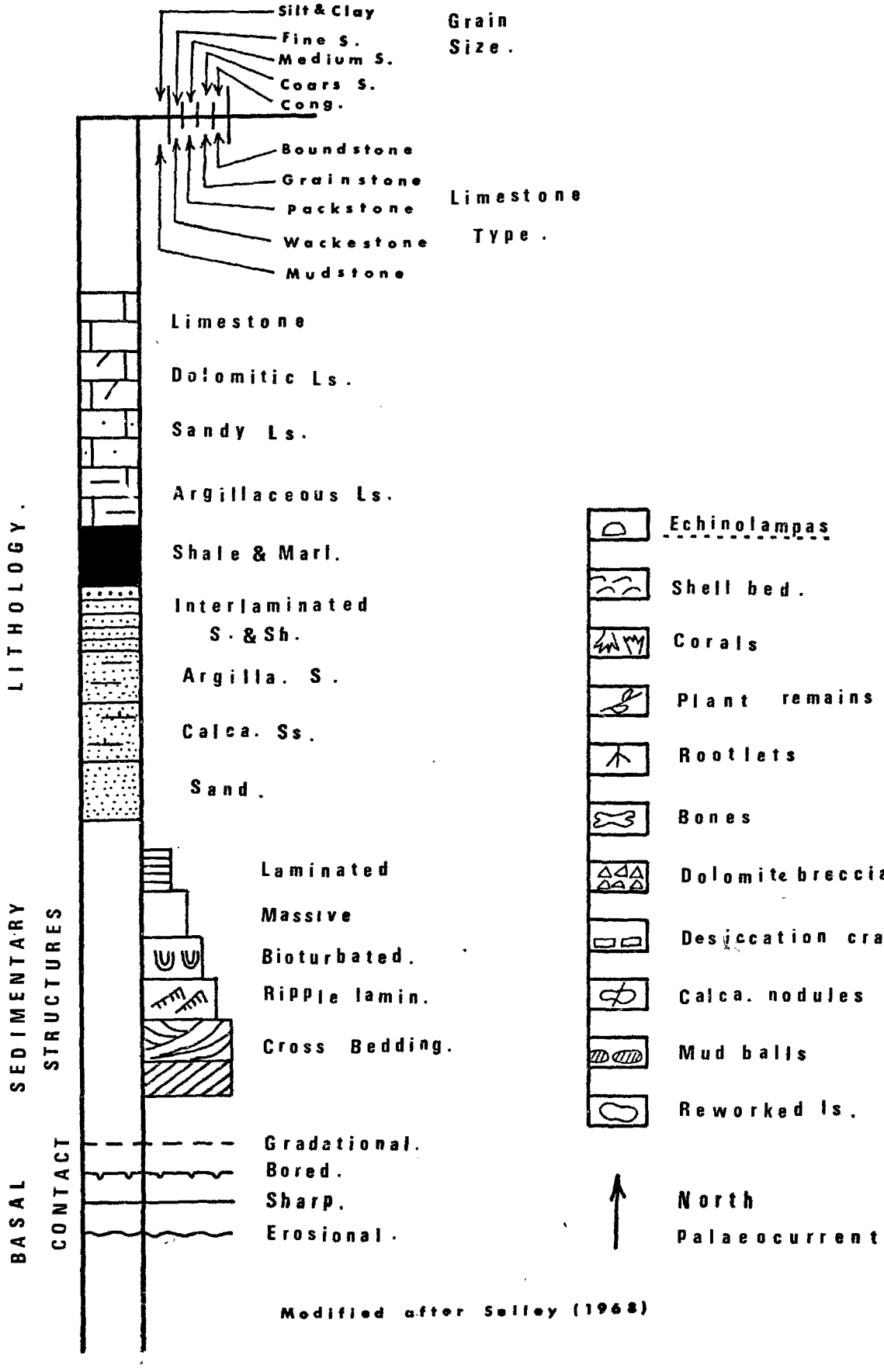
A total of 400 rock samples were collected (mostly limestones), and approximately 350 measurements of the azimuth of dipping cross bedding were made to determine the general palaeo-current pattern in the various sedimentary facies. Rock colours were noted by comparison with G.S.A. rock colour chart (Goddard, 1963) and bedding terminology broadly follows recommendations of MacKee and Weir (1953).

Detailed laboratory study of samples was carried out with 281 (75 x 37 mm) thin sections. Due to the lightly cemented nature of the rocks, samples were vacuum impregnated in plastic resin. The resin of 103 of the limestone samples was mixed with malachite green organic dye; this technique proved useful for the identification of the organic matter in thin sections. Colourless resin was used for the rest of the thin sections, of which one-third of their areas were left uncovered and used for Alizarine Red. S. staining.

The limestones are classified into boundstone, grainstone, packstone, wackestone and mudstone according to Dunham (1962). Terrigenous sediments, however, are generally classified as conglomerate, sands, silts and shales. Transitional facies between terrigenous and carbonates proved to be problematic especially when rocks contain apparently equal amounts of carbonate and terrigenous material of various size fractions. Terms like calcareous sandstones, sandy grainstone and sandy calcareous shales are used. It is recognized that this classification is qualitative rather than quantitative, and often field rock names were later modified after studying the petrography of these rocks.

The sedimentological data is plotted using a modification of the method described by Selley (1968, Fig. 2). Stratigraphic sections consist of columns showing rock type, to the

Plate 1-3 KEY OF SYMBOLS.



Modified after Selley (1968)

side of which is added a vertical histogram of grain size in the case of terrigenous units, and Dunham's classification (1962) in the case of carbonate-dominated units (Plate 1.3).

1.6 Sedimentary Facies of the Marada Formation

Broadly speaking, the limestone/shale succession of the Marada Formation changes southwards and at the base of the succession into sands and shales, calcareous sandstone channels, and interlaminated shale and sand facies; which were deposited under fluviatile, estuarine, and intertidal conditions (Selley, 1966; Doust, 1968). The limestone/shale succession is divided, almost at the middle, by a regional marker horizon of Echinolampas Sp. The two overlapping sequences are from the base to top: (a) interbedded shale and cross-bedded limestone units, (b) interbedded marl and massive limestone units.

The first sequence consists of interbedded units of the following facies:

1) Laminated shale.
2) Cross-bedded sandy grainstone.
3) Cross-bedded grainstone.
4) Dolomitic mudstone.

The latter facies (4) is exposed only at the northern sections of the Marada Formation at the top of the sequence.

The second sequence consists of interbedded units of:

1) Wackestone facies.
2) Marl facies.
3) Dolomitic mudstone facies.

The latter facies is exposed in sheets at the base and top of the sequence, in the southern sections of the Marada Formation. Table 1.3 summarizes the general characteristics of these facies.

Accordingly the first five chapters of this thesis discuss the following topics:

Chapter 2: The laminated shale facies.
Chapter 3: The cross-bedded sandy grainstone facies.
Chapter 4: The cross-bedded grainstone facies.
Chapter 5: The dolomitic mudstone facies.
Chapter 6: The wackestone and marl facies.

These chapters discuss their related facies, sedimentological profiles, and their petrography and diagenesis.

In Chapter 7, the construction of the facies cross-section, and the local and regional facies relationships are discussed. Finally, the factors affecting sedimentation, distribution and growth of the Marada sedimentary facies are discussed using facies cross-sections and isopach maps.

Facies	Lithology	Geometry	Sedimentary Structure	Fossils	Environment	
Marl	Marl and calcareous shale, sandy shoe-strings.	Wedges and sheets.	Large scale lamination, bioturbation, massive bedding.	Forams, ostracods, oysters, echinoids, bone and wood debris.	Delta fan	Open Marine
Wackestone	Wackestone, mudstone and a few grainstones.	Sheets.	Massive bedding, bioturbation and bored surfaces.	Bryozoa, algae, echinoid oysters, forams, molluscs.	Banks	
Dolomitic mudstone	Dolomitic pelletal mudstone. Dolomite breccia, packstone, quartz grains, gypsum pseudomorphs	Sheets.	Massive bedding, bioturbation, mottling, lamination, microcross-lamination, dissecation cracks	Reworked skeletal grains, patchy organic matter, local oyster beds.	Tidal flat and Sabkha	
Crossbedded grainstone	V. coarse-medium grainstone, packstone, skeletal sand, geopetal mud and silt.	Lenticular bodies and sheets. "less lime mud up"	Trough, planar, cross bedding (5^{o} to 16^{o}) and large scale foresets ($0\text{-}25^{o}$).	Bryozoa, coralline algae, echinoids, forams, molluscs.	Barrier bars and beaches	
Crossbedded sandy grainstone	Illsorted skeletal and terrigenous sand, silt and mud. Reworked intercl-asts, ooliths.	Shoe strings, sheets "fining up".	Trough and unilateral cross lamination, graded bedding	Reworked shells, wood and bone fragments.	Tidal channel & inlet	Lagoon
		Wedges and sheets, "coarsening up".	Parallel sets of low angle foresets Trough X-bedding		Tidal delta	
Laminated shale	Calcareous shale, sand and silt laminae, argillaceous wackestone, calcareous nodules	Irregular.	Large scale gently inclined lamination, washouts, burrows and rootlets.	Oyster banks and coralline algae.	Pond	

Table 1.3 Summary of the Sedimentary Facies discussed in this Thesis.

CHAPTER 2

THE LAMINATED SHALE FACIES

The laminated shales associated with the limestone facies of the Marada Formation were first described by Selley (1966), and later by Doust (1968). However, the use of the name laminated shale facies is restricted here to the shale units interbedded with the cross-bedded grainstone and sandy grainstone facies sequence, which is exposed below the Echinolampas marker horizon. Southwards (in Jebel Zelten) units of the laminated shales are interfingering with the calcareous sandstone and interlaminated shale and sand facies. They reach a maximum thickness in the Central Jebels area. The laminated shales show a gradational basal contact with the sand dominated facies below.

The laminated shales consist of a diverse lithologic types of gradational nature. These are:

(a) Interlaminated calcareous sand and sandy shale subfacies;

(b) Interlaminated calcareous shales and silt subfacies.

(c) Calcareous shale subfacies.

(d) Argillaceous wackestone subfacies.

and (e) Oyster banks.

2.1 Subfacies 1

Interlaminated Calcareous Sand and Sandy Shale:

The vertical profile of this subfacies is well exposed at the base of Dor Zuggut and Dor Marada. Their lower contact is transitional with the estuarine facies (Fig. 2.1). They grade upward into units of sub facies 2. Laterally, this subfacies extends for a large distance, and changes gradually to other shale subfacies.

Lithology:

Thickness of units belonging to sub facies 1 ranges between 2 to 5 metres. The rocks are yellowish grey to brownish green in colour, and consist of ill-sorted mixture of interlaminated sand and sandy shale. Towards the top of the units the sorting within laminae improves and the amount of shale increases.

The sand fraction consists of medium to fine, rounded to subrounded quartz, and reworked skeletal grains of oysters, bryozoa, foraminifera and coralline algae; but generally the amount of quartz is higher than the skeletal grains (Fig. 2.4). A characteristic feature of this facies is the presence of rounded aggregates or pellets measuring up to 5 mm in diameter (Fig. 2.3). These are probably produced by cementation of

Photo Plate II-1

Fig. 2.1 Cross bedded calcareous sandstone of the estuarine facies gradually changes laterally and upwards into a lagoonal laminated shale facies (subfacies 1).

Fig. 2.2 Large scale laminations in laminated shale facies. Lamination is gently dipping from right to left, away from the estuarine source as in 2.1.

Fig. 2.3 Close up of Fig. 2.2 showing detailed lamination and burrows. Notice the occurence of rounded aggregates.

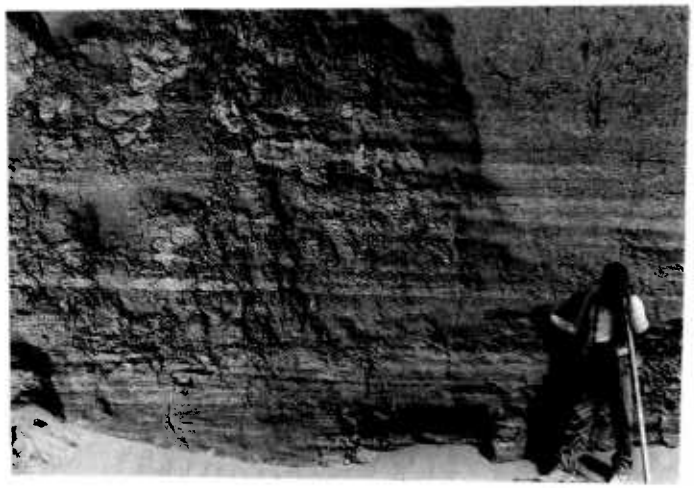
Fig. 2.4 Microphotograph of the interlaminated calcareous sand and sandy shale subfacies. NL.X3.

Fig. 2.5 Interlaminated shale and silt subfacies of the laminated lagoonal shale. Large scale laminae are gently inclined from right to left. The shales change gradually upwards into cross bedded sandy grainstone facies.

Fig. 2.6 Close up of Fig. 2.5 showing interbedded shale and silt penetrated by burrows. The scale is 6 inches.



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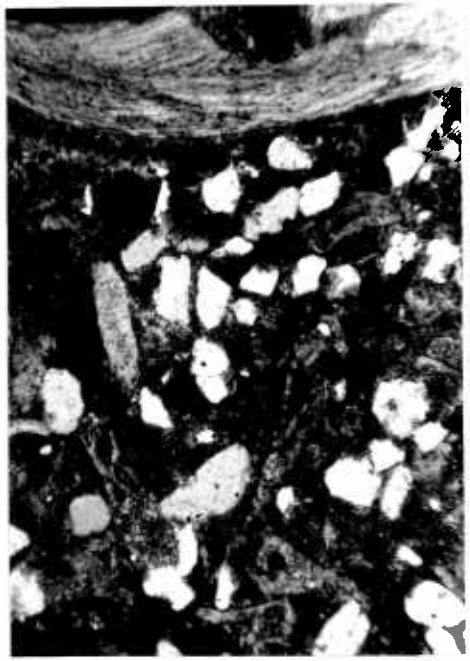


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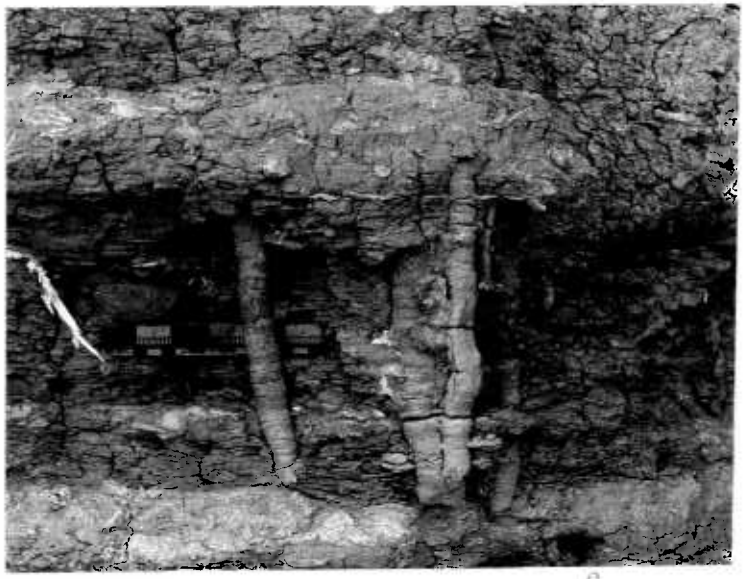
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sand and mud by aggregation or flocculation of the ferruginous material during deposition (Shepard and Moore, 1960). Reworked and dark coloured lime mudstone grains, wood and bone fragments are also present. They are commonly concentrated in pebble-size fragments at the base of washouts and small channels associated with this facies. The fine fraction consists of a variable mixture of lime and terrigenous mud.

Sedimentary Structures:

An extensively exposed outcrop facies, a pronounced large scale lamination and bedding can be traced for some distance (Fig. 2.2). Laminae dip very gently, presumably following the original slope of the depositional basin.

Small scale lamination of sand and mud rich layers is common. Laminae are variable in thickness and often show gradational contacts (Fig. 2.3). Thin laminae are vague; they become clear with the increase of the quartz content, as they develop a high relief on the outcrop surface. In apparently homogenous layers, lamination is indicated by imbrication of scattered skeletal shells. Laminations are of sublenticular character (Fig. 2.3). Most small scale laminae tend to pinch out laterally along a very short distance. Also, laminae sets tend to truncate one another. The impersistence of lamination is similar to those formed below the level of high tide in the Wadden Sea environment (Straaten, 1954).

Ripple lamination is not uncommon, especially in washouts, channels and at the contact with associated sandy grainstone facies. They characterize sediments with strong estuarine influence (Fig. 2.1).

Burrows found in this facies are restricted in numbers and widely separated. They are more than 1 cm in diameter, vertical or slightly inclined (Fig. 2.3); there is no evidence to suggest the presence of horizontal burrows. Burrows are filled with material from the surrounding sediments.

Interpretation:

The interlaminated calcareous sand and sandy shale subfacies bear some similarity to inter-tidal deposits. However, the absence of marsh sediments in the vertical profile, the ill-sorted nature of the sediment texture, and the uninterrupted lateral extension of the large scale sedimentary structures negate the interpretation of intertidal origin.

However, their close association with the estuarine and barrier bar facies and other lagoonal subfacies suggests deposition under shallow water conditions. The exclusive presence of vertical burrows suggests unfavourable conditions at the sediment-water interface (Rhoades, 1967), such as salinity lowering and/or high rate of sedimentation.

The large scale gently inclined lamination reflects the original depositional slope at the site of deposition. The gradational basal contact of this subfacies to calcareous sandstone estuarine facies indicates that they were deposited near channel mouths; similar to the modern areas in front of lagoonal deltas of the central Texas bays (Shepard and Moore, 1960; Kanes, 1970; Donaldson et al, 1970).

2.2 Subfacies 2 Interlaminated Shale and Silt:

The interlaminated shales and silt subfacies represent the greatest part of the laminated shale. This subfacies contacts with other shale subfacies is gradational both vertically and laterally.

Lithology:

Units of facies 2 range between 1 and 8 metres in thickness. The shale constitutes laminae and thin beds 5 to 20 cm thick, grayish olive (10 Y 4/2) to green grayish olive (5 GY 3/2) in colour. Individual laminae are 0.5 to 5 cm thick. In thin section, shale layers consist of wavy bands of golden brown clay flakes and dark organic matter (Fig. 2.8). The clay flakes are oriented parallel to the bedding plane; under polarized light they show a brush extinction.

The silt layers are of lighter colour (5 Y 6/4) and consist of fine sand to silt size quartz,skeletal grains and

Photo Plate II-2

Fig. 2.7 Cross bedded grainstone washout in laminated shale facies (subfacies 2).

Fig. 2.8 Photomicrograph of interlaminated shale and silt. The clay minerals show wavy lamination, and the quartz grains are subangular. The dark areas between grains are iron oxide; notice scattered broken skeletal grains (NL-X3).

Fig. 2.9 Laminated shale shows soft sediment deformations, and contains limestone pebbles and cobbles. Notice the irregular contact of the over-lying limestone.

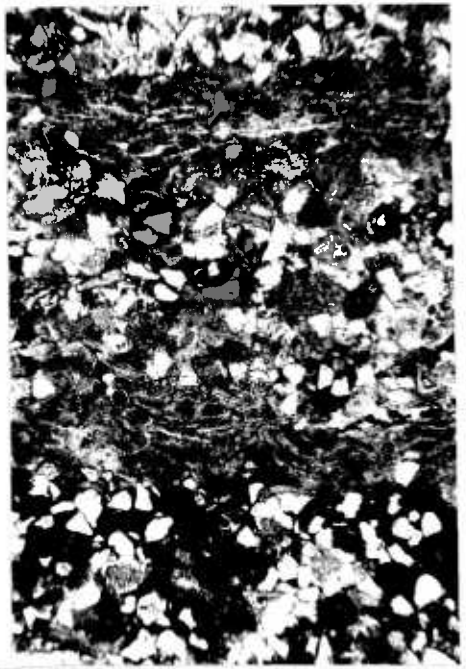
Fig. 2.10 Load casts at the contact of the limestone and laminated shale.

Fig. 2.11 Mottling in calcareous shale subfacies is produced by compacted horizontal burrows.

Fig. 2.12 Nodular rubble texture in calcareous shale subfacies.



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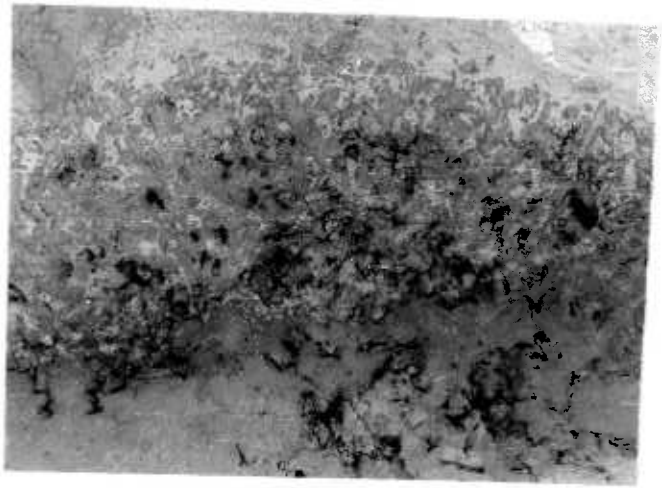
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pellets. The quartz grains are well sorted angular to sub-rounded. The skeletal grains represent up to 50 per cent of the coarse fraction and consist of molluscs, bryozoa and echinoid fragments as well as occasional complete foraminiferal tests. The intergranular pore spaces are filled by clay size matrix, often stained with iron oxide patches (Fig. 2.8). In general the amount of fine fraction is double the amount of the coarse fraction in this subfacies. But the coarse fraction increases a great deal when the shales are found interbedded with grainstone washouts (Fig. 2.7).

Calcareous nodules are commonly found in this subfacies, especially near the top of the unit Also, secondary gypsum veins are found parallel to, and cross-cutting, sedimentary lamination. In thin sections, gypsum porpheroplasts are found replacing the fine grain fractions and filling burrows; they are derived from the recent evaporation sabkhas nearby.

Sedimentary Structures:

Large scale well defined, gently inclined lamination is the characteristic sedimentary structure in this subfacies (Fig. 2.5). It consists of interlaminated shale, silt and very fine sand (Fig. 2.6). When closely examined, the shales occur in thick irregularly laminated units, 5 to 20 cm thick, and each individual lamina ranges between 1 to 5 cm in thickness. Some sand and silt laminae are semilenticular and show microcrosslaminatic

Finer interlamination of silt and shale is also common (Fig. 2.8); individual laminae are about 0.5 to 3 mm thick.

Cross bedded skeletal grainstone washouts are often found interbedded with the laminated shale subfacies (Fig. 2.7). Their lithology is similar to the barrier bar facies, which are often found overlying the shales. The lower contact of the washouts with the shale is sharp or irregular. A downwards thickening, wedge-like shale layer is often inter-cross-laminated with the foresets of the grainstone washouts.

Load casts are always found at the contact between shales and the overlying carbonate units (Fig. 2.10). Also, evidence of soft sediment deformation in shales (Fig. 2.9) suggests sliding and sinking of the more competent sediment masses possibly during high energy conditions. In many localities, large skeletal grainstone boulders are found floating in deformed thick shale units. This evidence strongly indicates the semi-fluid nature of the shales at the time of deposition.

Burrows are usually found at the top of the unit of this subfacies. In places they are clustered in a very small area (Fig. 2.6), whilst the rest of the unit is undisturbed. They are also found concentrated at the upper surface of the shale units, especially when in contact with cross-bedded grainstone units (Fig. 2.7). Burrows are mainly vertical but

horizontal and gently inclined types are found at the upper surface of beds. Burrowas range between 1 to 2 cm in diameter, and are filled up with coarse quartz grains and skeletal sand, and the sediment fill shows a downward curved lamina (Fig. 2.6). No walls were constructed by burrowing organisms to support the burrows, which indicates that the sediments were cohesive enough to prevent their collapse.

In a few places, plant rootlets are observed in this subfacies. However, they are less abundant than burrows.

Interpretation:

The interlaminated shale and silt subfacies shows similar characteristics to those of subfacies 1, except on the following points: a) this subfacies sediment is finer in grain size, better sorted, and the amount of shale is greater than the sands; b) the sediment contains more carbonate material in the form of skeletal grains, washouts and calcareous nodules; c) evidence of soft sediment deformation of the shales; d) burrows are very well defined and filled with sediments different from the surrounding shale, and the sediment fill is organized in concave layers.

The gradational relationships of subfacies 1 and 2 are reflected on the general similarity between the two subfacies.

The increase of shale content indicates that subfacies 2 was deposited away from the source of sand supply. Large scale inclined lamination indicates deposition at the marginal areas of the depositional basin. Skeletal rich washouts are a common feature in the seaward side of lagoonal areas behind the barrier (Shepard, 1960; Dickinson et al, 1972).

This subfacies is similar to the recent marginal lagoonal sediments deposited away from river mouths and described by Shepard and Moore (1960) from the Central Texas coast.

2.3 Subfacies 3

Calcareous Shale:

The calcareous shale subfacies occur interbedded with other shale subfacies, especially subfacies 4. The thickness of this facies' units varies from 50 cm to 3 metres. The lower contact is sharp and often burrowed (Fig. 2.11).

Lithology:

This facies is mottled grayish olive (10 Y 4/2) in colour. The shales contain large amounts of skeletal sand and silt. The coarse fraction consists mainly of bryozoa shells and benthonic foraminifera. The predominant bryozoa is Idmonea Spp, which occurs as a biostratigraphic marker horizon a few metres below the echinoid bed in Central Jebel sections (Doust, 1968). Specimens of this bryozoa are 0.5 to 1.0 cm long and are found lying parallel to bedding. According to Doust (1968), Idmonea Spp indicates near normal marine salinity.

Sedimentary Structures:

Physical structures are almost absent in this facies due to intensive bioturbation and mottling. Lamination,

however, sometimes escapes destruction by burrows, specially in thick units. Mottling in this subfacies is due to intensive activity of burrowing organisms. Most observed burrows are gently inclined and horizontal (Fig. 2.11). Burrows within the unit are often strongly compacted and develop a vague, irregular colour lamination. Those at the top of the unit escape compaction due to filling by sediments from the overlying beds, which give support to burrows.

Intensive bioturbation in shale and mixing with other beds often produce nodular rubble texture (Fig. 2.12). This texture is not uncommon in ancient rocks (Fursich, 1973). According to Wilson (1968) the nodular rubble which is observed in the oolite series in Southern England represents "a sponge stabilized lagoonal mud deposited in slightly deeper tranquil conditions". In fact this texture represents a cross-section of horizontal burrows with calcareous fillings which are crowded in a shale bed, or vice versa.

Interpretation:

All available evidence suggests that the calcareous shale facies were deposited away from the estuarine influence in quiet, possibly marine conditions. Fauna suggests near normal marine salinity. Idmonea Spp-carrying beds are used for regional correlation (Doust, 1968), indicating favourable conditions which have extended for some distance in the basin of deposition.

Horizontal burrows and the intense biological activity also indicate the favourable physico-chemical conditions at the sediment-water interface. Similar burrowing structures are described from recent subtidal environments (Rhoads, 1967) and ancient lagoonal facies (Wilson, 1968).

Recent environmental conditions similar to those prevailing during the deposition of subfacies 3 are described by Shepard and Moore (1960) from the deep central parts of the Aransas and Matagorda bays of the Texas coast.

2.4 Subfacies 4 Argillaceous wackestone and marl:

The argillaceous wackestone and marl subfacies are found interbedded with and grade into subfacies 2 and 3, and often underly units of grainstone and sandy grainstone facies. Units ar lenticular and extend laterally up to 400 metres with maximum thickness up to 3 metres.

Lithology:

Subfacies 4 is a dark yellowish orange (10 YR 6/6) in colour and consists of a mixture of shale and carbonates with variable amounts of quartz sand and silt. The grain framework consists of skeletal grains and complete shells of mollusca, bryozoa, foraminifera, coralline algal grains, algal oncolites, echinoids and occasional chela of crustacea. Oyster

Photo Plate II-3

Argillaceous wackestone and marl subfacies

Fig. 2.13 A branching coralline alga in growth position.

Fig. 2.14 A washout of coral rubble.

Fig. 2.15 A marl bed containing crowded Placenta miocenica shells.

Fig. 2.16 Photomicrograph of subfacies 4 containing foraminifera, P. miocenica, and bryozoan fragments as well as quartz grains.(NL.X3)

Fig. 2.17 Subfacies 4 containing gastropod shell.



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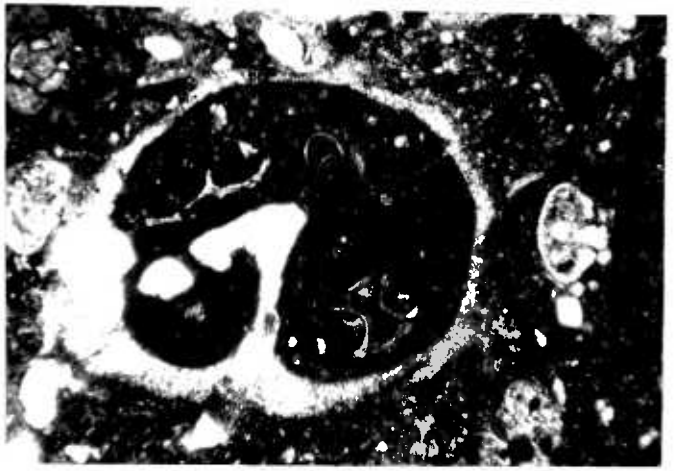
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shells, Placenta miocenica, are the most common bivalve in this facies.

Placenta miocenica are found scattered in this facies, and often are crowded in large numbers in the marls (Fig. 2.15). They are suspension feeders and can tolerate lowering of salinity. Rate of animal death accumulation is related to high rate of sedimentation (Doust, 1968).

Turreted gastropods are common (Fig. 2.17). According to Doust (1968) they are regarded as brackish and low salinity indicators. Cerithiids can tolerate even influxes of fresh water. Some species are found in the lagoons of the Rhone delta and on mud banks in front of tropical rivers (Doust, 1968).

Idmonea, Trigonopora (bryozoa), coralline algae, foraminifera (Fig. 2.16) and small echinoids represent normal marine salinity. Coralline algae and coral patches are often found in growth position (Fig. 2.13) associated with the wackestones and marls.

Calcareous nodules are common diagenetic features near the top of the sedimentary units. Their origin and diagenetic history are discussed later in this chapter.

Sedimentary Structures:

Units of subfacies 4 are massive and lack sedimentary structures due to intensive burrowing activity, and compaction.

Mottling and nodular rubble are common. In some localities lignite rootlets are also present.

Shallow washouts filled with coral and skeletal rubble and reworked calcareous nodules indicate occasional high energy conditions (Fig. 2.14).

Interpretation:

Fauna and flora associated with the argillaceous wackestone and marl facies indicate shallow water conditions, slow rate of sedimentation and normal to low salinity in the environment of deposition. Quiet water conditions must have prevailed judging from the amount of terrigenous and calcareous mud, bioturbation and lack of physical sedimentary structures. Washouts, however, indicate occasional storm conditions.

Coralline algal growths and patchy corals and water plants are common features in the recent lagoons of the Bahamas and Florida (Bathurst, 1971). In the meantime, brackish water fauna such as those of turreted gastropods are found in the Gulf of Mexico bays (Shepard and Moore, 1960) and the Rhone delta lagoons (Doust, 1968, p. 35).

The wackestone and marl facies were deposited in a shallow lagoonal environment away from the mouths of the estuarine channels. During influx of fresh water (rainy seasons)

Photo Plate II-4

Oyster banks

Fig. 2.18 Oyster bank in growth position.

Fig. 2.19 Oyster bed at the base of cross bedded sandy grainstone facies.

Calcareous nodules in shale

Fig. 2.20 A layer of calcareous nodules (N). The shale above the nodule is mottled due to burrowings, but that beneath is unaffected. Reworked nodules are found at the base of the grainstone unit at the top (scale 6 inches, right of centre).

Fig. 2.21 Impression of horizontal burrows on the upper nodule's surface (scale 6 inches).



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the salinity of the water was lowered allowing the brackish fauna to flourish, but during dry periods the salinity was restored to normal allowing marine organisms to be abundant.

2.5 Subfacies 5 Oyster banks:

The laminated shale facies of the Marada Formation exhibit biohermal growths of oysters which extend laterally for up to 700 metres and reach up to 1.5 metres in thickness. In the Central Jebel area a succession of autochthonous and allochthonous oyster beds and shales may reach up to 6 metres in thickness. In Dor Zuggut and Dor Marada oyster banks are associated with shale as well as wackestone and mudstone carbonate facies.

In his paleoecological study of the Marada Formation fauna, Doust (1968) identified the oysters as Crassostrea gryphoides. They are the Miocene equivalent of Crassostrea Virginica oysters, now living in the Gulf of Mexico bays (Doust, 1968).

Individual oysters are up to 30 cm in length. They are scattered as individual bivalves or single valves in shale as well as other facies. They are often found as a large deposit at the base of washouts, disconformity surfaces and channels. As channels lag, oysters may reach up to a metre in thickness (Fig. 2.19). In this case, oysters show

hardly any reworking apart from not being in growth positions.

When they are in growth positions (Fig. 2.18), oysters are arranged in clusters of banana bunch form, with their umbos oriented down. Oysters grow on top of each other from the base of the bed. At the centre of a bank, the first generation of oyster clusters appear to be sinking in the underlying beds. The spaces between oysters are filled by fine-grained sediments and skeletal sand.

Oyster banks show a gradual decrease in thickness away from the centre, as well as increase in reworking and fragmentation. In recent lagoonal environments oyster banks supply the surrounding area with a large amount of skeletal debris (Shepard and Moore, 1960).

The ecology of the Marada oyster banks can be related directly to their counterpart now living in the Gulf of Mexico (Doust, 1968). Oysters are suspension feeders. Therefore they indicate slow rate of sedimentation or non-deposition. Also, they tolerate low and intermediate salinities which prevail in the modern lagoonal environments (Shepard and Moore, 1960).

2.6 The Origin of Calcareous Nodules in Shales

Calcareous nodules are commonly found in the shale and marl units of the laminated shale facies. Calcareous nodules usually occur near the top of shale units as a semicontinuous layer about 10 to 20 cm thick. Some layers are traceable for long distances along the same stratigraphic level. Nodules are flat ellipsoidal bodies up to 60 cm in diameter (Fig. 2.20). They are sometimes connected together by narrow protrusions.

Sediments above nodular layers are often strongly bioturbated and burrows are filled by coarser material derived from the unit above (Fig. 2.20). Burrows are absent beneath the nodules horizons. Bioturbation and burrowing activity were inhibited below these layers due to early lithification of the calcareous nodules. The upper surface of a nodule is usually marked by horizontal grooves about 2 cm wide, which tend to criss-cross one another and are often traced around the nodule edge (Fig. 2.21); but in a few cases they penetrate through the nodule surface. The surface of the groove is ornamented by scratches similar to those found in Callianassa burrows in the chalk hard grounds (Bromley, 1967). These horizontal tracks were caused by burrowing organisms and indicate progressive hardening of nodule cores as bioturbation was in progress.

Calcareous nodules are very pale orange (10 YR 7/4) in colour due to the occurence of disseminated iron oxides; they are tough, brittle and sometimes jointed (Fig. 2.22); they weather in exfoliated fashion and show a sharp contact with the host sediments. They change laterally into softer, lighter coloured and less lithified material (Fig. 2.23), which shows concoidal weathering and partial penetration by vertical burrows (Fig. 2.23). The lateral and vertical contacts of these nodules with the surrounding host sediments appear gradational. In some shale units, two successive nodule horizons are found separated by a thin layer of the host sediment. The lower horizon is invariably less lithified than the higher one.

Calcareous nodules are composed of opaque lime mudstone material (Fig. 2.25). Silt size pellets with fuzzy outlines are often found floating in a crypto- to microcrystalline groundmass. Microscopic worm burrows are evident in most thin sections; their shapes may correspond to different stages of lithification of the nodules. These are: a) burrows of variable diameter showing ill defined walls and outlined by undulating filling of quartz silt and pellets; b) well defined burrows about 0.23 mm in diameter filled with closely packed pellets and angular quartz silt; they are scattered through the nodules but sometimes concentrated in small areas; c) the third type is 0.28 mm in diameter with

Photo Plate II-5

Fig. 2.22 Calcareous nodule (below the scale) showing a gradual change in colour and increase of brittleness from right to left.

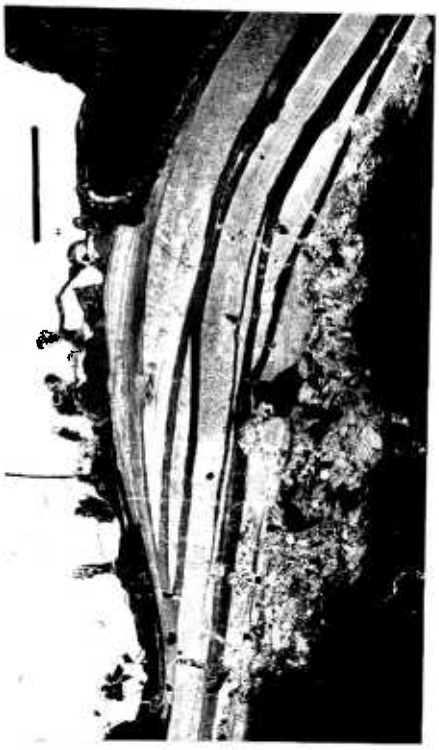
Fig. 2.23 A lateral extension of the nodule in Fig. 2.22. It shows light colour, gradational contact with the shale (left of centre),and vertical burrows (right of centre).

Fig. 2.24 A nodule at the top of shale unit (below scale). The unit above contains reworked pebbles and cobbles derived from the nodule, and oyster shells.

Fig. 2.25 Negative print of thin section of a bored calcareous nodule (light colour), which is encrusted by oyster shell. Bar is 5 mm.









well defined iron oxide stained walls; these burrows are left open and appear to have suffered no compaction.

Calcareous nodules were often exhumed by erosion of the overlying shales during high energy conditions. Reworked lime mud pebbles are also found at the base of barrier bars or lagoonal channel units (Fig. 2.24). Exhumed nodules and pebbles are dark yellowish orange (10 YR 6/6) in the outside and become lighter (very pale orange 10 YR 7/4) in colour towards the centre. This is due to the increase of disseminated iron oxide from the centre outwards. Nodules and pebbles are bored by a short flask shaped, 0.4 to 1.0 cm long, Gastrochaena squamulosa bivalve, and larger and more cylindrical types were caused by Lithophaga (Doust, 1968). Also small borings (unidentified) 1.8 mm long and 0.7 mm in diameter are common. These nodules are encrusted by oysters, bryozoa, serpulids and barnacles. These epifauna are often bored by worms, sponges and bivalves (Fig. 2.25).

Discussion

The Marada calcareous nodule layers are found in the shales and marls at a distance between 0 and 50 cm below disconformities and local erosional surfaces (below barrier bar or lagoonal channel units). Bioturbation and burrows caused by Callianassa and worms were inhibited by the

occurence of the layer of calcareous nodules, suggesting syndepositional lithification, which may have taken place at some distance below sediment-water interface. The occurence of Callianassa burrows below the disconformity surfaces (above nodules) indicates normal marine salinity and slow rate of sedimentation. These conditions must have prevailed over large distances judging from the prominent lateral extent of some calcareous nodule horizons.

As suggested earlier, most of the shales have been deposited during the influx of terrigenous sediments from estuaries (wet seasons). It is thought therefore that the calcareous nodules were formed during the dry season period, when the run-off water ceased and the salinity in the lagoon increased to allow the deposition of calcium carbonate layers (Tucker, 1973). Rusnak (1960) pointed out that calcareous nodules form under the present day conditions in the Lagoona Madre; he attributed their formation to a slow rate of sedimentation (terrigenous) and high salinity.

The occurence of Fe oxides is not uncommon in the lagoonal facies. They were carried by the Marada rivers and estuaries and were deposited in the lagoonal environment by coagulation as a result of the change of salinity and pH values. Therefore, Fe oxide occurence in the calcareous nodules is not

uncommon. However, exhumation of calcareous nodules for prolonged periods of time (during which borings and encrustation took place) on the lagoon's floor resulted in the concentration of disseminated iron oxide on the nodules' surfaces. It was noted that the more reworked nodules attain stronger colours than the unreworked ones. Hallam (1969) described disseminated pyrite in similar nodules from the lower lias of Dorset. He concluded that pyritization of the nodules started after lithification, exhumation and reburial.

2.7 Interpretation and Discussion

All available facts indicate that the laminated shale facies were deposited under a shallow water environment of a diverse physical and chemical conditions similar to those found in the modern lagoonal areas (Shepard and Moore, 1960; Straaten, 1959). The sedimentary sequence of interbedded shales, cross-bedded grainstone and sandy grainstone facies, occur below the Echinolampas key horizon which is the fair indication of open marine conditions. The calcareous sandstone and interlaminated shale and sand facies exposed to the south and at the base of the sequence are of estuarine and intertidal origin (Selley, 1966; Doust, 1968). The laminated shale units are always overlain by units of the cross-bedded grainstone facies. This general succession of facies is a reflection of the geographic distribution

of the facies area at the time of deposition (Walther, 1893-94). Straaten (1959) defined a lagoon as "a shallow body of water situated in a coastal plain, it may have a connection with the sea through inlets or passes, but in some cases it is completely separated from it by a beach barrier or spit". Therefore, it is reasonable to assume a lagoonal origin for the laminated shale facies of the sequence described above. This interpretation generally agrees with that presented by Selley (1966, 1969). However, his interpretation extends to all of the shale units including those above the Echinolampas horizon, which origin is regarded differently here. Doust (1968, p. 200), on the other hand, stated broadly that; "the shales (interbedded with the Marada limestones) may be related to a brackish water source, or estuary, and represent its seaward expression". This statement, though correct, does not positively indicate the occurrence of a lagoonal condition in a definite part of the stratigraphic sequence as described above.

Rusnak (1967) indicated that the depositional mechanisms in modern lagoons follow the classic format of energy gradients. The suspended and tractive sediment deposition in the lagoon is directly proportional to the transportation energy. Sedimentation in the lagoons may come from rivers and estuaries (positive filling), from the sea (inverse filling) and/or form in place (neutral filling). All these processes have contributed towards

the filling of the Marada Lagoons. The laminated shale facies show a gradational basal contact with the calcareous sandstone facies (estuarine) below, they grade upwards (and laterally) in an ideal cycle which shows a gradual decrease of the sand fraction and increase of the calcium carbonate content towards the top. The decrease of the sand fraction may indicate waning of the influx of terrigenous material from the estuaries (positive filling), whilst the abundance of $CaCO_3$ in the form of calcareous nodules and growth of coral and coralline algae indicate the decrease of the terrigenous influx and salinity increase (neutral filling). The occurrence of the skeletal washouts, and mass sediment deformation in the shales indicate sediment transport from the sea during storms.

This cyclic sedimentary pattern is a reflection of the cyclic climatic changes which took place during deposition. After studying the fauns and flora of the Marada Formation, various authors (Principi, 1932; Desio, 1935; Doust, 1968; Savage and Hamilton, 1973) postulated that tropical climate prevailed during the Middle Miocene times. Modern tropical climates are characterized by two season system of a wet and dry condition (Tucker, 1973). During the wet season, filling of the Marada lagoon was dominated by terrigenous sand and mud brought down from the rivers and estuaries, but carbonate sedimentation became dominant in the lagoons during the dry season.

CHAPTER 3

THE CROSS-BEDDED SANDY GRAINSTONE FACIES

The cross-bedded sandy grainstone facies occur in the Marada Formation associated with the laminated shale, and cross-bedded grainstone. Thus it is exposed below the Echinolampas key bed horizon. Units of this facies are pale-yellowish orange (10 YR 8/6), yellowish brown (10 YR 5/4) and grayish orange in colour. They consist of a mixture of skeletal and quartz sand with a variable amount of lime and terrigenous silt and mud.

Two types of geometries and vertical profiles are recognised in the field; these are:

A) Shoe strings with a fining upwards sequence.

B) Lobes and wedges showing a coarsening upwards sequence.

3.1 Subfacies A

Sandy Grainstone Shoe Strings (Figs. 3.1, 3.2)

The subfacies A are interbedded with and cutting across laminated shale facies, as well as the cross-bedded grainstone facies. The former are considered lagoonal channels and the latter are tidal inlets. The channel subfacies consists of three distinctive components. These are: (a) channel lag, (b) point bar, and (c) channel fill.

(a) Channel lag: consists of oyster shells, reworked calcareous nodules and blocks of other facies, as well as occasional wood and bone fragments. In the lagoonal channels oyster lag is up to a metre thick (Fig. 2.19) and may extend for some distance along the outcrop face. Single oyster valves and bivalves are common. Most oysters do not show extensive reworking or abrasions, which indicates that they were not transported for long distances. Because oyster banks develop as positive build-ups at the bottom of the lagoons (Shepard and Moore, 1960), channels are likely to form between banks. Oyster banks, therefore, are susceptible to reworking due to the soft nature of the sub-stratum.

Early lithified boulders are found at the base of tidal inlets (Fig. 3.3). They consist of grainstone and pelletal packestone blocks of grainstone and dolomitic mudstone facies These boulders are up to several metres across, their surfaces are often bored by organisms and encrusted by calcareous algae. In places overturned coral heads are often found in the inlet lag. The nature of the inlet lag deposits reflects the nature of other sub-environments on their banks. Dolomitic mudstone facies and corals are often found in situ on top of the grainstone bodies in the Marada Formation.

(b) Point bars: in cross section channel walls appear asymmetrical (Fig. 3.1), the steepest slope represents the scour side, but the depositional side slopes gently over the point bar deposits.

Point bars of the lagoonal channels are 1 to 4 metres thick, and extend laterally for tens of metres. They gently pinch out in two directions along the outcrop's surface. At one end (channel starting point) the point bar is wedge-like, which pinches out towards the top of the unit away from the erosional bottom, overlapping the shale facies. At the other end (latest channel position) the point bar side is inclined towards the channel trough. It is overlapped by channel fill sediments (Fig. 3.1).

Units show unilateral cross lamination (Straaten, 1954) with a constant direction of inclination of the laminae over the length of the exposure. They give the impression of being formed as the foresets of a delta, the laminae having been deposited in the direction of current. The dip of cross laminae is generally low (10 degrees) following the gentle slope of the channel. In some outcrops the dip gradually changes from flat at the unit's bottom to inclined towards the top. This indicates a change of the position of cross laminae in relation to the section of the outcrop, rather than a real change in dip,

suggesting a change in point bar position with time which was due to lateral channel shifting.

Extensive sheets of point bar units are produced by several channels laterally migrating side by side at a given time. It is commonly observed in Central Jebel area that the starting point of one channel point bar is in close proximity to the scouring end of another. These adjacent point bars may represent a benching system of a major estuarine channel running along the lagoonal floor.

Tidal inlets' point bars are up to 8 to 10 metres thick (Fig. 3.2) and also unilaterally cross laminated. The latter, however, show a higher degree of inclination (30 degrees) than those of the lagoonal channels.

The point bars of subfacies A contain quartz sands which vary in quantity from unit to unit, and even within a single unit. Terrigenous sands and silt often develop individual laminae as well as mixing within a carbonate sand and fine grained fraction (Fig. 3.4). Quartz rich laminae are clean and often friable; they sometimes contain bone fragments. Quartz grains are coarse to medium, rounded to subrounded. The amount of terrigenous mud and silt is particularly high in the lagoonal point bars.

Photo Plate III-1

Cross bedded sandy grainstone facies

Fig. 3.1 A panorama of a lagoonal channel, the point bar (at the man's head) consisting of a gently inclined unilateral cross lamination.

