"RECENT ALGAL MATS AND QUATERNARY CARBONATE SEDIMENTS OF AL-KHIRAN, KUWAIT".

BY

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ABSTRACT

The area of Al-Khiran is one of Recent carbonate sedimentation in a complex of barrier spits, ridges, lagoons, tidal channels and extensive tidal flats. The tidal flats lie behind oolite barrier ridges, and are fed by two channels (Khors) which lead in from the open sea. The tidal flats are therefore somewhat sheltered and have provided a suitable environment for development of algal mats. The mats, which cover an area of approximately four sq. km, extend from approximately mid-tide level up to the level of highest spring tides. Above the latter level, mats cannot grow because of the intense desiccation of the desert hinterland. The mats do not normally extend below mid-tide level due to the grazing activities of cerithid gastropods and other organisms. The width of the mat field varies from place to place and appears to be related to the local gradient of the tidal flats and to their positions relative to the prevailing northerly winds.

The algal mats show a variety of growth forms the most common of which are: subaqueous mounds, flat polygonal mats, tufted mats, discrete algal heads, crinkled and curled mats. Pools and other low areas offer the optimum conditions for the build up and preservation of growth structure. The mat building algae are all blue-green algae. The most common species is *Microcoleus chthonoplastes* which occurs in most mat forms, but *Lyngbya aestuarii* is the most abundant alga in the tufted mats. The distribution and morphology of the algal mats are controlled by the interaction of a number of factors which include the presence or absence of grazing and burrowing organisms; amount of wetting vis-a-vis desiccation; local differences in the strength of

tidal scour; salinity and the physical properties of the sediment substrate. Over the greater part of the algal flats the mats are uncemented, but in two places along the bank of tidal channels the mats have undergone cementation and are in fact stromatolites. Locally, fragments of the cemented mats break off and become further coated ultimately to form oncolites.

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CONTENTS.

ERRATA

Various objects, such as geological hammers, were used for purposes of scale in many of the field photographs. The following table lists the absolute size of these items.

Length of hammer = 33 cm

Length of shovel = 65 cm

Length of pencil = 16 cm

Length of pen = 13 cm

Diameter of lense cap = 6 cm

The scales of photomicrographs are given in terms of magnifications. Bar scale for the various magnifications are presented below.

x 13 = 1 mm

x 30 = 0.5 mm

x 40 = 0.5 mm

x 80 = 0.25 mm

x 130 = 0.1 mm

TABLE OF CONTENTS.

LIST OF FIGURES

CHAPTER 1.

CHAPTER 1

Introduction and general description of Quaternary sediments in Kuwait with particular reference to the Al-Khiran area

1.1 Introduction

This thesis deals with present day algal mats and their associated sediments in the coastal region of the southern part of the State of Kuwait at the head of the Arabian Gulf. The region was first studied sedimentologically by the present author in the course of research for the degree of Master of Science at the University of Kuwait: Saleh (1975). In that project the Quaternary sediments were mapped on a scale of 1:50,000, and emphasis was directed to the distribution and stratigraphic positions of the various Quaternary oolitic rocks and the diagenetic processes which affected them. The work together with other observations on the Quaternary sediments was presented as a joint paper with Dr. Picha: Picha and Saleh (1977). The research presented in this thesis followed on naturally from the earlier studies. Additional surveys were made of the Quaternary sediments with particular reference to the ways in which sedimentary processes had created the sub-environments which were conducive to the present widespread development of algal mats. This sedimentological background will be discussed later in this introductory chapter. Other chapters deal specifically with the algal mats and the factors which influence their distribution and morphologies. At two places along the banks of tidal channels the mats have undergone penecontemporaneous lithification, and are in fact stromatolites. These latter will be described in Chapter 4.

1.2 Methods of Study

The region over which the present day algal mats occur is known as Al-Khiran. The region was mapped by combining the interpretation of aerial photographs with field observations.

Sediment and algal mat samples were collected from all the principal sedimentary environments in the Al-Khiran region. The samples were studied megascopically and microscopically, and selected materials were further analysed by x-ray diffraction. Much useful information was provided by samples from a regional pattern of shallow boreholes put down by Sproule and Assoc. Ltd., 1974 in an investigation of limestone resources. The author was present when the boreholes were put down in the Al-Khiran area. Thin sections were made from most of the samples. It was usually necessary to impregnate the samples with resin before thin sections could be prepared. In the case of the algal mat samples it was necessary to dehydrate the material with ethanol before impregnation.

1.3 Review of previous work

To date relatively little research has been carried out on the Quaternary sediment of the State of Kuwait, compared with the considerable work which has been done on the sediments further south along the Arabian coast. It is useful therefore to include in this review a summary of the latter work in order to place the sediments and the algal mats of the

Kuwait area in their regional setting.

In Kuwait State the Quaternary sediments were described briefly by Fuchs, Gattinger, and Holzer (1968) in the notes which accompany their geological map of the State of Kuwait. Subsequently the mineral composition of the present beach sands of Kuwait was studied by Khalaf (1969), and the offshore bottom sediments were described by Al-Temeemi (1972). The distribution, composition and diagenetic history of the Quaternary oolitic sediments in southern part of the State of Kuwait were studied by Saleh (1975), Picha and Saleh (1977) and Picha (1978).

The first study of the sediments of the Arabian Gulf as a whole was made by Emery (1956). He found that the sediments were predominantly carbonates and that they become progressively fine-grained towards the axial trough. Terrigenous components were found only: immediately adjacent to the Tigris - Euphrates - Karun delta in the north, and, along the Iranian coast in the east. Emery concluded that the predominance of carbonate sediment was due in part to lack of supply of terrigenous sediments, and in part to the climatic regime. Sugden (1963) studied the sediments of the Gulf of Salwa, where he found parts of the intertidal and shallow subtidal areas were floored with thin but hard aragonite-cemented crusts. He attributed this surface cementation of the Recent sediments to the high evaporation rates which prevail there. He also speculated on the possibility that the Arabian Gulf could be a potential evaporite basin. He thought that this might be effected, either, by an overall shallowing, or, by creating a bar across the Strait of Hormuz.

Between 1961 and 1973 extensive programmes of sedimentological research were carried out along the coasts of Qatar and Sheikdom of Abu Dhabi, where the coastal sediments are dominantly carbonates, with local widespread development of intertidal algal mats. The list of references to the work in Qatar and the 'Trucial Coast' is now a very long one, and they were mostly summarised in the volume entitled 'The Persian Gulf' edited by Purser (1973). For this reason they are not all listed in the bibliography of this thesis. In many respects there are close similarities between the sediments of the Qatar and Abu Dhabi regions and the sediments which have accumulated along the coast of the southern part of the State of Kuwait. Gypsum and early diagenetic dolomite are present in both regions, as well as carbonates. However, there is one major difference. This is that the evaporite mineral anhydrite, which is abundantly developed in the coastal sabkha of Abu Dhabi is apparently absent from the Kuwait region, although climatic conditions are not markedly dissimilar. For the purposes of this introduction it is only really necessary to refer to those papers which relate to algal mat sedimentation.

Skipwith (1966) and Kendal (1966) in their Ph.D. theses described the eastern and western parts of Khor Al-Bazam along the coast of Abu Dhabi and directed particular attention to the distribution of intertidal algal flats. They demonstrated that there is a zonation of mat forms with respect to frequency and extent of tidal inundation and deliniated: flat, crinkle, polygonal and cinder mats zones (Kendal and Skipwith 1966, 1968, 1969). The mats of Abu Dhabi were later studied in greater detail by Park (1973, 1976, 1977), who dealt with the significance of algal lamination and discussed the preservation potential of the mats. The evolution of the algal belt in relation to evolution in Abu Dhabi was discussed by Kinsman and Park (1976).