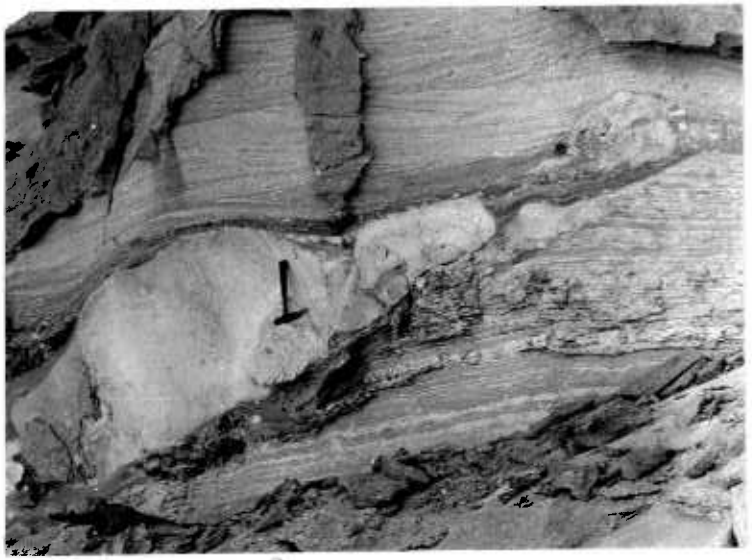
Fig. 3.2 A panorama of tidal inlet. The barrier bar is about 6 m thick (left), it is truncated by a tidal channel (dark, to the right). The point bar is to the right of the inlet.

Fig. 3.3 A close up of trough cross bedded tidal inlet sediment truncating lagoonal shales. A block of the barrier bar is at the base of the inlet unit.

Fig. 3.4 Microphotograph of the inlet facies, containing fragments of echinoid , Bryozoa, coralline algae, pellets and quartz grains (XN-X3).



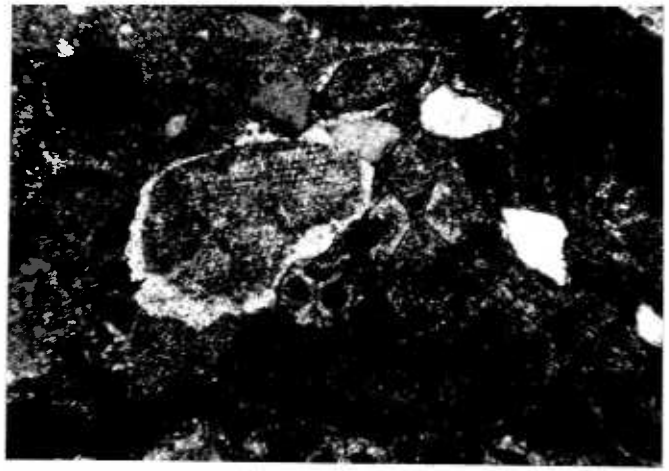
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The skeletal sand consists of bryozoa, echinoids, forams, coralline algae, molluscan fragments; complete oyster shells often occur at the base of the unit. Other carbonate grains such as pellets, interclasts and calcareous mud and silt are more abundant in the tidal inlets. All point bars are lightly cemented, specially those which contain high percentages of terrigenous material.

(c) Channel fill is the sedimentary material occupying the main channel trough on the scouring side of the point bar. Most lagoonal channels are 1-3 metres deep and 20 to 30 metres wide. Tidal inlets on the other hand consist of more than one channel separated by a grainstone body and dolomitic mudstone facies. The ebb channels (northerly palaeocurrents) are always larger than their flood counterparts. The former's trough is 5 to 10 metres deep and up to 100 metres wide.

The lagoonal channel fill contrasts strongly with their point bar units (Fig. 3.1). It consists of interlaminated and microcross laminated sands and shales similar to those of lagoonal shale (Subfacies 2). Sands are clean, friable and often calcareous. The amount of shales increases upwards and merges with the following shale units. Tidal inlets' channel fill merges gradually with the point bar unit along inclined but steep contacts. But, contrary to the point bar, channel

fill is trough cross-laminated (Fig. 3. 3) and changes gradually upwards into micro-cross-laminated finer material. The lithology of the channel fill material is similar to that of the point bar.

Discussion

Fining-up sequence in shoestring bodies is a classic occurence of a facies deposited by a uni-directional current in channels (Allen, 1965). Most channels of the lagoonal and tidal inlets indicate uni-directional palaeocurrents. Thus, as indicated, in inlets a pair of uni-directional channels must have existed in close proximity to each other (Price, 1963). An ebb channel which indicates a northward palæocurrent direction must have been scouring deeply in the underlying sediments due to high current velocity at the inlet. Flood channels are much shallower, and their sedimentary structures indicate a flood palæocurrent. This relationship may indicate a palaeocurrent reversal around intertidal shoals between the two channels. Lagoonal channels also indicate a similar palæocurrent relationship.

The absence of bipolar palaeocurrent readings in a given channel does not necessarily indicate that opposite current was non-existent. Instead it indicates that the sedimentary structures of a given current have never been

preserved either due to non-deposition or erosion by the opposite current. Thus only the sedimentary structures of the latter were preserved. Furthermore, reworking and mixing of terrigenous and open marine shell fragments in channels are the only evidence to suggest a bipolar palæocurrent in a channel. Also, the landward increase in the terrigenous sand versus carbonates supports this view.

Although the lagoonal channels were cutting a soft lagoonal sediment, they were unable to scour deeply. Instead, they were meandering and laterally migrating to produce relatively thin sheets of low angle, unilaterally cross-laminated point bar deposits. This suggests that current flow regime was not high enough to build dunes and ripples. All sedimentological evidence suggests that point bars were deposited by lateral accretion at the meander bends under low energy conditions. It is thought that these channels were like veins through which the fine grain terrigenous supply was maintained in the lagoon, as they were delivered from rivers and estuaries.

3.2 Subfacies B Sandy Grainstone Lobes and Wedges

The cross-bedded sandy grainstone bodies of subfacies B are organized in lobe-like sheets, smaller bodies are lenticular and wedge-like in cross section. This subfacies

Photo Plate III-2

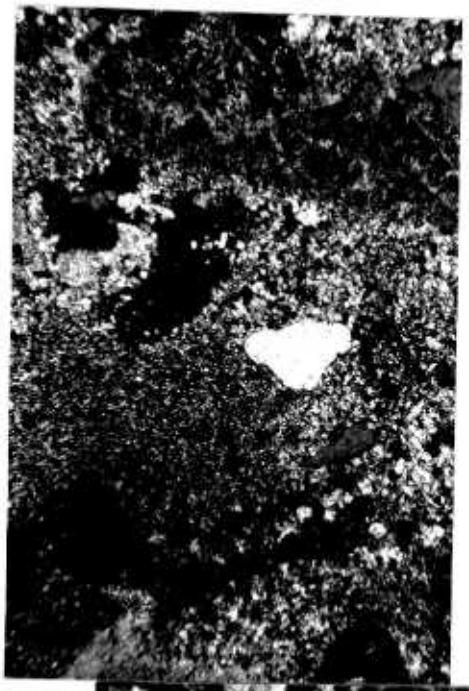
Cross bedded sandy grainstone facies
(tidal delta)

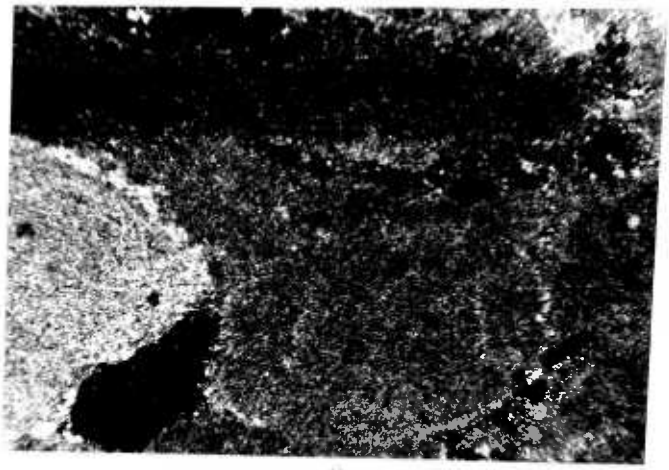
Fig. 3.5 A panorama of microphotographs showing graded bedded texture of interlaminated terrigenous and skeletal sand and silt (XN-X3).

Fig. 3.6 Microphotograph of pellets and skeletal sand. Interstices are floored by geopetal silt (XN-X3).

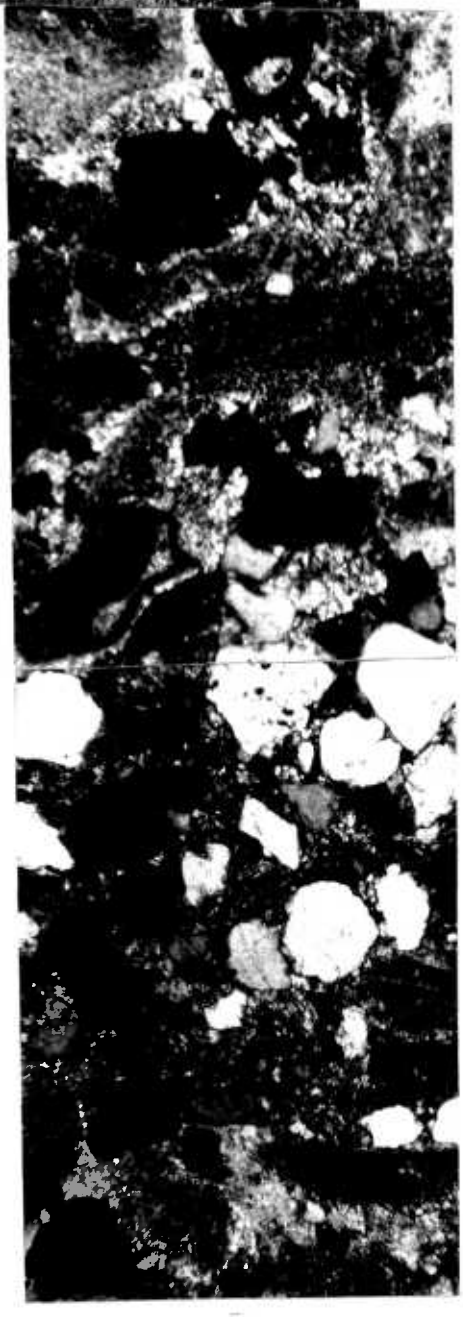
Fig. 3.7 Micrograded bedding in fine pelletal sand and silt laminae (XN-X3).

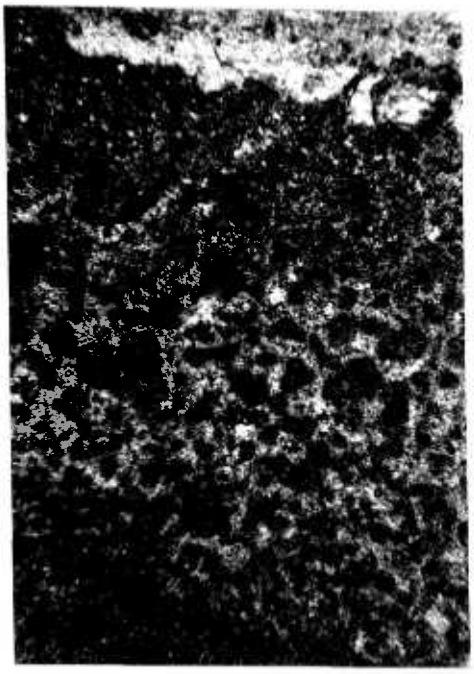
Fig. 3.8 Mixed oolitic and calcareous sandstone. Ooids are with a coarse quartz grain cortex. (XN-X3)



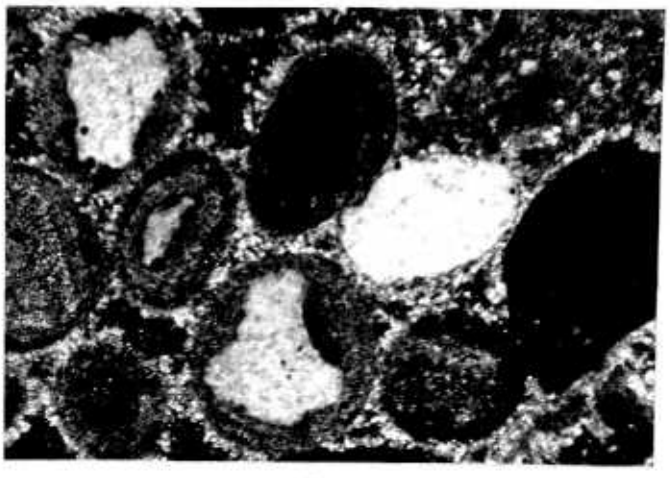


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represents the top unit of a coarsening-up vertical profile which is associated with laminated shale, tidal inlets and grainstone units.

Units of this subfacies are variable in thickness; they are 3 to 7 metres thick. In some cases a compound sequence of subfacies A and B reaches up to 15 metres in thickness in the Dor Zuggut sections. Laterally along the depositional strike units are correlated for up to 30 Km along the Dor Zuggut and Dor Marada escarpments, and along the Central Jebels area. The regional N-S cross-section (paleoslope) shows that subfacies B covers the whole area between the grainstone facies exposed in Dor Marada and the estuarine facies of Jebel Zelten. Smaller bodies extend for a few kilometres along the strike.

Most of the units show a flat top, and downwards curved lower contact. The lower contact of the units is generally gradational but often rippled, sharp, or bioturbated.

Lithology

Two microlithologies are recognised in this subfacies: (a) sandy skeletal grainstone and packestone (Fig. 3.5), and (b) oolitic grainstone and calcareous sandstone (Fig. 3.8).

The sandy skeletal grainstone and packestones are ill sorted mixtures of carbonate and terrigenous sand silt and

mud (Fig. 3. 5). Skeletal grains are pebbly, coarse to very coarse sand and consist of well worn and broken molluscs, bryzoa, echinoids, foraminifera and coralline algal fragments. Complete shells of oysters, flat bryozoa, bone fragments and fish teeth are also found. Sand and silt size pellets are arranged in an exclusive lamina (Fig. 3. 7) or mixed with skeletal sand (Fig. 3. 6).

Quartz sand is coarse to fine, occurs interlaminated with skeletal sand (Fig. 3. 5), and also scattered through the rock mixing with other components. Terrigenous and calcareous mud and silts are concentrated in lenses and discontinuous laminae, with clay flakes oriented parallel to bedding planes.

The different size fractions are organized in a textured graded bedding which can be observed in a megascopic (Fig. 3.11), as well as microscopic, scale (Fig. 3. 7). The megascopic size grading also shows mineralogical grading, indicating cyclic sedimentation which involves oscillation in source sediment supply as well as depositional energy. In some sense this grading is similar to the interlamination of sands in shales of the lagoonal facies.

Fine grained matrix of the carbonate and/or terrigenous mud and silt also occurs as intergranular geopetal sediments

(Fig. 3.6). The grain framework of this lithofacies is lightly cemented with first phase of calcite cement. Quartz rich laminae, however, are often friable. In a few cases, the first phase of cement is often dolomitized due to exposure of the units to supratidal conditions.

The second microlithology is well sorted oolitic grainstone (Fig. 3.8) and calcareous sandstone. The difference in the names of these microlithologies is a function of thickness of the oolite's coating. Oolites consist of skeletal or quartz sand cores of up to 0.7 mm in diameter. Oolitic coat, however, varies in thickness corresponding to the size of the core, the coarser the core the thinner the coat. Coats range in thickness from 20 to 135 microns.

The skeletal sand fraction is the same as the other microlithology except that here it is generally less in quantity. Textural and mineralogical graded beddings are common, but matrix is generally absent. Grains are cemented by a closely packed first phase calcite cement. Both grains and cement are stained by Fe oxides.

The size and abundance of quartz sand suggest that these rocks were deposited close to terrigenous source such as estuary mouths. The lack of fine grained matrix and development of oolitic coats on sand grains suggests prolonged reworking of shoals by wave action.

Sedimentary Structures

In the field, units of subfacies B are divided into two groups according to their sedimentary structures. These are: (a) low angle foreset stratified units, (b) megaripples and trough cross-laminated units. The lithology of these groups can belong to either of the two microlithologies described above.

The low angle foreset stratification units (Fig. 3.9) consist of multiple sets of foresets bound by bedding planes dipping in the same direction with the same degree of dip; indicating repeated currents of comparable dimension depositing sets of foreset laminae.

At the base of the unit, wedges of shale layers are inter-laminated with the foreset laminae and become tangential at the lower surface, merging with the shale unit below (Fig. 3.10). Foreset units are often resting on a rippled surface (Fig. 3.12).

Foreset laminae are marked by imbricated oyster shells and flat bryozoan colonies, as well as textural and mineralogical grading (Fig. 3.11).

Horizontal burrows and tracks (Fig. 3.15) are observed on the surface of foreset laminae. Vertical burrows are also found perpendicular to and following the surface of

Photo Plate III-3

Tidal deltas

Fig. 3.9 Low angle inclined foreset of a tidal delta. The foresets are inclined southwards (landwards). Dor Zuggut area.

Fig. 3.10 Inclined tidal delta foresets show interlamination with shale at the base of the bottom sets.

Fig. 3.11 Close up of Fig. 3.35; dark laminae are silt and mud rich layers and light coloured laminae are sand rich. Oyster shells show imbrication.

Fig. 3.12 Large asymmetrical ripple marks found on the surface of units below inlet/lagoonal delta units. Jacob's staff is about 1.5 m.

Fig. 3.13 Mega-asymmetrical ripples often found at the basal subunit of inlet/marine delta. Dark laminae are shale rich, light laminae are mixed oolitic calcareous sandstone (Fig. 3.33).



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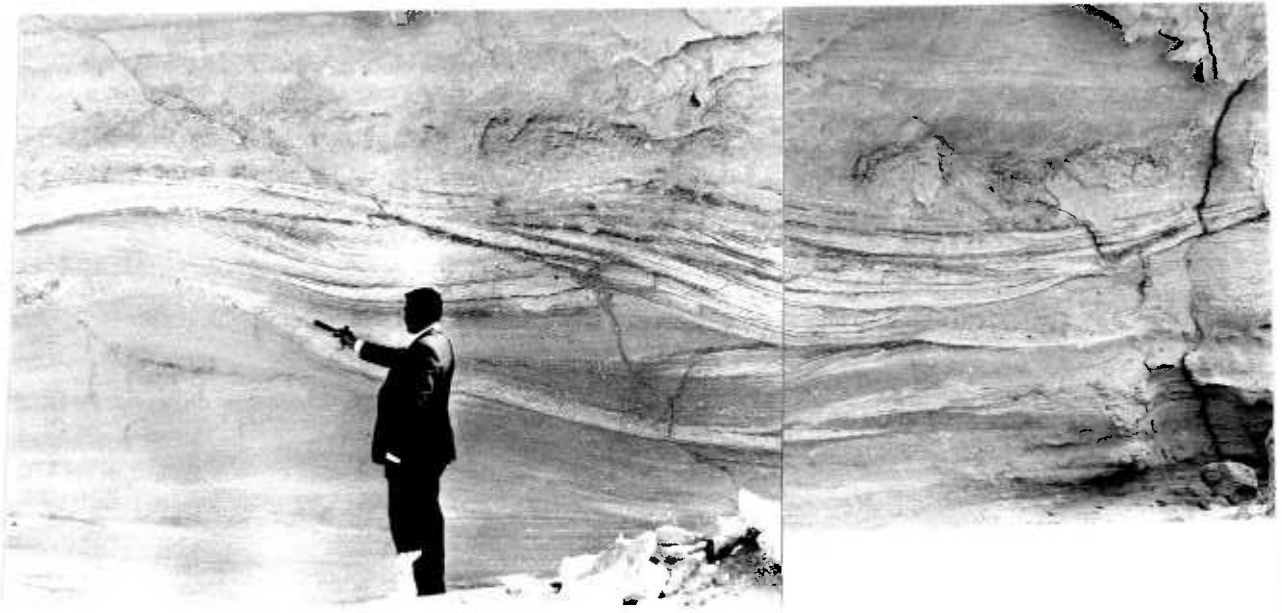
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a single foreset from the top of the unit to the base, suggesting a major break of sedimentation at a certain time during deposition. Foreset units are often truncated and reworked by channels and gullies (cf. subfacies A).

These sedimentary structures are identical to delta foresets which have been deposited in a quiet lagoonal environment (Carrigy, 1971).

The second primary structural group consists of two successive units. The lower one shows a fining-up sequence and consists of asymmetrical mega-ripples. The ripple troughs are filled with a layer of shale which thins up the ripple foresets (Fig. 3.13). This unit always contains large amounts of quartz which often forms the cores of oolitic grains. The second unit is trough cross-laminated. Sets are of erosional concave down contacts and cross laminae are tangential at the base of the set (Fig. 3.14). This unit contains more skeletal sand.

Interpretation:

The close association and similarity between subfacies (A) and (B) indicates that they are genetically interrelated. However, textures, sedimentary structures and field geometry of sunfacies (B) suggest that it was deposited as shoals in front of estuaries, tidal channels and inlets.

3.3 Vertical Profiles

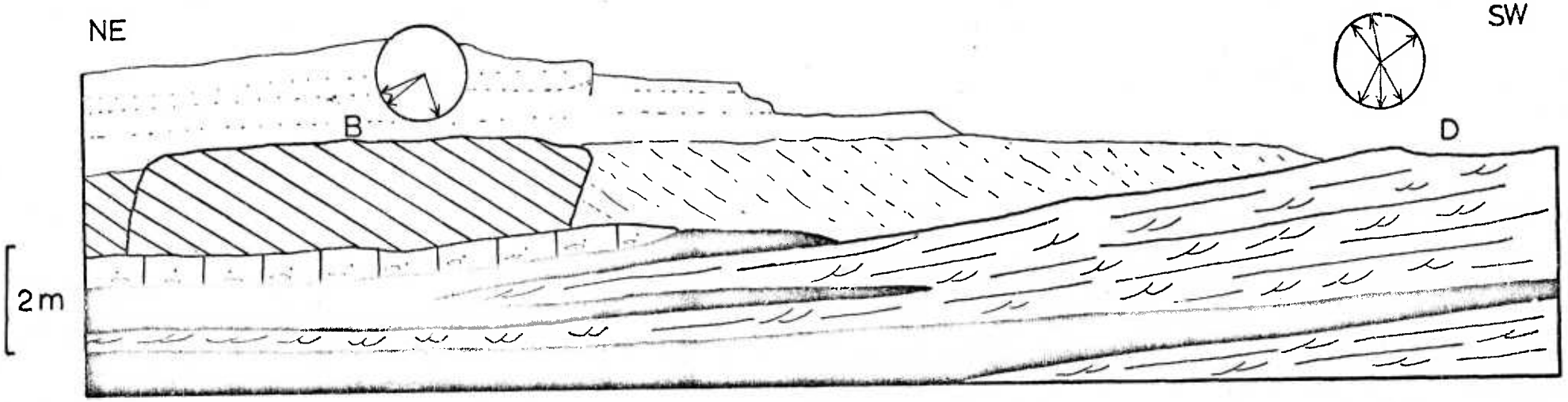
Associated with estuarine, lagoonal channels and tidal inlets are a group of rocks deposited as shoals. This facies associations are interpreted here as tidal delta deposits of the Marada Formation. Two major tidal deltas are recognized: (a) estuarine delta, and (b) inlet deltas.

3.3a Estuarine-lagoonal ebb delta:

This type of estuarine delta (Plate 3.2) is exposed at the base of section D7. It forms a wedge-like body of calcareous sandstone organized in a low angle set of foreset units either consisting of laminae or small scale cross laminae. Foresets are cut by calcareous sandstone channels. The palaeocurrent reading on the cross lamination is generally bipolar with a predominant northwards influence. Northwards the wedge interfingers with lagoonal facies (Plate 3.2). The latter is being overlapped by a unit of cross bedded grainstone facies which shows southward palaeocurrent direction.

Elsewhere in the Marada area, similar tidal deltas consist of low angle foresets of dolomitized sandy grainstone. Laterally the foresets are cut by a trough cross laminated friable calcareous sandstone. The former shows a northwards palaeocurrent direction, whilst the latter's current directions are bipolar.

Plate 3-2. Diagram of cross section & panorama showing Estuarine - Lagoonal Tidal Delta (D) facies being Overlapped by Barrier Bar (B) facies, Section D7.



Horizontal distance = 50m.



From the field relations of the various facies involved it may be concluded that the estuarine deltas were deposited behind the grainstone body in a lagoon.

Bates (1953) demonstrated that when a river or a stream enters a lake or shallow embayment, the salt water is flushed out due to influx of the fresh water. Under such conditions three-dimensional mixing permits deposition to take place immediately off the stream mouth with the result that the outflow is blocked. Under such conditions a mound of river water is formed just outside the river mouth and forces away all basin beneath the mound and the vertical boundary between river and basin water is slowly spread radially away from the orifice as more river water is introduced.

The vertical boundary concept requires that the homopyenal inflow develops partly subaerially, flat topset beds flanking the stream channels, which change gradually into foreset beds resting at an angle of repose immediately outside the distributory mouth. However, there is a limited deposition of fine grained material in the deep part of the basin as a thin bottomset (Bates, 1953).

Bates' model does not fit the Marada estuarine lagoon/delta for the following reasons: (a) the salt water in the lagoon was never completely flushed out, as indicated by fauna;

(b) the channel mouths were open as indicated by the bipolar current readings; (c) the delta foreset beds show low angle of dip less than the angle of sediment repose; and (d) the high proportion of fine grained sediments in the lagoon.

On entering a denser salt water body, the flow from the stream does not mix in the vertical plane but tends to spread out horizontally. This results in a wider dispersal of sediment and hence the lower angle of slope for the foreset beds than in the fresh water body (Bates, 1953). Another effect of salt water on the suspended load is to flocculate the clays and organic matter, which results in poorer sorting. Owing to the lower energy of the destructive forces in the lagoonal environment, the seasonal variations in the sediment load of streams are likely to be recorded as rythmic succession of sand and fine grained fractions, as well as cyclic sedimentation in the lagoon floor. These features are commonly preserved in the estuarine delta and the lagoonal facies of the Marada Formation.

During dry seasons, deltaic and lagoonal sedimentation stopped and as the sea transgression proceeded it pushed the cross-bedded carbonates landward over the lagoon, and drowned the deltaic channels, producing sedimentary structure indicating landward current direction. In the following wet season older channels were re-opened and younger ones cut across and reworked the older delta and the shallow lagoonal floor, and a new delta

prograded over the older one. As a result of fast sedimentation the new barrier is built further seaward as the lagoon widened. Reworking of the older barrier facies by lagoonal channels is certain. Therefore the younger estuarine deltas contain more skeletal sand than the earlier ones.

The Miocene estuarine deltas are similar to the Holocene Guadaloupe delta of Texas (Donaldson et al, 1970), which was formed in a glacial valley after it was drowned during the postglacial times as the rise of the sea level formed San Antinio Bay behind the Barrier Island. If one assumes a gradual rise in the present sea level to allow progradation of the barrier island over the San Antonio Bay, then one would expect drowning of the channels and reworking of the delta top. Also, estuarine conditions would prevail in the Guadaloupe River. Barrier island and younger lagoonal sediments would protect the estuarine delta from later destruction.

3.3b Inlet deltas:

Inlet tidal deltas are sand shoals formed on both sides of a barrier as the sand is swept in and out of the inlet by tidal currents (Davis, 1957; Price, 1963). Currents flow through tidal inlets as a result of sea level changes on both sides of the barrier, which in turn is a result of astronomical tides, stream discharge in the lagoon, wind tides or wave effect

on the inlet. For the higher sheet of water to get through the inlet, it must drain centripetally into it along all unobstructed radii, and issue in a flare-like horizontal jet on the other side of the barrier (Price, 1963). As a result of concentration of energy through the inlet, thus it occupies a deep trough with a maximum depth compared to the much shallower lagoonal floor described earlier. It has been noted in the Dutch tidal flats that the flood tides and specially at the turn of the tide following the flood, are an agency of deposition, whilst the ebb tides are typically an erosive flow (Straaten, 1954).

Two vertical profiles are interpreted here as inlet deltas. These are:

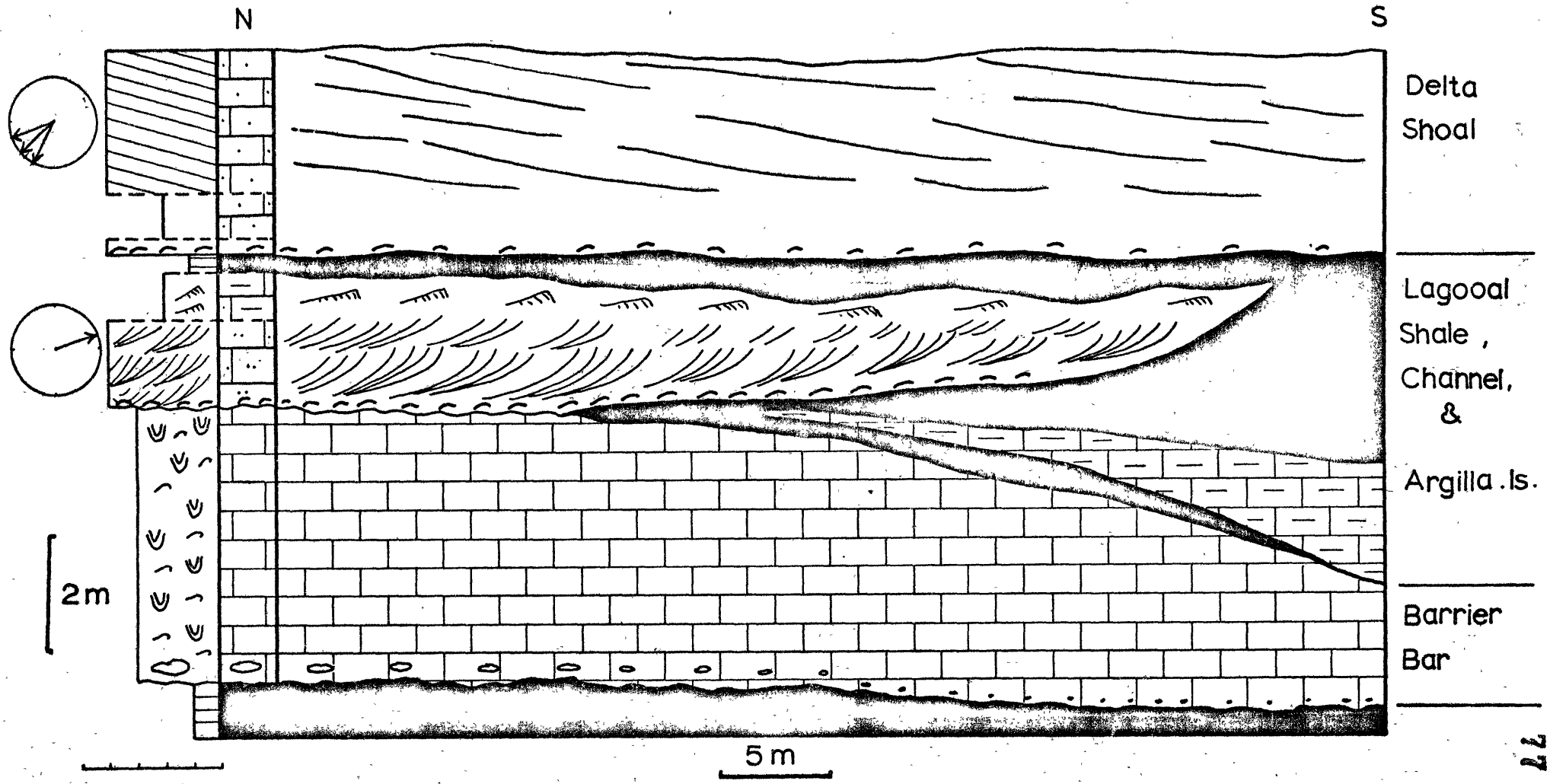
i) Inlet lagoonal deltas (flood deltas).

ii) Inlet marine deltas (ebb deltas).

i) Inlet lagoonal delta (flood delta)

The type section for inlet lagoonal vertical profile is exposed in section M3 (Plate 3.3). It consists of a lower unit of skeletal packstone of the barrier bar facies overlain by a sandy skeletal grainstone unit of the inlet facies. Both units pinch out southwards along the outcrop face and interchange with lagoonal facies. The lagoonal and tidal inlet facies are overlain by low angle inclined foreset units of

Plate 3-3. Stratigraphic Cross Section of Inlet - Lagoonal Tidal Delta, Section M3.



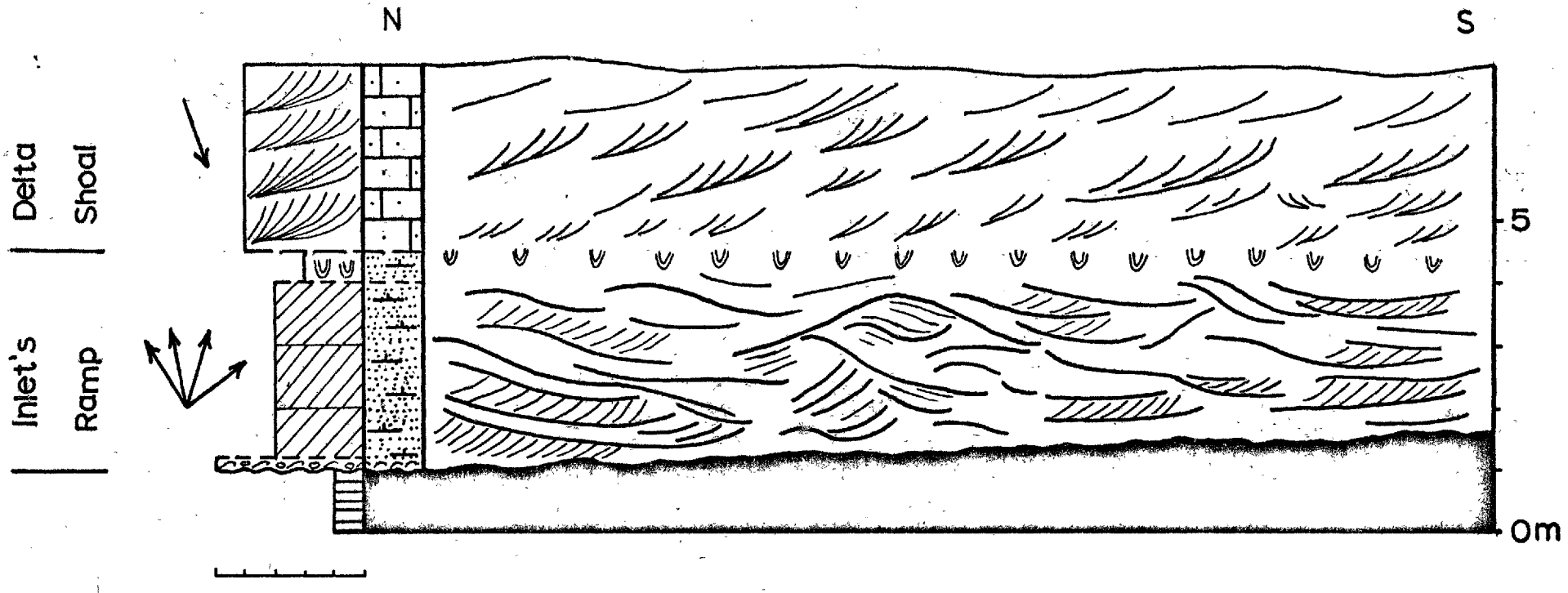
shoal facies. Sedimentary structures of the inlet and shoal unit indicates north and south palaeocurrent directions respectively. Elsewhere, other vertical profiles consist of lagoonal and shoal units, where the latter is truncated by channels which indicate the opposite current direction.

ii) Inlet marine delta (ebb delta)

Vertical profile of an ebb delta facies (Plate 3.4), like flood deltas, often occur on top of the barrier facies. Sedimentary structures of shoals indicate northerly palaeocurrent direction. Most ebb deltas vertical profiles, however, do not show barrier facies. Instead, they show a fining-up sequence of mega-rippled oolitic grainstone (Fig. 3.14). The sandy shale unit at the base of the profile is similar to the lagoonal subfacies 2. Sedimentary structures indicate northerly palaeocurrent readings at the lower unit and southerly on the upper. This sequence is similar to the estuarine delta vertical profile except the shoal of the latter shows low angle foresets.

The fining-up sequence and sedimentary structures of the lower unit indicate deposition by a lateral migrating channel. The trough cross lamination in the skeletal grainstone unit may indicate deposition as a result of migration of ripple forms. The vertical profile also suggests that ripple forms must have existed on the channel banks, the overlap of the two units was in response to lateral channel migration.

Plate 3-4. Stratigraphic Cross Section of Inlet - Marine Tidal Delta's Vertical Profile.



See details in fig's. 3-38, 39.

A similar set-up is described by Oertel and Howard (1972) at inlet entrances on the coast of Georgia, U.S.A. They indicated that the seaward extension of a tidal inlet (ramp) though shallow, consists of coarse to fine sane interbedded with layers of mud, whilst the ramp's trough has a veneer of coarse sand and granules. Ramps are flanked by shoals (tidal deltas) of asymmetrical ripples which have a steep slope towards the channel (Hoyt and Henry, 1967). Away from the ramp the shoals generally slope at an angle less than 10 degrees. These authors (Hoyt and Henry, 1967; Oertel and Howard, 1972) indicate that shoal morphology, orientation and channel migration are controlled by water circulation near the inlet in response to winds, currents and tides.

It is thought that Marada inlet marine deltas were formed during the wet seasons when the water level in the lagoon became higher than the sea level as a result of the influx of water from the estuaries and fast sedimentation in the lagoon.

3.3c Dolomitization of the cross-bedded sandy grainstone facies

Source of Material (Fig. 3.16)

Section C2 in the Central Jebels area (near Zelten oil field) shows a complete sequence of an estuarine tidal delta. The de shoal unit is 6 metres thick and consists of a tough yellowish br

(10 YR 5/4) foreset beds of sandy intra-skeletal packstone. Sets of foreset beds are gently inclined in a northerly direction and palæocurrent readings spread over 60 degrees.

Grainstone Framework (Photo Plate III-9)

In thin section the rock appears ill sorted (Fig. 3.18) with grain size ranging from silt to complete oysters. Skeletal grains belong to a worn echinoid, bryozoa, small gastropods and oyster shells. Iron stained and bored lime mudstone pebbles and pellets are the non-skeletal carbonate grains. Medium sand size quartz grains represent up to 30 per cent of the grainstone framework.

Cement and Matrix

The grain framework of the rock is cemented by closely packed dolomite crystals which project from the surface of the grains into the intergranular pore spaces. These crystals are arranged in a uniform rind 20-30 microns thick (Figs. 3.19, 3.20). The morphology of the original calcite cement has been completely obliterated.

The intergranular pore spaces are partly occluded by loosely packed dolomite rhombs up to 65 microns in diameter (Fig. 3.17). Also, mouldic porosity of the dissolved aragonite shells are

Photo Plate III-4

Tidal deltas

Fig. 3.14 Cross bedding found in the inlet/lagoonal upper subunit (above Fig. 3.38).

Fig. 3.15 Animal tracks on low angle foreset surface.

Dolomitization of sandy grainstone facies

Fig. 3.16 Low angle foresets of an estuarine/lagoonal delta, which exhibits dolomitization.

Fig. 3.17 Sandy grainstone pore spaces are filled by coarse dolomite rhombs (NL-X10).

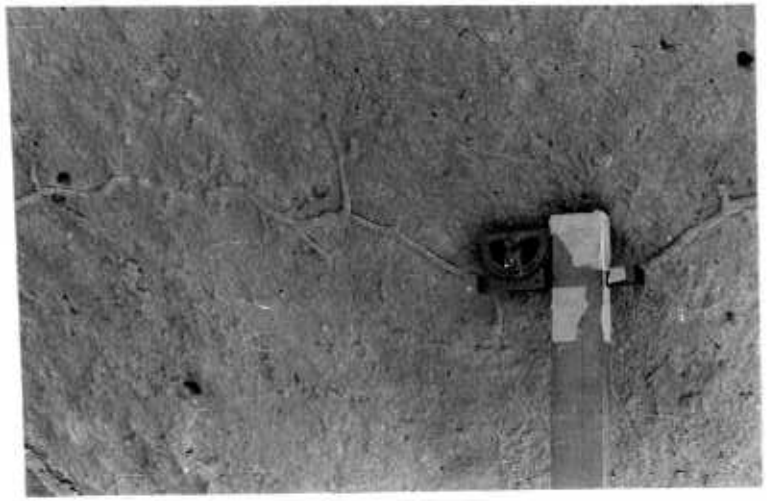
Fig. 3.18 General view of the sandy packstone with dolomitised matrix (XN-X3).

Fig. 3.19 The pellet and the first phase of cement (against the shell) are converted into fine dolomite rhombs, the porespace is filled by coarse dolomite but the oyster shell (originally low Mg calcite) remains unaffected (XN-X10).

Fig. 3.20 The first and second phase of cement are converted into dolomite but the shell fragment (right) and lime mud interclast (left) are unaffected). (XN-X10)



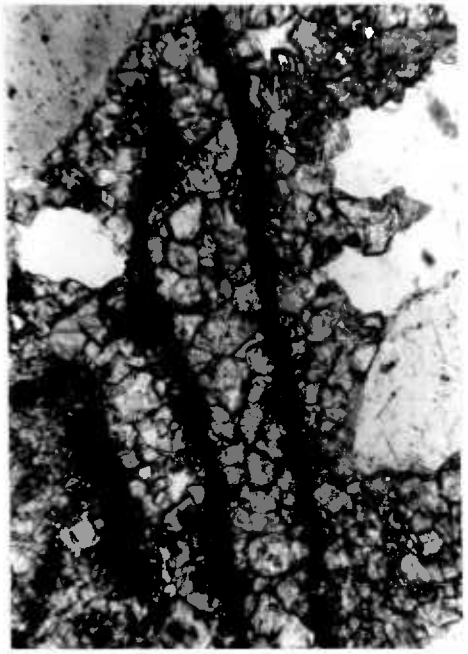
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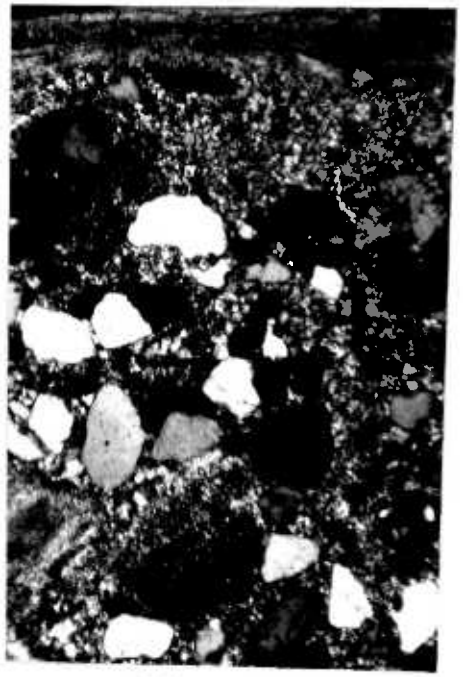
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completely occluded by dolomite rhombs similar to those filling the inter-granular pore spaces. Pellets and lime mud matrix have also been replaced by 15 to 25 micron dolomite rhombs (Fig. 3.19). Calcite shells and interclasts (Figs. 3119, 3.20 are not affected by dolomitization.

Discussion

The estuarine delta in section C2 is a part of a large deltaic shoal body which changes southwards into a major calcareous sandstone estuarine channel and interfingers northwards with barrier bar facies (see N-S facies cross section). The facies interrelation suggests that the deltaic shoal was formed in response to a major estuarine influx into the Marada lagoon. A fast rate of sedimentation may have created a state of local regression in the area, and subsequent intertidal lithification of the top of the delta. As the lagoon became shallower supratidal conditions were established on the top of the shoal. Under these conditions dolomitization of inter and intragranular pore filling calcite and fine grain material must have taken place.

Muller and Tietz (1971) described a similar diagenetic feature from the supratidally exposed Pleistocene beach rocks of the Canary Islands. In these rocks, the first phase of

cement is converted into dolomite whilst the sedondary pore filling cement as well as calcitic allochems are not affected. Thus one can explain the difference between the dolomite crystal size of the Marada first phase of cement (15-25 microns) and the cavity filling (65 microns) respectively.

As suggested by Müller and Tietz (1971), the occasional flooding of supratidal beach rocks by heavy seas would leave sea water ponds on the calcarenite surfaces. Thus, evaporation and concentration of brines (increased Mg/Ca) would percolate through the porous rock causing dolomitization.

3.4 Palaeocurrents of the cross-bedded Sandy Grainstone Facies

Palaeocurrent rose diagram of the cross-bedded sandy grainstone facies (Plate 3.1) indicates a general bipolar current direction. The northwards currents are spreading over 160 degrees with a NNE major component (20 per cent). The southward spread is relatively smaller (120 degrees) and less in number (maximum 11 per cent). The northward direction reflects the strength of the ebb flow.

3.5 Interpretation and Discussion

The cross-bedded sandy grainstone facies of the Marada Formation show a positive correlation with the calcareous sandstone facies exposed in Jebel Zelten. They also show a

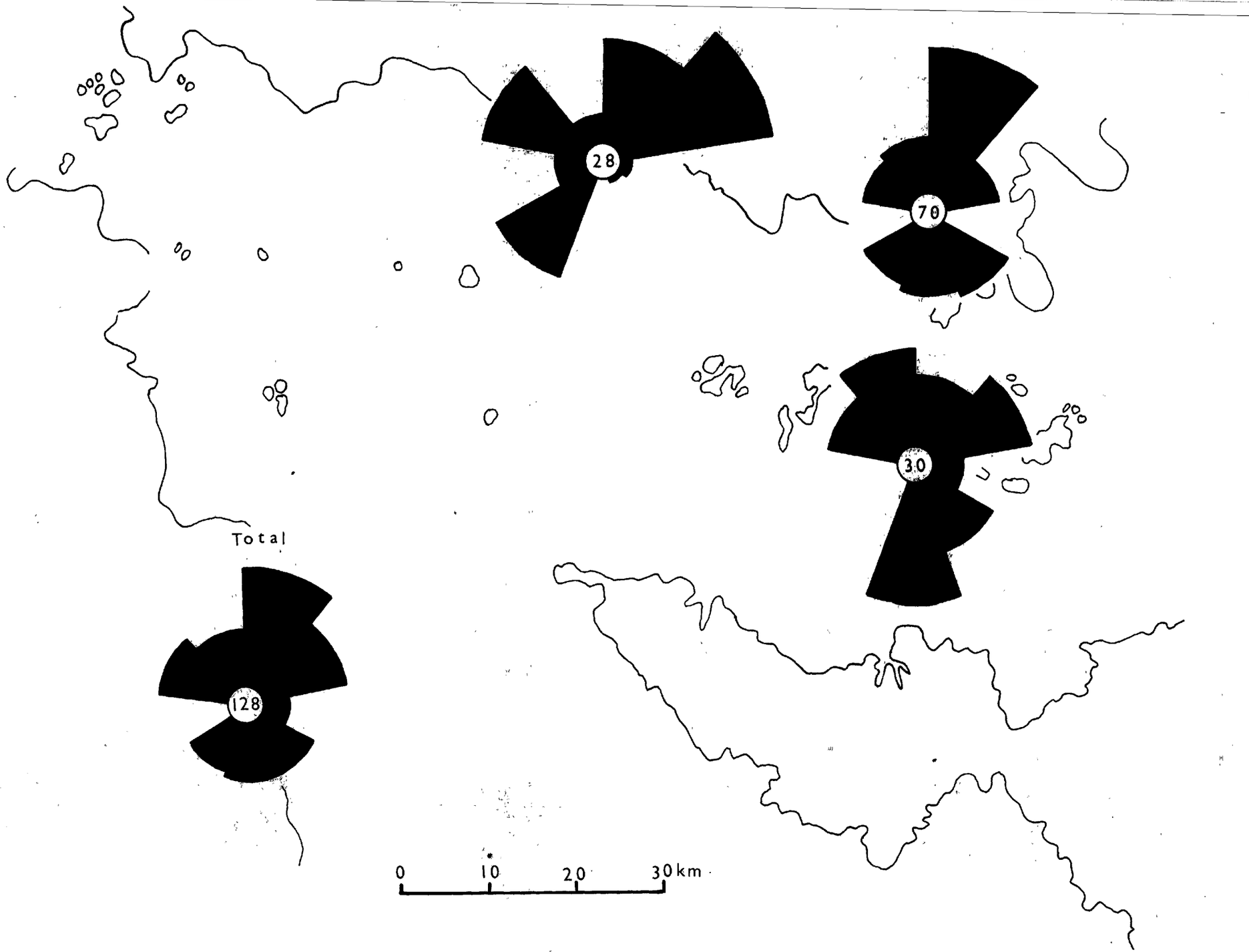


Plate 3-1 Palaeocurrent distribution in the sandy grainstone facies.

close relationship to the cross-bedded grainstone and laminated facies to the north. Reworking of the grainstone bodies by lagoonal channels and tidal inlets have contributed towards the increase of the skeletal sand and the decrease of the terrigenous material in the sandy grainstone facies. Deltaic shoals were formed as a result of the alternating influx of sediments from the land and sea, in front of estuaries and inlets. The textural and mineralogical rhythmic sedimentary pattern described in this facies corresponds to that found in the laminated shale facies. They reflect the oscillation of energy and alternation of the sediment sources during deposition. Palaeocurrent data, however, indicate that seaward current transport is by far the dominant.

Upon rise of the sea level, estuaries were developed as a result of river mouth drowning. During the wet season, tractive and suspended loads were carried through the estauries to be deposited in the lagoons. Part of the tractive load was deposited at the mouth of the estuaries as major estuarine deltas, and the suspended load was carried further towards the lagoons' centre. Lagoonal sediments graduated from sandy near deltas and channels into muddy further down. With the increased influx of the estuarine sediments and water, lagoonal channels by-passing the deltas cut across the lagoonal floor and the presumed barrier (grainstone bodies) through inlets. Inlet

deltas were thus built. As the sediment-water influx decreased, the lagoonal water cleared and oyster banks started to grow.

During the dry season, as the water salinity increased the marine life appeared in the deeper part of the lagoon, and carbonate productivity increased in the protected embayments. Tidal activity became more prominent and ebb currents then built ebb deltas in the lagoon, and established marine influence in channels. Delta shoals that formed in the lagoons show low angle foreset beds, whilst those formed in the marine areas show trough cross-bedded sets indicating the difference of energy levels on both sides of the barrier. Finally, filling of the lagoon is indicated by the lithification of the deltaic shoals, dolomitization of their cement under supratidal (elevated beach rock) conditions.

The deltaic sandy grainstone facies were not recognized by the previous authors; they were either interpreted as barrier bars (Selley, 1966, 1969), or as estuarine channels (Selley, cit.op.); Doust, 1968). Also, tidal deltas are rarely described from ancient sediments; however, only their morphology and surface sediments are described from the recent environments.

CHAPTER 4

THE CROSS BEDDED SKELETAL GRAINSTONE FACIES

4.1 GENERAL

The cross bedded grainstone facies units occur inter-bedded with the laminated shale facies, below the Echinolampas key bed in the Marada Formation. Units of this facies always overly the laminated shales, truncated by cross-bedded grainstone shoestrings and overlain by dolomitic mudstone and/or wackestone facies. This facies units are 3 metres thick on average, but some units are 9 metres thick. Exposed in section M2, a compound sequence of this facies is about 20 metres thick.

The underlying shale facies consist of inter-laminated shale and sandy silt subfacies, which is often interbedded with washouts of skeletal grainstone (Fig. 4.5). The lower contact of the units is erosional and often bio-turbated (Fig. 4.4); load casts are also common. Units geometry appears lenticular; bodies are discontinuous or connected to each other by shallow troughs. The upper boundary of the bodies is gently concave upwards along outcrops parallel to the depositional strike (Fig. 4.1). Along the sections perpendicular to the strike the upper boundary is asymmetrically concave up, with northward gently inclined (5-10 degrees) and southerly inclined (15-25 degrees) surfaces (Figs. 4.2, 4.3).

Photo Plate IV-1

Cross bedded grainstone facies (barrier bars)

Fig. 4.1 An outcrop showing the lenticular geometry of a barrier bar. Depositional strike section.

Fig. 4.2 Barrier bar, outcrop perpendicular to depositional strike. The man is standing on the northwards face of the bar.

Fig. 4.3 The same as in Fig. 4.2. The top boundary of the barrier bar is exhumed as a result of erosion of the soft encasing shale. It shows the seaward and landward slip surfaces. Cross bedding shows a northward inclination (hammer to the right of centre).

Fig. 4.4 The lower contact of the barrier bar unit with the lagoonal shale is erosional and bioturbated (hammer to the lower right of centre).









The small bodies appear to have been exhumed by erosion and field relations indicate that they are laterally encased in shales. Because the body is enclosed in more easily eroded material, its present dimensional proportions are taken as being about the same as before exhumation. They are about 150 metres long, 50 metres across and about 4 metres thick. It is hard to determine the exact scale of the larger bodies in the field due to truncation by channels and erosion of their upper boundaries. However, large bodies of the cross bedded grainstone facies when correlated appear lenticular and measure up to 50 kilometres in length, 25 kilometres in width, and 16 to 20 metres in thickness. These bodies are connected to one another through sheets averaging 3 metres in thickness (see regional correlation sections).

4.1.1 Lithology

The cross bedded grainstone facies appear in outcrops and samples, very porous, moderately indurated, and when rubbed they produce powdery material. They are white (N-9) to very pale orange (10 YR 8/2) in colour. In vertical profile units show a gradual upwards decrease in the amount of the lime mud and silt content, and also show a general increase of sorting and general grain size. In some places, the unit's top is often occupied by oyster shell bank (Fig. 4.6), coral heads, and/or red algal domes and encrustation.

Two sub-units are recognized in this facies; a massive and bioturbated lower sub-unit of intra-skeletal wackestone subfacies (Fig. 4.4), which consists of rounded pebble and flat boulder size skeletal grainstone and lime mudstone, red algal biscuits and oncolites, as well as complete oyster shells. The sand grains consist of echinoids, bryozoa, molluscs, crustacea, worm tubes (Fig. 4.13) and calcareous algal fragments. The non-skeletal material consists of quartz sand, silt and shale chips; occasional oolites and coated grains are also found. The grain framework is floating in a matrix of mixed lime and terrigenous mud and silt (Fig. 4.13). This subfacies has been reworked by burrows which often produce mottled texture. Burrows are sometimes filled by secondary gypsum and celectite which often replaces the fine grained matrix (Fig. 4.13).

The upper sub-unit consists of well to moderately sorted, cross bedded grainstone and packstone. The skeletal grains are of pebbly, coarse to very coarse sand size. They consist of variable amounts of complete and broken shells of bryozoa (Holoporella, Trigonopora, Idmonea), echinoidal spines and plates, benthonic foraminifera (Miliolidae, Peneroplidae, e.g. Boralis melo, Spirolina sp, Dendritina sp, etc.), Mollusca (gastropods and bivalves), calcareous algae (Dasycladaceae, Codiaceae, and red algae).

Similar faunal assemblage is described from the Marada Formation (Doust, 1968), and its time equivalent near the Egyptian border, Al Jaghbub Formation (Bellini, 1968; Annoncia, 1968).

Interclasts, algal oncolites and pellets are not uncommon. Most grains, however, have a rind of variable thicknesses of fine grained material (Figs. 4.7, 4.8) which were produced as a result of algal boring (Fig. 4.7) (Bathurst, 1966), or algal encrustations (Fig. 4.8), or both. These features are discussed in greater detail in a later part of this text.

The intersticies of the packstones are partly (Fig. 4.11) or completely (Fig. 4.12) filled by internal geopetal sediments. They were deposited preceding the first phase of cement (Figs. 4.10, 4.11, 4.12), which may suggest infiltration into a previously fine grained free sediment (Dunham, 1962). Patchy distribution of the fine grained material, however, is probably due to mixing by burrows (Dunham, 1962; Purser, 1972). The geopetal sediments consist of pellets (Fig. 4.10), calcareous silt (Fig. 4.11), or mud (Fig. 4.12). Pellets are rounded and oval in thin sections, and appear to be well sorted. Individual pellets are 5 to 58 microns in diameter and in a few places they show graded bedding. The geopetal silt is also well sorted and consists

Photo Plate IV-2

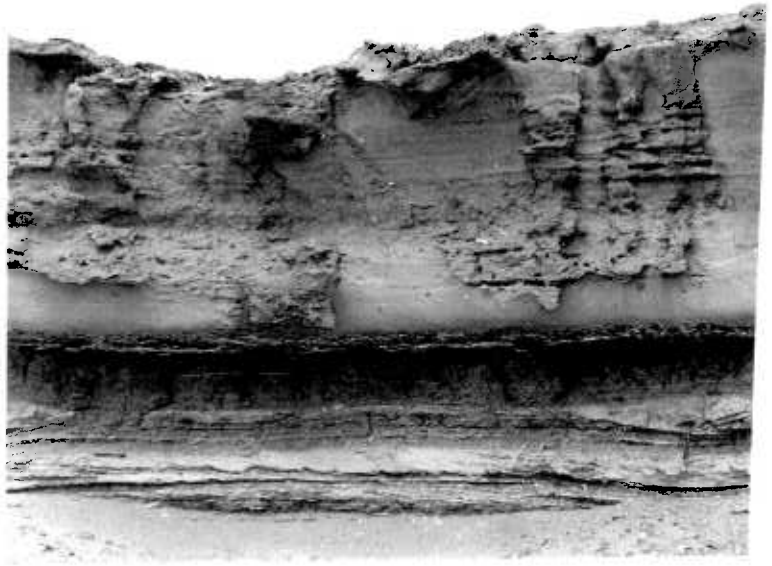
Fig. 4.5 The shale below barrier bar unit is interbedded with cross bedded grainstone washouts.

Fig. 4.6 A bed of small oysters (in growth position) occupies the top of a cross bedded grainstone unit.

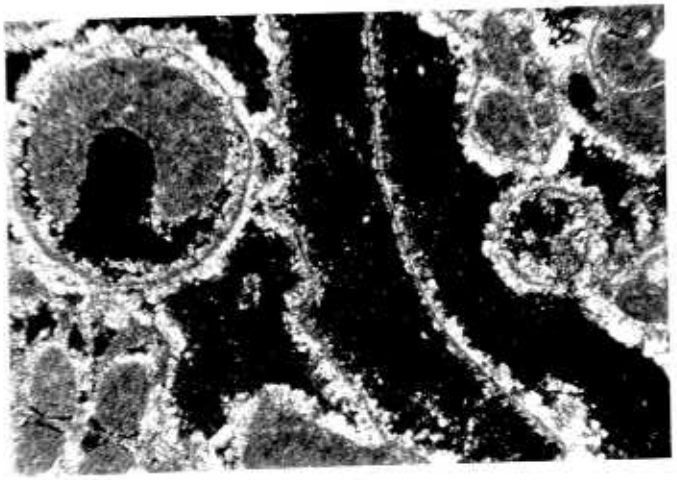
Fig. 4.7 Microphotograph of grainstone. Note isopachous fringe cement surrounding the skeletal grains. The mouldic pore spaces are either left open (centre) or partly filled (gastropod shell) (XN-X3).

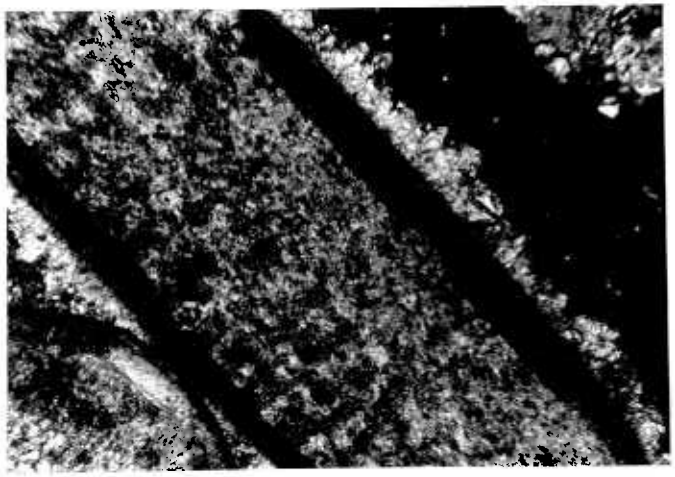
Fig. 4.8 Echinoid grain is encased by a thick algal envelope. Note bladed fringe cement (XN-X10).

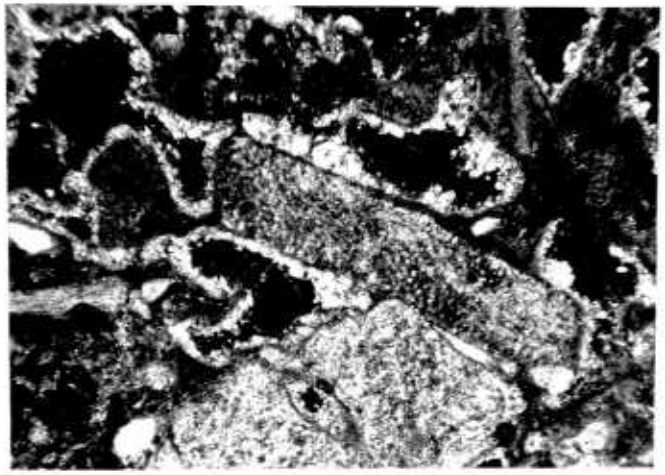
Fig. 4.9 Cryptocrystalline cement encases the skeletal grain and extends to grains made of similar material (left of centre), which often shows traces of algal structure. Cryptocrystalline cement contains fine skeletal and quartz grains (left). It is followed by a layer of clear fringe calcite cement (XN-X3).











of 5-10 microns of calcite mosaic; close examination suggests the presence of a fuzzy outline of silt size pellets. It is difficult to judge if the silt is the result of recrystallization of lime mud or not. However, sorting and geopetal texture strongly suggest detrital origin of the original sediment. Some internal geopetal lime mud (Fig. 4.13) appears as a dark clotted texture which freely absorbs the malachite green stain (of the plastic impregnation). It also contains algally bored fine skeletal grains as well as quartz grains. These features suggest the abundance of organic material in the lime mud. It is thought that they were probably produced by the disintegration of the algal material, and were either deposited with the skeletal sand or were later introduced as a result of mixing by burrows.

Cement: The intergranular pore spaces are lined with a regular rind of calcite cement which ranges in thickness from 35 to 45 microns and reaches up to 60 microns in some cases. Smaller intergranular porespaces are often completely filled by calcite mosaic (Fig. 4.10), the larger ones are always left open.

The calcite cement fabric is either fibrous or bladed. The fibrous cement is often replaced by the bladed fabric, ghost of the original fabric is often observed. Echinoid

grains show syntaxial overgrowths with zig-zag outlines (Fig. 4.12). In some cases the echinoid grain overgrowth was inhibited due to the presence of algal jackets.

Aragonitic shells of gastropods and bivalves were leached out, forming mouldic porosity (Figs. 4.7, 4.11), now supported by micrite envelopes and algal jackets. Generally moulds are left open, but lined with irregular fine drusy calcite

Micrite cement is not uncommon (Fig. 4.9) in the grainstones. It consists of a dark clotted micritic material which often contains fine skeletal fragments as well as quartz grains. It completely encases the skeletal grains, and is connected to nonskeletal micritic grains by protrusions of the same material. Algal cellular structures are often found on close examination of the cement and grains.

Cementation of the grainstones may have taken place under intertidal or subtidal conditions. Shinn (1969) reported lithified skeletal grains found six to ten feet below the mean sea level in the Persian Gulf; carbonate sediments are cemented with mosaic calcite, acicular aragonite and high Mg micritic cement. Taylor and Illing (1969); Friedman and Gavish (1971); and Moor (1973), reported fibrous, bladed and

micritic cements from the recent intertidal and beach rocks of the Persian Gulf, the Mediterranean, and the West Indies respectively.

4.1.2 Sedimentary Structures

Cross-stratified sets of the skeletal grainstone facies range from 50 cm to 6 metres in thickness. Most units consist of one or two sets. A positive correlation between thickness of individual sets and thickness of their respective crossbeds is evident. Small bodies have thin cross beds (Fig. 4.15), and large scale bodies have thick cross beds (Fig. 4.16).

The small scale bodies consist of trough-like cross-stratified units (Fig. 4.14). They are shallow and symmetrical where the width of the trough is greater than the depth. The plane view traces of the foreset beds show a very gentle concavity in the direction of inclination. Troughs appear truncating as well as truncated by inclined sets of the adjacent trough's wings (Fig. 4.15). At several localities the grainstone bodies consist of a single set of a uniformly inclined cross beds (Fig. 4.16), but often two sets of cross beds are inclined in different directions and constitute the units (Fig. 4.15). Often cross beds show a graded bedding.
Generally, the northward inclined foresets dip 5 to 12 degrees, and the southerly inclined foresets dip about 16 to 20 degrees.

Photo Plate IV-3

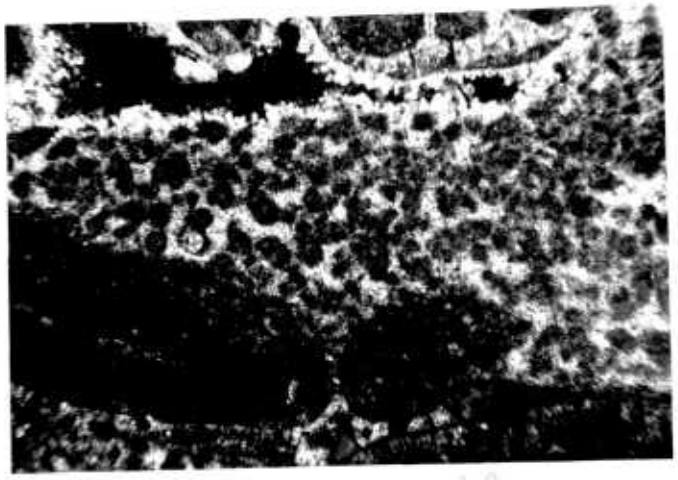
Fig. 4.10 Interstices of the packstone is floored by well sorted pellets (XN-X3).

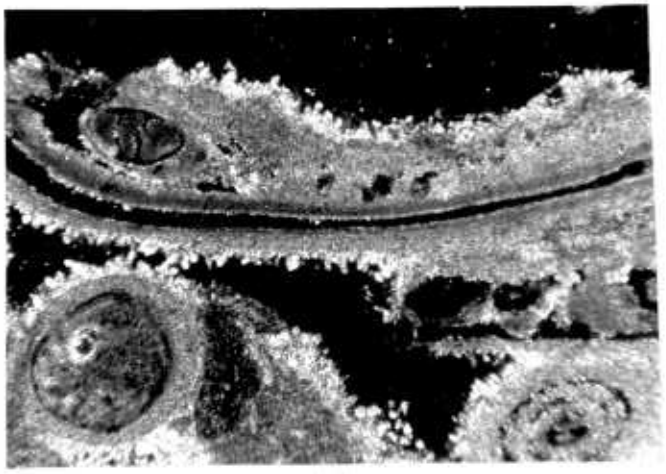
Fig. 4.11 Same as in Fig. 4.10. Geopetal sediment consists of calcareous silt (XN-X3).

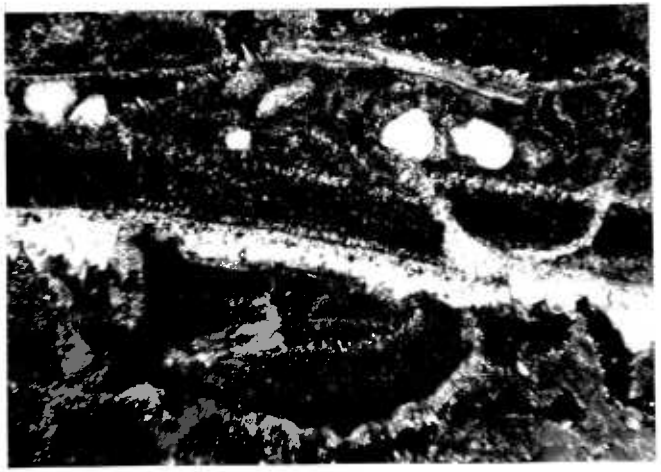
Fig. 4.12 The same, but geopetal sediment consists of a dense cryptocrystalline mud, and fine skeletal and quartz grains (XN-X3).

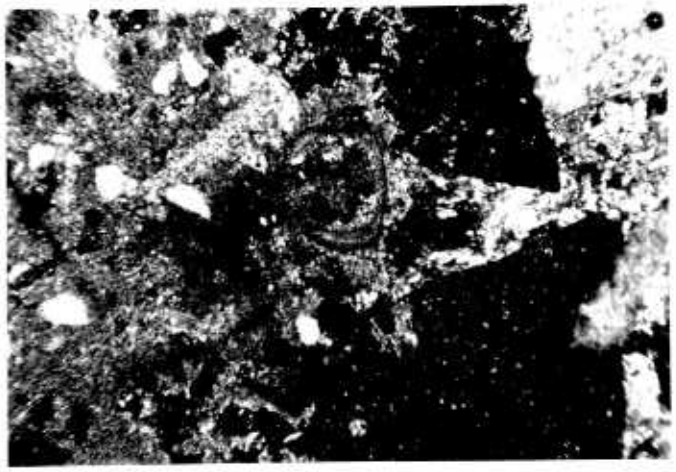
Fig. 4.13 Wackestone from the base of barrier bar unit, containing skeletal and quartz grains, calcareous worm tube (centre), and lime mud and silt matrix. Burrows are filled with a secondary celestite (lower and upper left), and gypsum (centre left) (XN-X3).

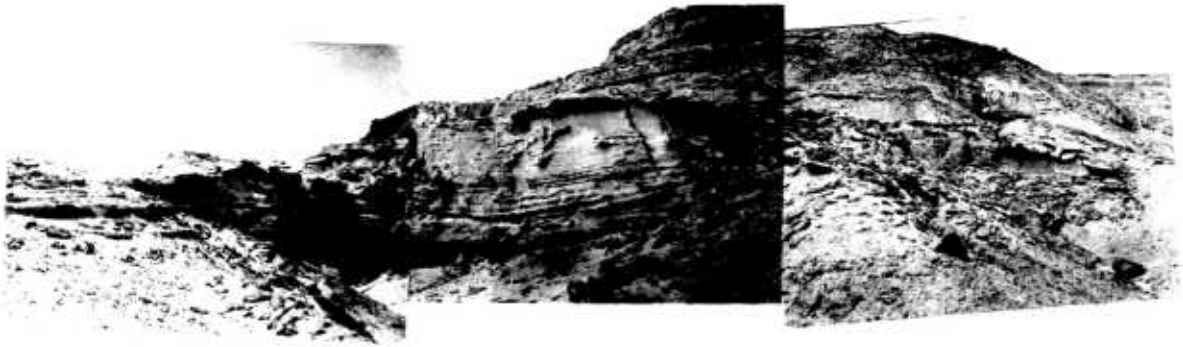
Fig. 4.14 A panorama of cross bedded grainstone showing wide gently inclined troughs. A man is standing just left of the centre.











Some units show low angle inclination in both directions. Thus the northward dip is significantly less than the mean of the southerly inclination angle. Both of these slope angles are less than the approximate 30 degrees angle of repose of medium sand size under the condition of ripple lee side avalanche deposition (Bagnold, 1956). It is thought that the movement of material down the lee slopes of the sand waves was accomplished by the action of tractive force exerted by the downslope components of current flow, as well as the influence of gravity. Hence the combination of graded grain size and low angle inclination ($<$ 30 degrees). Subtidal accretion ripples and dunes in the Bahamas (Imbrie and Buchanan, 1965) are formed by bottom traction during storms and hurricanes, and often have lee slopes less than the angle of repose. Cross laminae produced are half avalanche, half accretion and show low angle of dip.

The large scale cross bedded units have foreset beds that are tangential to the unit below them (Fig. 4.16) as well as in troughs separating two adjacent bodies (Fig. 4.17). The lower contact of the units with the underlying shale appears bioturbated. The amount of lime mud and silt in these foresets is generally greater than those in the smaller scale bodies. Also, the terrigenous mud and silt lines the surfaces of the

foreset beds at the base of the units, and specially in the troughs (Fig. 4.17).

Units consist of large scale cross beds with tangential basal contact. On the outcrop the basal toesets appear to be smoothly curved; they dip between 0 to 10 degrees, which changes gradually to 24 degrees up the foresets' surface. Most foresets of the large scale bodies are inclined northward; opposing inclination directions are only found in the troughs between bodies.

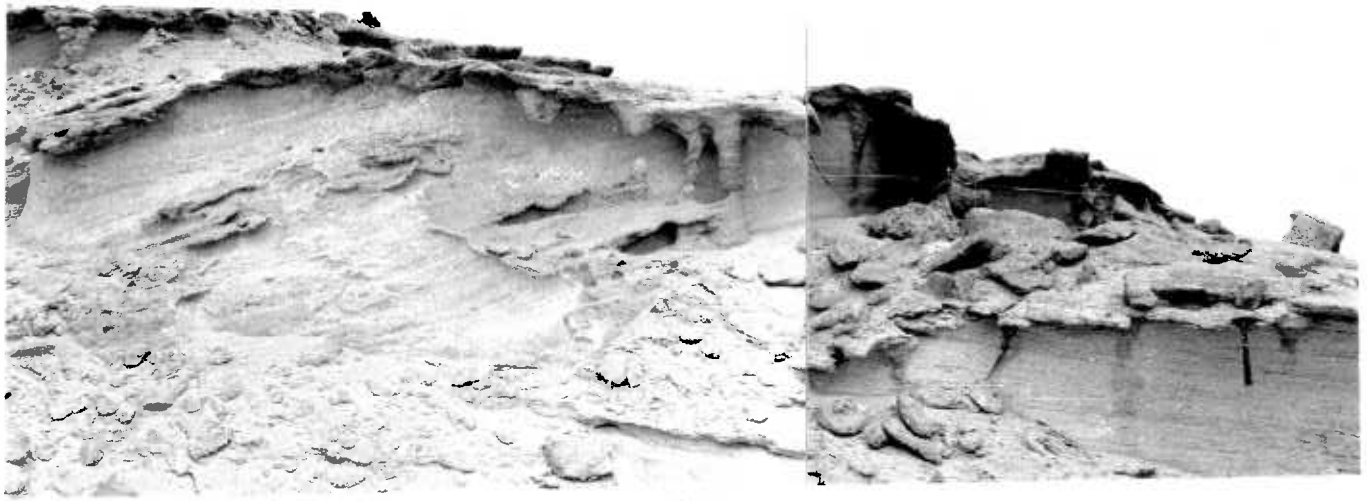
Bioturbation at the basal toesets indicates effective suspension transport. This is supported by the general distribution of grain size in the unit. Toesets and troughs have an extensive silt and clay size component of calcareous and terrigenous origin. In contrast, foresets are composed of fine to medium sand size skeletal grains as well as lime mud and silt (packstone). The almost total by-passing of the foreset by the fine-grained components indicates separation of sediment load into bed load and suspended load components.

Jopling (1965) has concluded from experimental studies that the development of tangential contact between the foreset and bottom sets is primarily dependent upon the amount of material transported in suspension. With an increase of the suspension transport, a greater proportion of material is carried

Photo Plate IV-4

Fig. 4.15 A cross bedded grainstone unit showing oppositely inclined foresets; those to the left are inclined at a higher angle than those to the right, but either show less than 30° inclination (notice the hammer to the right).

Fig. 4.16 Large scale cross bedded grainstone unit; its lower contact with the shale is bioturbated (left) and gradational (right). The foresets are tangential at the base (far right) and increase in dip towards the top of the unit.





beyond the foreset slope and deposited in the toeset section forming a tangential contact. An additional factor in the formation of the tangential contact is the depth ratio (the ratio of depth of stream to the depth of a basin; Jopling, 1965). A large depth ratio (basin shallow relative to current) would produce a pronounced tangential contact (concave up), while a small depth ratio (basin deep relative to current) would produce an angular basal contact. Therefore, in the present case, it is thought that a moderate depth ratio must have existed in conjunction with suspension transport.

The interbedding of the toeset beds with shales at the base of the units and in the troughs indicates pulsatory sediment transport associated with turbulent flow (Jopling, 1965a), and reverse circulation caused by flow separation (Jopling, 1965b).

The separation of the large scale bodies into toeset and foreset sub-units indicates deposition by avalanche on the lee side of megaripples or dunes under quiet water conditions. The northerly inclination of foreset units, and bioturbated contacts of toesets with bottom set shales, suggest regressive sequence, compared to the smaller accretion bodies which are mainly transgressive units. The change of the nature of lower contacts in some grainstone and packstone units from erosional

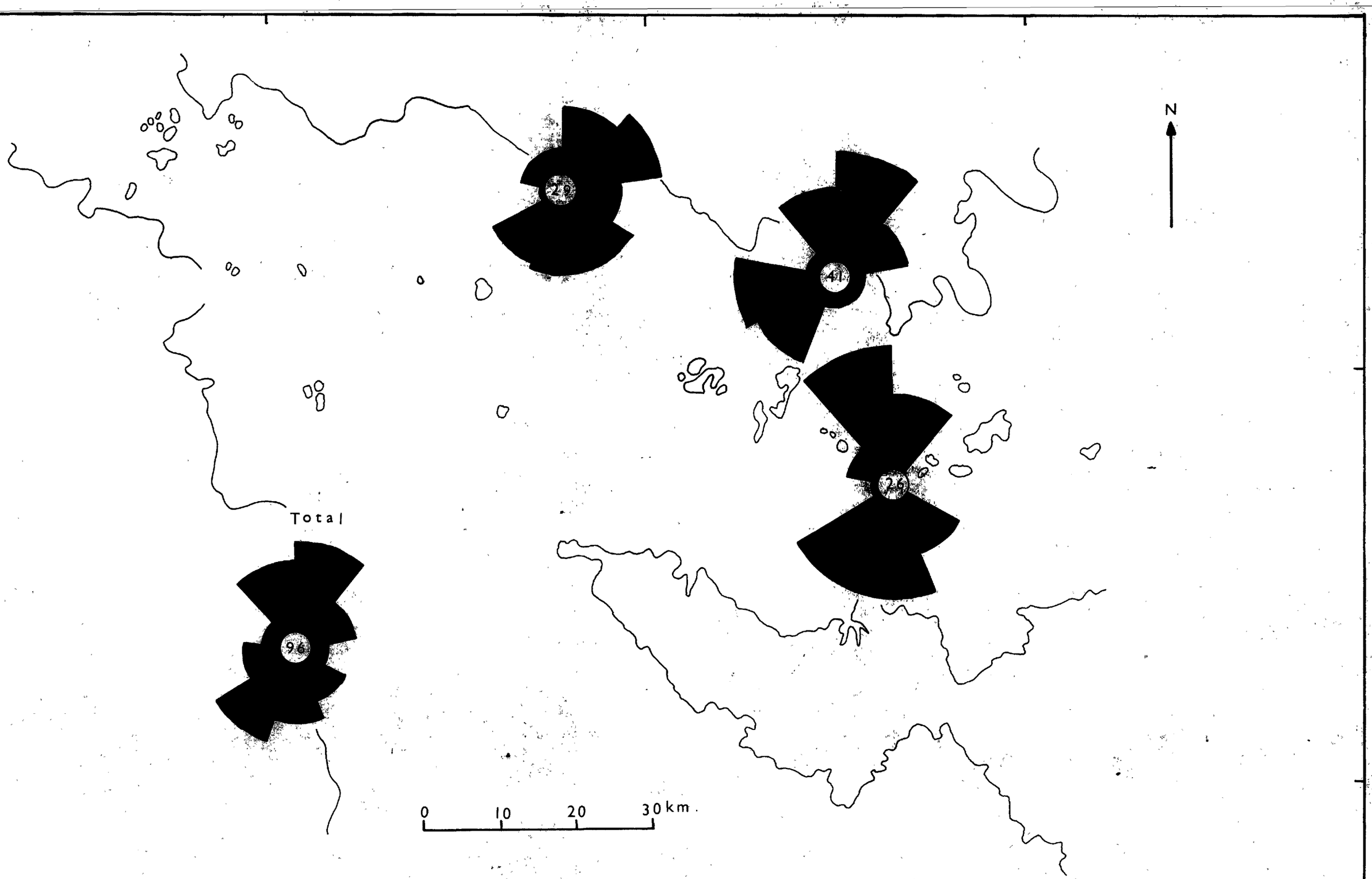


Plate 4-1: Palaeocurrent distribution in the grainstone facies.

to bioturbated and even gradational, suggests that large scale bodies were deposited during storm conditions in the form of accretion ripples and dunes (transgressive phase), then under fair weather conditions, deposition became mainly by avalanche on the seaward side of the sandwaves (regressive phase). Thus the periodic alternation between transgression and regression is due to pulsation of the rate of energy conditions and the supply of the carbonate sands. During high energy conditions (storms, hurricanes), accretion bars were transported landwards and over the lagoon, and regressive conditions occur due to seaward building-up of the barrier under fair weather conditions.

Palaeocurrents:The general distribution of the cross-bedded inclination direction is polymodal and suggests bipolar distribution, with a general north-south alignment. Both mean directions appear to be equal (Plate 4.1), which indicates that the flow separation at the crests of sandwaves that formed the cross stratification was well developed. It also indicates that the alternation of landward migration of the sandwaves during storm conditions and their seaward building-up during fair weather conditions have no influence on the balance of palaeocurrent distribution. Bipolar distributions have been taken as indicative of deposition in coastal environment under influence of tidal current (Klein, 1967).

Burrowing Structures

Burrows and trails are abundant in the basal sub units of the cross-bedded grainstone facies (Fig. 4.4). Most burrows are horizontal or gently inclined (Fig. 4.18) indicating quiet water conditions (Rhoads, 1967). The association of burrows with basal interclasts (Fig. 4.4) suggests that bioturbation follows the initial deposition of the basal subunit, preceding the deposition of the cross laminated sets. Also, burrows of the toesets' troughs of the large scale bodies (Fig. 4.17) suggest that areas between different bodies were the site of slow deposition compared to the foresets which are devoid of any burrowing activity.

In places where the cross-bedded grainstone bodies are truncated by tidal inlets, their tops are commonly churned by burrowing organisms (Fig. 4.19), which have destroyed all the sedimentary structures. The intensity of bioturbation decreases gradually down in the body, where cross-bedding is preserved. The burrows in this case are always vertical, reflecting the shoal conditions on the banks of tidal inlets. This type of burrow is partially responsible for introducing the fine grained geopetal sediments in the previously deposited (fine grain free) sands by infiltration and mixing. Doust (1968) indicated that 36 per cent of the Marada calcarenites contain Ophiomorpha burrows, which are produced by the shrimp Callianassa.

Photo Plate IV-5

Fig. 4.17 Tangential bottom set at the end of Fig. 4.16 shows interbedding with shale, which decreases up the foreset surface.

Fig. 4.18 Horizontal burrows.

Fig. 4.19 Barrier bar unit. Sedimentary structures are obliterated due to bioturbation towards the top. Traces of the original cross bedding are preserved at the bottom half of the unit (note the hammer at the lower right of centre).

Submarine barrier bars

Fig. 4.20 Archeolithothamnium algal dome found exhumed on top of barrier bar unit. It is intensively bored by bivalves and sponges.









VERTICAL PROFILES OF GRAINSTONE AND PACKSTONE FACIES

The cross bedded grainstone and packstone facies are found associated with two transgressive vertical facies profiles. They represent different sedimentary environmental associations which occurred in juxtaposition to one another at the time of deposition. These profiles are:

a) Submarine barrier bar profile.

b) Barrier beach profile.

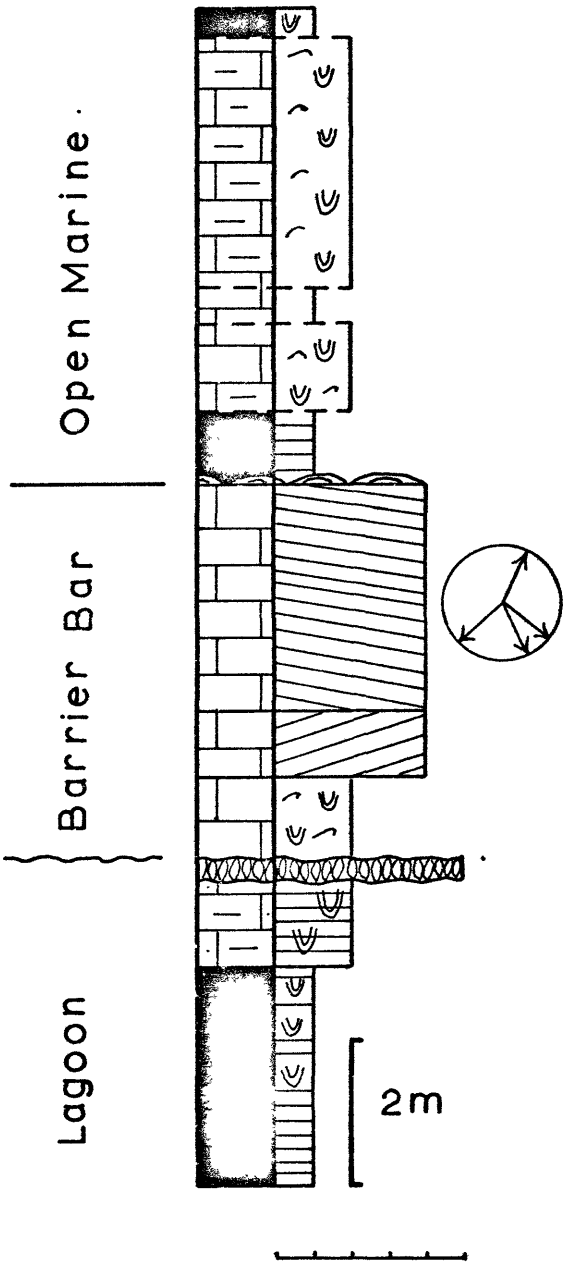
Each of these profiles is characterized by a distinct vertical facies sequence and diagenetic history.

A. Submarine bar vertical profile (Plate 4.2):

The Raguba-Brega roadcut (Section M1) reveals the most complete marine carbonate sequence in the Marada area. The regional facies cross-section shows that the barrier and tidal delta facies sequence below the echinoid marker horizon is interrupted by a tongue of open marine wackestone and shale facies which overlies a grainstone unit of the barrier facies. The barrier/open marine cycle (Plate 4.2) can be traced eastward for 15 to 20 Km.

The barrier facies consists of two units; the lower unit is about one metre thick and overlies laminated lagoonal

Plate 4-2. Submarine Barrier Bar Vertical Facies Profile.



shales and oyster banks; with an erosional and burrowed contact. It is white, skeletal wackestone, rich in marine fauna such as Laughs, bryozoa and algal oncolites. The second unit is about 4 metres thick of white to very pale orange (10 YR 8/4) grainstone and packstone, which changes towards the top into grayish orange (10 YR 7/4). The contact with the lower unit is sharp. This unit shows low cross bedded foresets which are arranged in wide troughs. Cross laminae are inclined at 5 to 7 degrees; they show northerly direction (seawards) at the lower metre of the unit, the upper three metres show southerly direction.

The top of the unit is collonized by Archaeolithothamnium algal domes (Fig. 4.20) and patchy coral heads (now replaced by celestite), They are now exhumed after erosion of the surrounding soft shales. Both algal domes and corals are intensively bored by bivalves. Foreset laminae and the upper surface of the barrier bar unit are also encrusted by a mat framework of Lithothamnium. (For discussion of Lithothamnium mats refer to Chapter 6, Subtidal algal mats.)

The grain framework of the cross-bedded grainstone and packstone is composed of Lithothamnium algal grains and oncolites, Halamida, mollusca, bryozoa and foraminifera, and also a few rounded quartz grains. Most of the skeletal grains are encrusted by a thin algal mucilage which has often

inhibited the syntaxial overgrowth of the echinoid grains (Fig. 4.21). The texture of the grain framework shows well to moderate sorting. The grain size is coarse to medium. Algal grains and oncolites may reach up to 3 to 5.5 mm in diameter. Cross laminae foresets show graded bedding.

Cement and Matrix

Three major types of cement are recognized to have precipitated early in the diagenetic history of the rocks in thin section examined.

(1) Acicular cement: It is composed of tightly packed needle-like crystals arranged in uniform isopach around the grains (Fig. 4.22). The first phase of cement is characterized by a golden or light-brownish colour, similar to the colour of most of the skeletal grains as seen under normal light. The acicular drusy crystals are oriented perpendicular to the grain surfaces. They are 25 to 30 microns in length (Figs. 4.23, 4.24) but rarely reach 50 microns. The first phase of cement is replaced by the second phase bladed cement.

(2) Bladed cement: This cement is composed of loosely packed colourless scalenohedral calcile crystals which were precipitated on the outer surface of the acicular first phase of cement and grow outward into the intergranular pore spaces. The growth of this cement is controlled by the space available;

Photo Plate IV-6

Submarine barrier bars (continued)

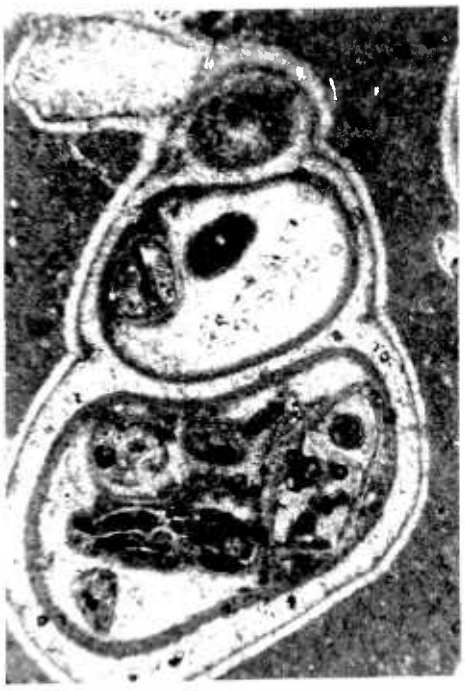
Fig. 4.21 Intergranular pore space lined by rim cement. Note that the echinoid's grain is not in optical continuity with cement (Sample MI-5; XN, X10).

Fig. 4.22 Gastropod shell with fibrous cement is resting on the micrite envelope and growing outward from the shell, cement is also resting on micrite cement and growing inward into shell chambers. Lime mud and silt matrix is filling the intergranular pore spaces. The shell's mouldic porosity is filled by calcite mosaic (sample MI-5A; NL-X3).

Fig. 4.23 The first phase of cement appears acicular, followed by a bladed secondary cement towards the centre of the porespace (sample MI-5; NL-X10).

Fig. 4.24 The same as Fig. 4.23 under X-nicols, showing that the acicular cement is replaced by the secondary bladed cement.

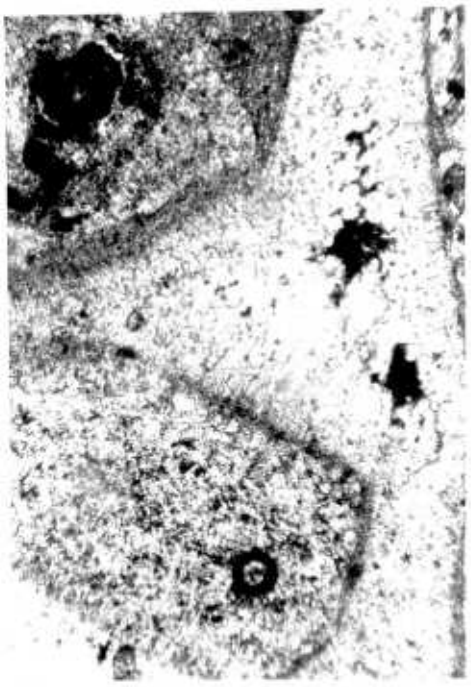
Fig. 4.25 The same as Fig. 4.22 (NL-X10).











therefore it has irregular thickness and reaches its maximum thickness on the lower surfaces of the grains (Figs. 4.26, 4.27, 4.28). The scalenohedral crystals are about 60 to 90 microns in length and 25 to 30 microns in diameter. Inclusions in the clear cement crusts indicate that the growth of the scalenohedra was interrupted at least once by introduction of fine grained material.

(3) Fine-grain geopetal matrix: Besides the acicular and bladed cement, most intergranular pore spaces are floored with fine-grain geopetal matrix. The geopetal sediment surfaces are either flat (Fig. 4.29), irregular (Fig. 4.26), or inclined (Fig. 4.27). It is interesting to note that pore spaces of the coarse grained sand laminae are completely surrounded by the matrix after the first phase of cement (Fig. 4.22). On the other hand in the fine grained sand laminae the intergranular pore spaces are partly filled with matrix (Fig. 4.26), or left completely empty except for the calcite cement (Fig. 4.23). The matrix does not show any internal micro-sedimentary structures. It is always observed resting on top of the first phase of cement. The surface of the geopetal sediments in intergranular pore spaces is always occupied by clear calcite crystals, which are often in contact with the bladed druze precipitated on the roof of the space. In few cases the calcite druse on top of the geopetal sediments is in turn covered by another layer of geopetal material (Fig. 4.29).

Photo Plate IV-7

Submarine barrier bar (continued)

Microphotographs of thin section MI - 5A

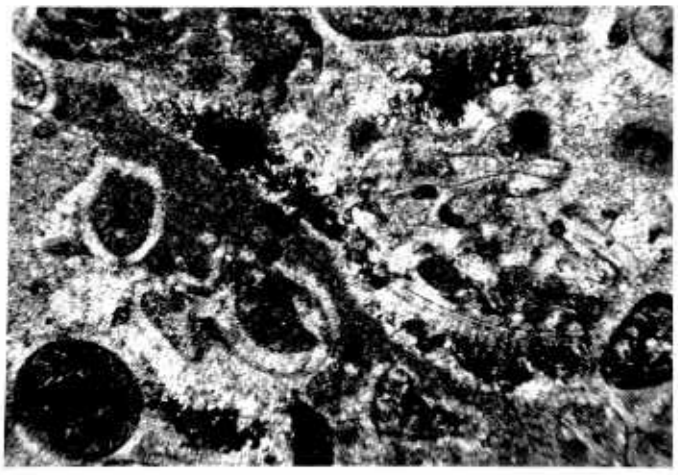
Fig. 4.26 Skeletal packstone, all grains are lined by isopachous fibrous cement. Interstices are partially filled with matrix. The bladed cement is growing down from the cavity's roof (XN-X3).

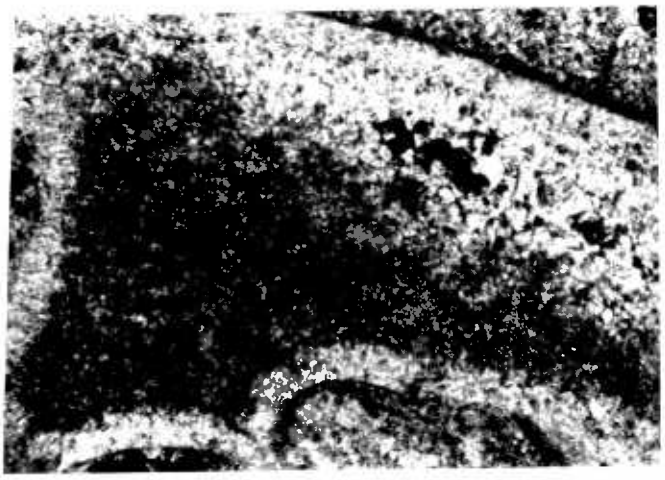
Fig. 4.27 Geopetal matrix showing an inclined surface. The bladed calcite cement is replacing the acicular cement as well as the foraminifera shell wall (just right of the centre (XN-X3).