The first detailed study of present day algal mats was that by Black (1933) in the Bahamas. He described four types of mats which had developed in different marine and brackish environments on the tidal flats of Andros Island. This work was followed in the 1950s by Ginsburg who treated the mats covering the intertidal flats of Florida and the Bahamas in greater detail (Ginsburg 1955; Ginsburg and Lowenstam 1958, and Ginsburg 1960). More comprehensive studies of Recent Bahamian algal mats were carried out by Monty (1965, 1967, 1972, 1976).

In the Shark Bay area of Western Australia, Logan (1961) described large cemented algal heads which occur on the intertidal platforms and around headlands of the bay. Since then these Recent stromatolites and those of Hamelin pool, Shark Bay, have been studied in greater details by many authors (Logan et al, 1964; Davis, 1970; Logan et al, 1974, Playford and Cockbain, 1976 and Hoffman 1976). Much research has been carried out on both modern and ancient stromatolites over the past few years, and most of this work has been compiled in a volume entitled 'Stromatolites' edited by Walter (1976). The details of these various pieces of work on modern algal mats and their relevance to the present study of the algal mats of Al-Khiran will be dealt with in other sections of this thesis.

1.4 General description of the Quarternary sediments of the State of Kuwait

The Quaternary sediments of the State of Kuwait rest on a 'basement' of Miocene and Pliocene detrital sediments attributed to the Fars Group, and the Ghar and Zahra Formations (Owen and Nasr, 1958; Milton, 1967; Fuchs et al 1968). Lateral and vertical variations of marine, lagoonal and terrestrial facies and the lack of fossils make subdivision and correlation in this complex of young Tertiary rocks very difficult. Because of this and the uncertainities about the position of the Plio-Pleistocene boundary, especially in southern Kuwait, Owen and Nasr (1958) called this sequence the 'Kuwait Group' and included the Pleistocene Dibdibba Formation in it.

The northern and southwestern parts of Kuwait are largely covered by the Dibdibba Formation; which consists of Pleistocene fluviatile gravels and sands which were deposited in a braided channel environment. The gravels, mostly derived from the shield and cover rocks of Saudi Arabia, form elongated ridges which are oriented fan-wise between NE and E at the exit from wadi Al-Batin: Fig. 1.1. The gravel ridges are mostly the result of selective erosion processes which have removed the fine grained interchannel sediments.

Because of lack of fossils and the poorly defined boundary between the Dibdibba Formation and the underlying Fars Group, the stratigraphic position and the lateral and vertical extent of the Dibdibba Formation is very difficult to determine in many places. Woletz (in Fuchs et al 1968) attempted to solve the problem, by using heavy minerals. Woletz distinguished two specific associations of heavy minerals in the superficial

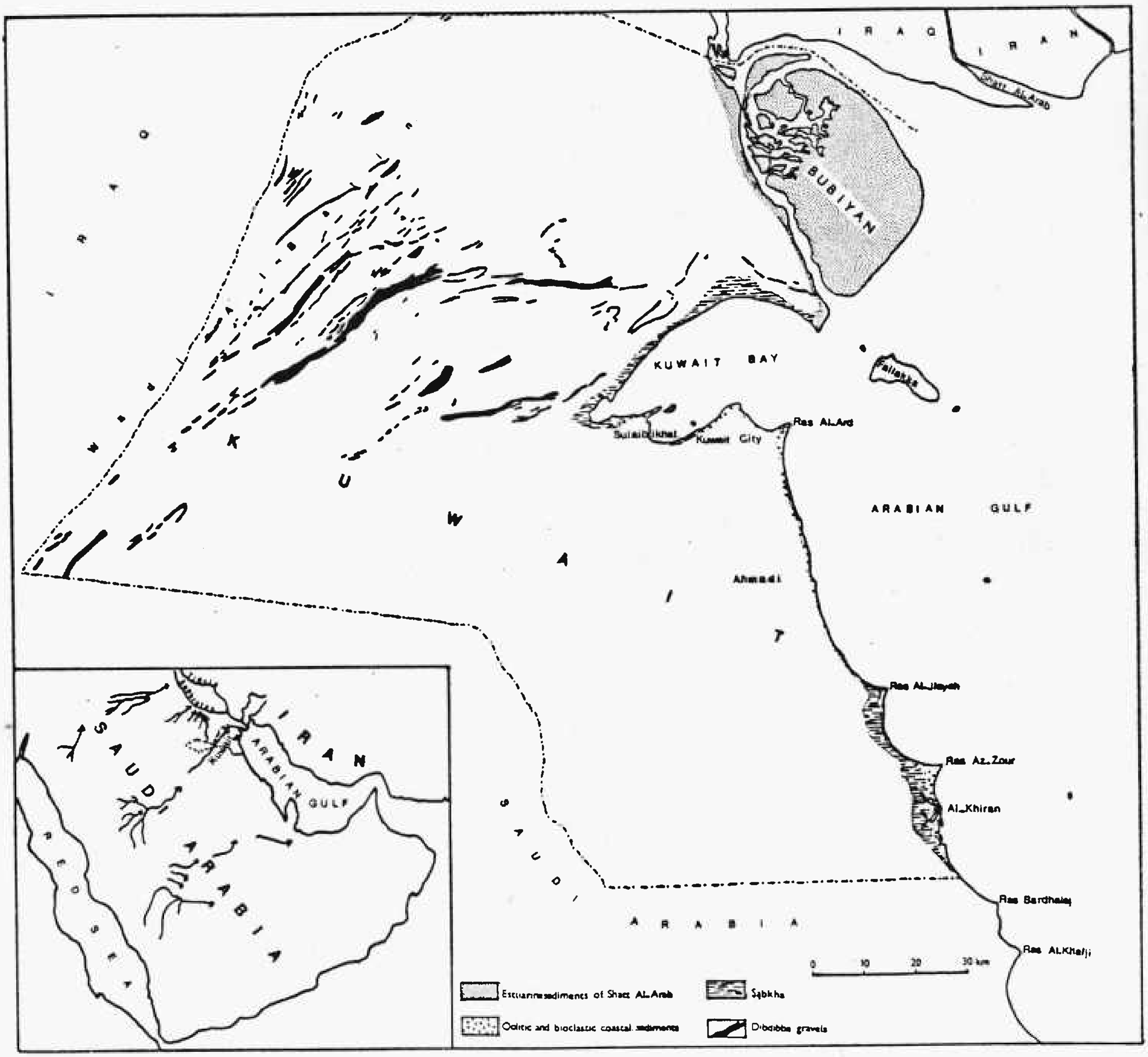


Figure 1.1.

Map showing the distribution of main Quaternary surface sediments in Kuwait.

formations of the Kuwait region. The older Miocene to Pliocene sequences (i.e. the Ghar Formation, the Zahra Formation and the Fars Group) are generally characterized by a predominance of zircon and epidote accompanied by amphibole, rutile, garnet and tourmaline. The predomenance of these minerals is attributed to acid igneous, metamorphic and reworked sedimentary rocks. The superficial fluviatile sands and gravels of the Dibdibba Formation yield assemblages of heavy minerals with high proportions of pyroxene and amphibole in addition to common epidote and garnet. This association strongly supports the idea that detritus from basic volcanic rocks was brought in during Pleistocene time. The sediments of the Dibdibba Formation are usually loose or slightly cemented near the surface, but they sometimes become strongly cemented by calcium carbonate and gypsum at depths of several decimetres up to about 5 metres. The pebbles and cobbles range in size from a few centimetres to more than 20 centimetres in diameter and occur in a sandy matrix which often also contains gypsum. The phenoclasts are mainly composed of quartz and volcanic rocks. The latter range in composition from rhyolites to olivine basalts. Less common are cobbles of granite, gneisses, and sedimentary rocks. The attitude of cross stratification seen in many gravel pits and the imbrication of the pebbles and cobbles indicate that the direction of transport was from the SW and W. The provenance of the Dibdibba gravels must have been the western part of the Arabian peninsula where Precambrian crystalline rocks are exposed, and where there are widespread Plio-Pleistocene volcanics. The gravels therefore must have been transported during a pluvial stage of the Pleistocene when large wadis, such as the Wadi Al-Batin, were developed.

The northernmost part of the Arabian Gulf is occupied by clastic sediment of the Tigris-Euphrates - Karun delta. These muddy terrigenous sediments extend for about 100 km into the northern parts of the Gulf, and comprise the low lying swampy islands of Warba and Bubiyan. In Kuwait Bay, which is very close to the Shatt Al-Arab, most of the mud which covers the tidal flats (for example in Sulaibikhat Bay) was supplied by the Tigris - Euphrates. These fine-grained sediments, which include skeletal fragments, quartz, heavy minerals, detrital and chemically precipitated carbonate mud and clay minerals were transported mostly in suspension to the sheltered environment of the bay by longshore and tidal currents. Part of the detritus may also have been carried by the 'Shamal' wind. This muddy terrigenous facies rapidly dies out along the coast of Kuwait City and south of Ras Al-Ard, where it gives way to carbonate sediments. The southern coastal area can therefore be considered as part of the carbonate province of the shallow Arabian shelf which extends southward to near the Strait of Hormuz.

The Quaternary carbonate complex in southern Kuwait, especially the Al-Khiran area will be the main concern of the rest of this chapter.

1.5 Quaternary sediments of Al-Khiran area

The Quaternary coastal complex in the Al-Khiran area comprises a system of coastal beach/dune ridges, barrier spits, lagoons, tidal channels, tidal flats and sabkhas. The complex extends for about 25 km from Ras Az-Zor in the north to Annuwaisib in the south: fig. 1.2 and plate 1.1. It has a maximum width of about 7 km in the central part. It is bordered to the landward side by an undulating terrain of Tertiary sediments, which becomes higher towards the south near Hadd Al-Himarah.

The essential features of the complex will be discussed under the following headings:-

(1) Beach/dune barrier complex

(2) Lagoons

(3) Tidal channels and tidal flat deposits

(4) Sabkhas

(1) Beach/dune barrier complex

The Late Pleistocene and Recent barrier complex of Al-Khiran can be separated into two parts which are distinctly different from one another in terms of mineralogy and texture. These are:

(A) The inner quartzose sandstone complex (Pleistocene).

(B) The outer oolitic barrier complex (Sub-Recent to Recent).

Both of these barriers enclose sabkhas or lagoons in their landward sides. The barriers consist of complexes of beach and dune ridges which range in elevation from 2 to 17 metres above sea level.

(A) The inner quartzose sandstone barrier complex

The inner quartzose sandstone ridge extends southwards from near the southern end of Khor Al-Mufatteh and terminates

Figure 1.2.

Map of the Al-Khiran area, showing distribution of surface sediments and major geomorphologic features.

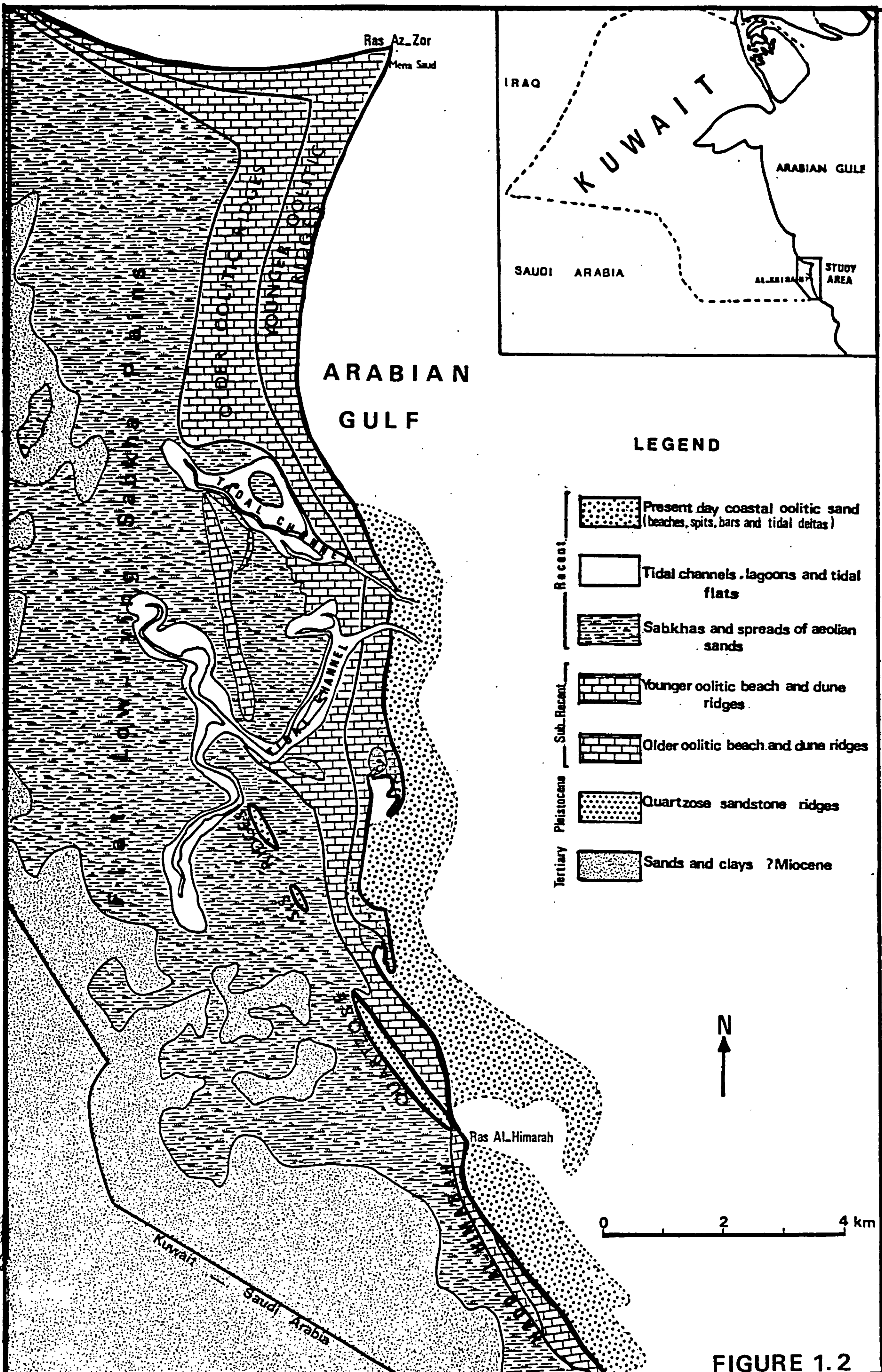
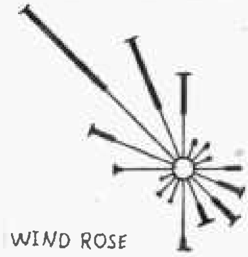