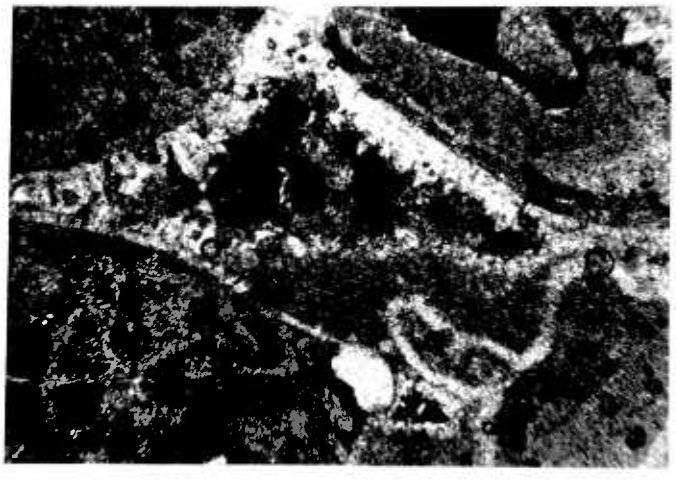
Fig. 4.28 A close up to show the fuzzy outline of pellets in the matrix; it also shows that the cement roofing the cavity consists of acicular cement and about two generations of bladed cement growing in optical continuity (NL-X10).

Fig. 4.29 The intergranular geopetal matrix is interrupted by one generation of bladed calcite cement (XN-X3).









The matrix is composed of crypto- to microcrystalline calcite which contains occasional silt size crystals, skeletal fragments and small forams (Fig. 4.25) which range in size between 20 to 100 microns. The skeletal silt represents a small fraction of the matrix composition. Examination of the matrix under high magnification indicated that the darker material is composed of closely packed pellets (50-100 microns in diameter) with fuzzy outlines, surrounded by microcrystalline calcite (Fig. 4.28).

Intragranular pore spaces are lined with a dark muddy layer which grades into acicular cement towards the centre of the chamber. The acicular cement is similar to the first phase of cement described above, except that it is composed of longer needles. The cavity centres are occupied by sparry calcite mosaic.

Discussion

Aragonite skeletal grains of pelecypods, gastropods and Halamida have undergone extensive dissolution. The empty moulds of the grains are preserved by the micritic envelopes or thin algal mucilage. The calcium carbonate dissolved from the aragonitic shells appears to have been reprecipitated as the low Mg-calcite of fringing bladed cement and mould fillings. Precipitation of clear bladed (scalenohedral crystals) cement over the fibrous cement, and the similarity between the mould filling (Fig. 4.25) and pore filling bladed cement suggests that dissolution of the aragonitic skeletal grains started after the precipitation of the first phase of fibrous cement. Precipitation of the bladed cement continued during the deposition of the geopetal matrix. Fig. 4.25 shows that the dissolved pledecypod shells are partly filled with scalenohedral calcite cement, while the Halamida shells are filled by sparry calcite mosaic. The dissolution and precipitation process is previously described by Khantaprab (1972) from Holocene hard grounds found in cores from the Persian Gulf. It was also described by Lands (1967), Bathurst (1964), and Friedman (1964).

In addition to pore space filling, replacement and recrystallization are common in the grainstones. The first

phase,acicular cement, was apparently replaced by the second phase, bladed calcite (Figs. 4.23, 4.24). The acicular habit and colour of the early cement become apparent only in normal light and when the bladed cement is in extinguished position. Replacement must have taken place early in the diagenetic history of the rock. This may suggest that the bladed calcite has replaced the earlier acicular aragonite (or high Mg-calcite), Furthermore, some shells appear to have been replaced by cement (fibrous and bladed); the replacement appears in optical continuity with the cement (Fig. 4.27). These replacement fabrics are similar to those described by Shinn (1969, Figs. 23, 24, 25, 26) from the Holocene submarine hardgrounds of Qatar.

From the foregoing analysis one would suggest that the cross-bedded grainstone-packstone unit is a part of a transgressive cycle of a lagoon, barrier bar (subtidal), and open marine facies. The grainstone unit has been deposited under increasingly high energy condition by accretion ripples or sandwaves (Imbrie and Buchanan, 1965). Early lithification, encrustation of the upper surface of sand waves by Lithothamnium algal mat and Archaeolithothamnium domes suggest a slow rate of deposition, possibly due to current activity and prolonged submarine exposure before burial. Stabilization of carbonate sand bars and shoals by subtidal algal mats is not uncommon in the recent environments (Bathurst, 1971, p. 122).

Lithification probably started by precipitation of isopacheous rind of fibrous aragonite (or high Mg-calcite) cement, which was followed by mechanical infiltration of the fine grained matrix. After dissolution of the aragonitic shells, calcium carbonate was redistributed and precipitated as colourless low Mg scalenohedral calcite druse in the intergranular pore spaces, and partly infilling the mouldic porosity. Aragonitic cement and high Mg-calcite shells were later replaced by the low Mg-calcite.

Precipitation of the bladed cement was interrupted at least once by the infiltration of the fine grained matrix. Filling of the pore spaces with matrix inhibited the precipitation and growth of the calcite cement. The diagenetic fabrics illustrated here have much in common with the Holocene hard grounds collected from the subtidal environment of the Persian Gulf (Shinn, 1969) and those described from the Jurassic rocks of Paris Basin (Purser, 1969). Thus, stratigraphic, sedimentologic and petrographic data indicate the submarine origin of the rocks discussed.

B. Barrier Beach Vertical Profile (Plate 4.3)

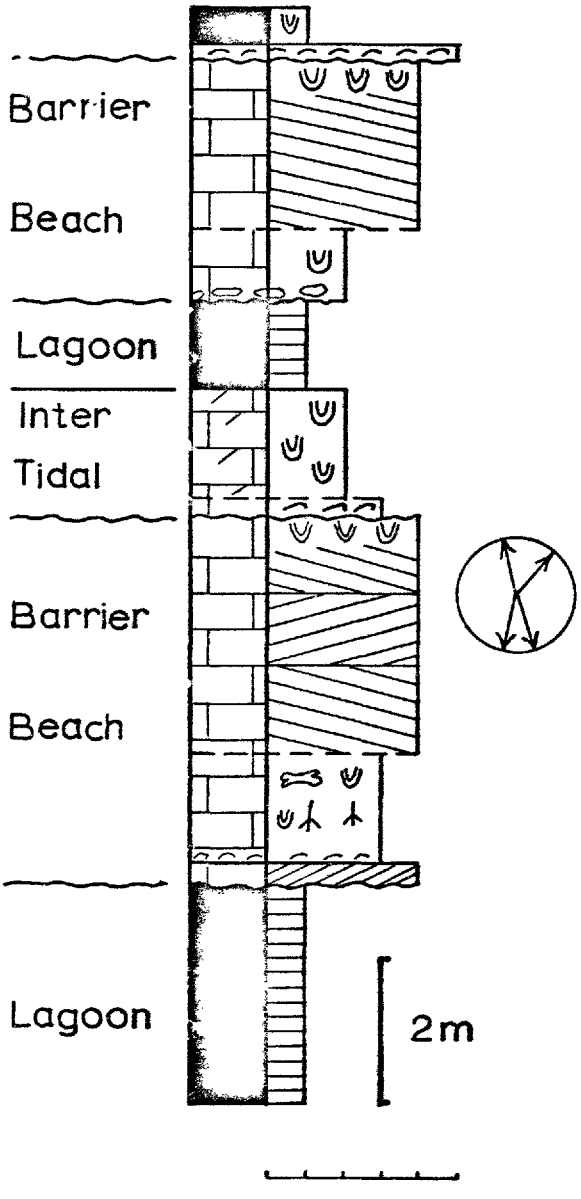
The cross-bedded grainstone and packstone barrier bar units of the Marada Formation are generally characterized by a light colour, high porosity and a moderate degree of induration. A few units, however, are thoroughly lithified and outcrop in prominent ledges in the field (Fig. 4.30). These units are often weathered into large blocks due to undercutting of the soft sediments underneath. Their colour ranges from a dark yellowish orange (10 YR 6/6) to olive gray (5 Y 4/1), which represents a striking contrast to the surrounding rocks. Hard specimens are dense, the grain outlines appear vague, and the pore spaces are totally filled by cement. From the field geologic evidence alone one can conclude that these units must have undergone an advanced diagenetic history more than those previously examined.

In Section D8, east of Zelten/Brega road, similar cross-bedded grainstone units are exposed in several horizons interbedded with intertidal and lagoonal facies (Plate 4.3). A typical cycle consists of the following:

Base: 1) Calcareous shale, laminated with calcareous sand strings, ranges between one to several metres.

2) Burrowed and/or erosional base. Skeletal grainstone and packstone crossbedded unit. This

Plate 4-3. Barrier Beach Vertical Profile



consists of two subunits:

(a) Massive poorly indurated argillaceous packstone and wackestone, containing well indurated thin micro cross laminate grainstone at the base; also contains bone fragments, lignite rootlets, calcareous nodules, oysters and Placenta. It is bioturbated.

(b) Well indurated, low angle trough cross-laminated olive grey coloured, skeletal grainstone and packstone. The lower contact is transitional, the upper boundary is erosional, contains burrows (or plant roots) which are enlarged by solution. In some places it is covered by a thin bed of oyster moulds left after solution of shells.

3) Dolomitized, well indurated, strongly bioturbated pelleskeletal wackestones. The lower few centimetres are poorly indurated lime mudstone with oysters.

Petrography of the cross-bedded unit

The skeletal framework is moderately sorted coarse to very coarse (0.3-1.0 mm) skeletal sand, which consists of

bryozoa, echinoids, mollusca, coralline algae and benthonic foraminifera (Fig. 4.31). Pellets and lime mud interclasts are common, but fine quartz grains are concentrated in clusters, possibly filling burrows or plant rootlets. All calcitic grains are stained by iron oxides, which causes the dark colour of the rock.

The early intergranular cement consists of equant loosely packed calcite crystals (11-54 microns). In some samples, however, it consists of closely packed brownish bladed calcite (Fig. 4.31). The crystal size increases towards the centre of the interstices which are often filled by a single syntaxial overgrowth of echinoid grains. At the grain contacts the intergranular cement is composed of fine calcite mosaic.

Geopetal matrix which precedes the first phase of the cement are observed in some samples flooring the interstices. It consists of uniform equigranular calcite (4.5-5.5 microns); at the base of the unit, the matrix is brownish and sometimes opaque possibly due to the presence of Fe oxides and clay minerals.

Aragonitic grains have been dissolved early in the diagenetic history of the rock. They are now completely filled by granular calcite (Fig. 4.31).

The rock framework of grain matrix and cement is often cut by microsolution cavities (Fig. 4.32), the walls of which are stained by brown colour. Radiating from its roof are closely packed bladed calcite crystals which exhibit blunted ends. The bladed crystals consist of successive layers of growth indicated by colour difference and lines of inclusions, in a micro-stalactite fabric (Muller, 1971b). The cavity floors are bare of any calcite cement (Fig. 4.32). In other samples from the top of the unit, solution cavities are completely filled by blocky calcite.

In the unit examined, there is a general tendency towards an increase of the degree of cementation and crystallization of matrix and grains, towards the top of the unit.

Discussion

Land (1971) described the diagenetic history of the Middle Pleistocene carbonate rocks along a beach profile in Bermuda; he found out that the beach rocks are lightly cemented by isopachously arranged aragonite crystals, whilst the eolianites are cemented by coarsely crystalline calcite at the lower part, and by meniscus cement (Dunham, 1971) at the upper part. Thus he concluded (Lands, 1971) that these rocks were cemented in a marine phreatic, meteoric phreatic and vados phreatic zones respectively.

Photo Plate IV-8

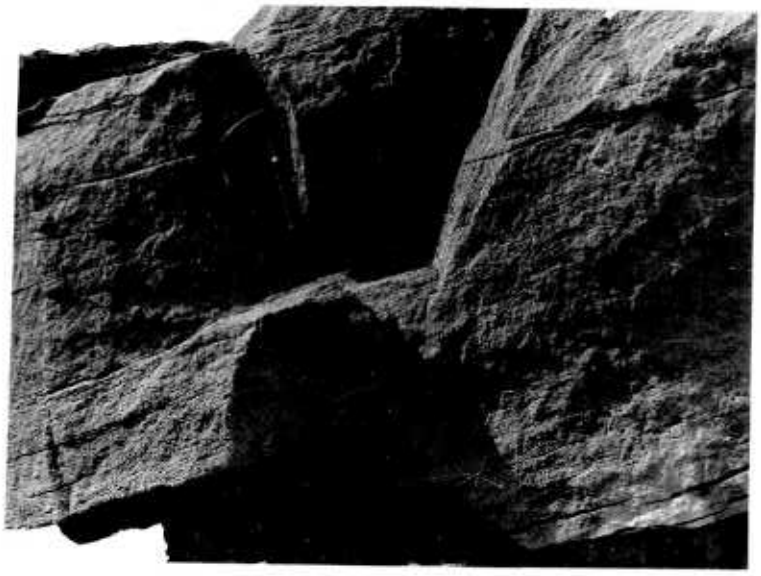
Barrier beach

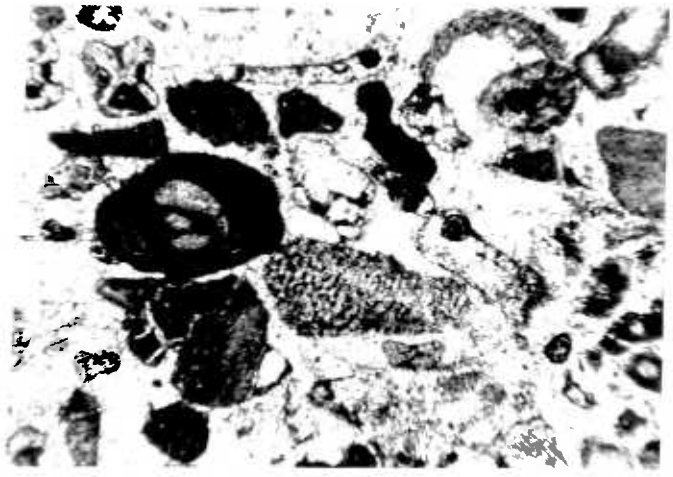
Fig. 4.30 An outcrop of well indurated cross bedded grainstone.

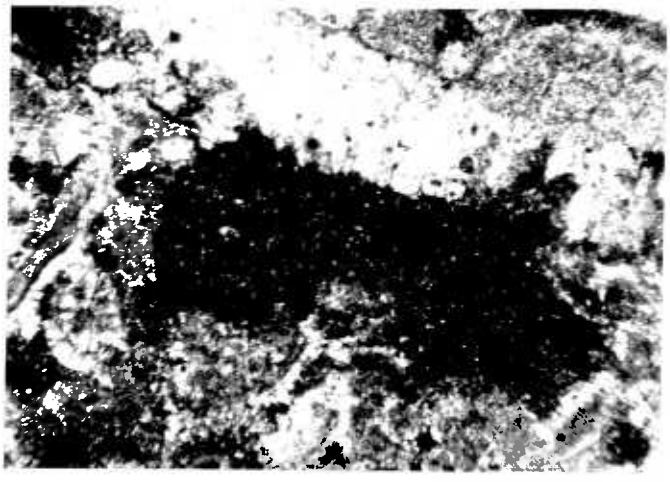
Fig. 4.31 Shows a general texture of the rock. All pore spaces are completely filled by calcite cement (NL-X3, sample D7-8).

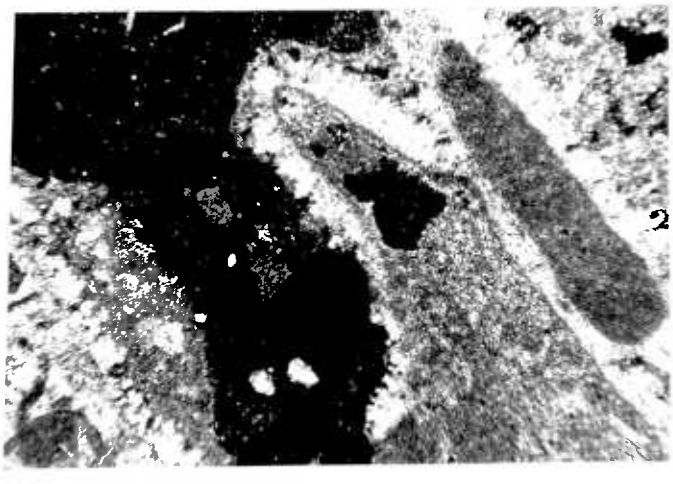
Fig. 4.32 Skeletal grains are cemented by bladed rim cement (lower centre). Grains and cement are truncated by solution cavity (centre) growing from the roof of which is a closely packed, bladed calcite crystals that show blunt ends (XN-X3, sample D8-5A).

Fig. 4.33 The skeletal grains of the grainstone are cemented by two generations of rim cement, both grains and cement are cut by micro-solution cavities now floored by lime mud and crystal silt (XN-X3, sample D8-B1-4B).









Muller (1971b) indicated that in the phreatic zone sand pore spaces are completely filled with water, therefore the cement derived from this interstitial water could be expected to form a crust around the grains. The vados zone, however, is characterised by two phase system of water-air, thus two types of cement are formed, a gravitational type (micro-stalactite) and meniscus type (Dunham, 1971) at the grain contacts.

Dunham (1971) pointed out that the blunted edges of the bladed cement (Fig. 4.32) result from $CaCO_3$ starvation at the tip of the calcite crystals when their growth brings them into contact with other objects such as other crystals, coated grains, or water-air interface. Pore rounding of the meniscus cement at grain contacts is caused for the same reason.

From this discussion one can suggest that the cross-bedded grainstone and packstone barrier unit was subjected to meteoric water diagenesis as indicated by the occurrence of solution cavities, microstalactites, blunted calcite crystals, and various other features such as colour, degree of cementation, recrystallization and pore filling. The increase in the degree of diagenesis from the base of the unit and the top can be explained in terms of various diagenetic environments (e.g. marine and meteoric phreatic) as suggested by Lands (1971). Also, the degree of cementation may have been affected by grain

size distribution and/or the distribution of the fine grained material brought by burrows at the top of the unit. Cementation is inhibited in the coarser grain because they were well drained (Dunham, 1971). Prolonged subaerial exposure of the upper part would possibly produce a difference in the degree of diagenesis. However, the presence of micro-solution cavities throughout the unit may suggest that the whole unit was subaerially exposed at some stage in its history.

The sedimentological data in the vertical profile of section D8 suggests that the grainstone units were deposited as a result of lagoonward (landward) migration of accretion sand-waves during high energy or storm conditions. Similar deposits and sedimentary structures are reported to have been formed in the Bahamian beaches and intertidal and subtidal shoals under similar conditions (Imbrie and Buchanan, 1965). Lowering of the sea level after storms or just high rate of skeletal sand accumulation would have exposed the sand waves above the mean sea level. Because of heavy rainfall during the Marada times (savannah climate), fresh water lenses were accumulated in the porous skeletal sand bodies (oceanic island model of Purdy, 1968) initiating the meteoric water diagenetic features described above. Later submergence of the lithified sand bodies under intertidal conditions is indicated by the dolomitized pelle-skeletal wackestone units on top.

4.3 RECONSTRUCTION OF THE BARRIER ASSOCIATION

The lithology and fauna of the cross-bedded skeletal grainstone and packstone barrier facies of the Marada formation clearly indicate open marine origin. Whereas the estuarine and lagoonal facies are predominantly terrigenous, the barrier bar and open marine facies are carbonate. The relative absence of quartz sand in the barrier composition is attributed to the continuous rise of the sea level, and the climatic conditions which prevailed during deposition. Swift (1968) indicated that under rise of the sea level (ravinement), river sand undergoes a residence period as flood plain, tidal flat, estuarine or lagoonal deposit before being reworked and introduced to the barrier.

Allen (1964), Curray (1964) and Swift (1968) have discussed the variables controlling transgressive shorelines, which include the rate of sedimentation, the rate of sea level rise, climatic and oceanographic factors, and the composition of the sediments. Price (1962) described barriers formed from offshore bars during periods of temporary high water associated with storms. The bars built vertically to slightly below the elevated water level and were left as barriers when the water receded. Curry (1964) concluded that submerged barriers tend to grow upwards during transgression until their enlarged

lagoons trap so much of their river-derived sediments that the barrier overlapped and the lagoon became an open sound or bay. During the following barrier transgression, the destruction of the preceding barrier is determined by the geometry of its body and the depth to which reworking occurs (Thompson, 1937). The disconformity occurs at the base of the barrier units and commonly separates the high energy barrier sands from the low energy and older lagoonal shales in a transgressive sequence (Swift, 1968; Fischer, 1961). Also, during sea level rise some barriers tend to grow outwards as well as upwards as indicated by Bernard and Le Blanc (1966), by their work on the Galveston Island barrier.

The Marada barrier bar facies are arranged in three distinct vertical profiles which are associated with transgressive and regressive sedimentological assemblages. Curry (1964) has shown that transgression can be divided into erosional and depositional varieties on the basis of the net rate of deposition relative to the rate of rise and fall of sea level.

a) The submarine barrier bar vertical profile shows that the near shore environments were actively migrating landward in a depositional transgression, with the result that open marine facies onlapping the barrier bars, suggesting a high rate of sea level rise.

b) The barrier beach vertical profile on the other hand indicates subaerial exposure and erosion before being buried by carbonate intertidal and lagoonal facies; suggesting transgression under slow rate of sea level rise. Thin sheets of the barrier beach lithology are often found interbedded with lagoonal facies, possibly indicating transgression under a stable sea level. The transgressive barrier bars and beaches stratification shows an inclination angle less than the angle of repose. They were deposited by accretion sand waves, which were subjected to bottom traction currents during storms (Imbrie and Buchanan, 1965).

c) A regressive depositional coast or shoreline prograding into subsiding basin may produce a thick sequence of high energy deposits (Curry and Moore, 1964). On subsiding coasts, such deposits are not eroded as the typical consequence of seaward environmental migrations. These high energy deposits prograde offshore and are often found associated with near shore and open marine deposits. In the Marada area they were deposited as large scale foreset bodies often overlain by lagoonal and inlet-marine tidal delta. These bodies were formed by avalanche conditions (Imbrie and Buchanan, 1965). Bottomset, toeset and foreset beds of these bodies are a result of segregation of transported sediment into distinctive bed load and suspended load sediments (Jopling, 1965).

The vertical profiles of the transgressive and regressive barrier assemblages clearly indicate that deposition and growth (vertical and lateral) of barrier bars was controlled by alternation of fair versus stormy weather conditions, as well as the rate of carbonate sediment supply, and the rate of sea level rise. The continuous repetition of lagoonal-barrier/tiday delta complex depends on several factors, such as the rise of sea level, geometry of the barrier and the morphology of the lagoonal features (Hoyt, 1969). The pulsatory sediment transport of carbonate sand from the open marine and the terrigenous clastics from rivers and estuary must have also played a vital role towards the control of barrier growth and development of sedimentary cycles. Both sediment sources were surely controlled by the periodic alternation of dry and wet seasons, and storm versus fair weather conditions of the Middle Miocene tropical climate.

The sedimentologic and petrographic interpretations presented here lend support to those presented by Selley (1966, 1973) for his detrital limestone facies. However, the present author differs from Selley (cit. op.) on the following counts:

a) Not all of the limestones of the Marada Formation were deposited as barrier bars and barrier beaches.

b) Not all of the cross-bedded grainstone bodies are transgressive.

c) Although the present author agrees on the net onshore transport of the detrital limestones during storms, proposed by Selley (1966, 1967); however, Selley's (op. cit.) palaeocurrent data indicate a bimodal pattern with a dominant onshore transport, which may suggest landward transport by avalanche mega-ripples and/or shoals (Selley, 1973, Fig. 7.4). The data presented here (Plate 1.4) indicates a bimodal palaeocurrent with equal onshore-offshore components, which together with the low angle of dip (less than the angle of repose) of the crossbeds indicates deposition by accretion mega-ripples forming under traction currents which dominate deposition during storms (Imbrie and Buchanan, 1965).

Doust (1968), however, disregarded the interpretation that any of the Marada limestone units had been deposited under barrier bar or beach conditions.

THE DOLOMITIC MUDSTONE FACIES

The dolomitic mudstone facies are composed of discontinuous sheet-like bodies, which are generally exposed at three stratigraphic levels in the Marada Formation in a restricted geographical locations:

A) In sections of Dor Zuggut and Dor Marada, units of this facies occur directly below the Echinolampas horizon, and overly the cross-bedded grainstone and laminated shale facies.

B) A sheet of this facies extends between sections of Jebel Zelten and the Central Jebels. In the former area it is inter-bedded with siliclastic units of the fluviomarine facies association (intertidal and estuarine). In the latter area it overlies the grainstone and shale facies and changes laterally (northward) and upwards into wackestone facies.

C) Another sheet of this facies also constitutes the top most units of the Jebel Zelten-Central Jebels area. It overlies the siliclastic facies in Jebel Zelten and the wackestone and marl facies in the Central Jebels. This sheet is followed by a disconformity surface which was caused by the Middle Miocene sea regression and marks the emergence of the Marada Formation.

The dolomitic mudstone facies are subdivided into three broadly defined subfacies. These are:

1) Mudstone subfacies.
2) Cross-bedded pelle-skeletal subfacies.
3) Dolomite subfacies.

5.1 The Mudstone Subfacies

This subfacies consists of a massive 150 to 200 cm thick, white (N9) unit, which often changes into pale yellowish brown (10 YR 6/2) and yellowish gray (5 YR 7/2) colour (Fig. 5.2). The lower contacts of beds are sharp and their upper boundaries are often intensively bioturbated (Fig. 5.3). Light colours are always found at the lower part of units whilst the darker colours are often confined to their upper parts.

Lithology

Some units of this facies contain skeletal shells and shell fragments, other units consist entirely of pellets and/or lime mud. Crassostrea oyster banks similar to those associated with the lagoonal facies are found on top of some of the facies beds. They often occupy the banks of tidal channels (Fig. 5.1). Oyster shells are up to 30 cm in length and are always found in growth position.

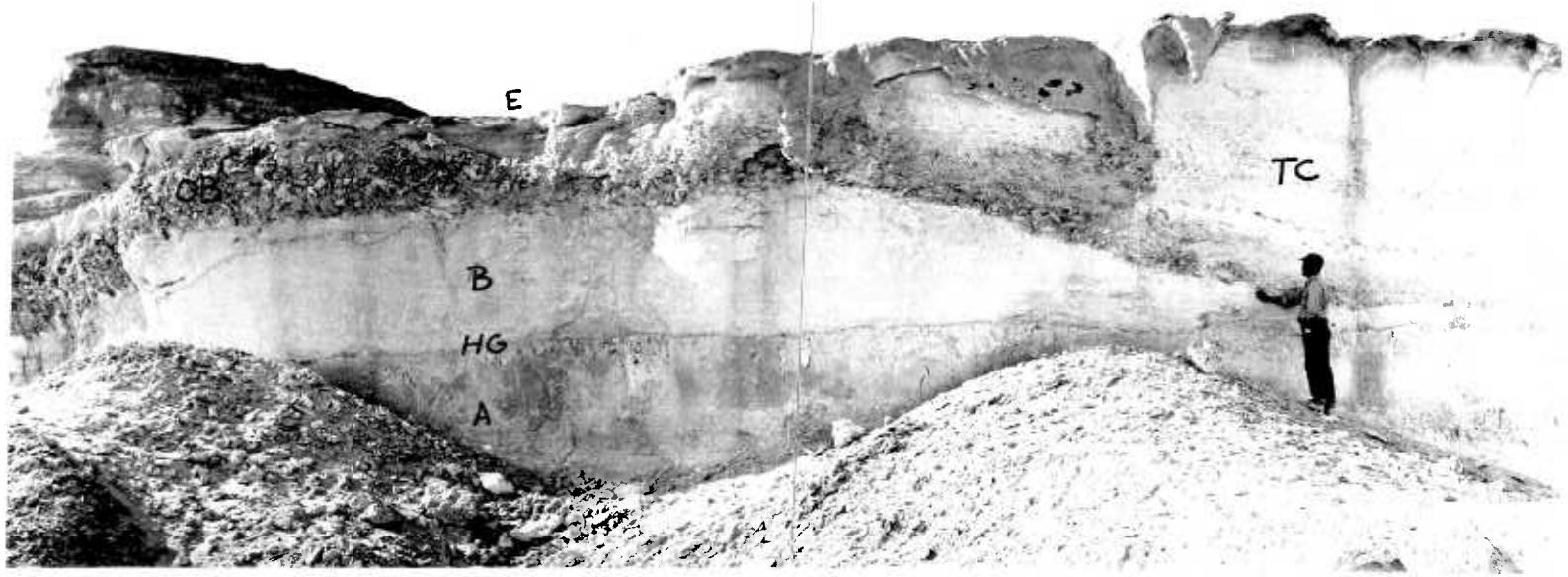
Photo Plate V-1

Intertidal facies

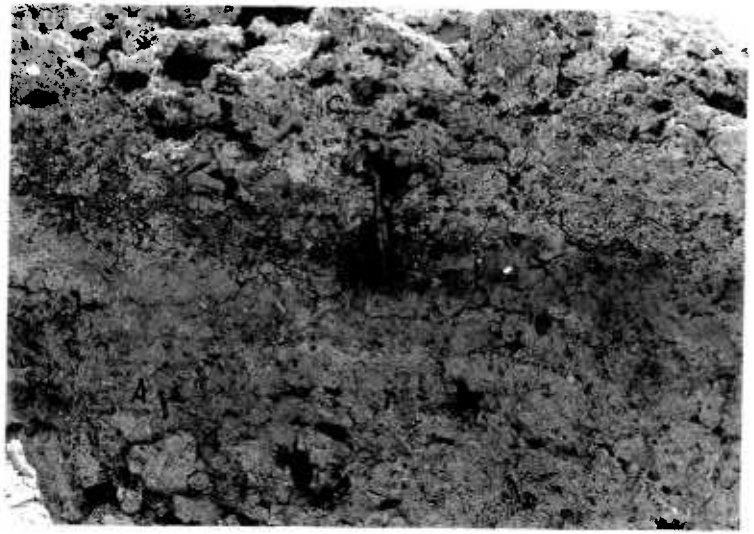
Fig. 5.1 Panorama of carbonate tidal flat facies, intertidal units A and B are separated by hard ground (HG). The top of unit B is occupied by an oyster bank in the growth position (OB), and truncated by a tidal channel (TC). Echinoids and other open marine fauna are found at (E).

Fig. 5.2 Thick sequence of intertidal facies shows a gradual increase in the degree of lithification and dolomitization from bottom (light colour) to top (dark beds).

Fig. 5.3 Close up of the dark coloured beds in Fig. 5.2 which contain vertical open burrows at the lower part (A) and open crab burrows (B) near the top; some of the crab burrows are filled by sediments (C).


E
OB
B
HG
A
TC




A

In some of the thin sections, skeletal grains are rarely preserved; they are dissolved leaving mouldic porosity (Fig. 5.7). Moulds of gastropods, bivalves and foraminifera are common, algal fragments (Fig. 5.6) and worm tubes (Fig. 5.4) are the only organic remains that are well preserved.

Pellets are rounded and elliptical, they range between 0.2 to 0.7 mm and often reach up to 1 mm in diameter. Lime mud flat pebbles of 1-7 mm interclasts are common in units closely associated with tidal channels.

Quartz sand grains are present in small quantities in the tidal flat facies of Dor Zuggut outcrops. In Jebel Zelten, however, this subfacies contains a large percentage of the quartz sand, often found interlaminated with the lime mud (Fig. 5.11). Other terrigenous minerals such as mica and clay minerals are also common.

Pellets are closely packed and cemented with a cryptocrystalline calcite (Fig. 5.4), which often merges with the grain outlines. A fine loosely packed granular calcite cement, 5 to 10 microns in diameter projects from the surface of grains into the intergranular pore spaces (Fig. 5.4). In places the cryptocrystalline calcite has been recrystallized into microspar (Folk, 1965) mosaic. The lack of compaction and preservation of the pellets' shape suggest early lithification (Shinn, 1968).

Photo Plate V-2

Fig. 5.4 Photomicrograph of pelletal packstone. Pellets are cemented with a loosely packed calcite druze as well as cryptocrystalline calcite cement (XN-X3).

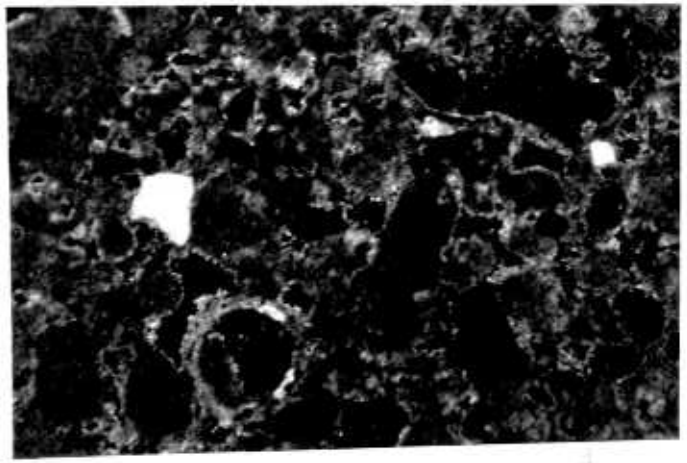
Fig. 5.5 Coarse pelletal packstone, pellets are replaced by a microcrystalline dolomite (XN-X3).

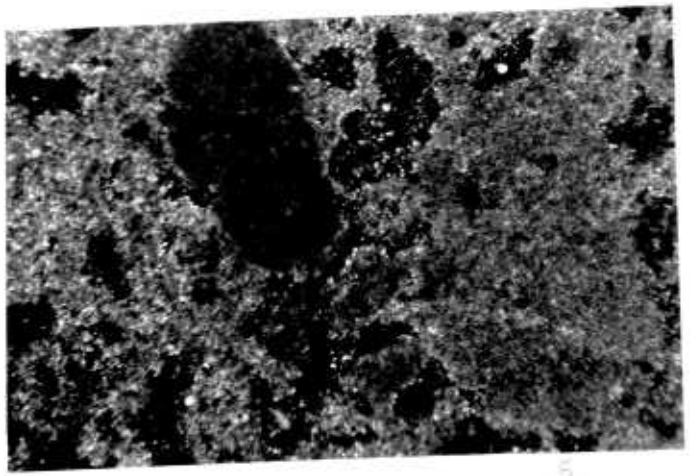
Fig. 5.6 Pelletal packstone containing quartz, skeletal and coralline algal grains (far right) (XN-X3).

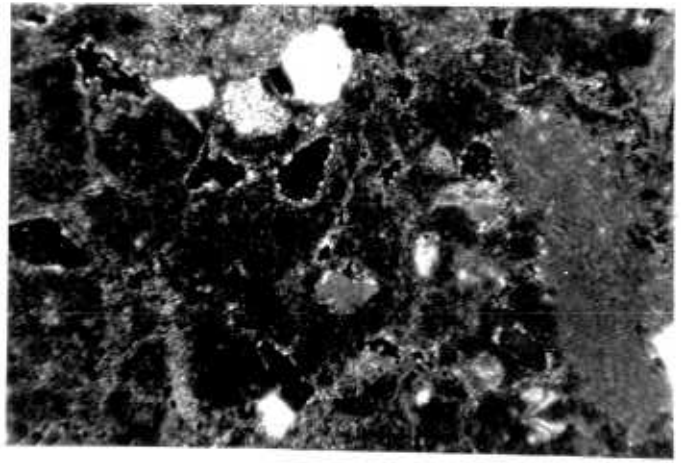
Fig. 5.7 Pelletal packstone replaced by microcrystalline dolomite, solution of skeletal grains produced the mouldic porosity (XN-X3).

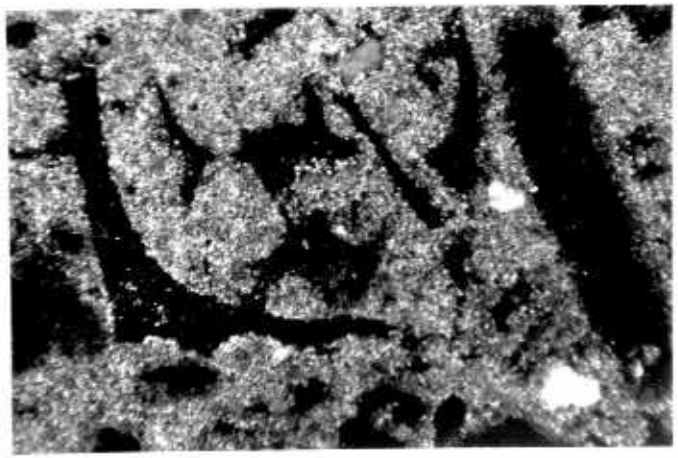
Fig. 5.8 Mudstone now replaced by fine grained dolomite (X3-NL).

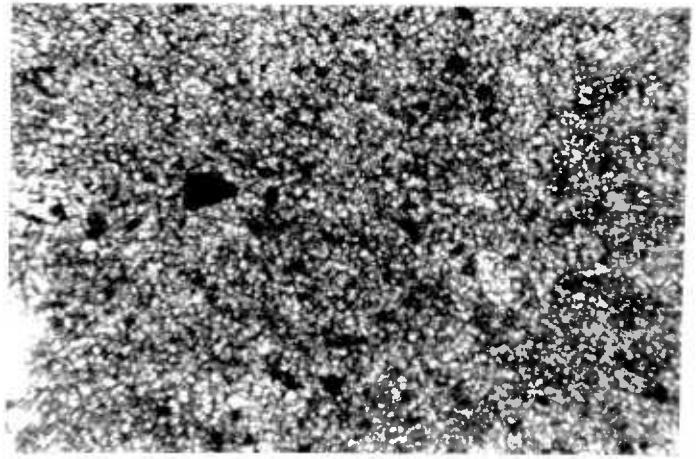
Fig. 5.9 A burrow now filled by dolomite, but the host rock (upper half of the photograph) is undolomitized (X3-NL).

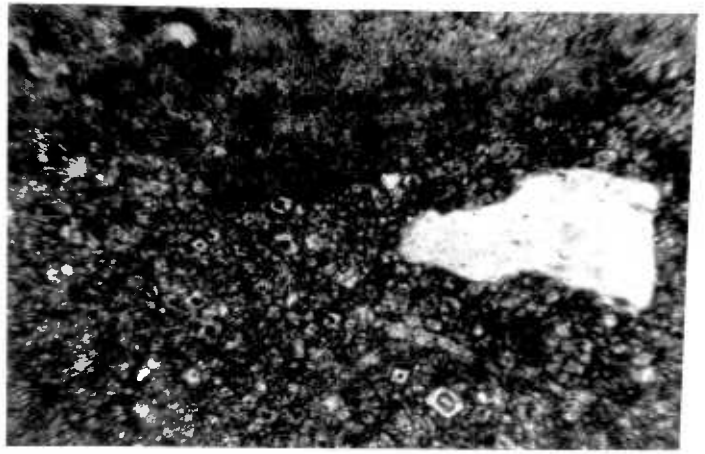












Finely laminated mudstone, and interlaminated mudstone and pelletal packstone units are often replaced by fine grained (5.5 microns) hypidiotropic to xenotopic (Friedman, 1964) dolomite rhombs (Figs. 5.7, 5.8). Flat pebbles associated with these units are also dolomitized. Dolomitization is common in recent tidal channel levees, high inter-tidal, and supratidal flats (Shinn, 1969).

The mottled pelletal and pelle-skeletal wackestone units (Fig. 5.15) contain a variable amount of dolomite. Dolomitization appears to have selected burrows, resulting in a mottled network of replacement in the rock. This replacement pattern is often parallel and sometimes perpendicular to the bedding planes. In thin section, dolomite patches range in thickness from a few millimetres to centimetres. Dolomite crystals are up to 75 microns in diameter and of hypidiotopic fabric (Fig. 5.9). They are in sharp contrast with the muddy nature of the host sediment (Figs. 5.9, 5.10). In Jebel Zelten samples of mottled dolomite are found associated with calcite (Fig. 5.10). Mottling always increases towards the top of the units, where they merge together and the rock becomes completely dolomitized (Fig. 5.15).

Dolomitization appears to have taken place early in diagenesis since burrows and other sedimentary structures control the alternation rather than joints and secondary fractures.

Sedimentary Structures

Most inorganic sedimentary structures in the mudstone subfacies are bedding, which ranges from massive to thin parallel lamination, interlamination and microcross lamination.

Lamination in Jebel Zelten pelletal facies is produced as a result of alternation of terrigenous rich and carbonate rich layers (Fig. 5.13). The repeating alternation ressembles graded bedding which occurs in the siliclastic tidal flat facies. The lower contact of the quartz rich layers is usually erosional and often shows a scour and fill feature. The fill is always coarse grained and contains quartz sands and flat lime mud pebbles.

Lamination in Dor Zuggut units also shows a repeated alternation of lime mud rich and pelletal rich layers which grade into each other, and often contain flat discoidal lime mud pebbles. The compositional mud grain size grading implies fluctuation of transporting currents as in the terrigenous tidal flats.

Micro cross lamination characterizes many laminated rocks in Jebel Zelten and Dor Zuggut. In the former, sets of cross laminae are not visibly size graded and are apparently of uniform size. Sets of individual foresets are distinguished

principally by slight differences in colour at the outcrops. In the latter, microcross laminae do not show any colour difference from cross laminae.

These sedimentary structures indicate that current action prevailed during the deposition of these rocks. In Dor Zuggut sections, they are closely associated with the tidal channels (Fig. 5.1). Dissecation cracks must have been common; they were later reworked by currents to produce the discoidal pebbles.

The rocks of the pelletal facies are extensively burrowed both vertically and horizontally (Fig. 5.15); vertical burrows, however, dominate over the horizontal (Fig. 5.14). The burrowing has generated considerable bioturbation and loss of primary structure and texture. In the rocks of interlaminated carbonate rich and sand and silt rich layers, it is observed that burrows in the carbonate rich layers are horizontal and those in the terrigenous rich layers are vertical (Fig. 5.13). This probably corresponds to the behaviour pattern of the burrowing animal in response to energy and/or rate of sedimentation. Under high energy conditions and/or fast rate of sedimentation the animals tend to burrow vertically away from the aggregated sediment-water interface. But under lower energy conditions and slow rate of sedimentation burrowing is generally horizontal. The relatively fast sedimentation also explains the preservation of the primary sedimentary structures in this case.

Photo Plate V-3

Fig. 5.10 Pelletal packstone showing differential dolomitization along burrows (NL-X10).

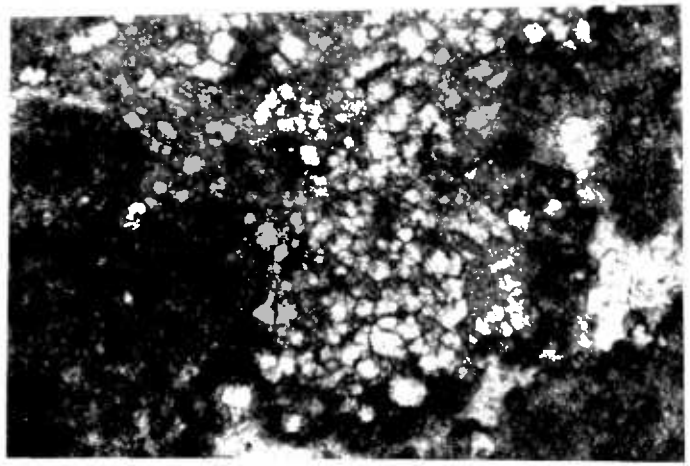
Fig. 5.11 Microphotograph of interlaminated quartz sand rich and lime mud rich layers. Note the presence of algae (centre) and foraminifera fragments; also note the presence of neomorphic calcite replacing the matrix in the quartz rich layer (Jebel Zelten, J-8), (NL-X3).

Fig. 5.12 Quartz sand filling a burrow in pelletal mudstone (XN-X3).

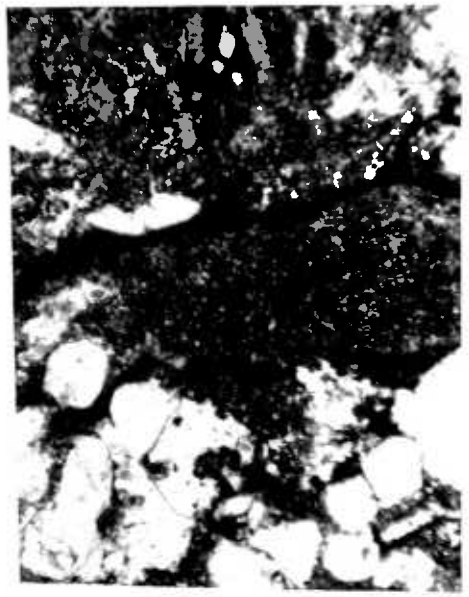
Fig. 5.13 Interlaminated quartz sand and lime rich layers penetrated by a burrow, Jebel Zelten.

Fig. 5.14 Vertical burrows in pelletal packstone, Dor Zuggut.

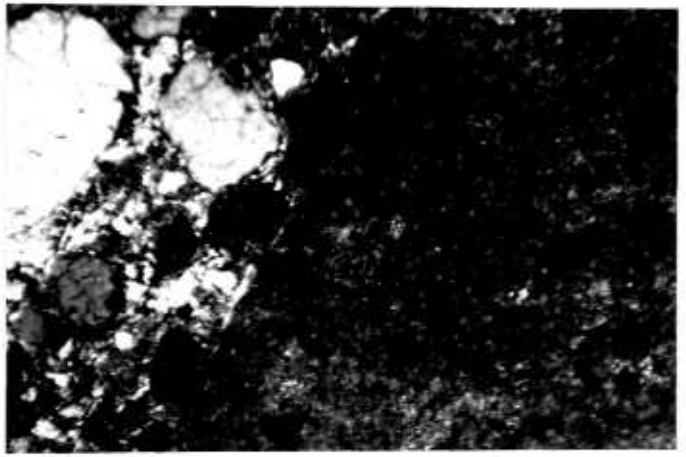
Fig. 5.15 Dolomite mottling in pelle skeletal wackestone. Dolomite is replacing sediments filling horizontal burrows. Note the increase of intensity of bioturbation and mottling at the top of the unit. Also note the domal structure (to the right of the hammer).



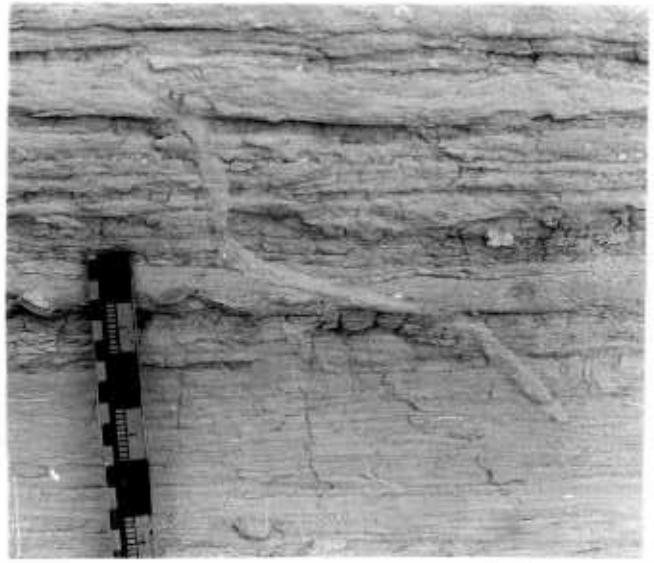
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OSLT

In the carbonate dominated units sedimentary structures are often partly or completely obliterated by burrows. Continuous bioturbation produces two main features in the outcrops. First, units contain cavernous features which are produced by lumps of sediment surrounding lenticular cavities and rounded open burrows which increase in size towards the top of the unit (Fig. 5.3). These cavities look like a larger scale birds eye structure than that described by Shinn (1968). The cavities and vugs are not connected as in solution channels. Earlier cavities and burrows seem to be filled by later loosely packed sediments, and often reburrowed. It is of interest to note that remnants of primary sedimentary structures, such as microcross lamination, are observed in the sediment in spite of the heavy bioturbation and reworking. All these associations indicate that these large cavities may have been produced by large organisms such as crabs. The change of the size of these burrows upwards and the partial preservation of the sedimentary structures indicate that bioturbation and lithification were progressing hand in hand.

Other units show colour mottling where burrows generally show signs of filling and partial compaction (Fig. 5.15). Sediments in these burrows are dolomitized. The top

of these units shows lumpy structures. On the surface of the bed, these features develop domal shapes of faecal mounds (Fig. 5.15). Similar mounds are described from recent tidal flats of Florida and the Bahamas. They are produced by the burrowing activity of Callianassa (Shinn, 1968) and polycheate worms (Shinn et al, 1969) respectively.

Depositional Environment

The sedimentological and compositional features of the rocks described above strongly suggest that they originated on tidal flats which were occasionally subjected to subaerial exposure. Primary sedimentary textures and structures closely resemble those modern carbonate tidal flats (Shinn et al, 1969; Taylor and Illing, 1969), and previously interpreted ancient tidal flats sequence (Laport, 1967; Matter, 1967; Roehl, 1967; and Braun and Friedman, 1969). The intertidal facies of Dor Zuggut are predominantly carbonate and were deposited within the tidal range. Channel levees and tidal flats were occasionally subaerially exposed during low tides which induced early lithification and dolomitization.

Lamination, cross lamination and ripple lamination indicate transport of carbonate sediment as clastic debris over the flats under a relatively high energy condition. Flat lime mud pebbles and scour surfaces indicate active erosion by flood

waters. The interclasts and pebbles represent redeposited fragments of a previously torn up and transported bed, regardless of whether they were originally semiconsolidated subtidal sea floor or dessecated tidal flat.

Further comparison with modern tidal flats supports the tidal flat origin of these rocks. Several beds in Dor Zuggut and Jebel Zelten show cyclic clay-carbonate sequences and micro-cross laminated carbonate rocks. The close association of these structures to tidal channels suggests that they were deposited along the banks of tidal creeks and channels. They closely resemble structures found in channel levees in the Bahamas (Shinn et al, 1969, p. 1211, Fig. 20). Sediments deposited on the levees during flooding were current bedded and scoured in regions of high current velocity. Waning currents produced graded bedding in the levees; repeated flooding gave rise to many such graded cycles.

The intensity of burrowing activity in the tidal flats is controlled by the rate of sedimentation and energy conditions. In areas of high rate of sedimentation burrows are isolated and the sedimentary structures are well preserved. In areas of slow rate of sedimentation burrows are abundant and the sedimentary structures are obliterated to a great extent. Vertical burrow structures in the tidal flat

sediments are in agreement with modern burrow distributions in Barnstable Harbour and Buzzard Bay, Massachussetts (Rhoads, 1967, p. 474). Organisms living in inter-tidal to supratidal regions were subjected to drastically fluctuating conditions of temperature, salinity, food supply and other ecological factors on the flats, and responded by making vertical burrows as a means of stabilizing the immediate physical environment. Burrows in the intertidal flats are usually filled up by loosely packed pellets or skeletal sediments; in areas influenced by terrigenous sediments, burrows are filled with coarse quartz sand.

Burrows in the mottled intertidal units appear to be generally horizontal. Rhoads (1967, p. 474) has shown that burrows in shallow subtidal and low intertidal regions are predominantly horizontal due to the uniform environmental conditions. Therefore horizontal burrowers live more or less close to the sediment-water interface.

The preservation of individual pellet outlines, open burrows and the presence of faecal mounds all suggest early lithification of the intertidal sediments. Colour and lithification features also increase in intensity towards the tops of the sedimentary units, which suggests that cementation starts at the sediment-water interface. Taylor and Illing (1969)

indicated that the lithification of the upper 30 centimetres of the recent tidal flat sediments in Qatar peninsula is attributed to the interplay of tidal interstitial water movement. PH changes with depth and the biological activity, which will lead to supersaturation and precipitation of calcium carbonate. Tidal flat and levee sediments are usually dolomitised during subaerial exposure (Shinn et al, 1969).

Roehl (1967) discussed the differences between terrigenous and calcareous mud and silt in the intertidal facies of Stony Mountain and Interlaken Formations (Ordovician and Silurian times) of the Willistone Basin, U.S.A. He indicated that the texture and structure of carbonate and non-carbonate deposits may be similar superficially because of comparable hydraulic environments, yet dissimilar in diagenetic history. The carbonates commonly attain early competence through cementation in the aerated zone (Ginsburg, 1957), whereas non-carbonate deposits in tidal flats are subject to frequent relocation, reprocessing and removal before ultimate stabilizing (Evans, 1965; Straaten, 1954, 1959). The very early diagenetic history is therefore commonly critical in determining what kind of preservation takes place.

Evans (1965) noted that the Wash inner and Arenicola sand flats are extensively burrowed, the vertical burrows are being preserved, other burrows are compacted beyond recognition

due to sediment incompetency. Relics of vertical and horizontal burrows and other sedimentary structures are widespread in the Marada carbonate intertidal flats. There are two dominant ways in which such fabrics can be destroyed without changing the general depositional environment; these are differential compaction and lateral removal by channels. Early cementation of the carbonates has reduced the effect of both substantially.

Oyster banks similar to those described in the lagoonal facies are often found in the intertidal facies of some of the sections examined. Straaten (1954) and Evans (1965) have described oyster banks in the siliclastic lower tidal flats of the Wadden sea of Holland and the Wash of England respectively.

5.2 Cross-bedded Pelle-Skeletal Subfacies

These are flat-topped lenticular or sheet-like bodies, which are interbedded with and cutting across the tidal flat facies (Fig. 5.1). These facies are very pale orange (10 YR 8/4), and units always have an erosional lower contact which appears gently inclined (about 5 degrees) along the depositional strike.

Lithology

This subfacies shows a variable lithology, which includes wackestone, packstone and grainstone. However, it shows a

Photo Plate V-4

Tidal channels

Fig. 5.16 Cross laminated grainstone blocks found at the base of tidal channel unit. Section D6.

Fig. 5.17 Trough cross laminated pelle-skeletal packstone, tidal channel unit.

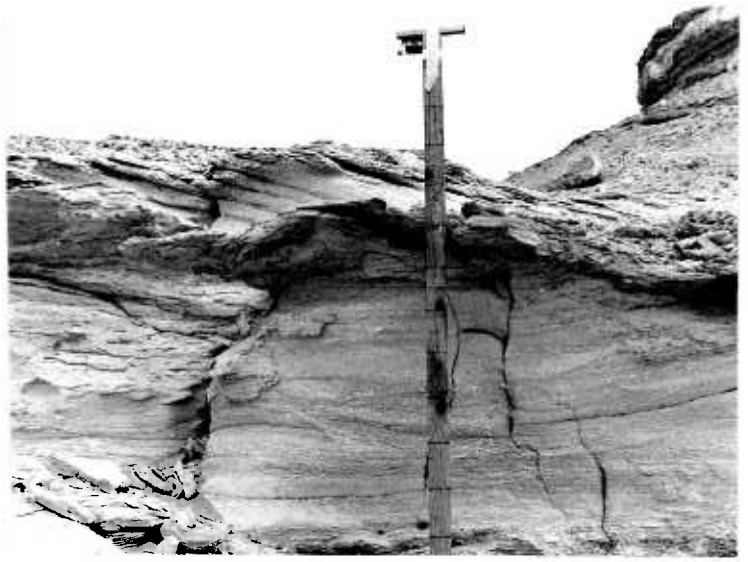
Fig. 5.18 Microphotograph of intra-pelle-skeletal packstone (from unit in Fig. 5.17). Note the increased amount of echinoid's fragments (XN-X3).

Fig. 5.19 Microphotograph of thin section of the skeletal grainstone block found at the base of tidal channel in Fig. 5.16 (XN-X3).

Fig. 5.20 The same as in Fig. 5.19. Note animal boring truncating the matrix and the quartz grain (XN-X3).



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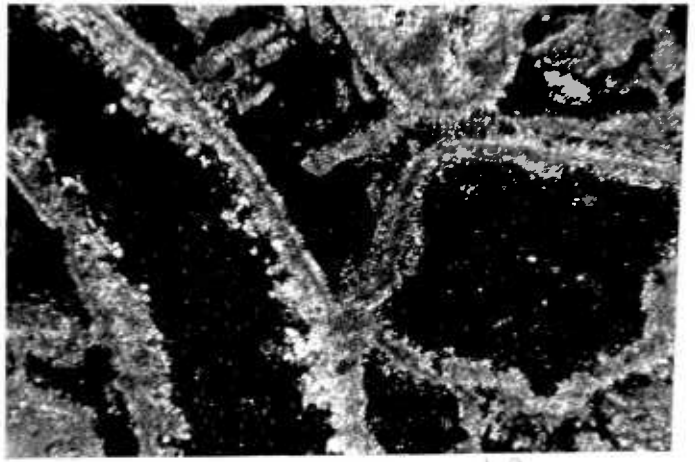
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general "upwards" decrease in grainsize, which characterizes channel sequences.

They contain shell fragments and complete shells of bryozoa, molluscs, foraminifera, algal fragments, oncolites and echinoid grains. Pellets are abundant; they show a different degree of deformation due to compaction between the more competent grains (Fig. 5.18). Flat lime mud pebbles are up to 5 millimetres in diameter; they are rounded to subrounded and consist of calcareous mud and silt or dolomite. The quartz grains are not uncommon. However, they are more abundant in the channel units exposed in Jebel Zelten.

The lag deposit of the channel fill consists of shell material, grainstone boulders and mudstone cobbles. Their lithology is notably different from that of the host sediment and often develop a higher relief on the outcrop face (Fig. 5.16). The grainstone block shapes are tabular and rectangular. They range in size from 20 cm up to 2.5 metres. They often show internal sedimentary structures such as lamination and cross lamination. Their surfaces are encrusted by calcareous algae and bored by bivalves and worms (Fig. 5.20).

Microscopic study of these blocks indicates that they are composed of whole shells or skeletal fragments such as those of molluscs, coralline algae, echinoids, bryozoa and foraminifera. The contents of quartz, sand and pellets are variable. All of the original aragonitic shells have been dissolved and mouldic porosity is now supported by the micrite envelopes (Fig. 5.19). Some of the intergranular pore spaces have been partly filled by widely spaced calcite druse (Fig. 5.20) but no complete pore filling is observed.

Crypto- to microcrystalline calcite cement is recognized filling the intergranular pore spaces. In places algal-like lamination is also present between grains. The micritic cement contains pellets and trapped fine skeletal grains; it is also present between skeletal as well as quartz grains (Fig. 5.20).

The crystalline cement consists of short fibrous crystals 20 microns in length and projects from the surface of the shells into the intergranular pore spaces (Fig. 5.19). Close to the surface of shells, fibrous cement and micritic cement are intergrown (Fig. 5.20). Sometimes the fibrous cement is replaced by cryptocrystalline calcite cement. Often the fibrous cement completely disappears around the quartz grains giving way to cryptocrystalline cement. The semi-opaque

cryptocrystalline band is then followed towards the centre of the intergranular pore spaces by fibrous calcite pore filling.

Braun and Friedman (1969) reported boulders belonging to intertidal facies at the bottom of channel facies in the Lower Ordovician of New York. They published an underwater photograph provided by R. Ginsburg of a lithified carbonate block at the botton of a recent tidal channel in the Bahamas.

The foregoing megascopic and microscopic description and the environmental association of the tidal channel boulders suggest that they were pencontemporaneously eroded beach rocks. They were dislodged after early lithification as a result of the lateral migration of the tidal channel. Lithification must have taken place under intertidal conditions similar to those described by Ginsburg (1957) from Florida, Taylor and Illing (1969) from Qatar and that described by Moore (1973) from the West Indies.

Sedimentary Structures

Trough, planar and microcross lamination, and even massive bedding are common in this facies. Most cross laminae show size grading of sand and lime mud. Thin strings of lime mud are often found following the configuration of the

troughs. During reworking they were ripped off and redeposited as flat pebbles at the base of the following trough (Fig. 5.17).

The grain size grading is also evident throughout the unit. The cross-stratified zone is overlain by finer grained zone which is micro-cross laminated or ripple laminated. This zone is either followed by laminated mudstone facies or calcareous shale.

Similar, carbonate tidal channel facies are described by Klein (1965) from the Great Oolite series.

Interpretation

Channel facies are found associated with various depositional environments in the Marada formation. Thus it is important to differentiate between the channel associated with carbonate tidal flat facies and those associated with other facies. An estuarine origin cannot be considered here, because of the great variety of fossils in the channel facies, and the limited number of marine faunal species in estuaries (Klein, 1967). Also, the tidal inlets and lagoonal channels contain more terrigenous material, and show different colour and geometry. The lithological associations are perhaps the most important difference. Because these channels are associated with the intertidal and supratidal flat facies, the conclusion is inescapable that these limestones are tidal channel sediments.

In arid climates such as the south-western coast of the Persian Gulf, the tidal channels seem to be confined to the intertidal zone (Evans et al, 1973). These channels show little or no meandering, and they cut deeply into the barrier island (7 metres), with an apparent shallow surface drainage at the gully heads on the land side of the lagoon. In these channels, the coarser sediments are found near the seaward side due to high velocity, but in their inner parts the lime mud content is high due to silting up (Evans et al, 1973). These channels resemble those of the Marada tidal inlets rather than those of the tidal flats.

In contrast, the Bahamas tidal flats are influenced by a wet climate with many large tidal channels which migrate laterally. This migration results from persistent water movement generated by storms and tidal influx. As a consequence meander loops, cut-off meanders and capture are common (Shinn et al, 1969). This appears to be due to the ease of the bank erosion as well as the movement of the water in the channels and scouring by the sediment load.

The sediments within channels are variable compared to the sediments of the tidal flats. Shinn et al (1969) attributed this variability to the variation of the current velocity within the channel system. Stronger currents and

coarser sediments are found at the meander bends, whilst slower currents and finer sediments are found at the straight parts of the channels.

Lateral migration in some of the Marada tidal channels is indicated by their occurence in sheet-like bodies and the abundance of grainstone boulders as lag deposits. Beach rocks and accretion ridges are found running normal to modern tidal channels in the Bahamas and Qatar (Shinn et al, 1969; Shinn, 1973). Boring and encrustation of these blocks suggests prolonged exposure at the base of the channel before burial.

The vertical erosion of the Marada tidal channels was inhibited by the occurence of a lithified surface which marks the top of the intertidal units below (Fig. 5.1). Shinn (1973) indicated that lateral channel migration in the Bahamas and Qatar tidal flats is enhanced by the occurence of a cemented layer below the channel belt.

Point bar deposits near the inner bank of meander bands of the recent tidal channel often consist of a coarse carbonate sand (Shinn et al, 1969). Trough cross lamination of the point bars often shows grain size grading. They are formed as a result of down current migration of dunes and ripples (Klein, 1965).

A fining-up sequence results from lateral channel migration and the overlap of channel deposits by levee facies (Allen, 1965). The levee deposits of Marada intertidal facies are laminated and strongly dolomitized, as in their modern counterparts (Shinn et al, 1969).

5.3 Intertidal Flats and Channels Vertical Profile (Plate 5.1

The following profile is exposed in Dar Zuggut area (section D6) where it overlies a sequence of laminated shale facies and is overlain by the wackestone facies association. It consists of the following:

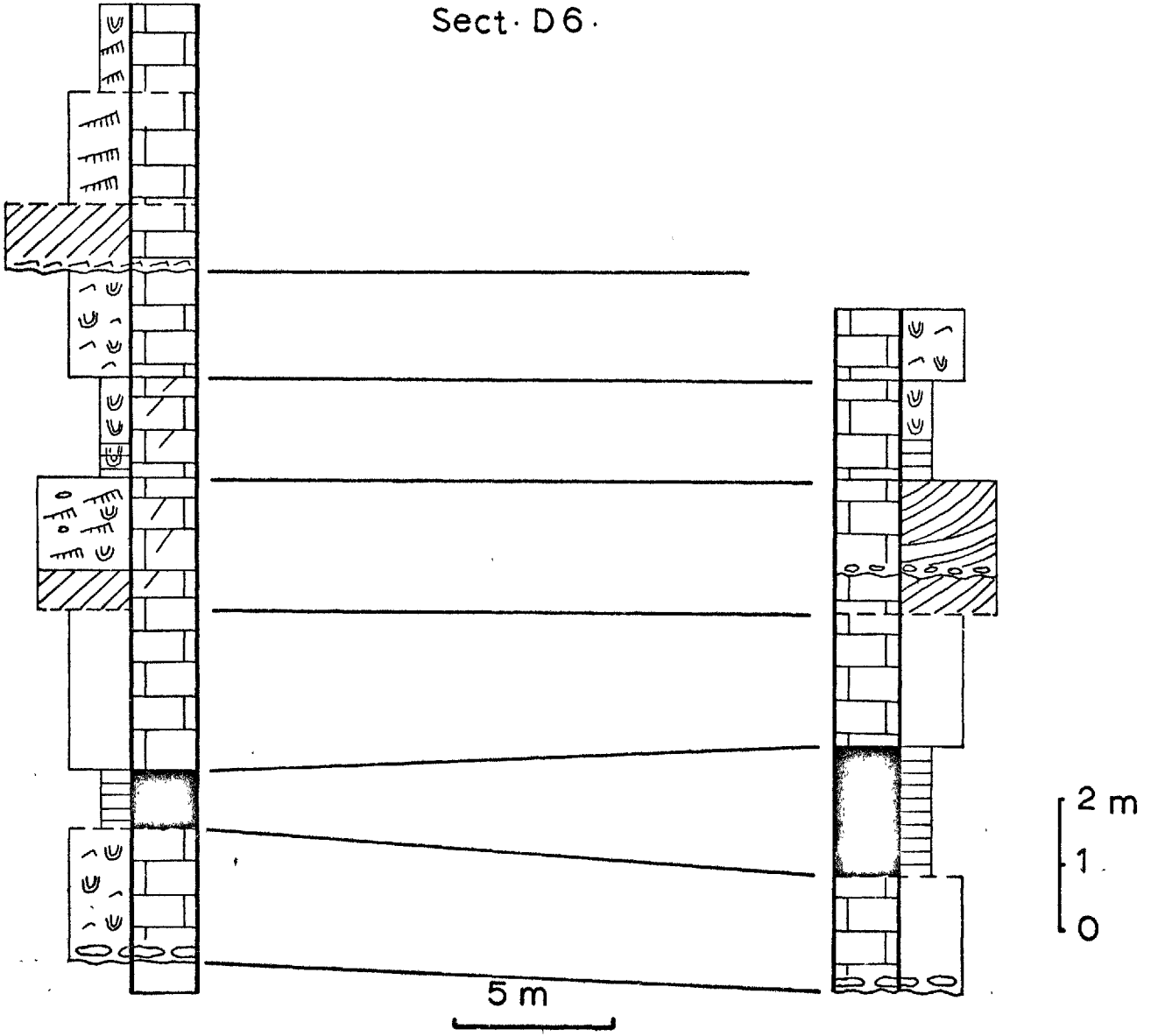
Base:

Unit 1: Fining-up sequence of skeletal wackestone and shale bioturbated and contains grainstone blocks at the base. The shale unit is lenticular (channel fill).

Unit 2: Massive, white, soft, pelletal wackestone, changes into a grey, tough lithified cross laminated pelletal packstone (lower intertidal-intertidal).

Unit 3: Dark grey, tough, bioturbated (Callianassa, crab), pelletal packstone, dolomitized, flat pebbles, micro-cross laminated, changes laterally in fining-up sequence of intra-pelle-skeletal grainstone (intertidal and channel).

Plate 5-1 Vertical profile of intertidal carbonate facies, Sect. D6.



Unit 4: Dolomitic mudstone, grey coloured tough, laminated dolomite at the base, bioturbated at the top (intertidal and channel levee).

Unit 5: Mottled pelle-skeletal wackestone, dolomitized bioturbated. Elsewhere this unit is overlain by oyster shell banks (intertidal-lower intertidal).

Unit 6: Fining-up sequence of cross laminated grainstone and microcross laminated sandy pelletal mudstone followed by Echinolampas bed (channel) which indicate open marine conditions.

This sequence represents the intertidal flat facies association in Der Zuggut area (north). Those in Jebel Zelten are strongly influenced by their proximity to the source of the terrigenous supply, and are dominated by the dolomite facies described below.

5.4 Dolomite Subfacies

Units of the dolomite subfacies are found interbedded with the terrigenous dominated intertidal and estuarine facies in Jebel Zelten as well as the capping limestone bed of the Marada formation in Jebel Zelten, the central Jebels, and the northwest sections of the area.

This facies ledge profile is about 150 cm. thick, it consists of beds about 30 cm thick. Units often show an

Photo Plate V-5

Supratidal facies

Fig. 5.21 Dissécation cracks in mudstone, the cracks are filled by calcite.

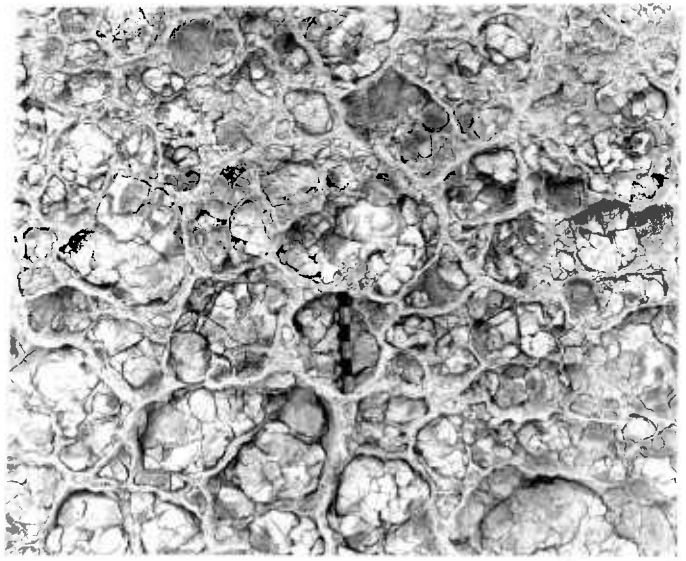
Fig. 5.22a Dolostone containing organic material of algal origin (X3-NL).

Fig. 5.22b The same as Fig. 5.22a; dolomite is replacing pelletal rock (X3-NL).

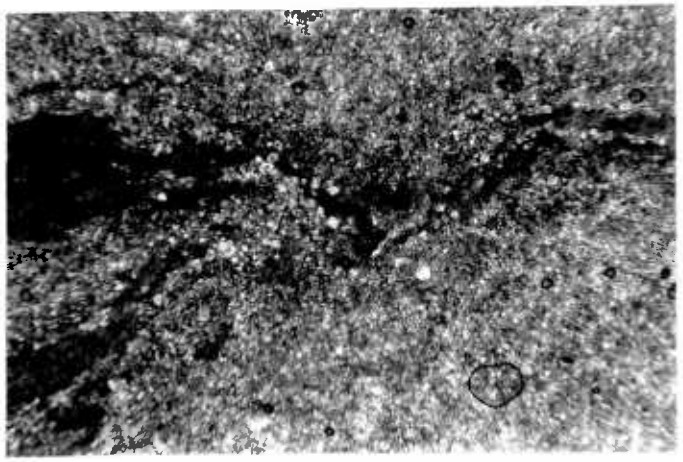
Fig. 5.23 Gypsum pseudomorphs in mudstone (NL-X3).

Fig. 5.24 Dolomite solution collapse breccia, found below disconformity surface capping the Marada Formation.

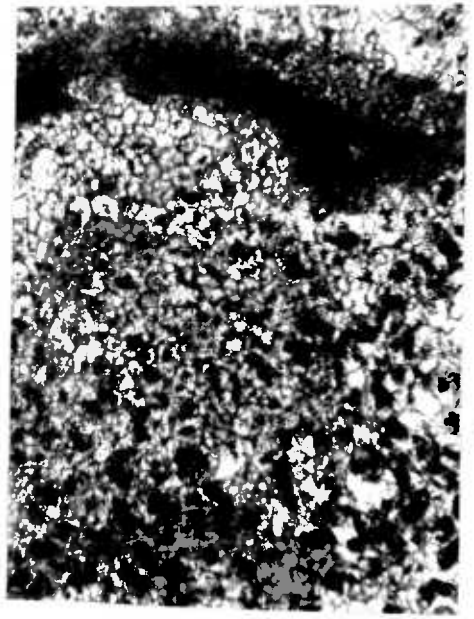
Fig. 5.25 Microphotograph of dolomite breccia clast containing gypsum pseudomorph, now filled by calcite. The clast consists of fine grained dolomite (NL-X3).



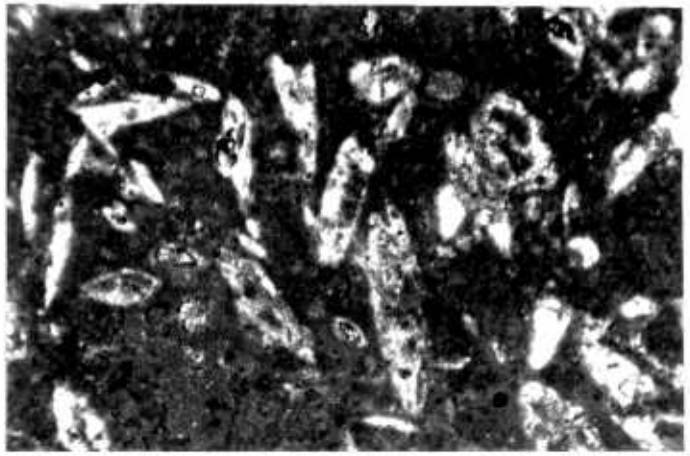
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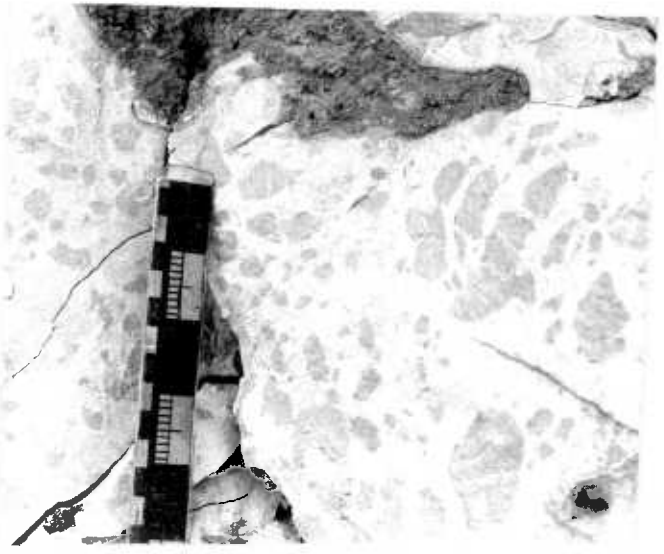
22a



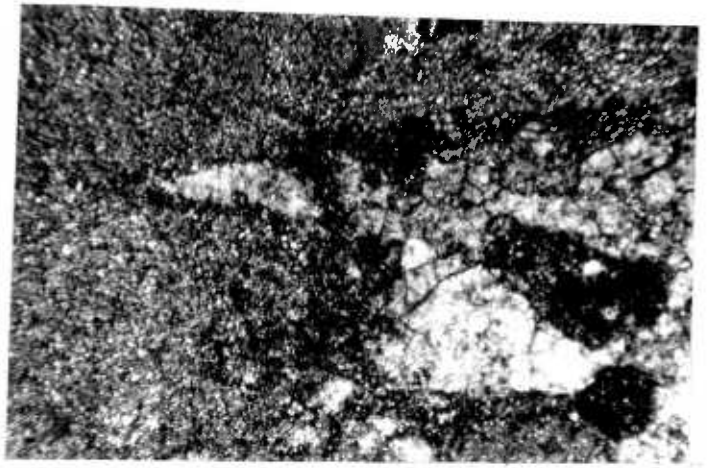
22b



23



24



25

erosional to sharp lower contact with the underlying units. Thinner beds are found interbedded with interlaminated sands and shales of the intertidal flat facies. The units' upper boundary is generally sharp or erosional, but sometimes gradational with calcareous shales.

Lithology

The rocks of this facies generally appear massive and unfossiliferous. Algal and organic materials are commonly found oriented parallel to the bedding planes. They are scattered and widely spaced (Figs. 5.22a and 5.22b), but algal lamination is generally absent. Worn skeletal remains of molluscs, forams are not uncommon. They are generally dolomitized, or dissolved away leaving mouldic porosity.

Quartz grains are common in most of the samples examined. They are well sorted and angular fine sand and silt size. The quartz grains found in the dolomite facies are different from those of the terrigenous tidal flat facies. The latter contain coarser and well rounded quartz grains. The former's quartz grains were possibly introduced by wind.

Rocks consist of inequigranular dolomite rhombs which range in size from 5.5 to 30 microns. They are of xenotopic to hypidiotopic fabric (Fig. 5.22a). Rhombs contain dark cores

of impurities , which show different size ranges (Fig. 5.22b). They are the relic s of the original lime mud and pellets. Abundant clay material is also found between the dolomite crystals; the clay minerals were probably expelled from the dolomite in some of the samples studied filling the inter-particle pore spaces. Replacement of dolomite rhombs by calcite is not uncommon. Some lime mudstone and dolomite samples contain lenticular moulds of pseudomorphs after gypsum (Fig. 5.23). The pseudomorphs are arranged in different orientation. They are found in thin sections either widely spaced or concentrated in patchy areas of about 2 cm wide. The pseudomorphs are about 0.15 to 1.5 mm long, and 28 to 200 microns wide. Moulds are partly filled with material from the ground mass (Fig. 5.23). Collapse of sediments in the moulds, after the solution of the gypsum, is not evident.

Sedimentary Structures

The most obvious sedimentary feature of the dolomite facies are polygonal mud cracks (Fig. 5.21). Most mud cracks are filled by sediments or calcite, which is slightly coarser than the host rock, and more resistant to weathering. The mud cracks are formed by drying out of carbonate layers which are exposed subaerially for extended periods. Mud cracks are also found in the lime mud and shale layers inter-

bedded with the dolomites. Successive generations of mud cracks may develop on top of one another, forming deep vertical joints between polygons.

Some units show mottled appearance, with clay minerals appearing to be concentrated along contorted and intersected lines. These features are possibly the work of burrowing organisms. Burrows, however, are not as common as those observed in the tidal flat facies.

Interpretation

The sedimentological and compositional features of the dolomite facies suggest that they were originated on supratidal flats which were subjected to prolonged subaerial exposure. The erosional lower contact, the lack of lamination, and the occurence in a terrigenous sediment dominated area may suggest that the original carbonate sediment was deposited during storms. Ball et al (1967) and High (1969) have shown that modern storms are capable of transporting large amount of sediment into supratidal flat areas. The gradational upper contact of the dolomite units with shales and sands reflects the waning competence of the water and the increased influence of the terrigenous source.

The occurence of gypsum pseudomorphs in some undolomitized lime mudstones (Fig. 5.23) indicates that the gypsum was precipitated before the onset of dolomitization. Precipitation of $CaSO_4$ is necessary towards the increase of Mg^{2+}/Ca^{2+} ratio in order to allow dolomitization (Liebermann, 1967). Illing et al (1965) indicated that lenticular gypsum crystals contain inclusions of carbonate sediments and grow in the recent sebkas of Qatar Peninsula; the size of the gypsum crystals increases with the dolomite content of the enclosing sediments. A similar correlation can be drawn between the size of gypsum pseudomorphs and the degree of dolomitization of the Marada supratidal facies. Subsequent solution of gypsum was probably induced due to lowering of salinity during flooding by sea water or rainfall.

Most dolomitized limestones of the Marada Formation show a gradual increase in the amount of dolomite towards the top of the units. This fact holds not only for the supratidal facies, but also for the dolomitized intertidal units (Fig. 5.2). Figure 5.15 shows dolomite mottling which increases in intensity towards the top of the unit, whilst towards the base of the unit dolomitization is confined to burrows (Figs. 5.9, 5.10). This suggests that dolomitization must have started at the top of the unit and the dolomitizing solutions have followed the

effectively porous channels created by burrows (Beales, 1953; Osmond, 1956).

It is thought, therefore, that dolomitization of the intertidal supratidal facies depended on evaporation of sea water at the sediment surface, and was followed by percolation of the Mg-rich brines.

5.5 Origin of the Dolomite Breccia

This subfacies occupies the topmost few metres of the Marada succession of the sections of Jebel Zelten and some of the sections of the Central Jebels. The thickness of the units examined ranges from 2 metres to 4 metres. In places this unit is completely absent due to erosion. The lower contact is always erosional. The top of the unit is marked by disconformity surface which is traceable for a long distance in Jebel Zelten and Central Jebels. Northward the disconformity is less prominent and the top of the sequence is occupied by mudstone and wackestone units which are often dolomitized, and affected by meteoric water diagenesis. However, a unit of the subfacies is found a few metres below the top of Garet Gohannam (section M8) in the NW corner of the area. It overlies cross-bedded oolitic grainstone unit (beach rock) and is overlain by dolomitic mudstone.

Photo Plate V-6

Fig. 5.26 Breccia clasts (dark) are floating in a crushed dolomite matrix (light areas), now replaced by pseudospare dedolomite (NL-X3).

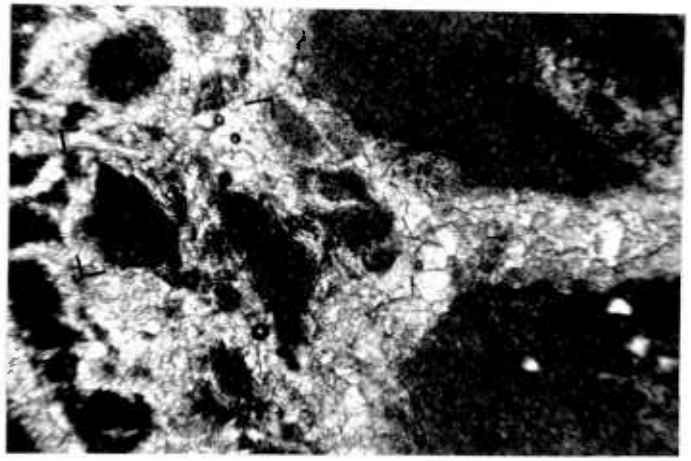
Fig. 5.27 Close up of marked area in Fig. 5.26 showing a secondary gypsum vein (A) running parallel to the surface of the dolomite clast. Dedolomite pseudospar shows a curved and irregular crystal boundary (b) along which tiny dolomite crystals are concentrated (NL-X10).

Fig. 5.28 Dolomite at (b) is a transitional area between clear dedolomite at (a) and the dolomite clast. Vein filling calcite at (c) is cutting across the clast and the transitional dolomite (NL-X3).

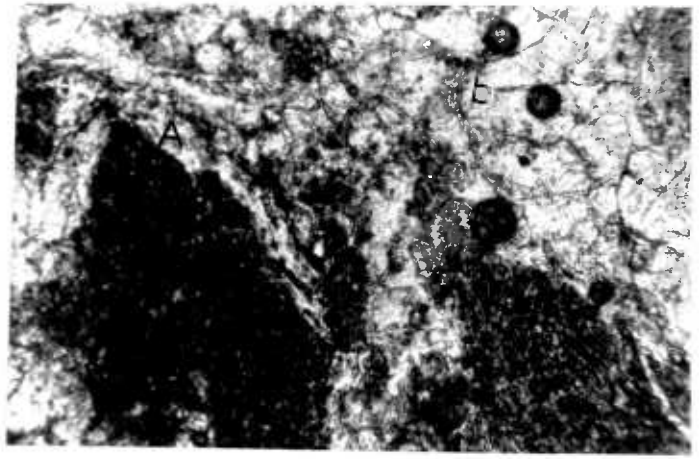
Fig. 5.29 Crushed dolomite matrix (b) being converted into fine blocky pseudospar dedolomite (a), which changes into coarse blocky and bladed (c). The bladed crystals are perpendicular to the clast surface and contain lines of inclusions running parallel to the surface of the clast (NL-X3).

Fig. 5.30 Close up of marked area in Fig. 5.29 showing details of the textures described above (NL-X10).

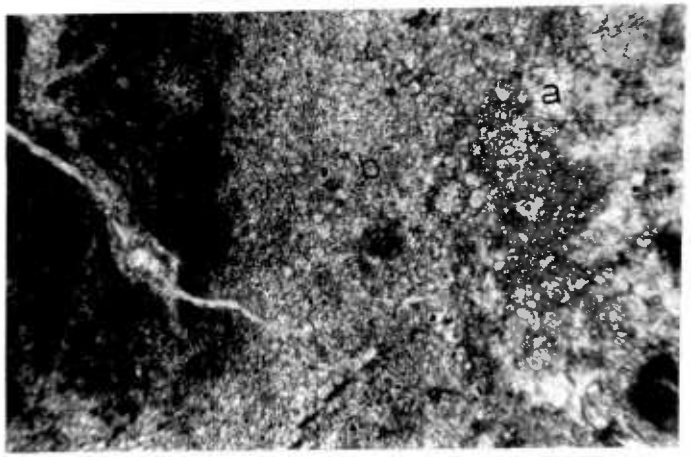
Fig. 5.31 The same as Fig. 5.29 under cross nicols, to show the pseudo cavity filling texture made up by pseudospar dedolomite (XN-X3).



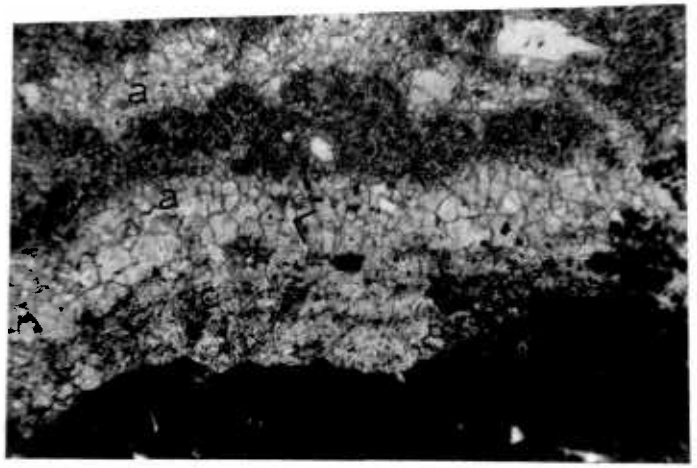
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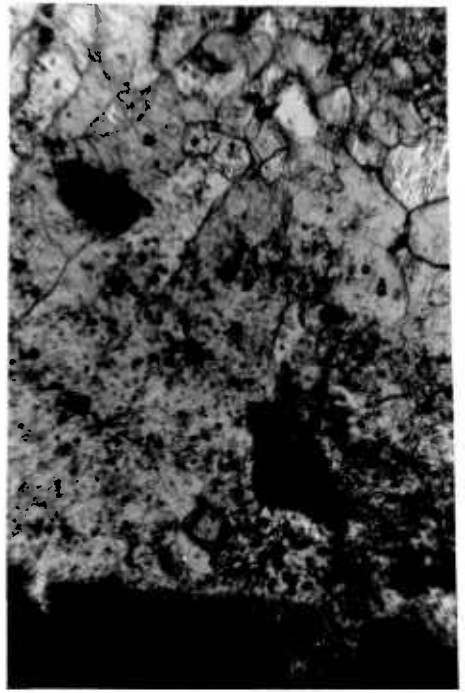
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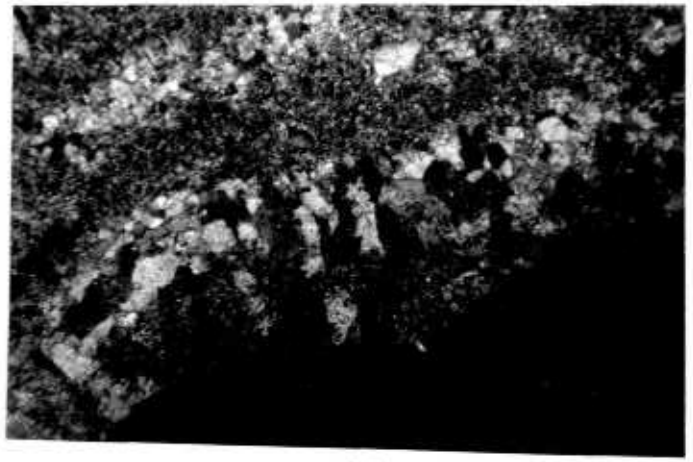
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Description

Beds of the dolomite breccia are massive, tough and fresh broken surfaces show concoidal patterns. Their upper surface is irregular at the disconformity surface due to solution cavities which are filled by friable red clays (terra rossa) (Fig. 5.24). The walls of the solution cavities are smooth, and the red stain penetrates only a few millimetres into the rock. Similar features were reported by Roehl (1967) on the weathered surfaces of Pleistocene limestone outcrops of Florida.

The rock consists of mottled patterns of reddish angular to subangular clasts floating in a pinkish white matrix. The clasts range in size from 5 cm to a few millimetres. They are irregularly distributed through the rock. Generally their longest axes are roughly oriented perpendicular or at an angle to the bedding planes.

The breccia clasts are made of a dolomitized pelletal mudstone. Pellets up to 22 microns in diameter show a vague outline. Angular quartz silt and also remnants of skeletal debris are present in the clasts' muddy groundmass. Both pellets and mud are replaced by equigranular (15 microns), closely packed xenotopic to hypidiotopic dolomite rhombs. The dolomite crystals are clouded by inclusions of the original sediment, and disseminated iron oxides.

Lenticular pseudomorphs after gypsum similar to the ones described earlier are found in some of the clasts (Fig. 5.25). The pseudomorph moulds contain remains of the original dolomite sediment enclosed during the gypsum crystal growth. The rest of the mould is now filled by clear coarse calcite spars.

Most clasts are cut by corrugated and wavy, calcite filled cracks (Fig. 5.28). Similar veins filled by clouded fibrous gypsum are also present. Gypsum fibres are oriented parallel to the wall of the cracks. Thin slices are exfoliating off the surface of breccia clasts by parallel gypsum veins (Fig. 5.27), reducing their size and smoothing their outer surface.

The matrix of the rock is translucent in thin section and consists of finer clast material (Fig. 5.26). Dolomite rhombs of the matrix are up to 27 microns in size. The cores of dolomite crystals are slightly clouded with inclusions. The matrix material is also cut by calcite and gypsum veins (Fig.5.26). Some clasts, however, show a gradational contact with the matrix (Fig. 5.28).

The matrix is replaced by pseudospar dedolomite which exhibits a wide range of textures and crystal sizes (Fig. 5.27, 5.29). Small pseudomorphs about 25 microns in size are replacing single dolomite crystals and produce equigranular texture (Fig. 5.28). Larger calcite crystals replace

more than one dolomite crystal and produce unequigranular pseudospar texture (Fig. 5.27). Sometimes large calcite crystals include dolomite rhombs giving poikilotopic texture.

Boundaries between crystals are highly variable, straight, curved and crenulated (Fig. 5.27). Curved boundaries seem to be predominant. At crystal boundaries, tiny dolomite grains and crystals appear to be concentrated.

Dedolomite crystals are generally equant in shape (Fig. 5.29). Those close to a clast appear to replace its wall along a continuous front and the new dedolomite crystals grow in optical continuity to those of the matrix. Pseudospars produced by this process are bladed in shape and the texture mimics that of normal pore filling sparry calcite cement and described by Bathurst (1958) (Figs. 5.29, 5.30, 5.31). The production of bladed pseudospar is possibly aided by gypsum vein running parallel to the surface of the clasts described above. The bladed pseudomorphs are ornamented by lines of inclusions which run parallel to the surface of the clasts. These inclusions include clay minerals, quartz grains, skeletal debris and tiny dolomite crystals and grains. A similar texture is also produced along calcite veins which are cutting across dolomite clasts.

Interpretation

The occurence of gypsum pseudomorphs (Fig. 5.25), secondary gypsum veins in dolomite breccia below a disconformity surface, strongly suggest that this subfacies is in fact an evaporite solution collapse breccia which results from fresh water action (Roehl, 1967; Blound and Moor, 1969; Moore, 1971; and Lucia, 1972).

Dedolomitization and the development of pseudospar cement must have occured under subaerial conditions after the dissolution of the gypsum, and before the development of terra rossa at the disconformity surface. De Grott (1967) has shown that high Ca/Mg ratios resulting from the dissolution of gypsum by fresh water can produce calcite from dolomite under normal nature conditions.

From the foregoing discussion one can draw the following sequence of events:

1) Dolomitization of carbonate sediments and growth of gypsum crystals under Sebkha conditions.

2) Solution of gypsum by fresh water and collapse of the surrounding dolomite producing breccia and crushed dolomite material. The size of the clasts depends on the size and the degree of abundance of the gypsum crystals.

3) Calcium sulphate solution converts dolomite to calcite (De Grott, 1967). Calcite is initially equigranular fine grained (Fig. 5.28) with islands of dolomite remains.

4) Continuing diagenesis in the presence of calcium sulphate solution converts most of the smaller dolomite clasts to calcite, and replaces the larger ones with an attendant increase in crystal size (Fig. 5.30).

5) The final product is a breccia with large dolomite clasts floating in a matrix of coarse pseudospar dedolomite that mimics normal pore filling calcite (Figs. 5.29, 5.31).

Finally, the intertidal, supratidal and sabkha carbonate facies were not discussed by the previous authors (Selley, 1966; Doust, 1968). These facies may have been regarded as a part of their limestone facies which were interpreted differently.

CHAPTER 6

THE WACKESTONE AND MARL SEQUENCE

The wackestone and marl sequence of the Marada Formation occupies the top half of the sections exposed in Dor Marada, Dor Zuggut, and Central Jebels. Units at the base of the sequence are marked by the occurrence of Echinolampas Sp. which forms a good marker horizon throughout the area. These facies attain a maximum thickness in Dor Marada. Southwards they progressively overlap the crossbedded limestone and shale sequence and interfinger with the terrigenous intertidal and estuarine facies in Jebel Zelten. The landward equivalent of the basal wackestone units in this area is a thin tongue of the dolomitic mudstone facies. The marl facies often contains calcareous sandstone shoestrings; cross-laminated grainstone and mudstone units are usually found associated with the wackestone facies.

In his study of the palaeoecology of the megafauna of the Marada Formation, Doust (1968) has identified the biological assemblage which is recognized in the wackestone and marl facies; also the foraminiferal and algal assemblages are recognized from the work of Bellini (1968) and Souaya (1963a, b) on the Middle Miocene rock of eastern Libya and Egypt respectively. The following fauna is recognized in the Marada wackestone and marl sequence:

A) Bivalves: Laupha plicatule, Ostrea frondesa, O. fimbriata, Chlamys spp., Pecten spp., Spondylus crassicosta, Cardium sp., Lithophaga lithophagus, Gastrochaena squamulosa, Pholas dujardini.

B) Gastropods: Vermetus sp., Turritella sp., Strombus bonelli, Cypraea, and Conus spp.

C) Bryozoa: Idmonea spp., Trigonopora moniliferum, and Holoporella spp.

D) Echinoids: Echinolampas spp., Echinodiscus fuchsi, Agassizia, and Asteroid plates.

E) Decapoda: Callianassa chela and crab carapace.

F) Foraminifera: Boralis melo (type fossil), Dendritina ragi, Peneroblis sp., Spirolina sp., Miliolidae (Quinqueloculina sp., Biloculina, and Globigerina; and Ostracoda.

The common algae which are recognized are generally from the red algal group such as Archaeolithothamnium Lithothamnium, Mesophyllum and Melobesia sp. (Souaya, 1963a, b). Doust (1968) suggested that most of these fossils indicate normal and near normal marine salinities and water depth between 0 to 40 metres.

Crassostrea oyster banks which are usually found associated with the laminated shale facies are also found associated with the wackestone and marl facies. Crassostrea banks are discontinuous and extend laterally for up to 200 metres and range between 20 to 50 cm thick. Individual oysters are often in growth position (Fig. 6.2). The occurrence of Crassostrea banks in these facies suggests occasional lowering of the marine water salinities, particularly in front of estuaries (Doust, 1968).

6.1 The Wackestone Facies

The wackestone facies represents the majority of the units of the open marine association. Units are regular bodies which are traceable for tens of kilometres without a great change in thickness. They are massive, 2 to 5 metres thickness (Fig. 6.1) units which show an erosional (Fig. 5.3), sharp and sometimes bioturbated lower contact. The upper boundaries of thick units are sharp or occupied by oyster banks in growth position (Fig. 6.2). The top few centimetres of the regional units often consists of tough, laminated and bored pelletal mudstone, and sometimes skeletal grainstones.