Ras Az_Zor
Mena Saud
IRAQ
KUWAIT
ARABIAN GULF
SAUDI ARABIA
STUDY AREA
ARABIAN
GULF
OLDER OOLITIC RIDGES
YOUNGER OOLITIC RIDGES
TIDAL CHANNEL
Ras Al_Himarah
Kuwait
Saudi Arabia
LEGEND
Recent
Present day coastal oolitic sand (beaches, spits, bars and tidal deltas)
Tidal channels, lagoons and tidal flats
Sabkhas and spreads of aeolian sands
Sub_Recent
Younger oolitic beach and dune ridges
Older oolitic beach and dune ridges
Pleistocene
Quartzose sandstone ridges
Tertiary
Sands and clays ?Miocene
N
0
2
4 km

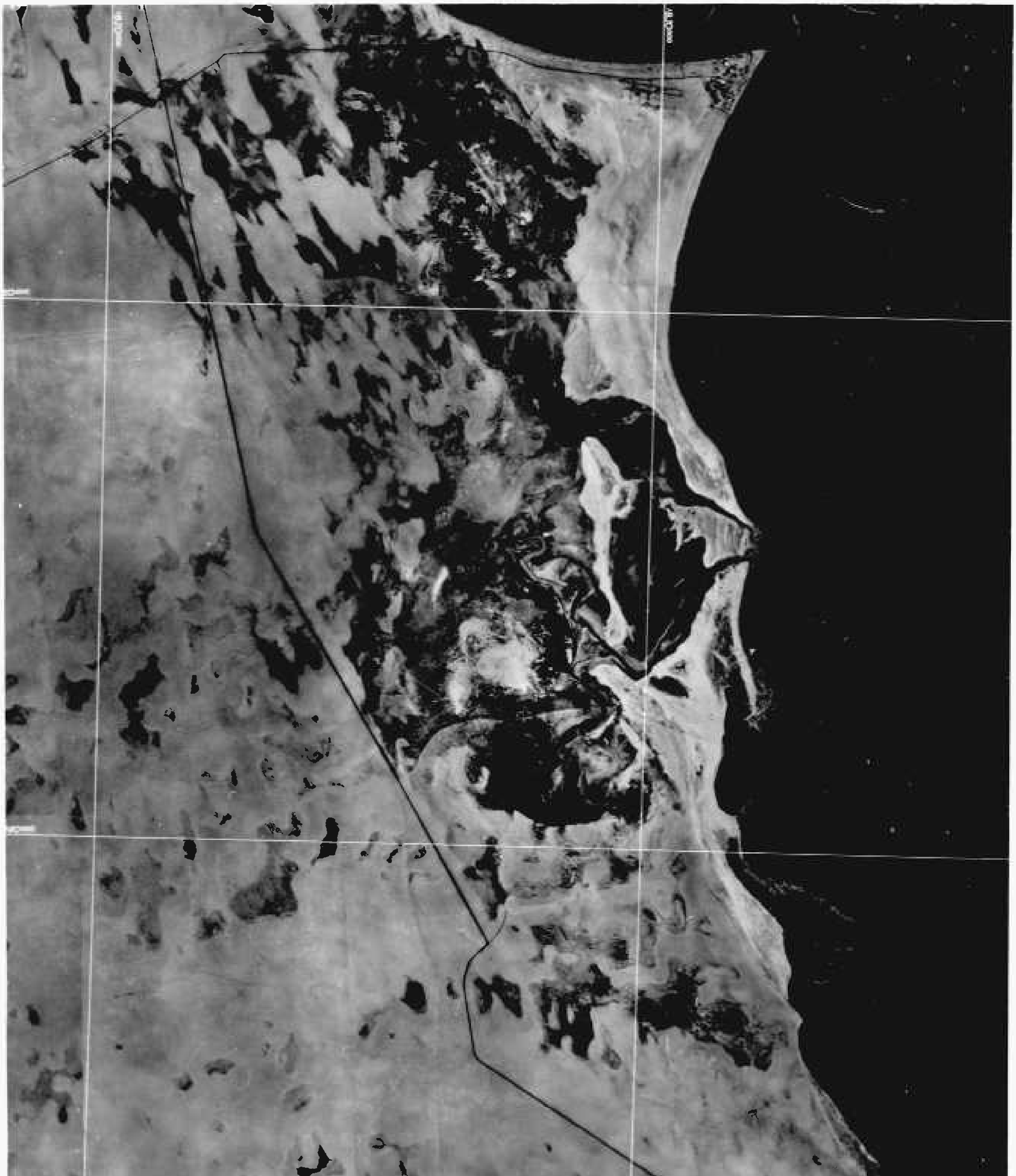
FIGURE 1.2

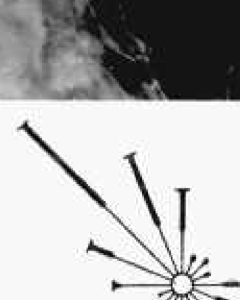
Plate 1.1.

Aerial photograph mosaic of the Al-khiran area. The overlay shows the positions of individual aerial photographs comprising plates 1.12, 1.13 and 1.14.



WIND ROSE





WIND ROSE

southwards at the sea cliff near Ras Al-Himarah. Similar sandstone ridges are also found north of the study area, bordering the central part of the oolitic complex between Mena Saud and Ras Al-Jlayah to the north. These sandstone ridges lie inland and are the oldest of the various ridges in the Al-Khiran complex. They range in altitude from 10-17 metres above sea level. This inner barrier runs obliquely to the present shoreline, and in this respect contrasts with the outer oolitic barrier complex which approximately follows the trend of the shoreline. The barrier is bordered on its landward side by the inner, i.e. the oldest sabkha and the Tertiary inlands. The continuity of the barrier is broken in two places. These probably represent former marine inlets.

The lower part of the ridge is composed of coarse grained quartz sand with some skeletal fragments and it is usually only slightly cemented. The upper parts of the ridge are strongly cemented and consist of coarse grained quartz sand with increasing proportions of oolites and a few skeletal fragments. The bedding of the upper part is laminar, and the laminae dip gently seawards. The likelihood is that the bedding was aeolian in origin.

In places where the lower part of the ridge is exposed, e.g. near the southern side of Khor Al-Mufatteh and in the cliff at Ras Al-Himarah, it displays a herringbone-type of cross-bedding with shelly layers: plate 1.2. This type of cross-bedding is clearly non-aeolian. It was most probably formed by bipolar tidal currents. The shelly cross-bedded base of the ridge is usually about 2.5 metres above present high water. In the base of the cliff at Ras Al-Himarah, the sands overly greenish clayey sands and clays of Tertiary age.

In the sea cliff at the south end of the outcrop the quartzose sandstone ridge is characterized by an abundance of fossil plant-roots. These occur as long straight calcareous root-casts which often project out from the exposures in consequence of erosion of the less-cemented host sediment: plate 1.3 a and b. Similar root-like structures found in Quaternary sediments of California were termed 'pedotubules' or 'rhizoconcretion' by Johnson (1967). Ward (1975) refered to similar root-cast structures in Quaternary eolianites of Yucatan, Mexico, as 'rhizocretions'. The Arabic word 'dikaka' which means scrub-covered dune sand was chosen by Glennie and Evamy (1968), to describe similar plant-root structures found in Late Tertiary and Quaternary aeolian dunes in Abu Dhabi and Qatar. The term 'rhizocretion' would appear to imply that the structures are casts after rhizomes i.e. underground stems. In Kuwait it has not been possible to decide whether the structures are casts of rhizomes or casts of the roots. Thus the word rhizocretion is used in this thesis as a general term and not as a specific one.