Photo Plate VI-1

The Wackestone Facies

Fig. 6.1 A sequence of thick and massive beds of the wackestone, open marine facies. The top of the sequence is occupied by an oyster bank in growth position, as seen on the eroded block to the left.

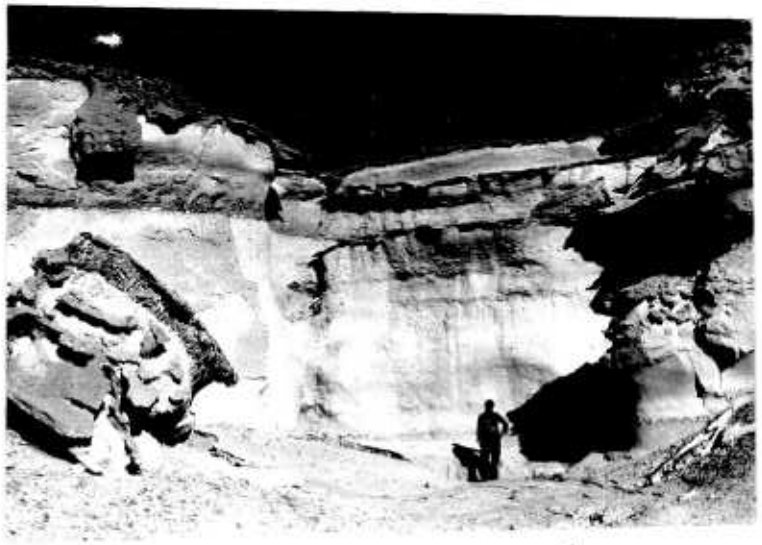
Fig. 6.2 Wackestone bed colonialised by oysters in growth position of Fig. 6.1, followed by a sequence of interbedded thin wackestone and shale. Notice that the base of the wackestone bed is sharp, it grades upwards into shale.

Fig. 6.3 The base of the open marine sequence is erosional, lamination in the massive wackestone is indicated by the horizontal orientation of shells.

Fig. 6.4 Photomicrograph of wackestone shows bryozoa shell (Trigonopora) and other skeletal fragments floating in a matrix (NL-X3).

Fig. 6.5 Archaeolithothamnium alga. Foraminifera and shell fragment in wackestone. Moldic porosity is partially filled by calcite (XN-X3).

Fig. 6.6 The matrix in the wackestone consists of dense pellets, skeletal grains showing algal boring (top centre); pore spaces are produced by solution of grains (XN-X3).



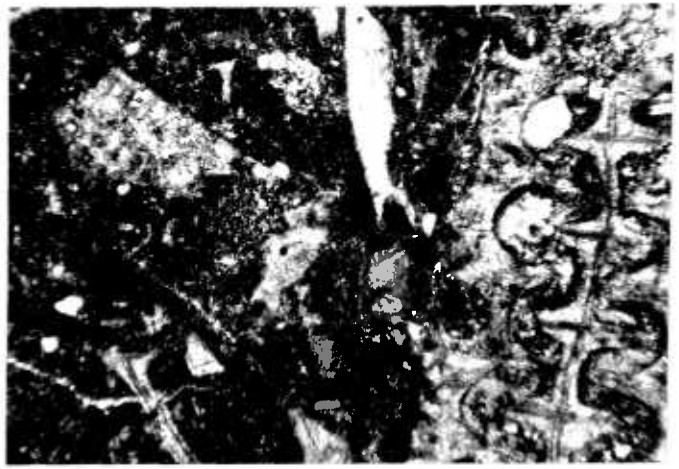
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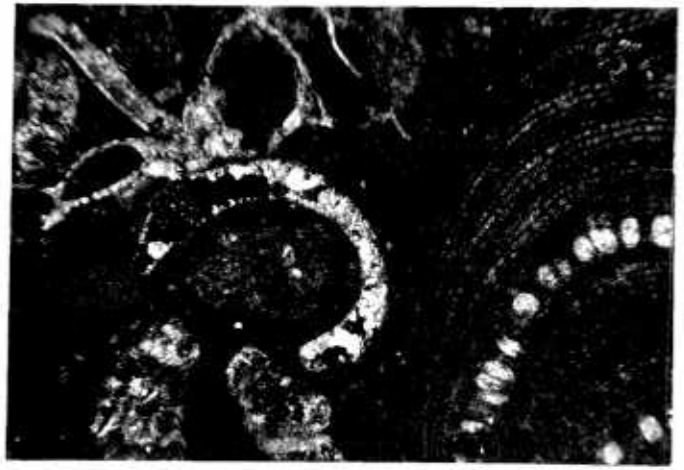
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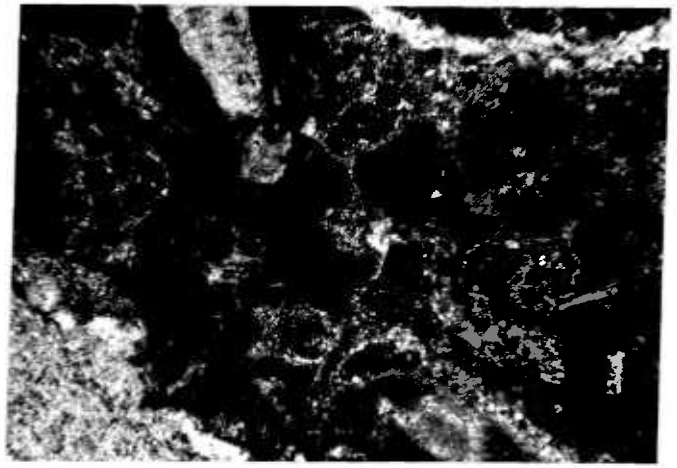
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6

Thinner wackestone units (100-30 cm) are often argillaceous and interbedded with fossiliferous green shale and marl units. The lower contact of the former is sharp and often bioturbated, and their upper contact with the shale is always transitional (Fig. 6.2). The more argillaceous and often thinner wackestone units show transitional lower and upper contacts.

Lithology

Units of the wackestone facies are chalky white (N-9) to very pale orange (10 YR 8/2). Samples are soft, and often crumble under pressure into a powdery material. Vaccum plastic impregnation was often necessary to give samples enough hardness in order to withstand thin section grinding. Also, malachite green dye was used to stain the organic material in thin section, which otherwise would have been inconspicuous from the lime mud of the matrix.

Rocks of this facies basically consist of complete and often articulated shells, sand and silt size skeletal fragments, pellets, and lime mud, occurring in different proportions to produce shell banks, wackestone and mudstone subfacies.

Shells of Laupha and Ostreas are the most common bivalves in the wackestone facies. They occur in a thin,

patchy bank on top of the units; they extend from 50 to 100 metres laterally, and they also concentrate at the base or as scattered individual bivalves, together with Spondylus and Pecten throughout the unit.

Trigonopora, Holoporella bryozoa shells and echinoid spines and plates are also common. Some shell fragments are up to 3 cm in diameter. Most shells and shell fragments are bored by algae (Fig. 6.6), sponge (Fig. 6.11), and encrusted by calcareous worm tubes, bryozoa and algae (Fig. 6.11).

The second size fraction consists of ill sorted and angular, medium to fine skeletal sand (Fig. 6.11). It shows different degrees of graded breakdown from complete shells and coarse fraction. This size fraction is often irregularly distributed through thin sections, and tends to form a closely packed skeletal clusters in the matrix. All grains show different degrees of corrosion by boring algae.

The fine grained matrix of the wackestone consists of calcareous silt which ranges in size from 5 to 50 microns and is scattered in a dark clotted cryptocrystalline calcite. It contains vague outlines of micritized grains, algal filaments and pellets (Fig. 6.11).

Algal encrusted grains and oncolites show diversity of sizes and shapes. Small oncolites are 0.3-0.8 cm complete spheres with slightly undulating surfaces or with well developed irregular protruberances. Others are evenly distributed through the sediment as no joining protuberances are found between them. The core around which algae precipitate is usually shell fragments, and lime mud pellets. Larger, smooth and elliptical oncolites, 2.5-5 cm in diameter, consist of a core of a complete shell and a thick asymmetrical algal coat. Algal material is sometimes bored by worms, sponge and encrusted by bryozoa, and/or reworked by burrowing organisms. These oncolites are similar to those described by Wagner and Togt (1973) from the recent offshore sediments of the Persian Gulf.

Crustaceous melobesoid algal forms are very common in the wackestones. They consist of horizontal and wavy thin layers often connected together by inclined branches enclosing and enclosed by surrounding fine grained sediments and shell fragments. They are often fragmented and disrupted by burrows. These forms are considered here as red algal mats analogous to recent subtidal algal mats described from the Bahamas (Scoffin, 1970; Neumann et al, 1970), and Bermuda (Gebelin, 1969). The significance of this algal form will be discussed in a later part of this chapter.

Two types of pellets are found in the Marada wackestones, sand size pellets which range in size from 0.3 to 1.4 mm, and finer size pellets (4.5 to 70 microns); both types of pellets are common. Some mudstone samples are formed of compacted pellets (Fig. 6.12). Production of lime mud from compaction of faecal pellets is common in the recent subtidal zones due to weight of the overlying sediments (Shinn, 1968). The large pellets often contain silt size skeletal fragments and are thought to be of faecal origin; smaller pellets, however, appear dark and clotty (Fig. 6.6); it is thought that they were formed by disintegration of algal material or micritization of fine skeletal grains.

The interclasts are often found at the base of the open marine sequence; they are of brownish colour and are 5 to 10 cm in size. Smaller interclasts 2-4 mm in diameter are also found. Interclasts consist of fine sand size pellets (0.14 mm), and are cemented by microcrystalline calcite. They also contain a few recrystallized foraminiferal shells and scattered quartz grains.

The terrigenous quartz grains are not uncommon in the wackestone facies. They represent a small percentage of the rock grain framework. They range from rounded coarse sand (0.5 mm), to angular very fine sand and silt (90 microns). Often they are completely absent in the rocks.

6.1.1

Origin of the fine grained sediments in the Wackestone Facies

The fine grain sediments are defined here as the silt size skeletal fragments (4-50 microns), and the lime mud, micrite or cryptocrystalline calcite (< 4 microns). The terms microspar and pseudospar (Folk, 1965) refer to fine grained carbonates that have undergone certain diagenetic changes, primarily recrystallization.

A. Algal boring and Micritization of skeletal grains:

Petrographic study of the skeletal grains of the Marada limestones in general and the wackestones in particular reveals the presence of abundant grains with a lime mud or micrite envelope (Bathurst, 1966). The micrite envelopes range in thickness from a fraction of a millimetre to one or more millimetres. In some instances up to 80 percent of the grains are altered into cryptocrystalline material. In thin sections the envelopes are dense, and consist of dark micrite which accepts malachite green dye. Micrite envelopes are different from the algal jackets, and oncolitic coats previously described. The latter often show faint concentric layers around particles. Those skeletal grains which show algal micritization are characterized by an irregular peripheral corrosion. Under high magnification, frequently one can see tubes of different diameters embedded in the skeleton near the grain

Photo Plate VI-2

Origin of micrite

Fig. 6.7 Molluscan grain shows algal boring. Bores are filled with cryptocrystalline calcite, the centre of some boring tubes is filled with microcrystalline calcite.

Fig. 6.8 A micritized bryozoa shell, the fringe calcite lining the chambers remains unaltered. Shell cavities at the left of the photograph are filled by cryptocrystalline calcite (XN-X3).

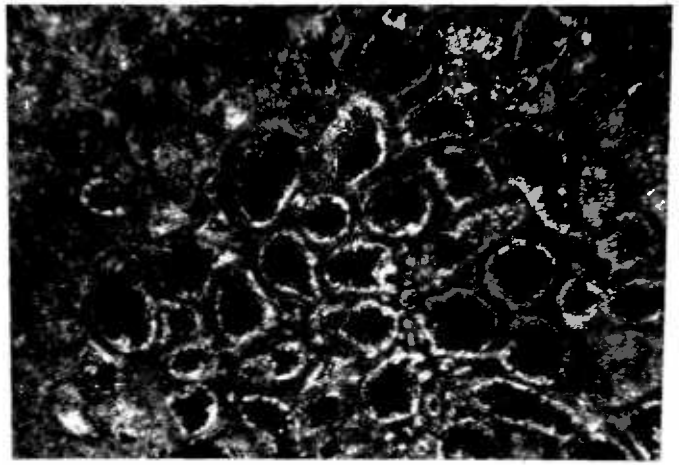
Fig. 6.9 Bryozoa shell chambers are filled with cryptocrystalline mud and silt. The calcitic shell and fringe cement are progressively micritized and reduced into faint areas of calcareous silt (XN-X3).

Fig. 6.10 The end product of progressive micritization of the bryozoan calcitic shell, and filling its chambers by lime mud. Note that calacareous silt is concentrated along irregular lines (centre) and the remains of the original bryozoa (at the lower left) (XN-X3).

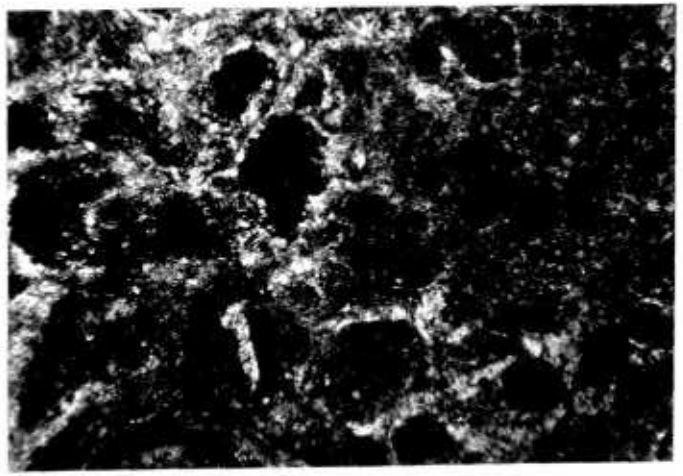
Fig. 6.11 Molluscan shell encrusted by coralline red alga (Melobesia), algae on the upper surface has lost its cellular structure. Animal boring in the shell is filled by a clotted cryptocrystalline calcite, and skeletal debris. Note the similarity between the texture of the matrix and those in Fig. 6.10 (XN-X3).



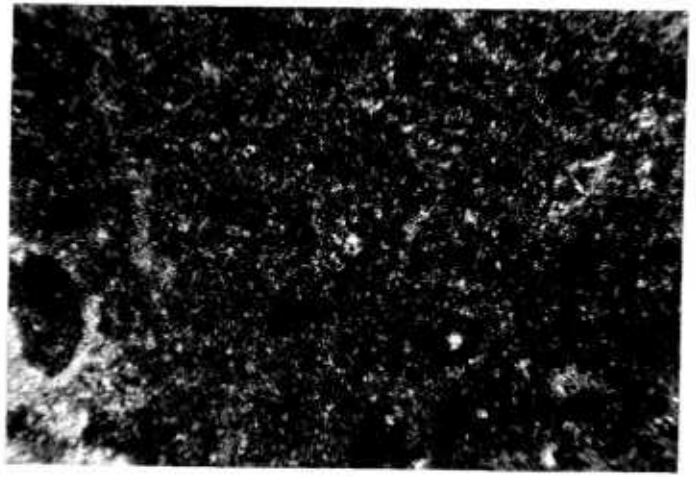
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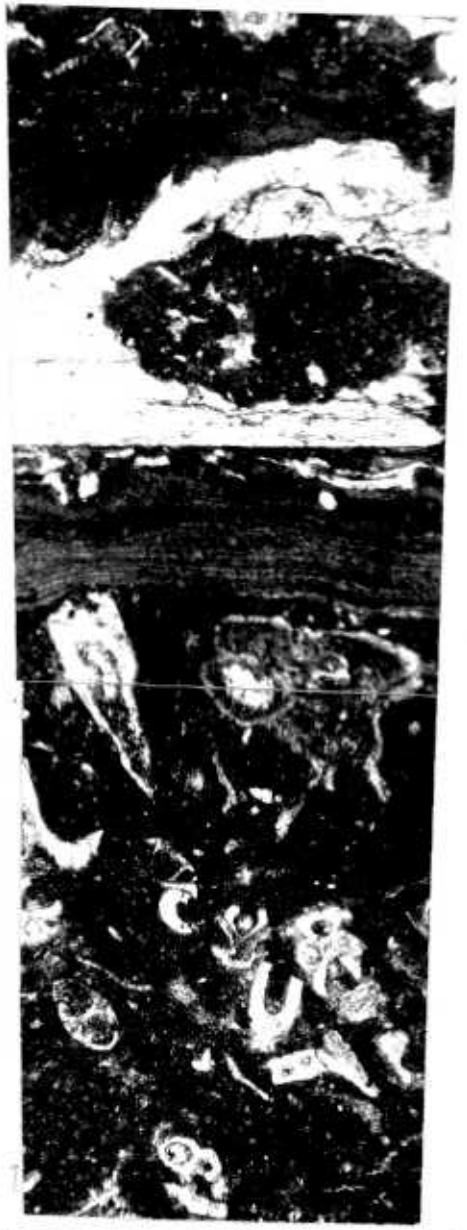
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envelope contact. Large boring tubes of uniform diameter about 10-12 microns (Fig. 6.7) with well defined micritic walls are closely intertwined showing branching and sometimes showing intersection. These tubes are usually filled with a cryptocrystalline mud, but frequently outlined by a thin micritic wall and filled by microcrystalline calcite. The micrite lining may indicate early micrite sheath surrounding the boring algal filament (Klement and Toomey, 1967; Ginsburg et al, 1971). Algal tubes fuse into uniform mass of micrite towards the exterior of the envelope. The second type of algal boring is finer (2-6 microns). Apart from the borings' diameters, they are generally similar to the ones described above.

Bryozoa, mollusca and foraminifera shells and fragments are the most susceptible to peripheral corrosion. The delicate skeletal structure of bryozoa is particularly susceptible to algal borings, complete destruction of the crystalline structure of the shell wall often takes place (Fig. 6.8).

Bathurst (1966, p. 20) indicates that the micrite envelope in recent molluscal shells, which have also been algally bored and corroded, are formed in three successive stages: (a) the skeletal grain is bored by an algal filament

[possibly also by fungi and non-photosynthetic algae (Friedman, 1971) or bacteria]; (b) the algal filaments die and decay; and (c) the empty algal tubes are filled with micrite. Algal penetration of the skeletal grains coupled with allocheme corrosion is the ultimate reduction and obliteration of the grains to micrite, thus demonstrating that algal boring and algal decay is perhaps one of the many effective biological agents at work in fine grain formation (Bathurst, 1966; Klement and Toomey, 1967; and Alberstadt, 1973).

Algae as a source of micrite:

It has been suggested that different types of blue-green algae, green and red algae are always surrounded by thin micritic components (Ginsburg et al, 1971). This algal micrite association is also expressed by the term "algal dust" (Wood, 1941), referring to the lime mud accumulation around algal filaments. Wolf (1956) claimed that it is possible for an early diagenetic change to occur in some algal filaments such as that cellular structure to change to fine grained carbonate. Hadding (1958) and Newell (1970) suggested that the decay of the algal tissue by bacteria caused the calcareous part of the algae to collapse and crumble. Land (1970) found that coralline red algae Melobesia disintegrate and produce high Mg calcite mud and silt at a high rate which is equal to platform accumulation.

The Middle Miocene carbonate rocks of Libya are particularly rich in coralline red algae, in general, and Melobesia sp. in particular (Rainier, 1925; Doust, 1968). They are also abundant in the Middle Miocene rocks of Egypt (Souaya, 1963a, 1963b) and Iraq (Johnson, 1964). The Melobesiod algae occur in the wackestone facies as fragments, encrusting sediments and circumcrusting skeletal grains.

Figure 6.11 shows Melobesia algae coating molluscan shell, the coat on the lower surface of the shell exhibits a clear cellular structure of the alga. Its counterpart on the upper surface is micritized but shows a vague concentric layering of the original algal laminae. The cryptocrystalline mud produced by the disintegration of Melobesia sp, is made of dense, clotted material which heavily absorbs the malachite green stain. It is strikingly similar to the fine grained material of the matrix and those filling colina boring of the shell (Fig. 6.11). Chambers of bryozoa shells are often filled by collapsed algal material (Fig. 6.9). Progressive algal boring and filling of these shells and their chambers produces a homogenous fine grained texture of calcareous silt and mud, which resembles those of the matrix (Fig. 6.10). However, close examination of the end product (Fig. 6.10) reveals that the calcareous silt is more or less

concentrated along lines which represent remnants of the original calcitic wall and cement lining the bryozoan chambers. Thus it is evident that initially the entire algal coating possessed internal cellular structures but subsequently collapsed, which results in their obliteration and disintegration into a fine grained material now filling shell cavities and algal pores, and produces a mudstone texture (calcisiltite). The resulting texture shows no relation to that of the original wackestone framework.

Several authors (Land, 1971; Cadot in Ginsburg et al, 1971; and Daziel in Ginsburg et al, 1971) stressed the importance of the coralline red alga Melobesia sp. as a major contributor of high Mg lime mud to the recent carbonate sediments. The following table shows their estimates of the mud rate production by Melobesia sp.

a)	Cadot (op. cit.)	Bermuda	20-40 mm/1000 years
b)	Dalziel (op. cit.)	Florida	20 mm/1000 years
c)	Land (1970)	Jamaica	30-130 mm/1000 years.

Land's estimate represents sediment contribution by both algae and serpulides which produce aragonite mud. He further claims that such a rate of lime mud production is identical with the average rate that platform carbonate

sediments accumulate. This similarity of the sedimentation rate demonstrates the significance of Melobesia sp. as a source for carbonate mud in the Marada wackestones as well as in the recent sediments (Land, 1971).

B. Bioturbation and skeletal breakdown:

Well defined burrows are common in the wackestone units. They are often marked by a grey mottling due to late dolomitization along burrows, or colouration contrast due to the argillaceous nature of burrow fill. But generally wackestone units appear homogenous, most burrows specially those caused by worms are not obvious unless rock outcrops and samples are examined closely.

Two major groups of burrows are recognized in the Marada limestones in general and the wackestones in particular. These are large burrows of Ophiomorpha-Thalassinoides group, and the small ones of Caegichnus group (Doust, 1968). The former is thought to be caused by suspension filter feeder crustacea such as Callianassa sp. The latter burrows are caused by sediment-eating scavengers such as polychaete worms. Both groups of organisms have had a profound effect on modification and alteration of the original sediment texture of the Marada wackestones.

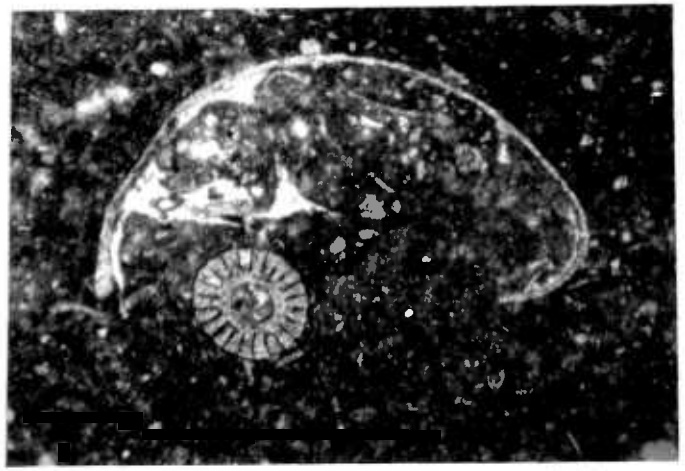
Photo Plate VI-3

Origin of micrite (continued)

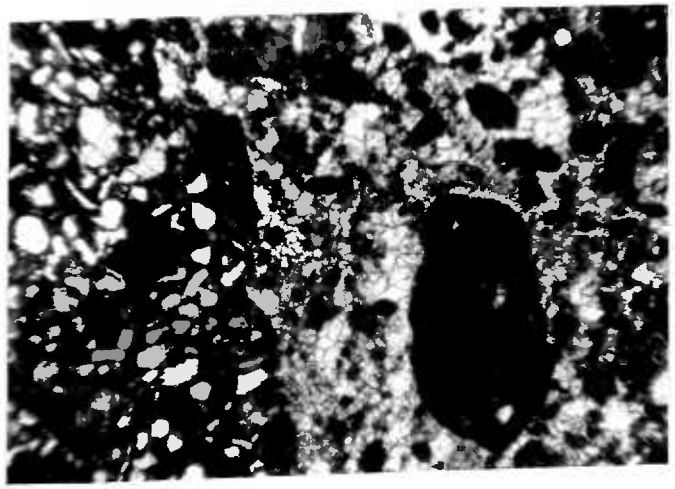
Fig. 6.12 Echinoid's shell provides pellets with a protective umbrella from compaction. The matrix is produced by early compaction of pellets (X3-NL).

Fig. 6.13 Well preserved pellets in a wall of Callianassa burrow (right); no pellets are observed in the host sediment (left) (NL-X3).

Fig. 6.14 A negative print of a thin section shows textural grading from complete shells to sand, silt and mud. Large shells exhibit sharp edges which are bent or twisted (T), the fine skeletal sand and silt (sf), and mud (m) show a patchy textural distribution. Calcitic worm tubes are common (wt), as well as open worm burrows (b).



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1) Ophiomorpha-Thalassinoides burrows (Doust, 1968, p. 155-167): these burrows are produced by the same organism through a different behaviour pattern. The Ophiomorphes are found in the skeletal grainstone and packestone facies. The Thalassinoides burrows are usually found in the wackestone and mudstone subfacies. However, transitional burrows between Ophiomorphas and thalassinoids are not uncommon. The former usually consists of a warty wall (0.2-1.8 cm thick) which was built by the animal to support the burrow from caving; the latter is usually found in muddy sediment, thus the wall is absent.

Burrows consist of a horizontal framework connected by vertical shafts. The central tube of the burrows is 0.4 to 3.2 cm in diameter and is commonly filled with loosely packed sediment of unconsolidated skeletal sand and mud. Before lithification of the sediments, burrows may have been filled and reburrowed many times. The sediment may have been reworked numerous times but only the last burrows have their diagnostic features (Fig. 6.23). When the sediment is brought to the surface by a burrowing shrimp (Weimen and Hoyt, 1964) it is pumped into the water. Much of the finer fraction stays in suspension and is carried away by currents, while the coarser fraction settles and forms a mound (Shinn, 1968). Early lithification of the pelletal sediment should produce

a pelletal packstone or grainstone (e.g. in tidal flats). Early compaction of the recycled pelletal sediment can produce a mudstone (Fig. 6.12, 6.13), a sediment which otherwise would produce a coarser grained rock.

Open burrows found associated with hard grounds (Fig. 6.23) often show laminated structures. Preservation of sedimentary structures suggests lithification started during or just before the sediment becomes too hard. In this case most burrows are left open, possibly due to the continued use of the burrows by the animal after lithification, suggesting a minimum rate of sedimentation at the sediment-water interface.

2) Worm burrows: these are sediment-filled burrows which range in diameter between 0.1 to 2 cm, and are up to 30 cm in length. Burrows are vertical, horizontal and show irregular branching of Y or 90 degrees shapes. They often meander around shells and sometimes bore through them as they burrow in the sediments (Fig. 6.16). Most burrows show a concentric thin wall, which was built by agglutination of skeletal debris in sandy sediments, but in muddy sediments the burrow wall is absent (Neumann et al, 1970). Reworked, elongated skeletal grains inside the burrows are aligned roughly parallel to the burrow walls, resulting in a concave

or spiral pattern within the burrow. Kuenen (1961, p. 73) described similar structures which he suggested may have formed as coprolitic filling pressed into the tube while the animal chews its way through the sediment. Burrow fill appears in thin sections open packed (Fig. 6.16) or closely packed skeletal debris of fine sand and silt, which shows a patchy texture (Fig. 6.15) in thin sections.

Generally, bryozoan shells are particularly susceptible to reworking by burrowing organisms, specially if the shells are encrusted by calcareous algae and/or already weakened by boring algae. Thin sections examined show that elongated shells of bryozoa or molluca are often twisted, bent, and sometimes broken and chewed up as a result of the pressure created by browsing animals as they burrow in sediments and scrub the shells for organic matter (Fig. 6.14).

The result of the sediment reworking is that a patchy and strongly ill-sorted texture is produced (Fig. 6.14). As shown by Sorby (1879) such ill-sorted texture of continuous spectrum of the grain size described above, is compatible with sediment production by disintegration of skeletal material. The grain size reduction of the skeletal grains was definitely enhanced by progressive algal boring of all reworked skeletal components and successive reworking by burrowing organisms.

Photo Plate VI-3

Origin of micrite (continued)

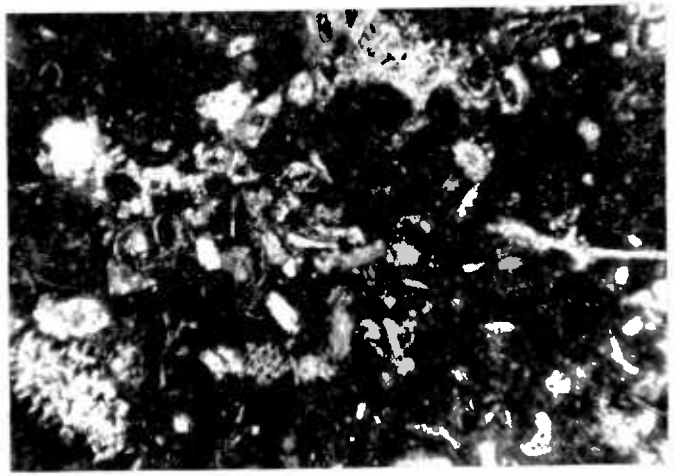
Fig. 6.15 Fine skeletal sand and silt in wackestone show angular grains and patchy texture (X3-NL).

Fig. 6.16 Bryozoan shell (Trigonopora) in wackestone. The shell and matrix are penetrated by a worm burrow, which remains partly opened (X3-NL).

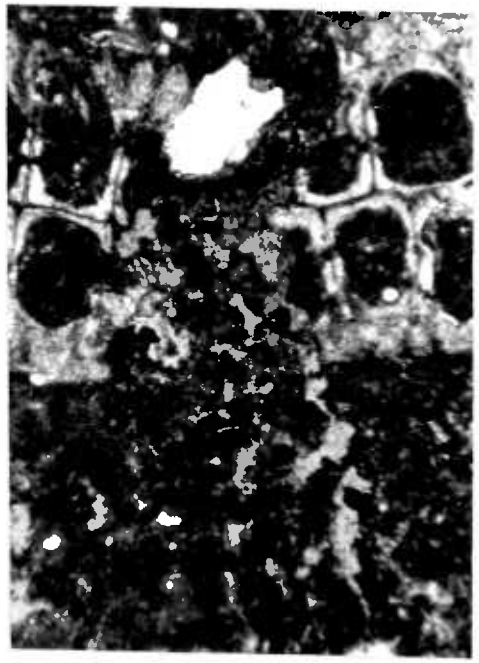
Subtidal Algal Mats

Fig. 6.17 A close up of Rhodothamniella-like red algal mat showing the cellular structure of the alga and the sediment trapped between the algal branches (X3-NL).

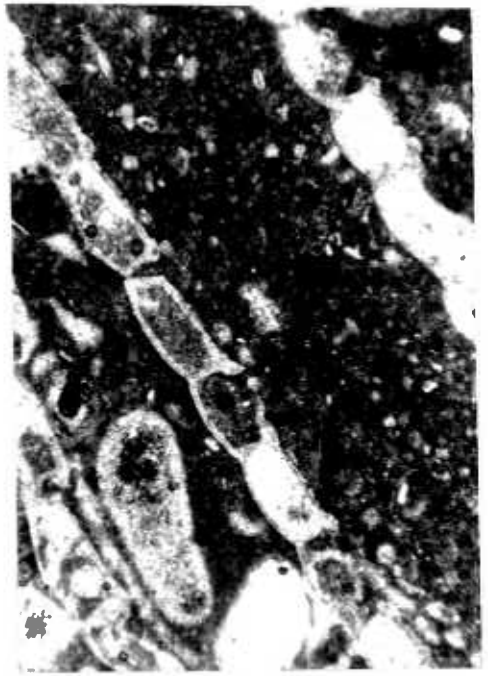
Fig. 6.18 A negative print of a thin section showing the framework of the erect form red algal mat (as in Fig. 6.17). Note the graded grain size exhibited by the trapped sediment (light areas) below the open cavities (dark areas), which indicates deposition by infiltration.



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C. Role of coralline red algae in sedimentation (Subtidal algal mats):

Algae are recognized as an important agent in the physical stabilization of subtidal clastic sediments in the modern shallow marine carbonate environment. Ginsburg and Lowenstein (1958) mentioned the influence of the blue-green algae on the depositional environment of sediments. Bathurst (1967) observed areas in the great Bahama bank where calcarenite grains were bound together by gelatinous substance which immobilized the sand even in the presence of tidal currents strong enough to erode loose grains. Gebelein (1969) noted that in Bermuda, blue-green algal enmeshed grains in the framework of filaments and mucilage produced stromatolic structures whose morphology was controlled by the current velocity and the rate of sediment transport over the bottom. The in situ experimental work of Scoffin (1970) and Neumann et al (1970) indicates that the bare sediments were more readily eroded than sediment covered with algal mat. Neumann et al (1970) described in detail the biological components and the internal microstructure of a variety of subtidal algal mats in the Bahamas. They indicated that mats consist of various assemblages of green algae, red algae, blue-green algae, diatoms and animal-built sand grain tubes (e.g. by polychaete). Green algae, red algae and/or sand grain tubes provide a rigid

open framework into which sandgrains infiltrate and are trapped, and the mucilaginous accretion of both blue-green algae and diatoms in association with filaments of blue-green algae bind the grains to each other and the mat framework (Neumann et al, 1970). Homeril and Rioult (1965) compared the structure and morphology of mats consisting of Rhodothamniella floridula (red algae) and Microcoleis chronoplasts (blue-green algae) and concluded that the perpendicular filaments of the former filter off transported grains, while the mesh of creeping filaments of the latter immobilized sediments deposited by settling.

Three forms of subtidal red algal mats are found in the Marada limestones. These are: Rhodothamniella-like algal mat, Lithothamnium algal mat, and Melobesoid algal mats. The first two are found associated with the cross-bedded grainstone facies, and the third is found in the wackestone facies.

(a) Rhodothamniella-like algal mat (Figs. 6.17, 6.18):

The Rhodothamniella-like algal mat consists of rounded to ellipsoid bodies measuring about 5 to 10 cm in diameter. These bodies are found in the lower wackestone

subunits of the crossbedded grainstone facies. These bodies are composed of a framework of algal layers, about 0.1 mm thick each and sediment layers about 0.6 mm thick. Each algal layer is leaf-like and formed of one row of horizontally elongated cells measuring (0.1 x 0.3 mm) surrounded by a 20 micron thick calcitic wall. The algal leaves are convex upwards, they overlap and converge but never intersect. The sediment observed between algal leaves is composed of oolites, coated grains, foraminifera, fine skeletal sand and silt, pellets, quartz grains and lime mud (Fig. 6.17). The sediment shows a graded grain size, and flat top lined with a cavity-filling calcite between algal branches (Fig. 6.18).

It is clear that the algal leaves framework was more or less rigid, similar to the leaf structure of a vegetable (e.g. lettuce). The convergence of each leaf, however, is not at one single point. The accretion and growth of these mat forms is different from those of the blue-green algal mat (Neumann et al, 1970) because the walls of the algal leaves are rigid and erect forms due to precipitation of $CaCO_3$ in the cell walls by photosynthesis, and the algal materials are between sediment masses not encrusting individual particles. The sediment particles were deposited as a result of mechanical filtration between the algal leaves as they show random grain orientation and a graded grain size.

This algal form is similar to the Rhodothamniella floridula red algal mats described from the recent subtidal areas of the Normandy coast (Homeril and Rioult, 1965; Fig. 3A, C), as these algal mats are erected forms with filaments partly moving in the sea water. Thus the Marada elliptical algal bodies may have resulted from reworking of the erected filaments during the migration of the subtidal grainstone bodies.

(b) Lithothamnium algal mat (Fig. 6.19):

Lithothamnium algal mats are found associated with barrier grainstone facies (see subtidal barrier bar vertical profile). They are found on the surfaces of the cross bed trough foresets as well as on the top of the units, which are also encrusted by Archaeolithothamnium algal domes and coral heads. In the field it is difficult to recognize these mats; they often look similar to the rock texture. In thin sections and peels they are up to 10 cm thick and consist of many horizontal crusts or thalli about 0.2 mm thick, which are connected by vertical components up to 0.4 in diameter. Crusts consist of rows of closely packed cells with polygonal cross section, and commonly rectangular in longitudinal section. Cells measure 8 to 28 microns in height and 6-16 microns in width.

The horizontal crusts often change into rounded, oval and elongate forms which range in size from 2 to 4 mm. They are always connected together by short protrusions. Associated with these forms are skeletal grains up to 5 mm in diameter; they consist of bryozoa, codianceae algal grains and molluscs. All skeletal grains are also encrusted by algae.

Cavities between algal crusts, oncolites and skeletal grains are filled by calcareous mud and silt; also scattered are fine pellets and skeletal debris are found. Calcareous mud is by far the dominant size fraction (Fig. 6.19). It is dark, dense and sometimes hard to differentiate from the dense algal components. Some of the cavities are partly filled by micrite, thus showing flat and inclined surfaces lined with first phase cavity filling calcite cement.

The outcrop of the subtidal barrier bar which contains the Lithothamnium algal mats is particularly interesting for many reasons; namely, (a) lithothamnium oncolites are abundant, (b) all skeletal grains of the grainstones are encrusted by algae, (c) cementation is interrupted by geopetal sedimentation, (d) encrustation of the grainstone bar surfaces by Lithothamnium and Archaeolithothamnium.

Photo Plate VI-3a

Lithothamnium algal mat

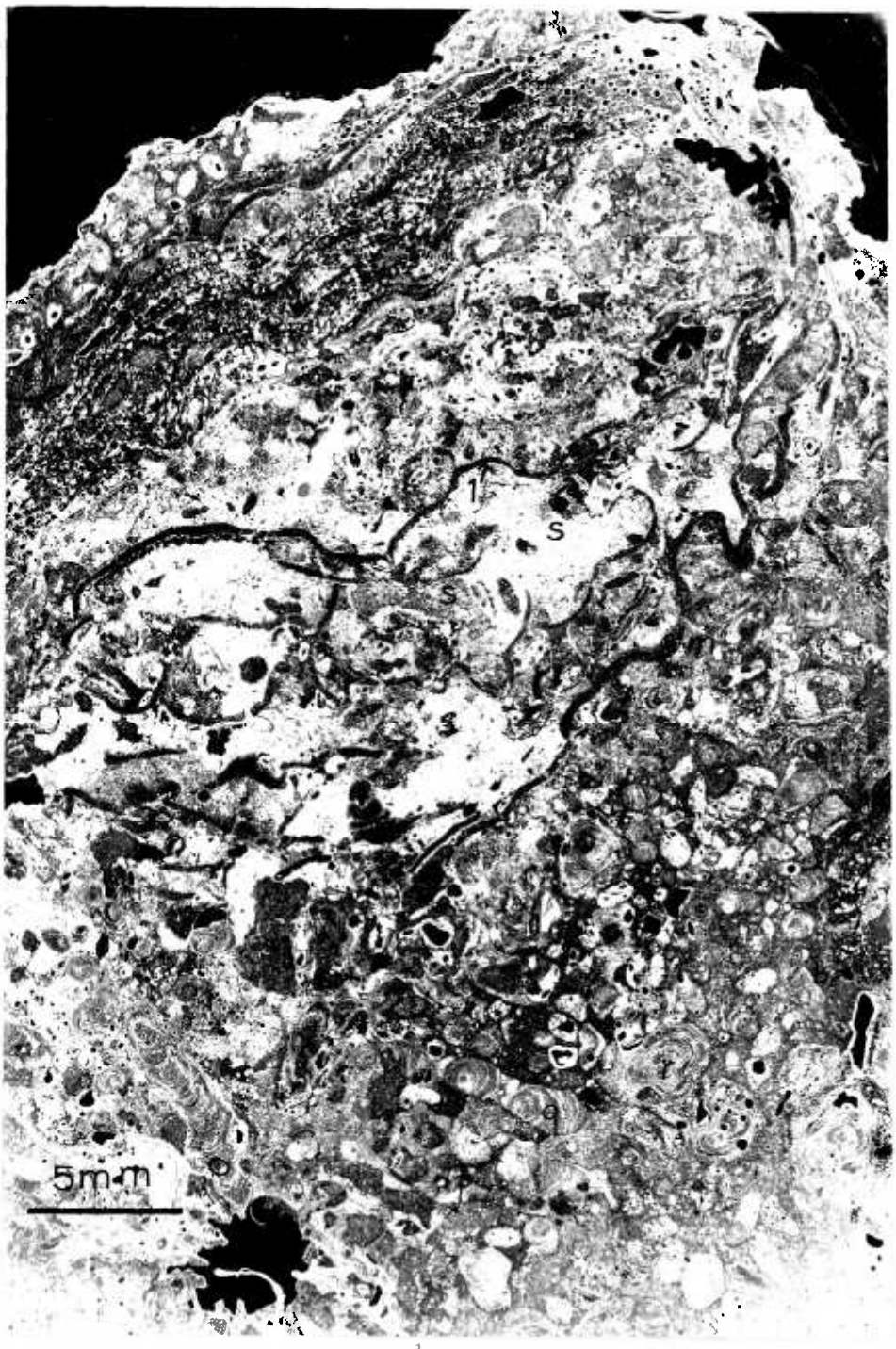
Fig. 6.19 A negative print of acetate peel; the mat framework consists of crustose form of lithothamnium (l) and oncolites which show different forms of growth (o, p, q, t). Also, some skeletal grains of bryozoa (b) and foraminifera B-melo (m) are also found.

Photo Plate VI-3b

Melobesoid algal mat

Fig. 6.20 A negative print of a thin section showing coralline red alga Melobesia (?) encrusting sediment masses (1), skeletal grains (E), and bryozoa Holoporella colonies (2) which show micritization (3). Encrusting forms often protrude into the surrounding matrix (4). Rounded and elliptical algal forms are also present (5) (sample D3-22).

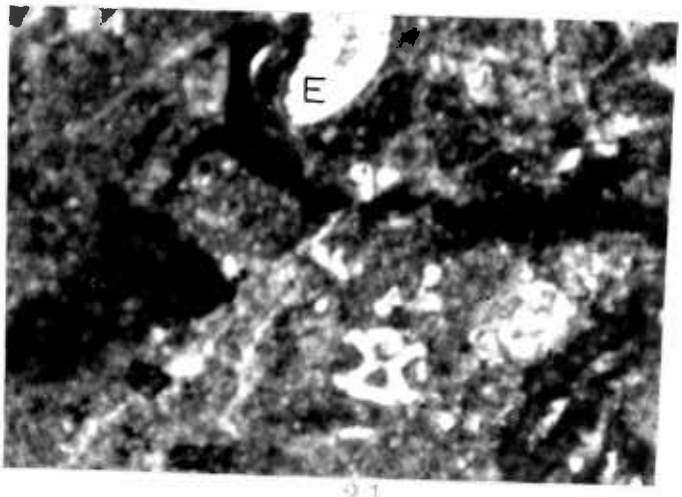
Fig. 6.21 A photomicrograph magnification of part of the thin section (corresponding to E on Fig. 6.20) showing algal encrusting echinoid's grain (E) and sediment masses which contain bryozoa (NL-X3).



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The occurrence of algally coated grains and algal oncolites indicates the abundance of algal material in the grainstones. Also, algal mats must have helped the fixation of the sand surface of the subtidal mega ripples and shoals as in the recent sediments (Bathurst, 1967). But carbonate sand encrustation by lithothamnium mats must have followed lithification of the bar sands; as indicated by the absence of cement in the mats prior to the infiltration of geopetal sediment. However, it is clear that formation of the Lithothamnium algal mats was by encrustation of the lithified skeletal sand body, which was followed by infiltration of the fine grained material under subtidal conditions.

(c) Melobesiod algal mat (Figs. 6.20, 6.21)

The Melobesiod algal mats are often found in the wackestone facies. The framework of the Melobesiod algal mat consists of three main components; these are: (a) algal forms, (b) bryozoa colonies, (c) skeletal sand and silt, and lime mud.

Different types of coralline red algae such as Archeolithothamnium, Lithothamnium, Mesophyllum and Melobesia are present in the wackestone facies. However, the morphology of the red algal mats is the most significant feature. Algal crusts are about 0.1 mm thick, and extend

for up to 10 cm in length. They are marked by a wavy line of dense organic material which accepts malachite green stains. The cellular structures in these crustose forms are absent, possibly due to the collapse of their internal structure. These forms are similar to coralline red algae, Melobesia sp., previously described by Land (1970 and Ginsburg et al (1970). The algal crusts are gently branching and interconnected to one another surrounding sediment masses of lime mud, silt and skeletal grains (Figs. 6.20, 6.21). Also, pentagonal and hexagonal, thin walled, calcitic worm tubes are found enclosed in the sediment masses and surrounded by algal branches.

Algal material is also found encrusting bryozoa colonies. Protrusions of the algal crusts are commonly found extending into the surrounding sediment masses (Fig. 6.20). Although discontinuous, they can be traced laterally across the thin section, to the crustose forms surrounding the sediment masses. Oncolitic and fragmented algal forms are not uncommon. The discontinuous and patchy nature of these encrusting algal forms is due to bioturbation and reworking by burrowing organisms.

Two types of bryozoan colonies are found associated with the melopesoid algal mats. According to Doust (1968), Trigonopora is an erect bilaminated fenestrate zooarium on a

broad flat sheet which may reach 15 cm in length parallel to bedding. The Zooaria are flexible structures which follow the shape of the substrate. The more abundant bryozoan colony is Holoporella, which consists of complex zooaria showing a large ramose structure with numerous radiating sub-horizontal branches arising from a massive vertical disposed centre (Doust, 1968). Simpler forms occur as branched or unbranched cylinders 2.0 - 3.0 cm long.

Research on the recent subtidal algal mats indicates that sedimentation in mats is produced by aglutination of sediments by blue-green algae and diatoms, and by infiltration between the rigid structure of red algae and burrowers' tubes (Neumann et al, 1970). Therefore it is thought that the melobesoid algal mat of the studied wackestones are developed primarily by infiltration of the lime mud silt and sand, through the rigid structure of bryozoa colonies, calcitic worm tubes and red algae, and also by encrustation of the sediment masses by creeping algal crusts over the trapped sediments. It is difficult to evaluate the extent of sediment trapping by agglutination, but one can argue that blue-green algae, when present, must have played a secondary role in trapping sediments.

Neumann et al (1970) indicated that recent subtidal algal mats surface is a dynamic entity, continuously building

up and deteriorating; sediment moving on the bottom is trapped on the mat by various processes. Algae and invertebrates grow and move upwards to remain at the sediment-water interface. Particles in and below the mat are dislodged and brought to the surface by burrowers. Thus sediments lack lamination, which is more characteristic of intertidal and supratidal sediments, where sedimentation and mat growth are discontinuous and burrows are less active.

D. Mechanisms for forming Fine-Grained Sediment

Evidence available from the study of the wackestone facies suggests that the finer grained matrix originated by biological and possibly mechanical breakdown of the skeletal grains. However, the abundance of muddy material, ill sorted texture and bioturbation seem to negate any extensive mechanical breakdown by current and wave agitation. Biological breakdown, however, does seem to have occurred. Carbonate grains weakened by biological agents may require only minor agitation to disintegrate. Vigorous abrasive action might not have been necessary to disintegrate algal crusts of Melobesia sp (Land, 1970), and oncolite coatings around some of the grains. In any case, the binding nature of the algal mats would protect the sediment underneath from erosion and reworking by moving currents (Neumann et al, 1970). Boyer (1972) observed that

cementation in muddy sediments might be inhibited by the presence and abundance of organic matter. If this is true, such lack of cementation could make the skeletal fragments more susceptible to breakdown by burrowing organisms. Algal mats and coats in the wackestones are often destroyed by burrowing scavengers, and reduced to small fragments which grade down into the matrix.

It is still difficult to conclude what is the origin of all the matrix in the wackestone, but such a conclusion seems reasonable from the qualitative viewpoint. Recent studies by Land (1970), and others, indicate that epibiotic growth of coralline red algae Melobesia and serpulide worms on the marine turtle grass produces fine grained carbonate at a rate high enough for platform building. Neumann and Land (1969) indicated that the green algae (Halamide and penicellus) can provide more than sufficient quantities to provide all the carbonate fines on the Little Bahama Bank.

Mechanical disintegration will undoubtedly proceed faster if the organic binders within the skeleton are weakened and destroyed by decay, and/or boring by microorganisms (Swinchatt, 1965). Bathurst (1966) pointed out that micritized skeletal grains become increasingly rounded presumably as a

result of abrasion after the shell surface has been weakened by algal borings. He (Bathurst, 1971) indicated that the breakdown of most skeletal grains into their ultimate components would release crystals all within the micrite size range.

Finally, Stockman et al (1967), Mathews (1966) and Swinchatt (1965) agree that mechanical disintegration of skeletal grains usually takes place in the wave agitated areas and swept to be deposited into areas of less agitation. The available stratigraphic, sedimentologic and petrographic evidence from the Marada Formation indicates that the wackestone facies deposited in quiet water conditions. Thus the mechanical breakdown of skeletal grains was only feasible during storm conditions when carbonate sediments were transported shorewards from the open marine area (Ball et al, 1967).

6.1.2 Regional bored surfaces of the Wackestone Facies

Several prominent bored surfaces are observed on top of the persistent wackestone units exposed along the Dor Zuggut-Dor Marada escarpment. These hardgrounds consist of several segments, which extend for 25 kilometres each. Segmented bored surfaces are correlated for up to 65 kilometres along a single stratigraphic level. In sections where bored surfaces are absent, vertebrate bones are found (Fig. 6.24).

Photo Plate VI-4

Hard grounds in the Wackestones

Fig. 6.22 An early lithified wackestone layer (B) containing Callianassa burrow now filled with soft sediment from bed (A); it consists of a vertical shaft and a horizontal burrow system. The surface of the hard ground is also bored by Lithophaga (L).

Fig. 6.23 The same as Fig. 6.22. The hardground appears finely laminated, and Callianassa burrows are open. The pencil in the centre for scale.

Fig. 6.24 Photomicrograph of pellets truncated by Lithophaga open boring (X3-NL).

Fig. 6.25 An open boring truncating ostracod shell (X3-NL).

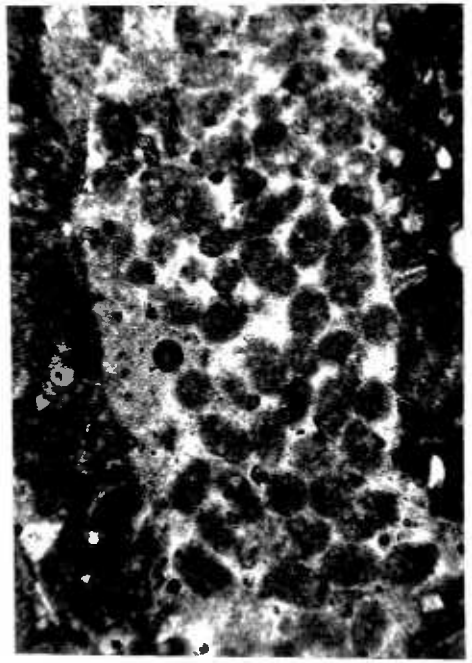
Fig. 6.26 An open boring filled by uncompacted pellets (X3-NL).



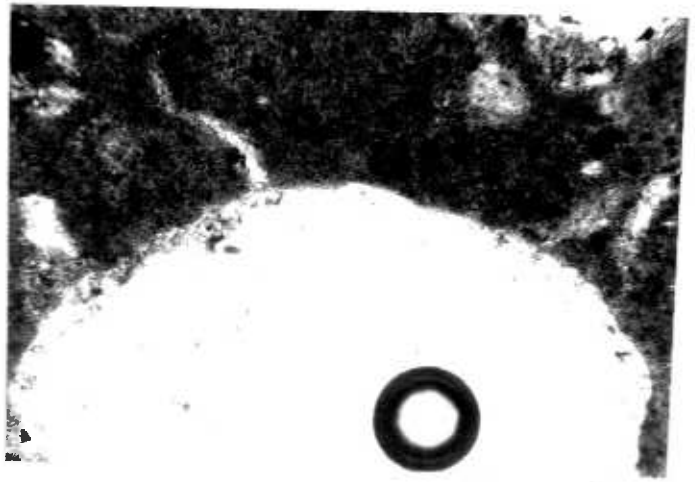
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The bored and lithified horizons are 20 to 100 cm thick, and show a transitional or sharp lower contact with the soft wackestone unit underneath. They are tough and grayish orange (10 YR 7/4)in colour, possibly due to iron oxide staining.

Hardgrounds are massive or interlaminated pelletal packestone and mudstones. Laminae are 0.5 to 2.0 cm thick and show gradational contacts. Small gastropods and ostracods (Fig. 6.25) are often found in these rocks.

Burrows: In hard grounds, burrows are straight or gently curved with rather dichotomous branching at acute angles. In cross section they are circular or elliptical, 0.5 to 3 cm in diameter. Burrows appear mainly horizontal (Fig. 6.23) and are connected to the surface of the beds by a vertical shaft (Fig. 6.22), which were often eroded leaving only the horizontal component. The inner burrow surface shows a characteristic of scratches, which were caused by the burrowing organism. Burrows are usually left open (Fig. 6.23), but sometimes are filled with a friable internal sediment (Fig. 6.22). Similar burrows are described from the Cretaceous hardground of Europe, Asia, and North Africa by Bromley (1967, 1968). He attributed them to the work of crustacian shrimp Callianassa.

Borings: Two types of borings are recognized penetrating the surfaces of the hardgrounds and truncating grains and matrix;

(a) Flask-shaped borings which penetrate 3 cm or more deep from the surface and which are produced by bivalves; they are either empty (Fig. 6.22, 6.24) or filled by friable material from the overlying unit. These borings are thought to be the work of Gastrochaena squamulosa and Lithophaga (Doust, 1968).

(b) Finer borings are 0.3 to 1.0 mm in diameter and penetrate up to 10 cm from the surface of the hardground. These borings are straight or slightly curved, and show a Y-shaped branching at acute angles. These borings are often filled by loosely packed pellets (Fig. 6.26), or left empty (Fig. 6.25). These borings are produced by worms.

Successive borings often intersect with burrows, and often produce a pebble layer on the surface of hardground (Fig. 6.23) or destroy the hardground altogether. Pebbles produced by this process are angular and often triangular in cross section.

Formation of Hardgrounds

Lamination and interlamination of pelletal mudstone and packestone in hardgrounds suggest gentle currents of possibly alternating strength have prevailed during the deposition of the hardgrounds. Preservation of the primary sedimentary structure in spite of the burrowing activity of burrowers

suggests an early lithification. Bromley (1967) indicated that horizons of early lithification (hardgrounds) contain burrows that were constructed before the sea floor was cemented. These burrows remained occupied after cementation.

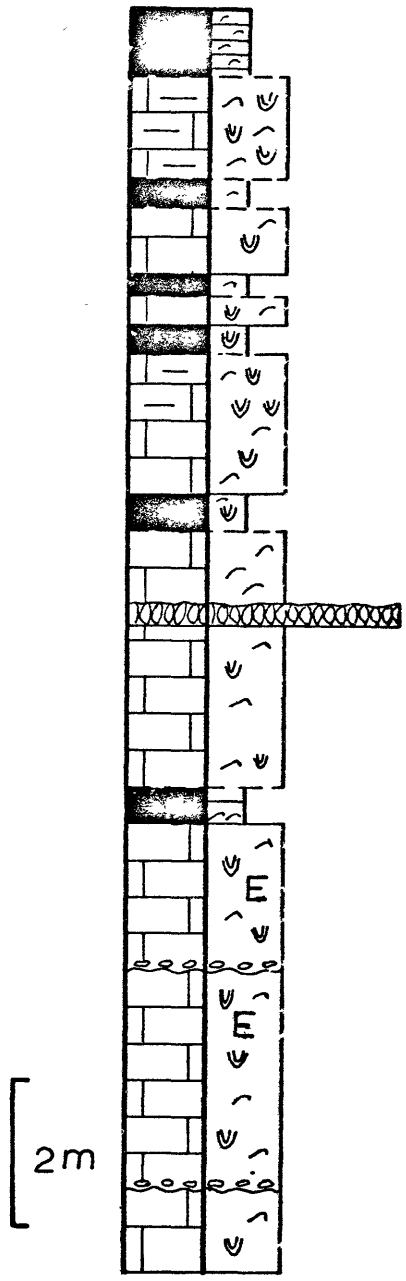
The regional extension of the bored surfaces also indicates that hardgrounds were produced as a result of a regional non-depositional event. Pequenat et al (1972) reported the occurrence of a bored and lithified ironstone layer which extends for great distances in the Gulf of Mexico off the Mississippi delta fan. They attributed its occurrence to bottom currents and slow rate of sedimentation. Also, Friedman (1964) and Milliman (1966) reported an early lithified hardground from current-swept localities on the sea mounts and guyots of the Atlantic.

Conditions similar to those described above must have prevailed during the formation of the Marada hardgrounds, and before the overlying marl facies were deposited.

6.1.3 Vertical Profile of Wackestone Facies (Plate 6.1)

The type section of the Wackestone facies is exposed in section D2, about 5 kilometres west of Brega-Zelten road. The vertical profile (Plate 6.1) consists of a lower sequence

Plate 6-1. Vertical profile of submarine Wackestone bank facies, Sect. D2.



Cycles of Wackestone - shale.

Oysters in growth Position

Massive Wackestone Units with Echinolampas

of massive wackestone units (Fig. 6.1) and upper cyclic sequence of wackestone and shale units (Fig. 6.2). The two sequences are separated by an oyster bank with shells in growth position (Fig. 6.2). The lower wackestone units consist of intra-pelleskeletal packestone and wackestones. The lower contacts of units are erosional and contain flat pelletal grainstone cobbles, pebbles (Fig. 6.3). Units, although massive, show vague lamination of flat shells of Echinodiscus (Fig. 6.3). These units often contain Echinolampas sp. and other open marine fauna elements and ar extensively bioturbated specially near their tops.

The upper sequence of the vertical profile consists of successive cycles of wackestone and shale units. The average thickness of cycles is about one metre. The wackestone unit at the base of the cycle shows a sharp and often bioturbated lower contact and it grades up into laminated calcareous light green fossiliferous shales which often are strongly bioturbated and contain high concentrations of Ostrea, Laupha, and bryozoan shells as well as foraminifera and ostracods. Towards the top of the sequence the wackestone units become more argillaceous and show a transitional contact with shale units below and above.

Interpretation

The faunal and floral content of the wackestone facies and shales suggest open marine condition of normal

marine salinities, and water depth up to 40 metres (Doust, 1968). The biological activity in this facies has played an important role in sedimentation (constructive role) and grain size degradation (destructive role). The fine grained matrix is produced by animal and algal boring of skeletal grains, micritization and disintegration of algal tissues and reworking of the grain/matrix framework by sediment and suspension feeders. Deposition and growth of wackestone units were aided by the stromatolitic build-up of subtidal algal (Melobesiod mats) and possibly by agglutination of sediment material by burrows, and the blue-green algal mucilage.

Both destructive (grain size reduction) and constructive (sedimentation by algal mats) biological processes have altered the grain/mud ratio of the wackestones. Finer sediment material is often produced (mudstone) as a result. Therefore, it is misleading to equate the intensity of the energy conditions of these rocks with their grain/matrix ratio (Klement and Toomey, 1967; Shinn, 1968; and Neumann et al, 1971). However, the overall characteristics of the wackestone facies suggest a slow rate of deposition in a relatively quiet water condition compared with those of the crossbedded grainstone facies.

Although most wackestone bodies are transgressive, their upper boundaries are non-depositional. Therefore they

are intensively bioturbated and marked by in situ oyster growth and/or occupied by hardgrounds.

The wackestone units at the lower half of the vertical profile are transgressively overlapping the barrier and the lagoonal facies. Towards the top of the profile the growth of the wackestone bodies was inhibited by a marked influx of terrigenous sediments. Thus, one can assume that the open marine sequence is also transgressive.

The sheet geometry of the vertical profile units suggests a deposition on a flat sea floor. The wackestone bodies are built up as an extensive bank in response to high carbonate productivity and rise of the sea level. The increase of water depth (offshore) and/or rain influx of the fine grained terrigenous clastic would inhibit the bank growth.

6.2 The Marl Facies

The marl facies occurs above the Echinolampas level in sections of the Marada Formation. They reach a maximum thickness in sections of the Central Jebels area where they are frequently associated with the calcareous sandstone shoestrings. Northwards in sections of Dor Zuggut and Dor Marada, they are interbedded with the wackestone facies and

Photo Plate VI-5

The Marl Facies

Fig. 6.27 Laminate marl facies; laminae show a gentle northwards inclination.

Fig. 6.28 Interbedded wackestone and shales sequence changes upwards into marl facies. This sequence is located above that in Fig. 6.2.

Fig. 6.29 Bone fragment found in the marl facies.

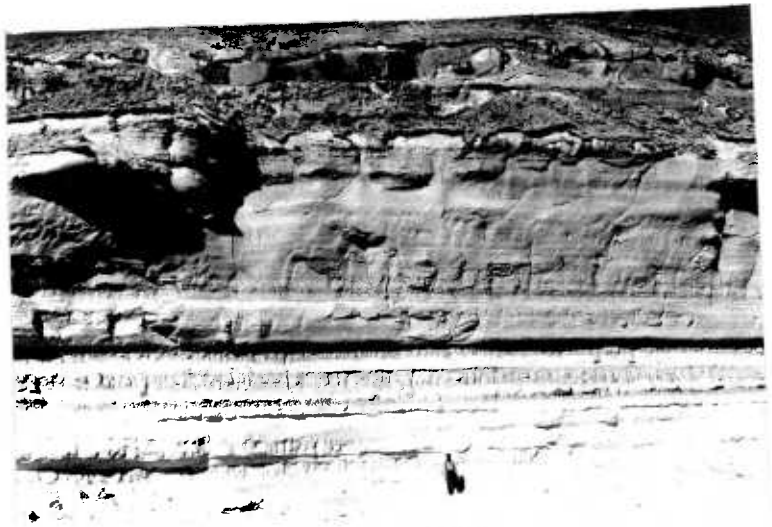
Fig. 6.30 Microphotograph of laminated marl facies showing micro-interlamination of quartz and foraminifera rich layer, and argillaceous rich layer (NL-X3).

Fig. 6.31 A marl rich in quartz silt, skeletal fragments and foraminifera (NL-X3).

Fig. 6.32 Foraminifera and echinoids' fragments in marls; quartz is less abundant than in Figs. 6.30 and 6.31 (NL-X3).



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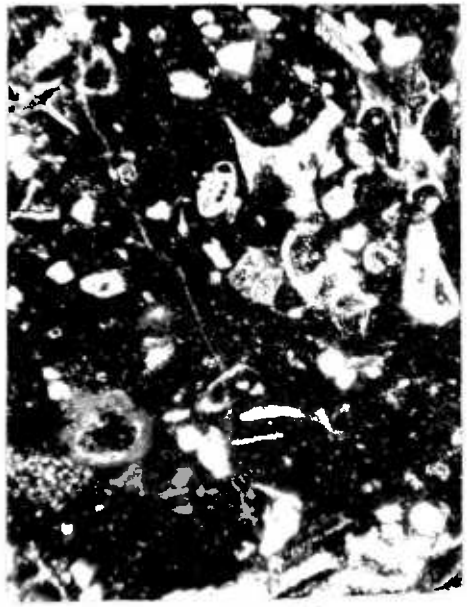
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often overly a bored hardground horizon. Calcareous sandstone shoestrings are also present in these areas, but with lesser magnitude than in the Central Jebels.

The marl facies are sheet deposits; their lower contacts are sharp to gradational (Fig. 6.28) but locally erosional (Fig. 6.27). Laterally units are intertongued with the wackestone facies.

Lithology and fauna

The marl facies are transitional facies. They cover a gradational ground between three main lithofacies of carbonate and terrigenous sands, silt, and mud. The colour of these facies ranges between brownish gray and green colours; however, grayish yellow (5 Y 3/4) and grayish yellow (5 GY 7/2) are the most common.

In general the fauna associated with the marl facies is similar to that of the wackestones. However, the remains of some organisms are more abundant than others, and some are only present in the marls. Crassostrea and Ostrea often occur in allochthonous shell units embedded in a sandy marl matrix, up to one metre thick. Echinolampas and Echinodiscus are uncommon; Ophioroids remains, however, are abundant. Bryozoan species such as Trigonopora and Holoporella, and microfauna are characteristic of this facies. Foraminifera

species are benthonic, planktonic; arenaceous species as well as Ostrocoda are present. In the more calcareous marls, gastropods and bryozoan shells are found encrusted by coralline red algae. Oncolite surfaces are smooth and elliptical in cross section, and the algal coats are asymmetrical in thickness. The most characteristic organic remains, however, are the vertebrate bone fragments (Fig. 6.29), and the occasional silicified wood trunks found in the more sandy units of the marl facies.

Due to their variable and gradational lithologic components, the marl facies are sub-divided here on the bases of their internal sedimentary structures. These are laminated and massive subfacies.

The laminated subfacies units are 3 to 5 metres thick and consist of laminae and thin beds which range from a few millimetres to a few centimetres, which are traceable for some distance along the outcrop surface. Laminae are horizontal (Fig. 6.28) or gently inclined ($<$ 5 degrees) to the north (Fig. 6.27).

In thin sections, however, laminae appear to be the result of mineralogic and grain grading (Fig. 6.30). The sandy laminae consist of subrounded to angular, fine quartz sand and silt, as well as fine skeletal debris dominated by

ostracod valves and forams. Occasional complete shells of bryozoa are found imbricated along laminae.

The fine grained laminae consist of dark argillaceous lime mud and scattered fine silt. Flat lenses or discontinuous laminae of clay minerals are 12 mm to 8 mm thick and are frequently present. Clay flakes are oriented parellel to laminae and show a wavy pattern.

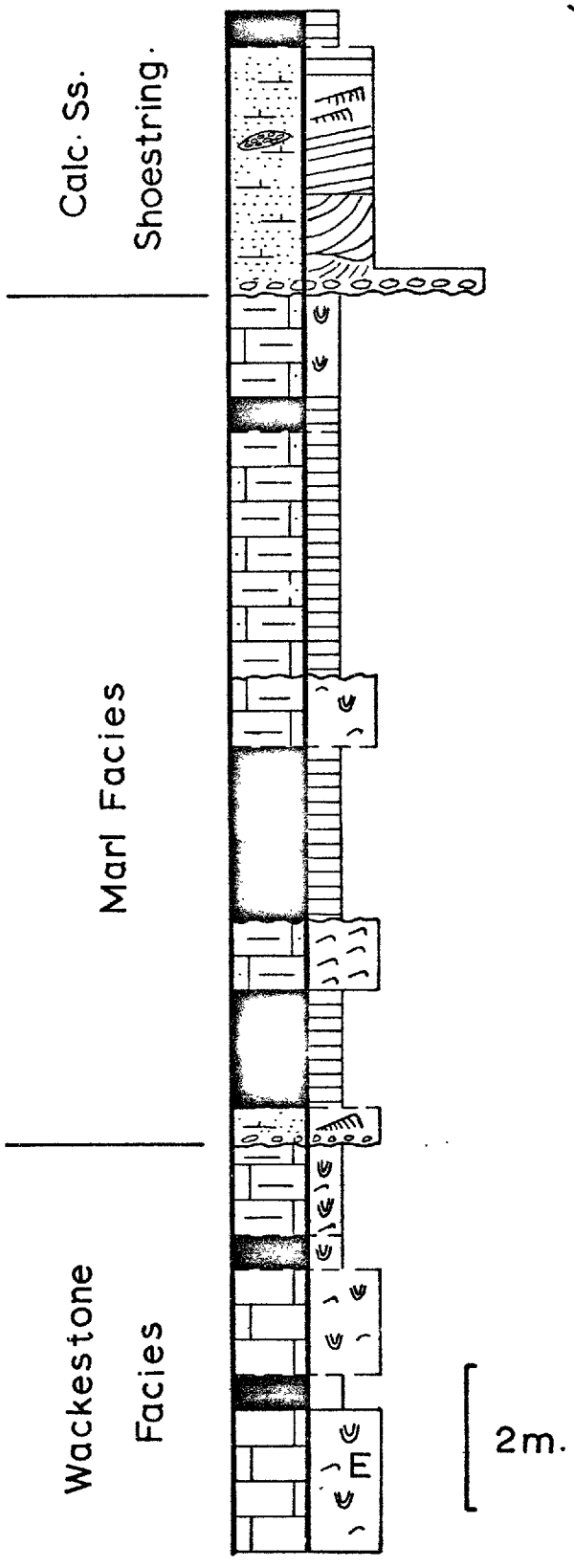
Thin beds are vaguely laminated and contain more skeletal debris than the laminated units (Fig. 6.31). Terrigenous sand is finer and the clays are disseminated within the lime mud matrix.

The massive sandy marl subfacies units are about 1 to 2 metres thick. They are often bioturbated and show a burrowed or gradational lower contact. Shells of molluscs, bryozoa and ophioroid plates are common (Fig. 6.32). The terrigenous sediments are mainly muds and silts. It contains less quartz sand than the laminated facies. More calcareous units contain calcareous algae, bryozoa and gastropods.

6.2.1 Vertical Profile and Lateral Change of the Sandy Marl Facies

The association of calcareous sandstone channels within the marls' vertical profiles suggests the close

Plate 6-2. Vertical profile of the marl facies (Submarin Delta) near estuarine mouthes, the Centeral Jebels, Sect. C1.



relationship between the two facies. In the Central Jebels sections, vertical profiles (Plate 6.2) consist of lag deposits, fine sand and laminated sandy shale, which may pass gradually upwards into marls and/or argillaceous wackestone. Other cycles consist entirely of laminated and massive marls.

Northward and away from the estuarine source, the marls' vertical profiles are more refined and consist of a single cycle intertongued with the wackestone facies. The upper boundary of the wackestone units are invariably early lithified and bored, beneath the major marl units (Plates 6.3, 6.4). When bored surfaces are absent a bone bed is often found at the base of the marl.

In the northern outcrops vertical profiles of the sandy marl facies are about 10 metres thick. The lower contacts of it are erosional (Fig. 6.27) and change laterally into sharp, and gradational along the sedimentary strike. It is noted that the lithological characteristic changes gradually upwards within the vertical profile. This general change involves a decrease of the terrigenous sand, silt and clay, and increase of the carbonate content, as well as a change of the sedimentary structures from laminae to thin and thick massive bedding. Bioturbation and faunal content shows a general increase towards the top of the sequence. The sandy facies and calcareous

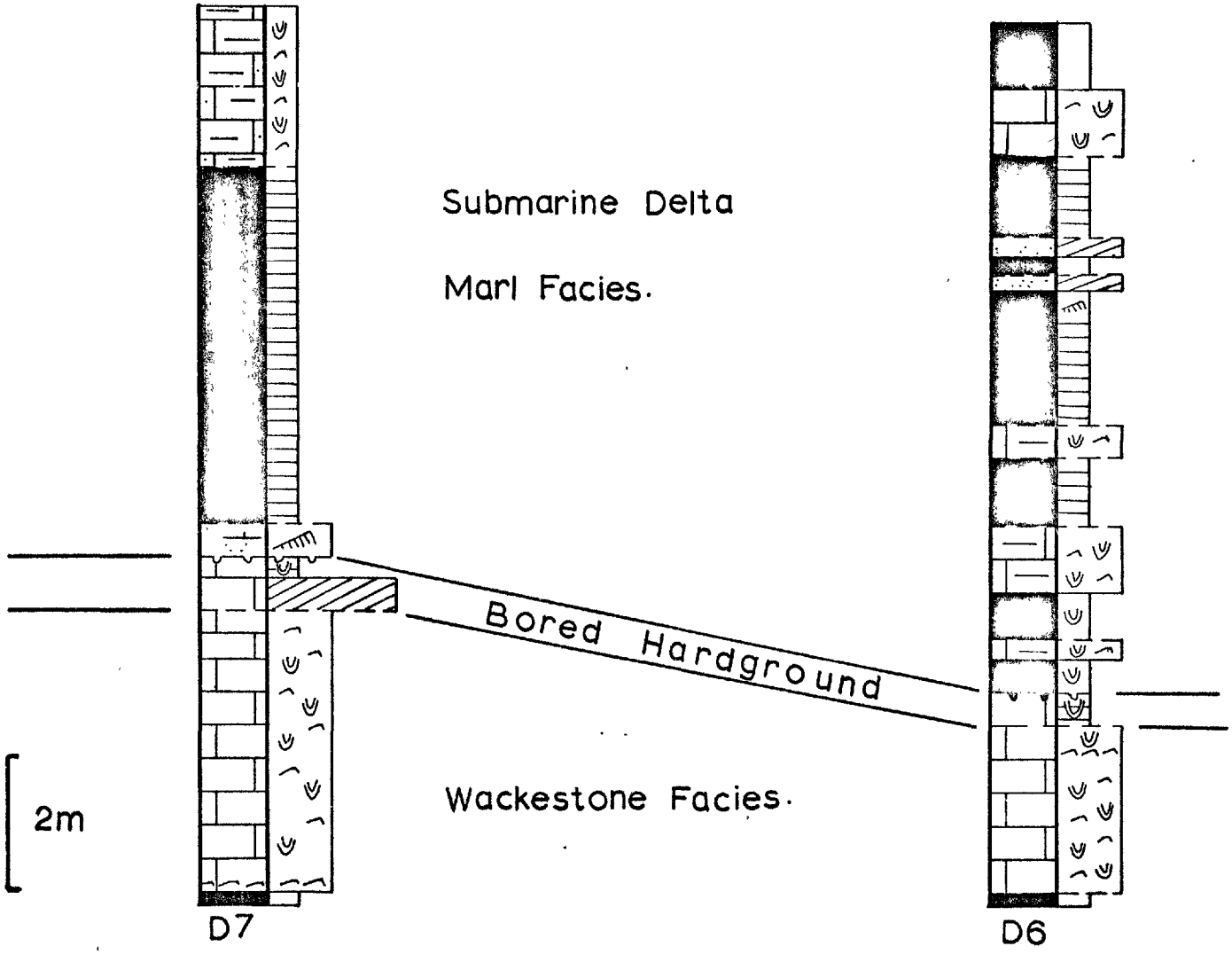
sand shoestrings contain bone fragments and plant debris. The laminated subfacies contains ostracods, forams, bryozoan and ophiuriod debris, while the massive and carbonate-rich subfacies contains molluscs and possibly algae.

The change in the vertical profile is also noted laterally along the strike. The laminated and inclined sandy subfacies shows an erosional lower contact, which gradually changes into horizontal laminae and bedding with a lower gradational contact. Thus one can conclude that the shoestring and sandy facies are the centre or the axis of the marl facies (Plate 6.3); the farther away from the axis, the more calcareous are the sediments (Plate 6.4). Although this argument is not qualitative, the gradual changes within the marl units are evident from the field and petrographic data. These changes also take place down the depositional slope (from south to north) and along the depositional strike (East-West) away from the estuarine channels' influence (Plates 6.2, 6.3, 6.4).

Interpretation

The vertical change and lateral distribution of the marl facies is similar, if not identical, to the modern submarine deltaic marl deposits off the Iranian coast, Persian

Plate 6-3. Vertical profiles of the marl facies (Submarine Delta) away from estuarine mouthes, Dor Zuggut, Sect. D6,7.



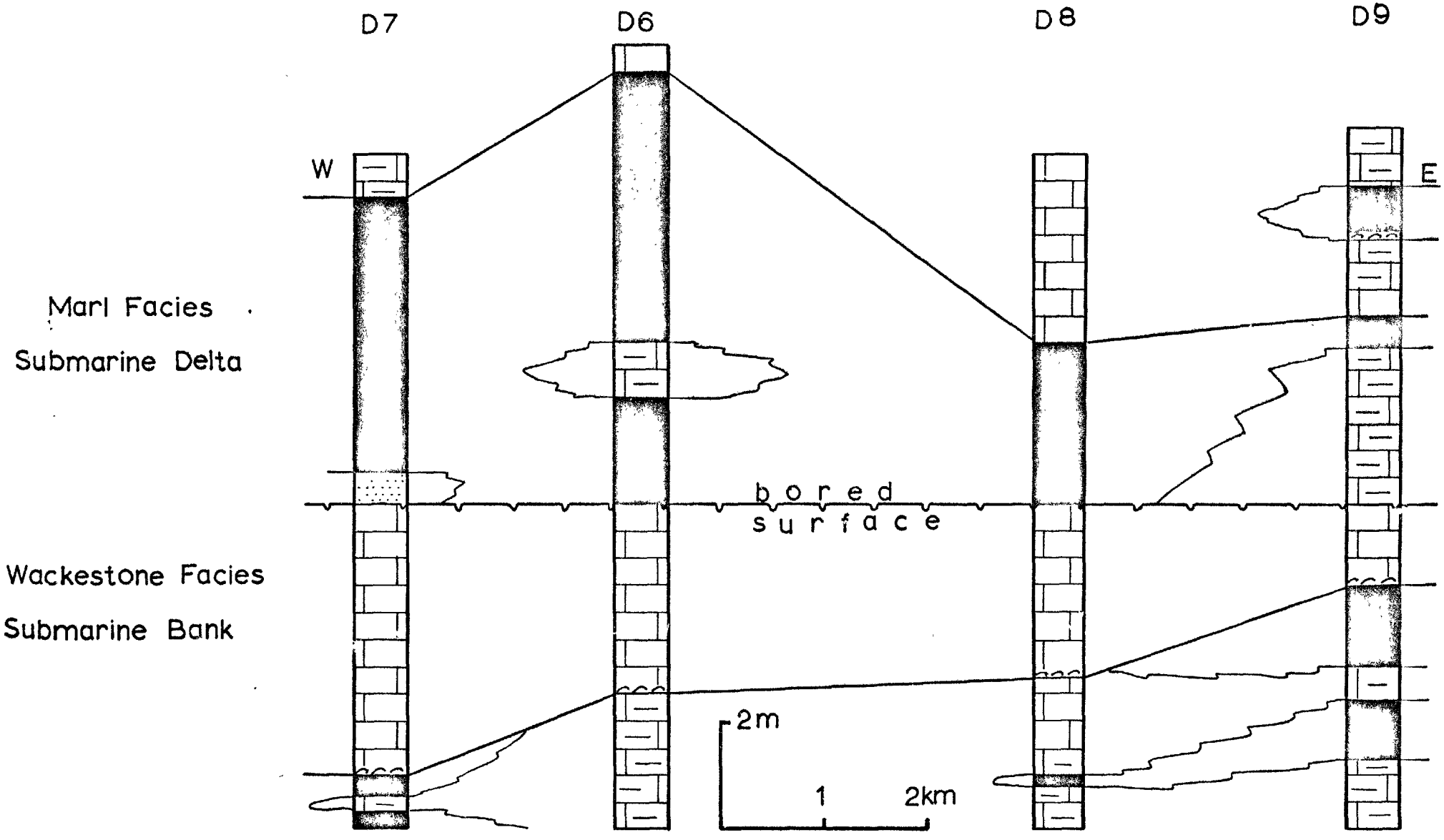


Plate 6-4. Stratigraphic cross section of the open marine facies along Dor-Zuggut Escarpment.

Gulf (Sarnthein and Walger, 1973; and Seibold et al, 1973). According to Sarnthein and Walger (1973), the submarine marly deltas consist of gradational but mappable facies of; (a) fine sandy calcareous marls (inner delta), (b) foram/ostracod marl (delta axis), (c) foram, mollusc echinoid marl (outer delta), (d) mollusca coarse grained marl (off delta), (e) large foraminifera coquina arenite (bank), plus relictiferous shelf plain facies.

The calcareous sandstone shoestrings and the laminated and inclined sandy marl subfacies are usually resting on an erosional contact with the underlying units. The localized nature of this contact and the high content of terrigenous quartz suggest that these facies represent the main path of sediment transport from the estuarine mouths into the open marine. The concentration of sediment transport along a narrow path indicates that as sediment-laden water leaves the estuaries it flows near the bottom and is driven by gravitational force as in the case of density currents. These currents were produced as a result of inland flash floods caused by a seasonal heavy rainfall which characterized the Marada climate. It is thought that these subfacies correspond to the inner delta and delta axis sediment of their recent Iranian equivalent (Sarnthein and Walger, 1973).

The high rate of sedimentation has clearly decreased seawards and laterally away from the delta axis gives way to the biological activity. Thus oyster banks and the massive calcareous marl subfacies correspond to off and outer delta sediments (Sarnthein and Walger, 1973).

6.3 Reconstruction of the Open Marine Facies Association

The open marine facies of the Marada Formation consist of wackestone and marl facies. The recent model for the formation of a fully marine marly and carbonate sequence is described by Sarnthein and Walger (1973); Seibold et al (1973); and Melguen (1973) from the shelf area off the Iranian Coast of the Persian Gulf.

The wackestone and marl facies were deposited on a gently sloping sea floor, off the tidal flat and estuarine channels complex of the Marada shore line. This palaeogeographic set-up was produced as a result of rapid rise of sea level and the elimination of the barrier/lagoon complex which had previously separated the open marine from the estuarine-tidal flat complex.

As the climate during the Middle Miocene times of Libya was tropical, the seasonal alternation of dry and wet climates was reflected in the pattern of sedimentation in the

open marine shelf area. During the dry season calcium carbonate organic productivity prevailed in the offshore environment, and wackestone banks were built up as a result of the continuous rise of sea level. During storm conditions the carbonate banks were transported landward to supply the barriers and lagoons with carbonate detritus.

During the wet seasons, onland flash floods brought terrigenous detritus into the open marine area through rivers and estuaries. The sediment-laden water flowed over the bottom by gravitational flow of density currents. The sediments were later deposited as a submarine delta fan as marly facies.

As the deltas prograded seawards, the carbonate rich, shelf bottom in front of the delta was non-depositional and was subjected to gentle currents which caused lithification and subsequent boring of the shelf surface along an extensive area. Similar recently lithified and bored surfaces are found on the Gulf of Mexico shelf off the Mississippi delta fan (Pequenete et al, 1972), where the shelf surface consists of a thin lithified ironstone layer which was caused by lithification of shelf sediments by oxygenated currents and slow rate of sedimentation. Seibold et al (1973) also indicated that the outflow from estuaries carries well oxygenated water over the bottom of the Persian Gulf.

The regional bored surfaces on top of the wackestone units (Plate 6.4) are therefore a chronostratigraphic surfaces and were formed in response to the slow sedimentation rate and oxygenated currents which have swept the shelf surface in front of the prograding delta. The occurence of several separated surfaces on a single stratigraphic horizon along the depositional strike in Dor Zuggut and Dor Marada areas indicates the occurence of several adjacent delta lobes. Furthermore, the occurence of two major, successive bored surfaces reflects the major successive estuarine influxes into the open marine.

Finally, the interpretation of the wackestone/marl sequence of the Marada Formation as open marine facies is in agreement with that presented by Doust (1968) for his limestone/shale succession (above the Echinolampas horizon) after studying the invertebrate fauna. Although he related the deposition of shales to the influx of terrigenous sediments from estuaries, yet he thought that the shale units (marls) are too thin to be considered deltaic. On the other hand, Selley (1966) regarded this sequence as a part of the barrier bars and lagoonal deposits (his detrital limestones and shales).

CHAPTER 7

DISCUSSION AND CONCLUSION

"... the strength of geology is derived from its uniformitarian basis, and that the geologic record is to be interpreted in terms of contemporary phenomena. Indeed, modern students demand actualistic models of sedimentation."

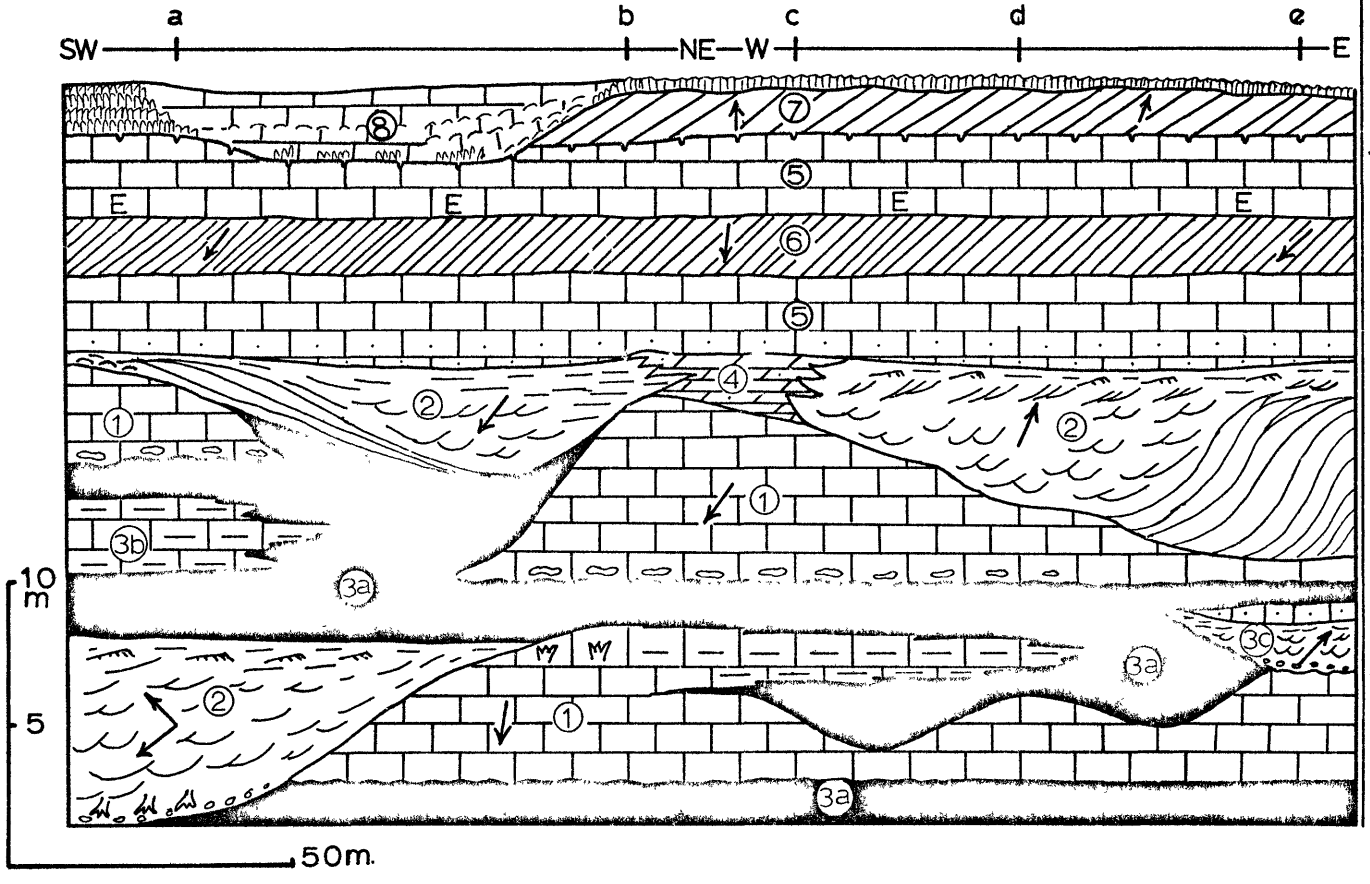
K.J. Hsü, The Odyssey of Geosyncline, 1973.

A. THE LATERAL AND VERTICAL FACIES RELATIONSHIP

7A.1 Construction of the cross sections

The distribution of the outcrops in the Marada area provided excellent exposures and a good access for section measurement along lines perpendicular and parallel to the depositional strike. As indicated in the introduction, recognition of the depositional facies proceeded with section measurement in the field. Vertical facies profiles (a few metres thick) were measured and described in great detail. Most of these profiles were correlated laterally by walking along the outcrop face for hundreds of metres in directions perpendicular and/or parallel to the depositional strike. In type areas, however, a series of vertical profiles were measured, 50 to 100 metres apart, and were later correlated (Plate 7.1). A total of 350 photographs were taken to show detailed structures and local facies relationships. The information produced from the detailed vertical profiles was

Plate-7-1· Stratigraphic cross section of a transgressive sequence of lagoonal - barrier - open marine facies complex in section D4.



Legend.

1 Barrier bars

2· Tidal inlet

3a· Lagoonal shale

b· " argilla. ls.

c· " channel

4· Inter tidal

5· Subtidal wackestn.

6,7· " grainstn·

8· " channel.

E· Echinolampas horizon

. Oysters in growth posit.

. Corals " "

. Paleocurrent direction.

Bored surface ·

a - e Sections.

used in recognition of the succession of facies during section measurements. Regional marker horizons such as Echinolampas bed and bored surfaces in the limestones, and local calcareous nodules horizons in the shales were used as reference lines in the field to relate one measured section to another. The succession of facies in measured sections have aided construction of facies cross sections perpendicular to the old shore line in north-south direction (Plate 7.2A) and parallel to the depositional strike along Dor Zuggut/Dor Marada escarpment (Plate 7.2B) and across the Central Jebels area (Plate 7.2C). The sedimentological details of measured stratigraphic sections in these areas, as well as those of Jebel Zelten, Jebel Raguba and Garet Guhannam areas are presented in the appendix. The datum used in constructing the cross sections is the recrystallized limestone bed capping the Marada Formation. In Jebel Zelten and Central Jebels areas a disconformity surface is found below the capping limestone bed; the same surface is also found locally in the northern areas, in sections M2, M3 and M8. The same disconformity surface was used by Selley (1966, 1969) to hang his stratigraphic sections from. Doust (in Selley, 1969), on the other hand, considers that the capping limestone bed was neither a good lithostratigraphic nor a good biostratigraphic marker. However, Dr. M.F. Ridd (in Selley, 1969, p. 460) stated that, in his experience of

Libyan geology, he found that the uppermost bed of any mesa is usually synchronous. He pointed out that Hamada el Hamra plateau's (of north Central Libya) upper surface is covered by a bed of Maestrichtian limestone over thousands of square kilometres; therefore he accepts the capping bed of the Marada Formation as a time stratigraphic datum. Professor W.D. Gill (in Selley, 1969, p. 458) recognized the importance of the intimate local correlation of facies, and accepted Selley's datum.

The present author has found Selley's (1969) datum a suitable basis for correlation, as explained below:-

a) In Jebel Zelten and Central Jebels as well as in the north-western area (in Section M8), the beds immediately below and/or above the disconformity surface consist of evaporite solution collapse breccia, which changes northwards and north-eastwards into dolomite and dolomitic wackestone, and in some cases packestone and grainstone, which may represent a normal lateral facies change. In most localities the Middle Miocene foraminifera Boralis melo is found.

b) In places where the breccia is absent, limestone solution is recorded along the disconformity surface, even in the northern sections such as in M2, M3.

PLATE 7-2A; N-S FACIES CROSS SECTION OF THE MARADA FORMATION.

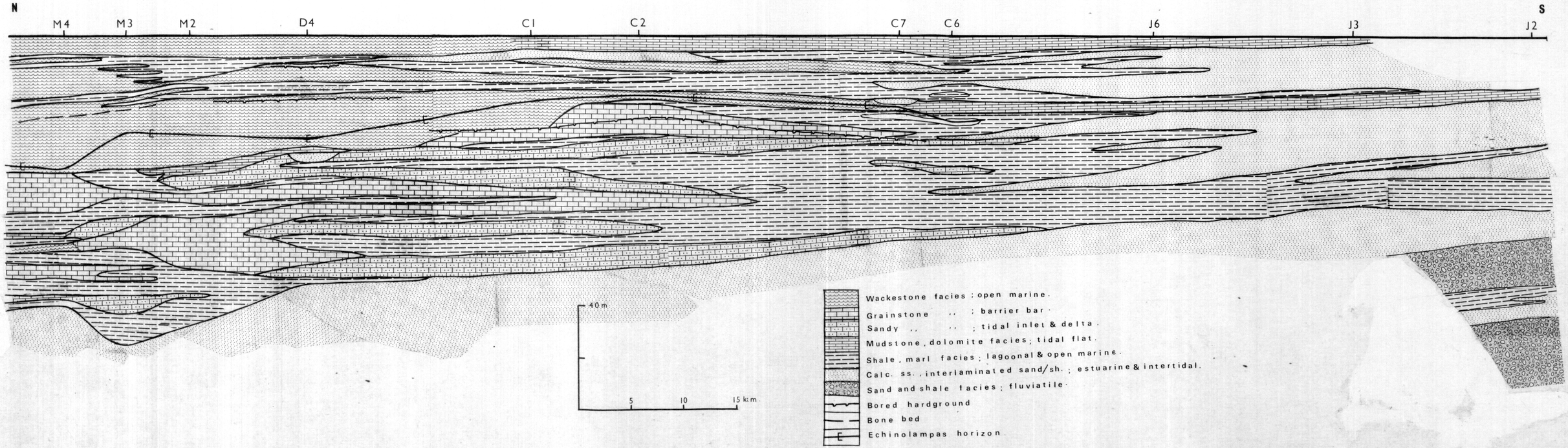


PLATE 7-2B. E-W FACIES CROSS SECTION ALONG DOR-ZUGGUT, DOR-MARADA ESCARPMENT.