In the cliff exposure at Ras Al-Himarah, the upper half of the exposed quartzose sandstone is riddled with extensive root structures (rhizocretions) to the extent that much of the original bedding has been obliterated: plate 1.3a. Few of these structures penetrate deep into the lower cross-bedded part of the sandstone. Some of these rhizocretions occur as calcareous sheaths around hollow root moulds, while others are solid casts with no internal hollows.

The processes which form the casts are not fully understood, and it is likely that the casts are the result of interaction of many factors. One process is the preferential cementation of sand grains at the interface between the root and the surrounding sediment. Another is decay of the organic matter with subsequent centripetal filling of the space with fine-grained carbonate and other materials.

Thin section studies have shown that the casts are cemented by cryptocrystalline calcite: plate 1.4. Quartz grains are incorporated in the casts and they are in part replaced by the cryptocrystalline calcite. In some instances gypsum crystals are found lining the hollows of the moulds. The quartz grains and gypsum crystals are usually concentrically arranged. The cement in the host rock is only developed near grain-to-grain boundaries.

Thin sections of the well cemented oolitic quartzose sandstone from the top of the inner barrier near Khor Al-Mufatteh, show that the carbonate of many of the ooids and most of the skeletal fragments has been leached out to leave moulds: plate 1.5 a and b. The shapes of the former aragonitic grains are retained by micritic envelopes.

The mouldic porosity in the upper part of the ridge reflects a high degree of leaching by percolating rainwater. In the course of dissolving the aragonite of the grains, the percolating water became saturated or supersaturated with respect to calcium and carbonate ions. This led to precipitation of low-magnesian calcite as cement in the intergranular pore spaces and as drusy linings to skeletal and other moulds. In some instances complete calcite casts after former aragonite shells can be seen. Most thin sections show that the intergranular pore spaces in the upper part of the ridge are almost completely filled by calcite cement.

Plate 1.2.

Herringbone-type of cross-stratification of inner quartzose sandstone barrier ridge.

Plate 1.3a.

Upper part of inner quartzose sandstone ridge. N.B. plant root structures (rhizocretions): Ras Al-Himarah: see also Plate 1.3b.

Plate 1.3b. Close up of Plate 1.3a showing root-casts projecting out from the exposure in consequence of erosion of the less cemented host sediment.

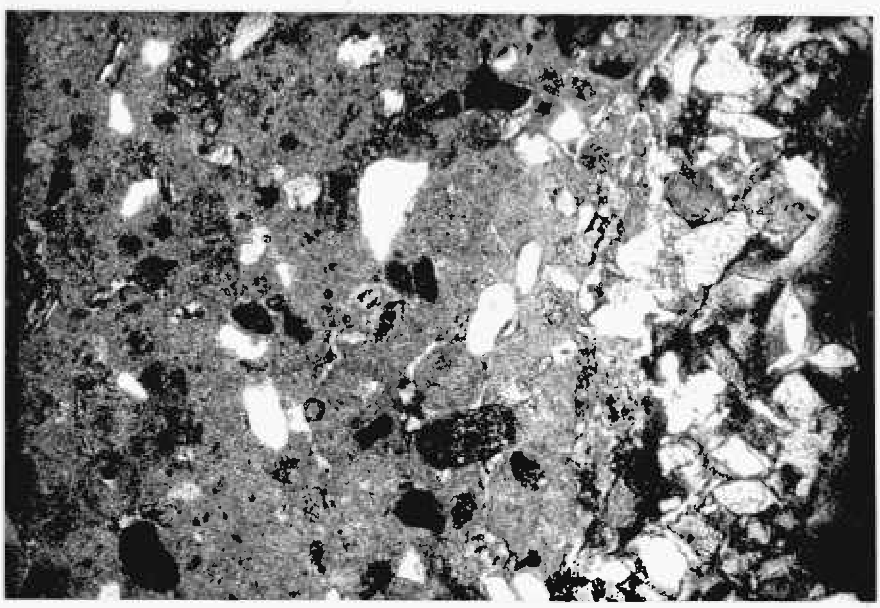


Plate 1.4.

Photomicrograph showing zone of cryptocrystalline calcite cement around the mould of a former plant 'root'. The mould, on the right side of the photograph is lined with gypsum crystals. Crossed-polars, (x 30).

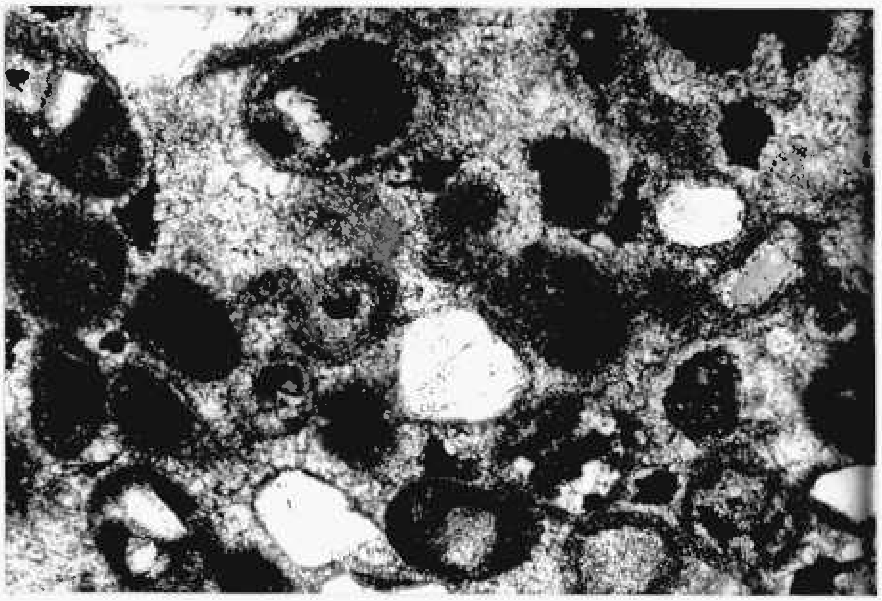


Plate 1.5a.

Photomicrograph showing oomouldic porosity. Note that the intergranular pore spaces are almost completely filled by granular calcite cement. Upper part of the inner sandstone barrier ridge. Crossed polars, (x 80).

Plate 1.5b.

Photomicrograph from the same sample 1.5a above showing a skeletal mould. Outlines of the former skeletal grains are marked by a micritic envelope and the mould is lined with drusy calcite. Crossed polars, (x 80).

(B) The outer oolitic barrier complex

The outer oolitic barrier complex comprises beach/dune ridges, barrier spits and bars. The ridges were formed during prograding of the shorelines as beach ridges or barriers spits which were later capped by aeolian coastal dunes. Similar oolitic coastal ridges extend far to the south along the Saudi Arabian coast. Towards the north of the Al-Khiran area the proportion of oolites in the sediments decreases gradually with a proportional increase in quartz sand grains. However few oolitic ridges are found along the Bay of Kuwait near Doha.

In the Al-Khiran area, the oolitic barrier complex is cut by two tidal channels which divide it into three segments: fig. 1.2. The widest part of the oolitic barrier complex and the maximum accumulation of oolites is found in the central segment and around the tidal channels. The width of the complex and the number of ridges decreases gradually to the south. The oolitic ridges show some variations in the degree of cementation and the megascopic and microscopic detail of the oolites. The most strongly cemented material is found in the innermost ridges, and those nearest to the present coast are only very lightly cemented. It is possible to divide the outer oolitic barrier complex into three main units on the basis of extent of diagenetic alteration and cementation. These are:

(iii) Present day coastal oolitic sediments.

(ii) Younger oolitic limestone ridges.

(i) Older oolitic limestone ridges.

(i) The older oolitic limestone ridges

The older oolitic limestone ridges are mostly composed of 'chalky white' oolites. These give the ridges a dazzling white appearance which distinguishes them in the field from other younger oolitic ridges: plate 1.6. The elevation of these ridges ranges from 4 - 10 metres above present sea level. They are bordered to the landward by the inner quartzose sandstone barrier and intervening sabkhas, while on the seaward side they give way to the younger oolitic ridges. They are usually cross-stratified and are locally capped with a brown surface crust. This type of ridge makes the most extensive accumulation of oolites in the oolitic complex.

Seen under a stereoscopic microscope the surfaces of the oolites are dull, and they lack the lustre of those which comprise the younger ridges. The cortices of the oolites are very soft, and they can be easily disaggregated with point of a pin. The average diameter of the oolites is about 0.25 - 0.3 mm, and they are slightly larger than the oolites which are found in the upper part of the inner quartzose barrier ridge. The nuclei are mostly structureless carbonate pelletoidal grains or quartz sand grains. Shell fragments and grains of feldspar, amphibole and other detrital minerals are occasionally present as nuclei. The thickness of the cortices of the oolites are generally in the order of 0.1 mm. As well as normal oolites there are others such as superficial oolites, multiple oolites and a few skeletal fragments.

The cement is low magnesium calcite, but unlike that of the upper part of the inner quartzose sandstone ridge, the cement does not entirely fill the intergranular pore spaces, so that considerable porosity remains.

The aragonite of most of the oolites in the upper part of the ridge, i.e. in the vadose zone, has been partly leached out and replaced by granular calcite: plate 1.7. The patches of calcite which replace the aragonite usually cut across the original concentric structure of the oolites, but relict concentric features are sometimes locally preserved. At the base of the ridge, in the phreatic zone, the oolites have retained their primary aragonitic composition and crystal fabrics unaltered: plate 1.8.

(ii) The younger oolitic limestone ridges

The younger oolitic limestone ridges are found very close to the modern shoreline. They range in elevation from 2 metres to 8 metres above sea level. Several ridges are present and they run parallel to one another, and to the present shoreline. The ridges are composed mainly of oolites with an average size of 0.33 mm. The only difference between the old and younger oolitic ridges is that the latter have undergone less diagenetic alteration and are only weakly cemented. The surfaces of the oolites are characteristically cream coloured and lustrous. Their cortices are more resistant to disaggregation than those of the older ridges. The calcite of the cement is present only at grain contacts and is analogous to the meniscus type of cement described by Dunham (1971). The bulk of the intergranular pore space remains unplugged by cement. Most of the oolites have retained their original aragonitic mineralogy and their internal structural detail unmodified.

In many places, especially near the inlets of Khor Al-Mufatteh and Khor Al-Amah, the younger oolitic limestone ridges are capped by a cover of recent wind-drifted loose oolite sand, which ranges in thickness from several centimetres to few metres.

The geometry of the younger oolitic ridges varies from place to place and the differences appear to be related to the orientation of the shoreline with respect to the prevailing Shamal wind. Along the shores of the bay areas, the ridges are arcuate parallel to the shoreline. Most of the foresets are long and are gently dipping, but a few are relatively steep: plate 1.9. Measurements show that the foreset direction is mostly SSE. The ridges are deflated to ground level near the headlands: e.g. near Ras Az-Zor.

In areas where the shoreline extends in an almost east-west direction, i.e. facing the prevailing northerly winds, the ridges are presently being eroded by waves, as to west of Mina Saud. Low cliffs are formed which expose underlying beach ridges which have been capped by the dunes. Exposures of the beach ridges show about 2 metres of thinly bedded alternating layers of coarse and medium carbonate sands: plate 1.10. The sand which comprises the coarse-grained laminae is mainly skeletal. The dunes which cap the beach ridge along this part of the coast are small and hummocky. They are characterised by short and low-angle foresets. These dunes are usually built around obstructions such as dune plants: plate 1.11.

Plate 1.6.

The older "chalky white" oolitic limestone ridge showing low angle dune cross-stratification.

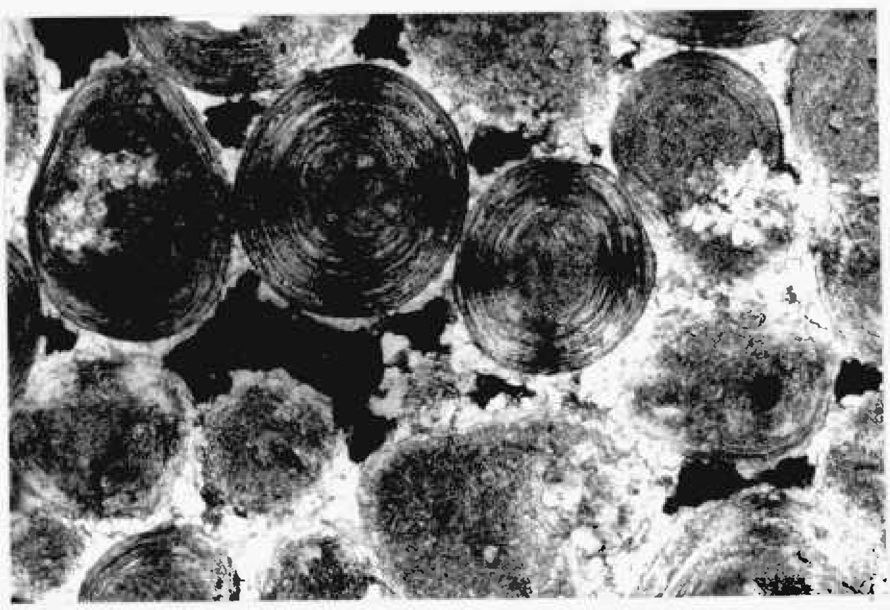


Plate 1.7.

Granular calcite cement partially filling interoolite pore spaces in the upper part of the older oolitic ridge. N.B. the original structure of some of the ooids have been partially obliterated and replaced by granular calcite. Crossed-polars, (x 80).