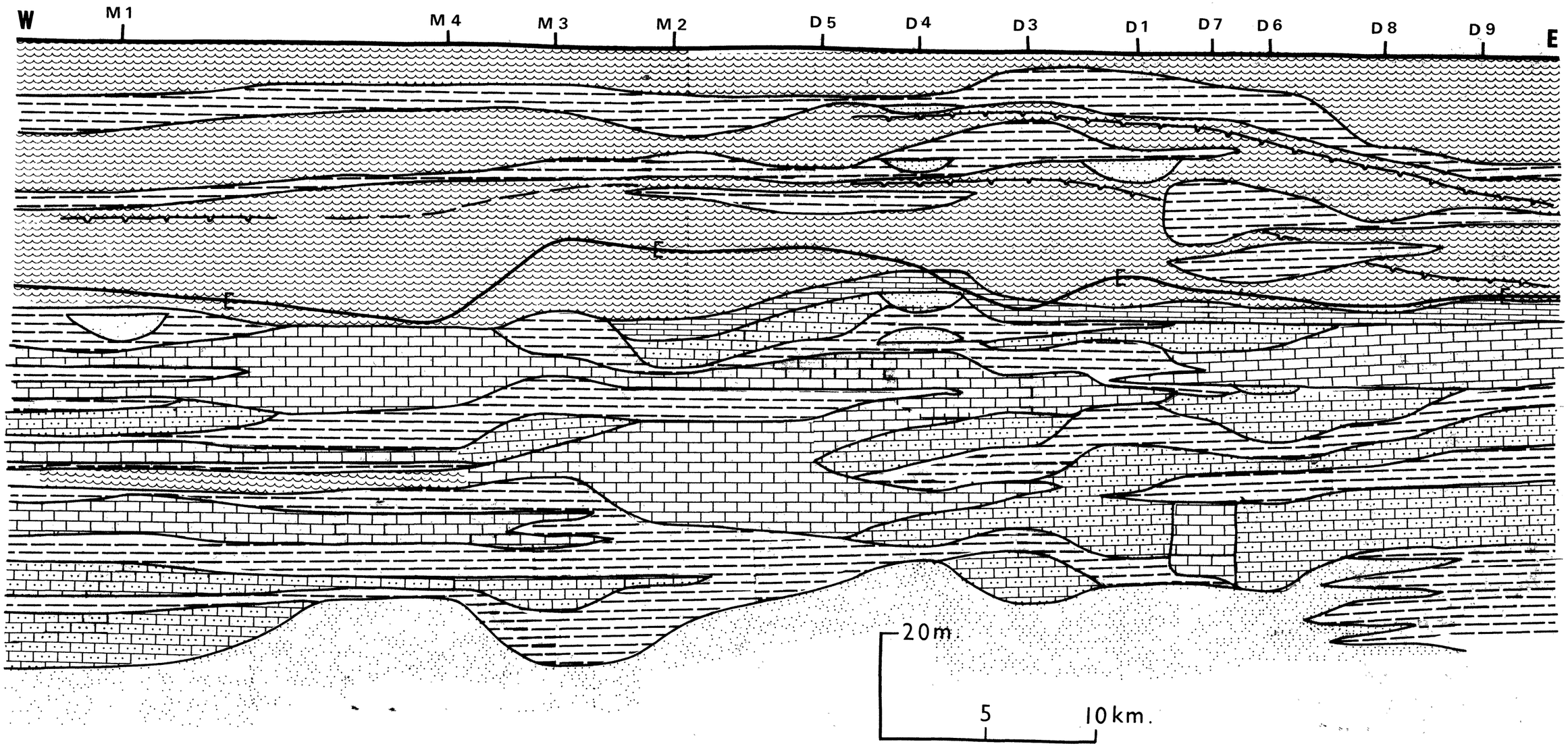
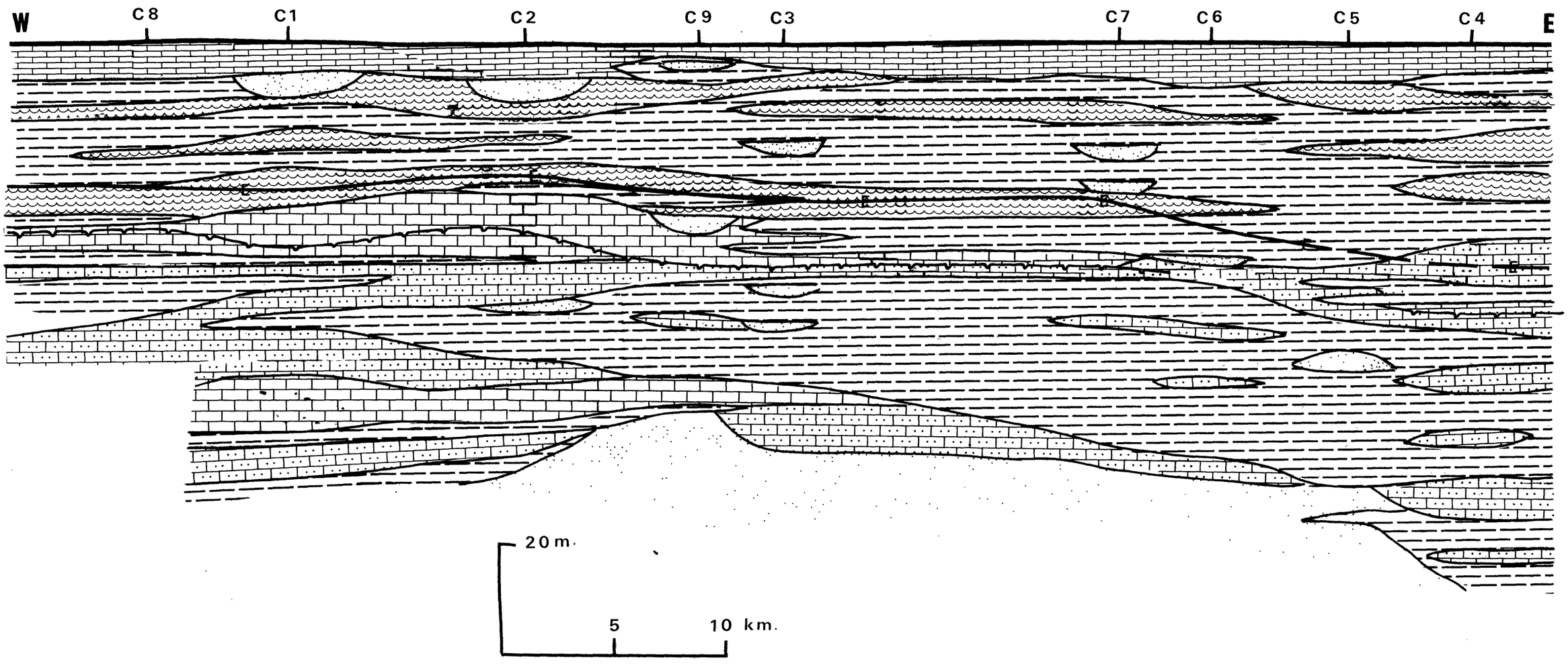


PLATE 7-2C E-W FACIES CROSS SECTION ACROSS THE CENTERAL JEBELS AREA.



c) Facies cross-sections produced by using this datum illustrate an undistorted lateral facies relationship. The capping limestone and disconformity surface may have been slightly distorted by syndepositional subsidence (see discussion on the subject later). However, the deformatiom produced is comparatively smaller than in the older marker horizons in the formation (e.g. bored hardgrounds, Echinolampas horizon).

Finally, all evidence suggests that the limestone bed capping the Marada Formation was deposited before the rapid regression of the Middle Miocene sea, and for all practical reasons it is regarded here as a reasonably good datum for correlation.

7A.2 Description of the facies cross section

Deposition of sediments of the Marada Formation took place during marine transgression, during the Middle Miocene time. The pattern of juxtaposed depositional environments is reflected in the stratigraphic cross section as vertical sequence of rocks representing these environments (Walther, 1893-94). All facies cross sections (Plate 7.2A, B, C) of the Marada Formation show three distinct depositional episodes, which are from base to top; (1) fluviatile, intertidal and estuarine sands and calcareous sandstones, (2) lagoonal barrier complex of interbedded cross-bedded limestone, sandy limestone and shale, and (3) cpen marine complex of wackestone banks and deltaic marls. The north-south cross section (Plate 7.2A)

extends for about 140 Km across the Middle Miocene shoreline; it shows that the landward equivalent of the depositional episodes 2 and 3 are the same as in episode 1. The carbonate dominated episodes 2 and 3 were the subject of this thesis. However, highlight attributes of the earlier terrigenous dominated episode are presented here in order to establish and understand their influence on the other carbonate dominated episodes.

7A.2.1 Depositional Episode 1:

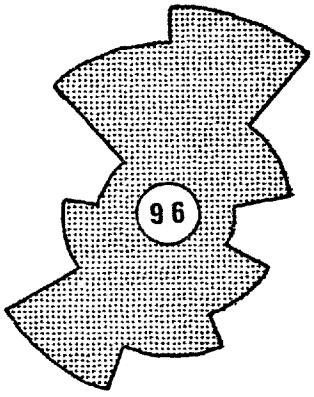
The base of the terrigenous dominated facies is not exposed in the sections examined, but an erosional base is suggested by Selley (1969). All previous authors agree on the origin of the terrigenous facies (Selley, 1966, 1969; Doust, 1968). For practical reasons the present author used Selley's (1966, 1969) subdivisions of these facies. However, the descriptions presented here are based entirely on the author's data from measured sections.

(a) The cross-bedded sands and shale (Selley, 1966) facies are exposed at the base of Jebel Zelten. They constitute a series of fining upwards cycles each of which shows an erosional base. The sand beds, internally, show trough and planar cross bedding; horizontal, wavy, and micro-cross-lamination characterize the silt and shale beds. The latter beds often contain

ferrigenous calcareous nodules and plant rootlets; bones and silicified tree trunks are found as lag deposits in the sands. Most cross-bedding shows a northwards azimuthal palaeocurrent direction (Plate 7.3). All these features indicate deposition on flood plains as suggested by Selley (1966) and Doust (1968).

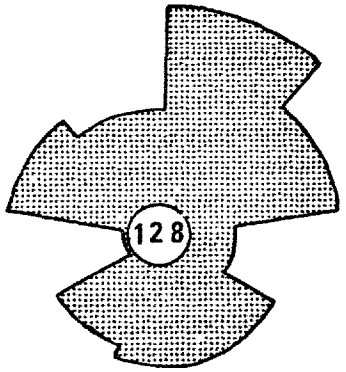
(b) The interlaminated shale and sand facies (Selley, 1966) generally occur above and to the north of the fluviatile facies. Units consist of a "fining up" and/or "coarsening up" cycles of medium to very fine grained sand and shale. These cycles occur in beds as well as laminae. Beds show lamination, micro-cross-lamination, lenticular and flaser bedding. Bioturbation, burrows, trails, faecal mounds and lignite rootlets are common. Flat topped lenses of channels are truncating the horizontal bedding, where flat pebbles of shale and lime mud are common. Generally this facies becomes less friable, lighter in colour and more calcareous northwards across the depositional strike and upwards towards the top of the sequence in Jebel Zelten, where they are associated with the calcareous sandstone channel facies. However, beds that are associated with the cross-bedded sand and shale facies (fluviatile) are darker in colour due to the presence of carbonaceous material and iron oxides. Interpretation of this facies as tidal flats and marsh sediments is in accordance with the conclusions reached by Selley (op. cit.) and Doust (op. cit.).

Plate 7-3 Palaeocurrent distribution Patterns of various facies.



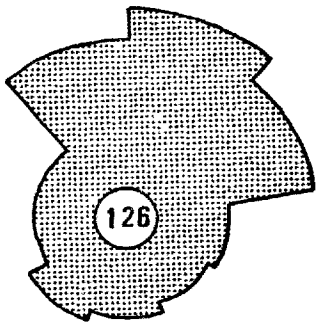
A The Grainstone Facies

Barrier Bars



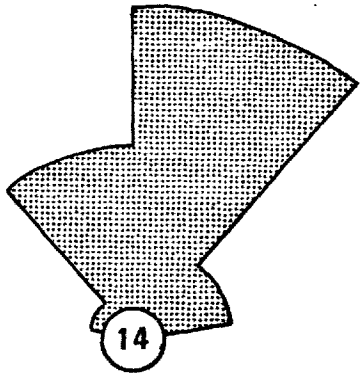
B The Sandy-grainstone Facies

Tidal Inlet-Delta Complex



C The Calcareous Sandstone Facies

Estuarine Channels



D The Sand Facies

Fluviatile Channels

(c) The calcareous sandstone facies consists of coarse to fine sand mixed with lime and terrigenous mid and silt. Ooliths and coated sand grains are found to the north. Aquatic vertebrate remains of teeth and bones, and silicified wood fragments are common. Northwards and upwards in the succession reworked marine shells and shell fragments are more abundant. Lag material consists of silicified wood, bone fragments, shells and reworked calcareous sandstone boulders. This facies is arranged in "fining up" cycles with erosional base. Trough and semi-tabular cross-stratification, micro-cross-lamination, climbing ripple lamination and interlamination of sands and shales are common. Bioturbation and burrows are the only biogenic features found in place. The azimuthal distribution of the cross-bedding dip orientation (Plate 7.3) shows a polymodal dispersal pattern with a very strong northward and a weak southern, eastern and western component. These features strongly support the estuarine origin of this facies as indicated in the previous work (Selley, op cit.; Doust, op. cit.).

Shoestrings of the estuarine channels are found associated in the fluviatile facies at the base of Jebel Zelten. Northward they appear filling a wide trough. This feature together with the increase of the carbonate content in the sediments upwards (and northwards) in Jebel Zelten sequence, indicate that river mouth drowning was the initial phase of

the Middle Miocene sea transgression.

In depositional episode 2 of Jebel Zelten, the estuarine/tidal flat facies complex is overlain by a tongue of dolomitic mudstone facies (intertidal/supratidal) which marke the beginning of the third depositional episode. In cross-section, there is a positive correlation between Jebel Zelten's estuarine/tidal flat facies complex and the laminated shale facies (lagoonal pond) and the cross-bedded sandy grainstone facies (lagoonal channel/delta complex) in episode 2; and the deltaic marl facies of episode 3.

7A.2.2 Depositional Episode 2:

This phase consists of lenticular bodies and sheets of the cross-bedded grainstone (barrier facies), wedges and sheets of the cross-bedded sandy grainstone (lagoonal channel/delta complex) facies which are interbedded with the laminated shale (lagoonal pond). The interbedding of the grainstone bodies with shales represents cycles of carbonate build-ups and terrigenous sedimentation. In the north-south cross section, shale reaches a maximum thickness immediately behind the barrier grainstone bodies, and in front of the estuarine/tidal flat complex of Jebel Zelten. The position and thickness of the barrier grainstone bodies change in response to the development of the sandy grainstone facies, which in turn show a positive

correlation to the estuarine channel complex to the south. The difference in palaeocurrent azimuthal distribution of these facies is shown in Plate 7.3. However, the overall relationship of the barrier grainstone bodies is transgressive. The last and younger body lies landward of the underlying ones.

A sheet of dolomitic mudstone (intertidal flat) facies is present to the north overlaying the barrier bar, and tidal delta facies, immediately below the open marine facies of depositional episode 3. The presence of this facies suggests that at some stage the tidal flats were occupying the landward and seaward sides of the lagoon during deposition.

7A.2.3 Deposition Episode 3:

This episode consists of successive sheets of wackestone banks interbedded with deltaic marl facies. The basal units of the wackestone facies contain the characteristic fossil Echinolampas Sp. which forms a regional stratigraphic marker throughout the area. The basal wackestone units change southwards into a unit of dolomitic mudstone facies (marginal intertidal and supratidal environments), which indicate the initial sea transgression during depositional episode 3.

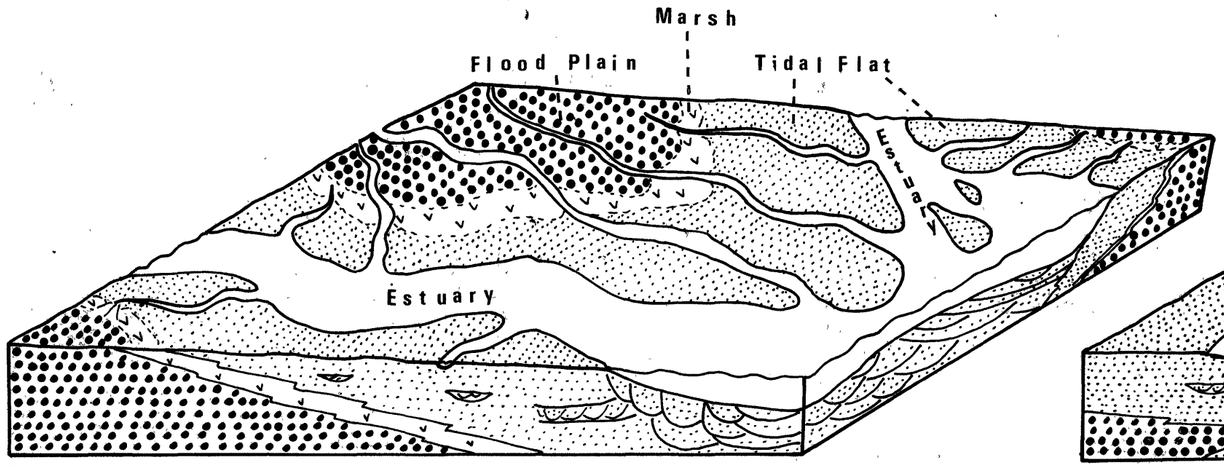
B. FACTORS AFFECTING DEPOSITION, DISTRIBUTION AND GROWTH OF THE MARADA FACIES

The fluviatile, fluviomarine, lagoonal, barrier, carbonate intertidal and open marine sedimentary environments of the Marada Formation (Plate 7.2A, B, C) have evolved during the Middle Miocene transgression. In space, these sedimentary facies were deposited beside each other, though in vertical profile we see them lying on top of one another (Walther's law, in Middleton, 1973). One must point out that there is an interesting sedimentary event in the building of the Marada facies complex, namely the carbonate deposition in the open marine/tidal flats, and barrier bars, which otherwise would have been overwhelmed by influx of terrigenous material from the rivers and estuaries. Then one must ask the inevitable questions, such as: what are the factors that held the balance between carbonate and terrigenous sedimentation in a given area? and when did mixing occur? and why?

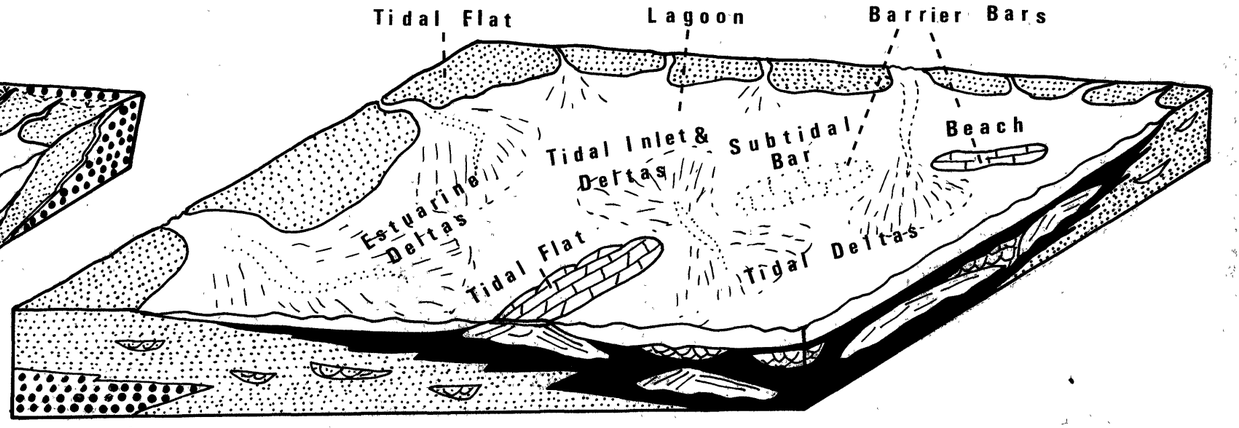
It is thought here that the primary control in the evolution of the Marada limestones was the rise of sea level, the tropical palaeoclimatic conditions, and the structurally controlled palaeotopography in the area.

7B.1 The Middle Miocene sea level rise (Plate 7.4)

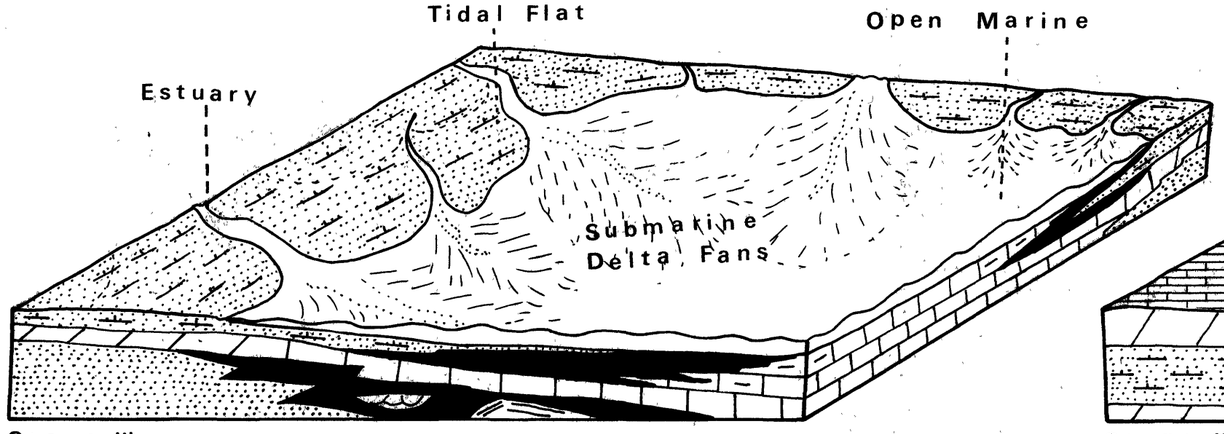
Stage 1: The calcareous sandstone shoestrings which are exhumed at the southern foot of Jebel Zelten represent the maximum early advance of the estuarine influence, and river



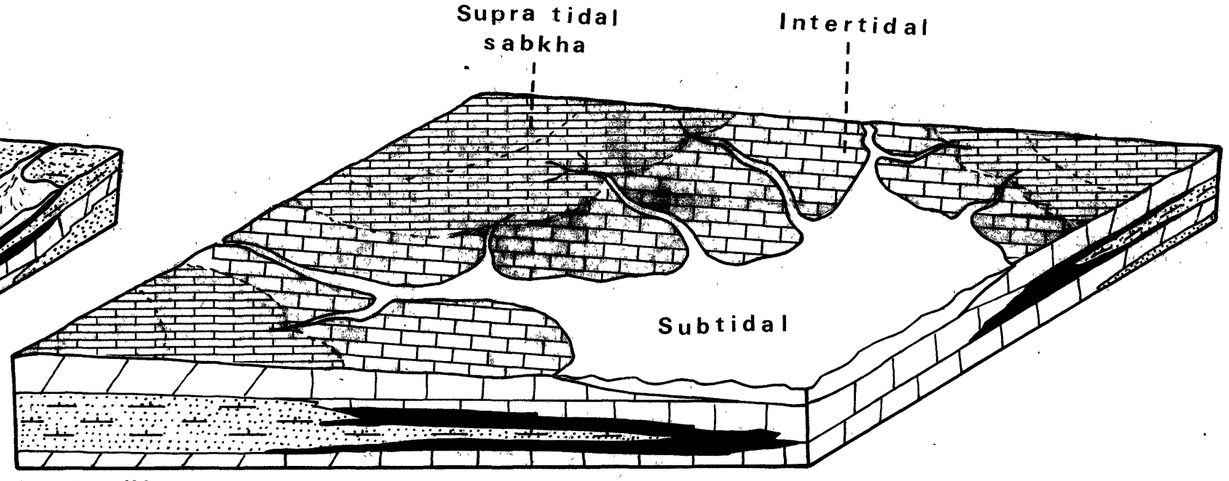
Stage I



Stage II



Stage III



Stage IV

Plate 7-4 Sketch block diagrams illustrating the distribution of sedimentary environments of the Marada Fm. at different

mouths' drowning of the Marada flood plain. They indicate the beginning of the Middle Miocene sea level rise.

The rise of sea level has caused a greater rate of upbuilding of the flood plain by alluvial sedimentation. The effect of sea level rise on flood plain aggregation has been documented by Russel (1967) for the Holocene sea level rise. He demonstrated up to 100 metres of alluvial sedimentation within the last 20,000 years in the flood plains of rivers of Turkey and the United States. The rise of the sea level also disrupted the profile of equilibrium in the near shore (fluviomarine) area with the result that there was a high rate of sand deposition in the increased space available, in order to reach a new equilibrium profile.

Stage II: Silting-up of the flood plain and sand sedimentation in estuaries and tidal flats combined to reduce the rate of sedimentation of bed load and suspended load into the offshore area. In this less turbid environment an abundant fauna thrived, and because the rate of addition of the terrigenous material was low for long periods, carbonate banks and barrier bars were formed, creating lagoonal area which has further separated the fluviatile/fluviomarine complex from the carbonate dominated shelf. The alternation of sea level rise (barrier advance)

and terrigenous influx (relative regression), produced an alternating sequence of calcarenite and shale.

Stage III: As the sea level rise has reached its climax the barrier bars were eliminated and the open marine facies overlapped those of the lagoon, and carbonate sedimentation was extended landward to dominate the tidal flats (the Jebel Zelten and Garet Guhannum limestone tongue). This indicates that the rise of sea level was faster than the rate of barrier deposition (Curry, 1964).

With cessation of the sea level rise, equilibrium was restored in the near shore area, and in the absence of the barrier bars the supply of the terrigenous sediments from the estuaries was resumed directly to the shelf area. Thus submarine delta fans were formed in front of the estuarine mouths. The pulsatory terrigenous influxes produced a sequence of limestone (wackestone) and marl of the open marine facies.

Stage IV: Finally, as the Middle Miocene sea receded rapidly northwards, intertidal, supratidal and Sebkha conditions prevailed allowing the formation of dolomite and evaporite facies capping the Jebel Zelten and Marada Formations. This was followed by subaerial exposure and solution of the evaporite minerals by meteoric water and the formation of solution collapse breccia.

7B.2 Climatic Factors controlling Sedimentation

i) Wet versus Dry Season conditions:

Fauna and flora found in the Marada rocks suggest that tropical climate has prevailed during the Middle Miocene time (Desio, 1935; Savage and Hamilton, 1973; Selley, 1966, and Doust, 1968). Modern tropical areas have a two season climate, a wet season and a dry season. Tucker (1973) gave the following table, which shows the general climatic characteristics in the Freetown Peninsula, Sierra Leona, West Coast of Africa.

Season / Criteria	Wet Season	Dry Season
Months	June-September	December-March
Temperature	$21^{o}C$ - $25^{o}C$	$22^{o}C$ - $29^{o}C$
Rainfall	280 cm	30 cm
Wind	Southwesterly	Westerly

Tucker (1973) indicated that there is a marked difference between the wet and dry season sedimentary processes. The wet season is a period of high river discharge when much of the sediments carried out of the estuaries are formed by off-shore directed currents. Flood bed forms are commonly destroyed by tropical rainstorms (Tucker, 1973). On reaching the lagoon, estuarine channels deposited their bed load, and lagoonal ebb estuarine deltas were formed. During exceptionally high

river discharge, estuarine channels by-pass the delta and run seaward over the lagoonal floor and through the tidal inlets.

The combination of high rate of sedimentation and run-off have raised the water level in the lagoon above the sea level. Reworking of the barrier by inlet channel migration, and the formation of marine ebb deltas, were brought about during the influx of the water and sediments out of the lagoon into the open marine. Often the rate of sedimentation in the lagoons was so high that the fine grained detritus spilled over and overlapped the barrier to be deposited in the shelf area. Therefore the wet season has been a period of tactical regression, whereby the barrier growth was checked and encased by terrigenous fine-grained detritus; and the lagoon was possibly enlarged, pushing the new barrier seaward or forming an open bay.

During the dry season, river discharge became low or negligible and flood currents dominated estuaries and inlets. It was above all a period of high biological activity and carbonate productivity in all sedimentary environments. In his study of modern tropical estuaries, Tucker (1973) noticed that during the dry season estuaries become clogged by sediments brought from the offshore areas, algal mats build up in the intertidal flats and blind estuaries. He also noticed that evaporation leading to hypersalinities and mud cracks become common in these environments.

Evaporation and cessation of the run-off water in the Marada area during the dry seasons has lowered the water level in the lagoon. Subaerial exposure of the lagoonal estuarine deltas is indicated by their lithification and dolomitization. Also, wave activity and flood currents have produced flood deltas, which are relatively smaller than those caused by ebb currents. As the salinity rises, carbonate productivity increases in the open marine and the nearshore area, and evaporites were formed in the intertidal and supra-tidal zones.

ii) Fair Weather versus Stormy Weather Conditions:

Fair and stormy weather conditions have influenced sedimentation in the Marada area. These weather conditions can occur either in the wet or the dry season. However, during the wet season, sedimentary processes are overwhelmed by rain-storms and run-off conditions.

Sedimentary structures and geometry of the Marada barrier bar facies indicate that they were formed under high energy conditions. Ball et al (1967) indicated that the growth and movement of the Bahamanian sand mega-ripples are influenced by hurricanes. Stratification in the Bahamanian beaches, and intertidal and subtidal shoals, and sheet deposits are formed

by bottom traction (accretion deposits) during major storms (Imbrie and Buchanan, 1965). Tidal inlets and flood tidal deltas are formed in the sandy Key of Florida bays during storms (Bathurst, 1971, p. 149). After studying the hurricane and storm deposits on the British Honduras coast, High (1969) concluded that under high energy conditions tidal deltas grow into the lagoon and form extensive mud flats along the rear edge of the barrier, but on the other hand he found that the balance of force responsible for the formation of tidal deltas is upset locally due to blocking of tidal inlets by barrier ridges. He also emphasized that "normal" sedimentary processes such as; filling the lagoon with mud and shell debris; encroachment by the mangrove marshes; and gradual elevation of supratidal flats, are enhanced during these conditions.

Thus landward migration of barrier bars and beaches; the development of flood deltas, washouts and slump features in the Marada lagoon strongly suggest that storms and hurricanes have prevailed during deposition. Also, meteoric water diagenesis of the barrier beaches, dolomitization of flood and ebb lagoonal deltas, and progradation of the intertidal and supratidal facies over the barrier bars, may indicate diagenetic conditions that prevailed following sedimentation during storms.

Most "normal" sedimentological processes, such as seaward progradation of the barrier bars, ebb deltas, tidal flats, and the biological activity, must have prevailed under fair weather conditions.

Plate 7.1 shows the relationship between the barrier bars lagoonal shales, tidal inlets, intertidal tidal deltas and open marine facies. The barrier landward advance and growth were interrupted by influx of terrigenous sediments and were cut by ebb and flood channels. The top of the barrier bars are colonialized by corals or oysters and also overlain by dolomitized intertidal carbonate facies. This relationship may indicate alternation of dry and wet seasons followed by the advance of the open marine.

7B.3 Structural Control of the Marada Sedimentation

The Sirte Basin was formed at the beginning of Late Cretaceous times as a result of the collapse of Tibesti-Sirte uplift (Colley, 1963). A number of tilted horsts and grabens of the rift fracture were formed. Subsidence of the Sirte Basin continued from Late Cretaceous through Tertiary. The rift faulting increase in throw northwards away from the stable African craton, where thickness of Mesozoic-Tertiary section in the parallel troughs between the tilted horsts may attain over 20,000 feet (Hea, 1971).

The Late Cretaceous and Paleocene transgression in the Sirte Basin (where most Libyan oilfields are found) shows a similar pattern of sedimentation to the Marada Formation and its lateral equivalent. It resulted in deposition of basal sandstone followed by alternating shale and carbonate rocks (Conley, 1971). The limestones were deposited on a broad, shallow shelf surrounding the open marine basin where shale was accumulating. The calcarenites and reefs were deposited in turbulent water on old highs (horst) and along the southern shoreline, while calcilutile or shale were deposited in quieter water in the adjacent lows (grabens). While along the shoreline intertidal and supratidal dolomites accumulated (Conley, 1971). Most of the old highs are assymmetrical in cross section; they generally show a gentle inclination eastwards and a steep drop to the west, as in the case of Zelten (Fraser, 1967), Amal (Roberts, 1970) and Idris "Intesar" (Terry and Williams, 1969, Fig. 5) oilfields.

Selley (1971, Fig. 4) suggested that the sedimentation of the Marada facies was also structurally controlled. He indicated that the position if Zelten and Raguba estuaries was due to synsedimentary subsidence along synclinal axes, which were formed as a result of negative tectonic movement that occurred along the pre-Miocene "palaeohighs" during the Miocene time (Selley, 1973, p. 130). He also claimed (ibid) that the barrier

calcarenites are concentrated in the Central Jebels area where they are located on top of an "east-west" trending anticline which was also formed during the Miocene (Selley, 1971).

A series of isopach maps were constructed for the various sedimentary facies of the Marada Formation to show the influence of pre-Miocene structural features on the distribution of these facies (Plates 7.5, 7.6, 7.7, 7.8 and 7.9).

19°

19°30'

20°

N

29°

28°30'

40 35 30 25 20 15

50

45

40

35

30

25

20

45

40

35

30

25

20

Plate (7-5) Isopach map of the sequence above the open marine transgression (Echinolampas horizon) and their southern and western equivalent (Intertidal ls. tongue).

Contours in meters.

19°

19°30'

20°

N

29°

28°30'

RAGUBA HIGH

Raguba Estuarine Channle

EN - LA - HIB HIGH

Shoe-strings

JEBEL - ZELTEN

Zelten Estuarine Channel

WAHA HIGH

Plate 7 - 6

Inferred Palaeogeography at the base of the marine transgression.

Structural configuration:

From the study of the Marada facies cross section it is clear that the Echinolampas key horizon represents the base of the open marine transgression which overlaps the lagoonal barrier complex and extends landwards as a major limestone tongue in Jebel Zelten and Garet Guhannum (Stage III, Plate 7.4). Thus an isopach map of the sedimentary sequence above the base of the transgression would reflect the palaeotopography of the area at this stage (Plate 7.5).

The paleogeography of the area (Plate 7.6) consists of a "north-south" trending and gently northwards sloping structural high. The axis of this high runs from Jebel Zelten in the south (Section J8), to the central Jebels (Section C8, C1), and between Dor Marada and Dor Zuggut (Section M2, D5) in the north. The axis is slightly curved eastward in the central Jebels area, where the high shows maximum width. The structural high coincides with a series of subsurface oil field structures located along the axis of Jebel Zelten (Jebel field), Central Jebels (Zelten field), and in Dor Marada, Dor Zuggut area (Lahib field and others). Another structural high (Raguba) occurs at the north-west part of the area, its axis shows a "north east-south west" trend; a third high was possibly present to the south-east where the Waha oilfield is located.

The Jebel Zelten/Lahib structural high is bordered on the west side by a "NE-SW" trending trough, and on the north eastern side by a "WNW-E" trending trough. In Jebel Zelten area, however, the eastern trough is wide and runs in a NE-SW direction parallel to the axis of the high. Both the eastern and western troughs are the site of Zelten and Raguba estuarine channels respectively (Plate 7.6).

Facies isopach maps:

a) The isopach map of the shales associated with the barrier calcarenites (lagoonal shales) and the open marine wackestones (shales and marls) lends more support to the structural features discussed above (Plate 7.7). The shale facies reach a maximum thickness in the troughs in front of the estuaries, while decrease in thickness on the axis of the structural high. Also, the thickness of the shales increases northwards along the high axes, and it follows the palaeoslope . In cross section, the shale thickness distribution increases gradually to the trough east of the high and increases rapidly to the west, suggesting asymetrical nature of the structural high.

b) The isopach map of the barrier facies suggests that they are concentrated along "WNW-ESE" trend in Dor Zuggut and Dor Marada area. Contrary to the previous claim (Selley, 1971,

19°

19°30'

20°

N

29°

30

40

30 20 20 30 40 50

28°30'

Plate 7-7

Isopach map of the total shale thickness of the Marada Formation
(Associated with grainstone, sandy grainstone and wackestones)

Contours in meters.

19°

19°30'

20°

N

29°

29°

20
15
10
5
0
25
20
15
10
15
10
10
5
0
15

28°30'

28°30'

Plate 7 – 8

Isopach map of the cross-bedded grainstone facies (Barrier Bars). Contour lines in meters.

19°

19°30'

20°

19°

19°30'

20°

N

29°

29°

25
20
15
10
5
0
25
20
15
10
5
0

28°30'

28°30'

Plate 7 - 9

Isopach map of sandy grainstone facies of the Lagoonal Association

Contours in meters.

19°

19°30'

20°

Fig. 4), they are roughly perpendicular to the north-south axis trend of the structural high (Plate 7.8). They reach a maximum thickness (26.8 metres) in section D5 on the high, and decrease gradually to ENE and WSW direction, away from the axis. Southward along the structural axis (in the Central Jebel), the grainstone barrier facies are up to 18.4 metres thick and decrease gradually southwards. In cross section, the barrier units in the Central Jebels area are stratigraphically higher than those to the north. They represent the last occurrence of barrier bars before being eliminated by the last major (Stage III) transgression.

It is clear that the barrier facies distribution and thickness is controlled by the structural high and the position of the sea level. The local thickness variations, however, are possibly attributed to erosion by tidal inlets. The southern, eastern and western limits of this facies are controlled by the terrigenous sedimentation in the troughs, and reworking by the marine transgression southward along the highs. The northern limit of the cross-bedded grainstone facies is not known due to the lack of outcrops,

c) The reworking of barrier bar facies by tidal inlets is indicated by an isopach map of the sandy grainstone facies

(tidal inlets, tidal deltas, and lagoonal channels) in Plate 7.9. In correlating this facies isopach maps with those of the barrier facies and the estuarine channels, it became clear that the sandy grainstone facies reaches its maximum thickness in front of the major estuaries, and in areas of reduced barrier bar thickness. They also show a decreased thickness along the estuarine channels and shoestrings, as well as increase of maximum barrier thickness. This positive correlation indicates the close relationship between the cross-bedded sandy grainstone facies (tidal deltas, lagoonal channels and inlets) and the estuarine channels and the barrier bars.

In the final analysis, the isopach maps indicate that the deposition of the cross bedded grainstones took place on the Palaeohigh, whilst the maximum deposition of the shales took place in the troughs in front of the estuaries. Also, the regional stratigraphic markers (Echinolampas horizon and bored surfaces) show a gentle folding along the east-west cross sections (Plate 7.2B, C) with the highest points coinciding with the palaeohigh; whilst the isopach maps suggest a syndepositional subsidence along the troughs. The syndepositional subsidence is attributed here to differential compaction of shales along the palaeohigh and in the troughs. The latter

was the site of maximum shale accumulation whilst the former was the site of reefal growths and calcarenite accumulation since the formation of Sirte Basin (Conley, 1971). However, if one takes into account that the palaeohighs are not merely lines, but a broad tilted block (Hea, 1971); thus the pre-Miocene differential local reefal growths (Terry and Williams, 1969) may have altered the local palaeogeography on these highs. Local highs and lows have affected the general pattern of sedimentation of the Miocene rocks; and only under these circumstances channels were formed on the major palaeohighs (Plate 7.6, e.g. Zelten estuarine channel between Lahib, Zelten and Jebel; and Waha local highs). This conclusion negates the syndepositional tectonic movement theory (Selley, 1971), which suggests the development of a "positive" E-W trending anticline (perpendicular to the palaeostructural trends) in the Central Jebels area; and N-S trending synclines which were formed as a result of a "negative" movement along the palaeohigh (Selley, 1971, Fig. 4; 1973, p. 130). Selley's negative movements, however, may correspond to subsidence along local palaeo-troughs as a result of differential compaction.

The discussion presented here indicates that syndepositional subsidence has taken place throughout the sedimentological history of the Sirte Basin. The pre-Miocene structural configuration (Palaeotopography) has played an important role

in the distribution of various facies of the Marada Formation. It is equally evident that the inherited palaeostructures have influenced the distribution of the pre-Miocene sedimentary facies (Conley, 1971; Fraser, 1967; Roberts, 1970; Terry and Williams, 1969) in the same way as it influenced the Marada Formation. Several oilfields are located in the subsurface along the same major north-south palaeostructural high described above; they include, from north to south; Arshad, Lahib, Sorra, Meghil, Zelten, Raha, Jebel, Waha, and Defa oilfields.

Finally, if the relationship between the palaeostructures and the distribution of the sedimentary facies of surface exposures, and subsurface formations is as true as it may seem; thus the application of sedimentological studies of exposed formations as presented in this thesis could have a far-reaching significance in the exploration for oil in the Sirte Basin.

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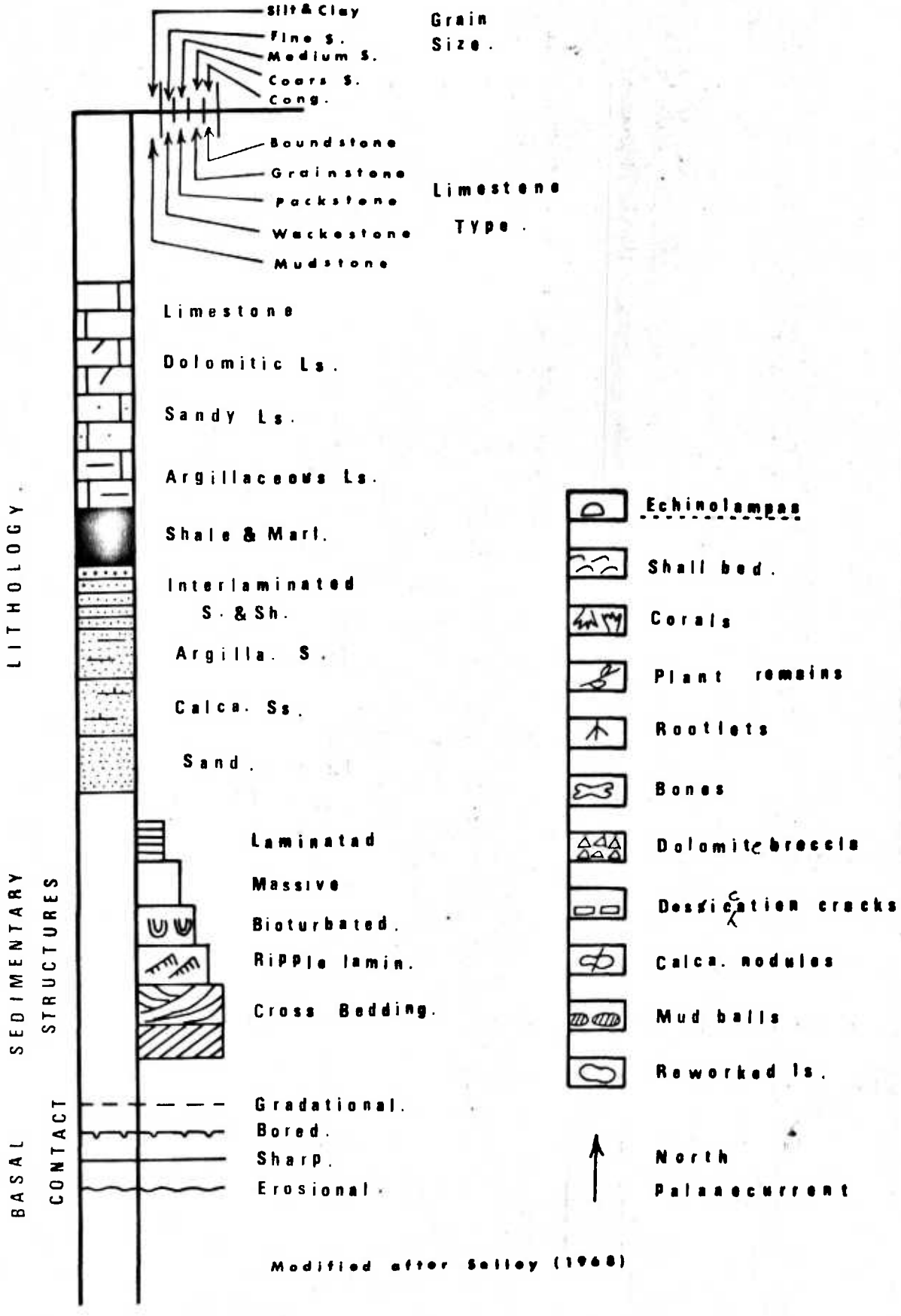
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APPENDIX

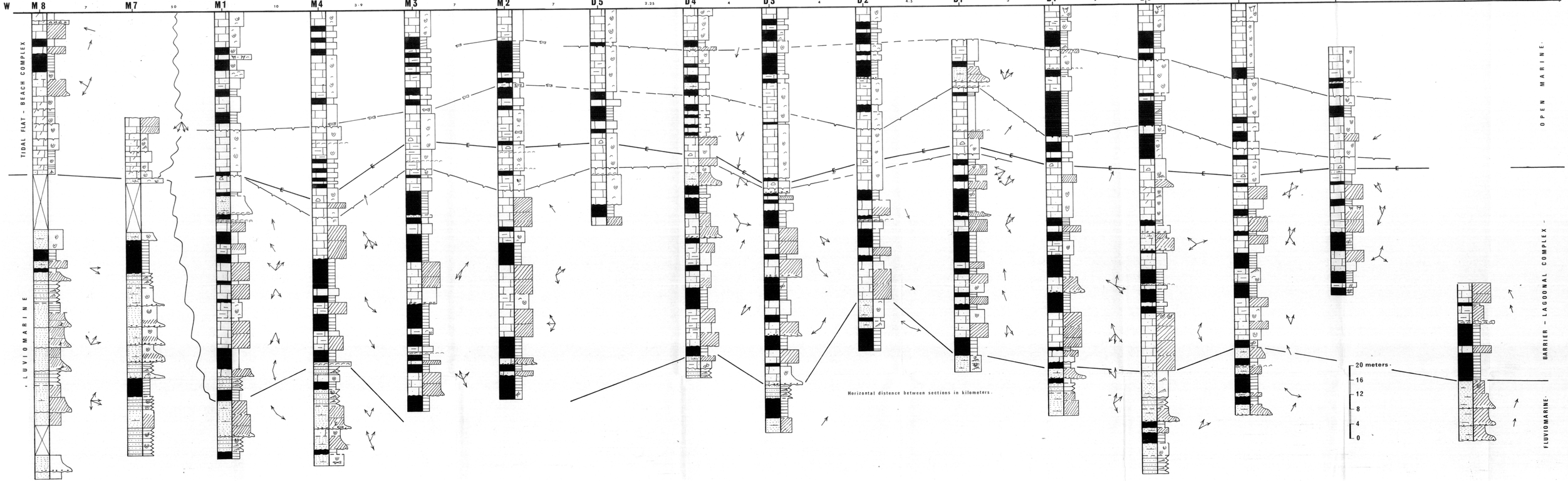
STRATIGRAPHIC CROSS SECTIONS OF MEASURED FIELD SECTIONS (LOGS)

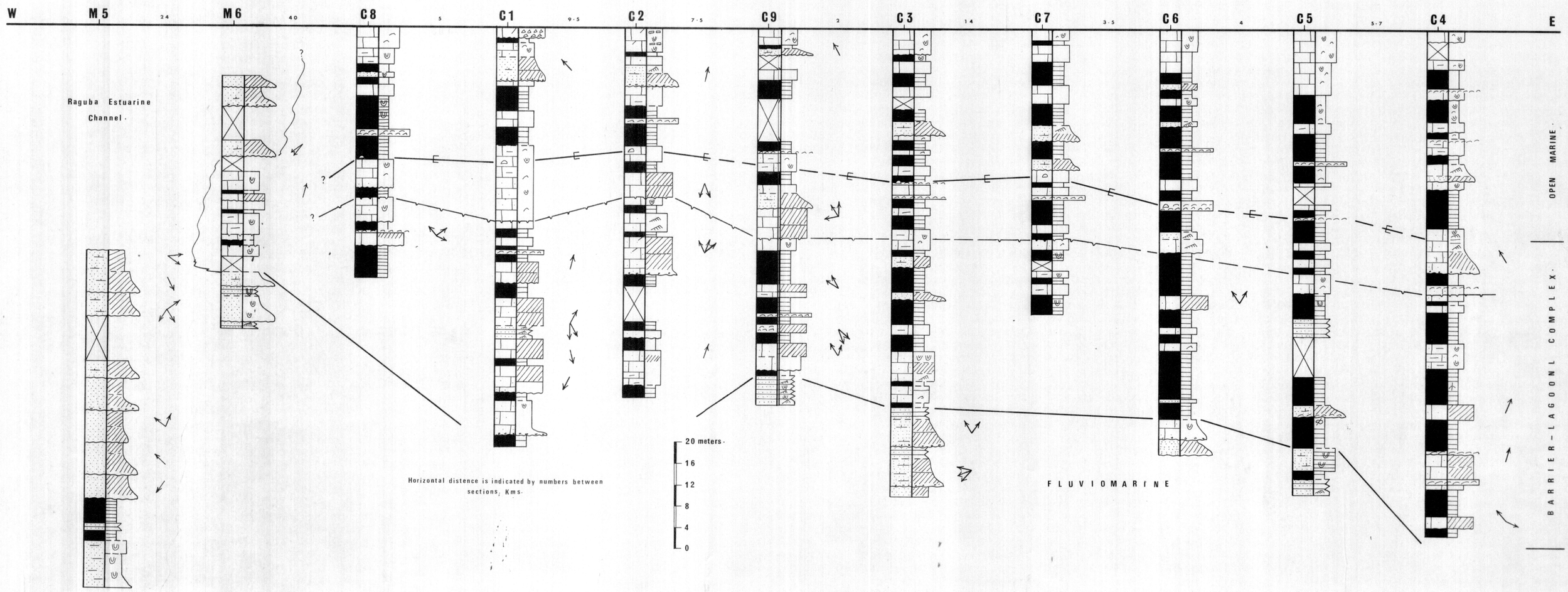
Plate 1_3 **KEY OF SYMBOLS.**



Modified after Selley (1968)

East-West Stratigraphic Cross Section of Measured Sections Across Dor Zuggut-Dor Marada Escarpment & Garet Guhannam Area .





East-West Stratigraphic Cross Section of Measured Sections Across the Centeral Jebels & Jebel Raguba·

W J4 20 J5 15 J8 23 J2 27·5 J6 8·5 J1 18 J3 18 J7 E

INTER-TIDAL & ESTUARINE

FLUVIATILE

20 meters.
16
12
8
4
0

Numbers between sections indicate horizontal distences in kilometers.

East-West Stratigraphic Cross-Section Across Jebel Zelten Area.