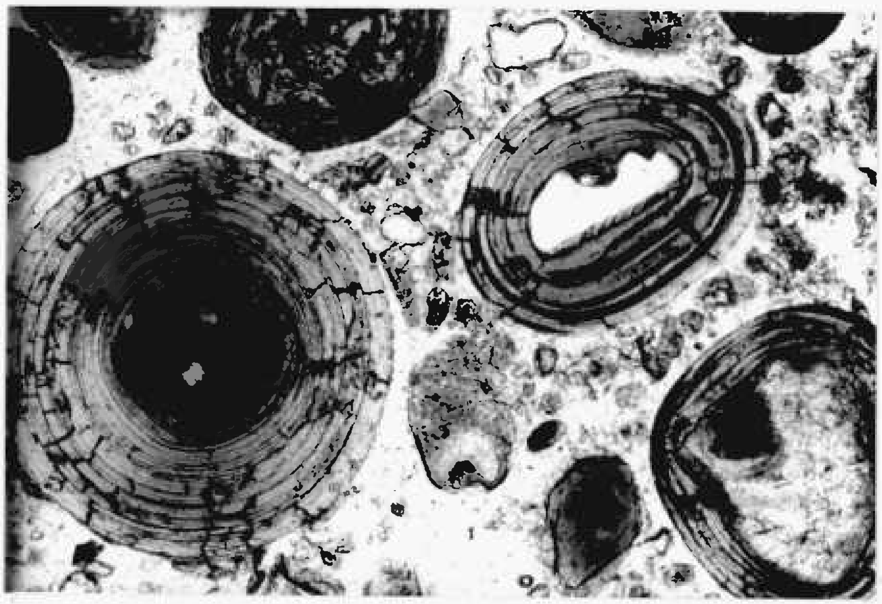


Plate 1.8.

Photomicrograph of sample from the base of the older oolitic limestone ridge. Note that the original structure of the ooids and aragonite mineralogy is completely preserved. The sample comes from the phreatic zone and contrasts with the ooids in the vadose zone shown in Plate 1.7, (x 83).

Plate 1.9.

The younger oolitic limestone ridge, showing relatively steeply inclined foreset laminae, capped by long continuous foresets which are gently inclined.

Plate 1.10.

Exposed beach ridge sediment of the younger oolitic limestone barrier. Low cliffs west of Mina Saud. Note the thinly bedded alternations of layers of coarse and medium carbonate sands.

Plate 1.11.

Small hummocky dunes of the younger oolitic limestone ridge.

iii Present day coastal oolitic sediments

Most of the beaches in Al-Khiran are wide and covered with carbonate sands. Sand bars, submarine barrier spits and megaripples are widespread over the intertidal flats and shallow subtidal areas along the southern segment of the beach-dune, barrier complex: plate 1.12. It is only around headlands, such as in Ras Al-Himarah, and in places where the coast trends at right angles to the prevailing wind, such as west of Ras Az-Zor, that the beach is characterised by a narrow intertidal zone. In these places the sea has eroded the coastal ridges to form low sea cliffs. Apart from these limited areas, the coast is mainly a prograding one.

Beach sediments are mainly composed of oolites with some skeletal fragments and few quartz grains. The oolites are cream coloured and lustrous, and x-ray diffraction analyses have shown that their cortices are composed entirely of aragonite. Some of the oolites may have been derived from the oolitic dunes which cap the coastal ridges by offshore winds.

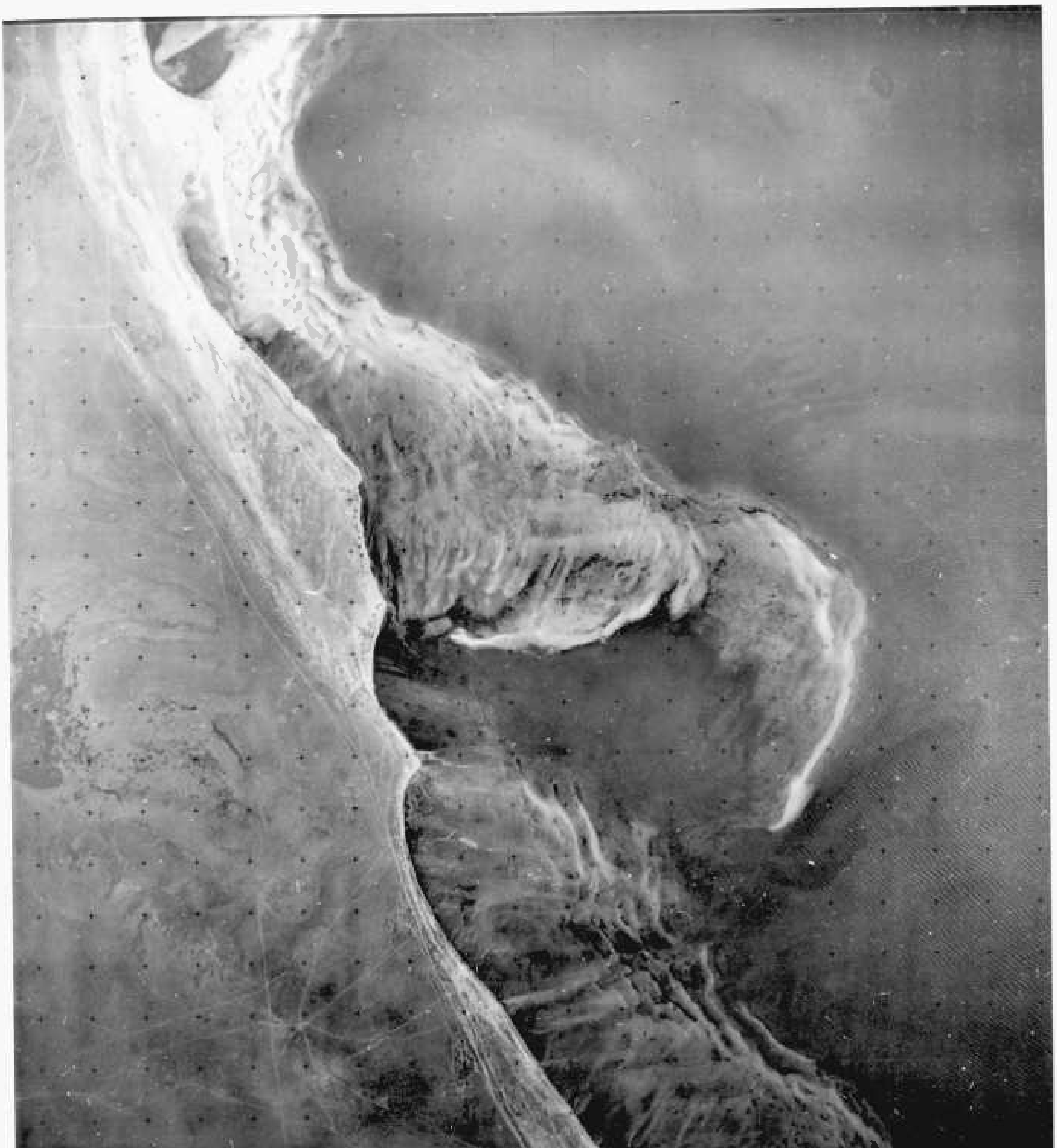
Quartz grains become abundant towards the south and were probably derived by erosion of the sandstone cliff of Ras Al-Himarah.

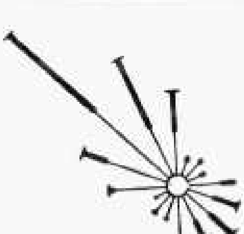
In some places in the intertidal zone the oolitic and skeletal sands have been slightly cemented by aragonite to form beachrocks. These beachrocks are often partly obscured by loose sands. In most places the beachrocks have been 'attacked' by boring organisms of various types, from molluscs to minute boring algae.

Plate 1.12.

Aerial photograph of the southern part of the Al-Khiran area, showing: sand bars, submarine barrier spits and megaripples.

WIND ROSE





WIND ROSE

In most of the bay areas all geomorphic units of the beach are well developed. There is a wide intertidal platform with a relatively steep beach face and a near horizontal berm in the supratidal zone. The beach ridges or barrier spits which involve the berms are constructed of the coarsest grained sediments. They are formed mainly by storm waves which carry large quantities of skeletal debris and other coarse grains up into the supratidal zone, thus causing the beach ridges to prograde. The beach ridges or berms are exposed to the wind which causes a measure of deflation. Oölitic sands from the beaches and from the intertidal platform dry out during low tide and are blown inland by the onshore winds to form coastal dunes which are held in place by halophytic plants. The growth of barrier spits results from littoral drift, the direction of which is mainly from north to south.

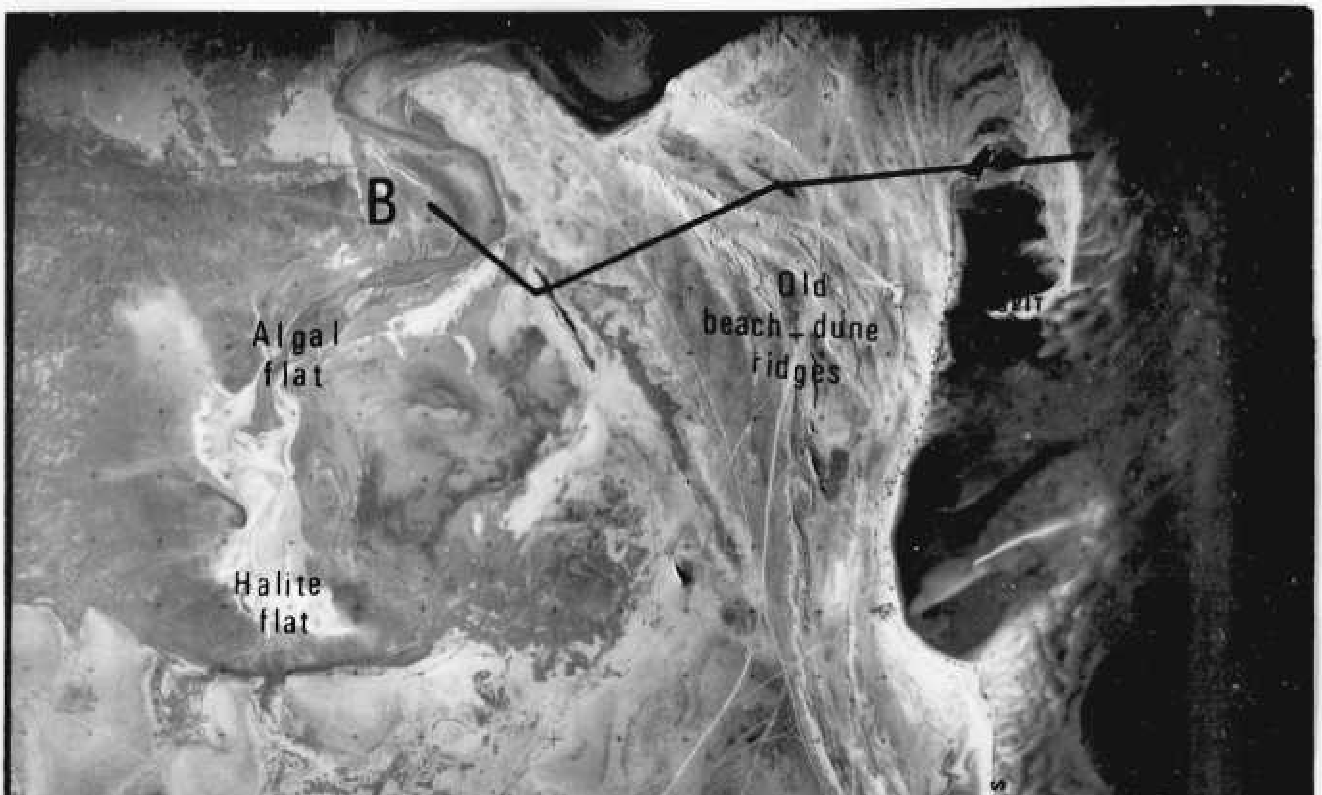
(2) Lagoons

The development of barrier spits restricts the circulation of water on their lee sides, thus creating protected areas or lagoons. The lagoons are usually elongate NW - SE i.e. parallel to the length of spits which are in turn parallel to the prevailing Shamal wind: plate 1.13.

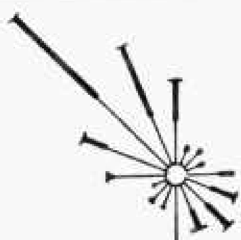
Circulation in the lagoons becomes progressively more restricted as growth of spits proceeds and as accretion takes place near their inlets. This leads to increase of salinity and results in changes in the biota and the type of sediment. The fauna of the lagoon becomes restricted mainly to cerithid gastropods and imperforate foraminifera, and the upper intertidal flats around the lagoons become colonized by algal mats. Due to cut off of the external supply of sediment

Plate 1.13.

Aerial photograph south of Khor Al-Mufatteh showing barrier spits, lagoons and old beach/dune barrier ridges. The section along the line indicated in the north of the photograph is drawn in Figure 1.3.


B
Algal flat
Halite flat
Old beach-dune ridges
KHOR
QUARTZOSE S.S RIDGES
1 km

WIND ROSE



WIND ROSE

Figure1.3 The main physiographic and sedimentary features as seen along profile A_B

the sediment of the lagoons become mainly aragonite muds and pelleted muds with skeletal debris from the cerithid gastropods and the foraminifera.

The present-day sheltered coastal lagoons are very shallow, and greater part of their floors are exposed during low tide. They silt up progressively, mainly with carbonate mud, carbonate mud pellets and fine sand sized carbonate grains; all of which are generated within the lagoon itself. They ultimately become completely cut off from the sea as their inlets close due to the development of spits. The ultimate result of coastal barrier accretion and silting up of lagoons is the production of series of small coastal sabkhas located between beach/dune ridges. The present coastal sabkhas evidently formed in this way, and the conclusion is supported by the fact that their sediments comprise carbonate muds rich in imperforate foraminifera.

(3) Tidal channels and tidal flat deposits

Tidal channels

Tidal channels and their associated tidal flats form a large triangular-shaped area with its apex directed towards the sea. There are two main tidal channels, locally known as Khor Al-Ama and Khor Al-Mufatteh. They both extend several kilometres inland and they are in lateral contact across supratidal flats or sabkhas which surround former small barrier islands. The strongest tidal currents develop between the tips of the oolitic barrier ridges, in and near the inlets to the Khors. It is there that the narrowest and deepest parts of the Khors occur. The weakest tidal currents occur in the upper reaches of the channels, far from the inlets, where the Khors shallow abruptly and pass over the upper intertidal zone. Wave action in the tidal channels is relatively low due to the protective barriers which lie offshore.

The exits of both Khor Al-Mufatteh and Khor Al-Ama are marked by tidal deltas: plate 1.14. The deltas are made up of radially arranged bars of oolite sand with channels in between. At their eastern seaward parts the channels trend E-W, almost at right angles to the coast line. Long bars of channel sand can be seen there, especially in the eastern part of Khor Al-Mufatteh before it bifurcates inland. The landward parts of the khors, i.e. those parts which lie behind the oldest oolitic barrier ridges and the inner quartzose sandstone barrier, are much more meandering and dendritic than the seaward parts. A tidal point bar is commonly formed on the inner bank of each curve. In some cases gravel and pebble size clasts of semilithified mud accumulate on the channel floor after erosion of the outer bank.

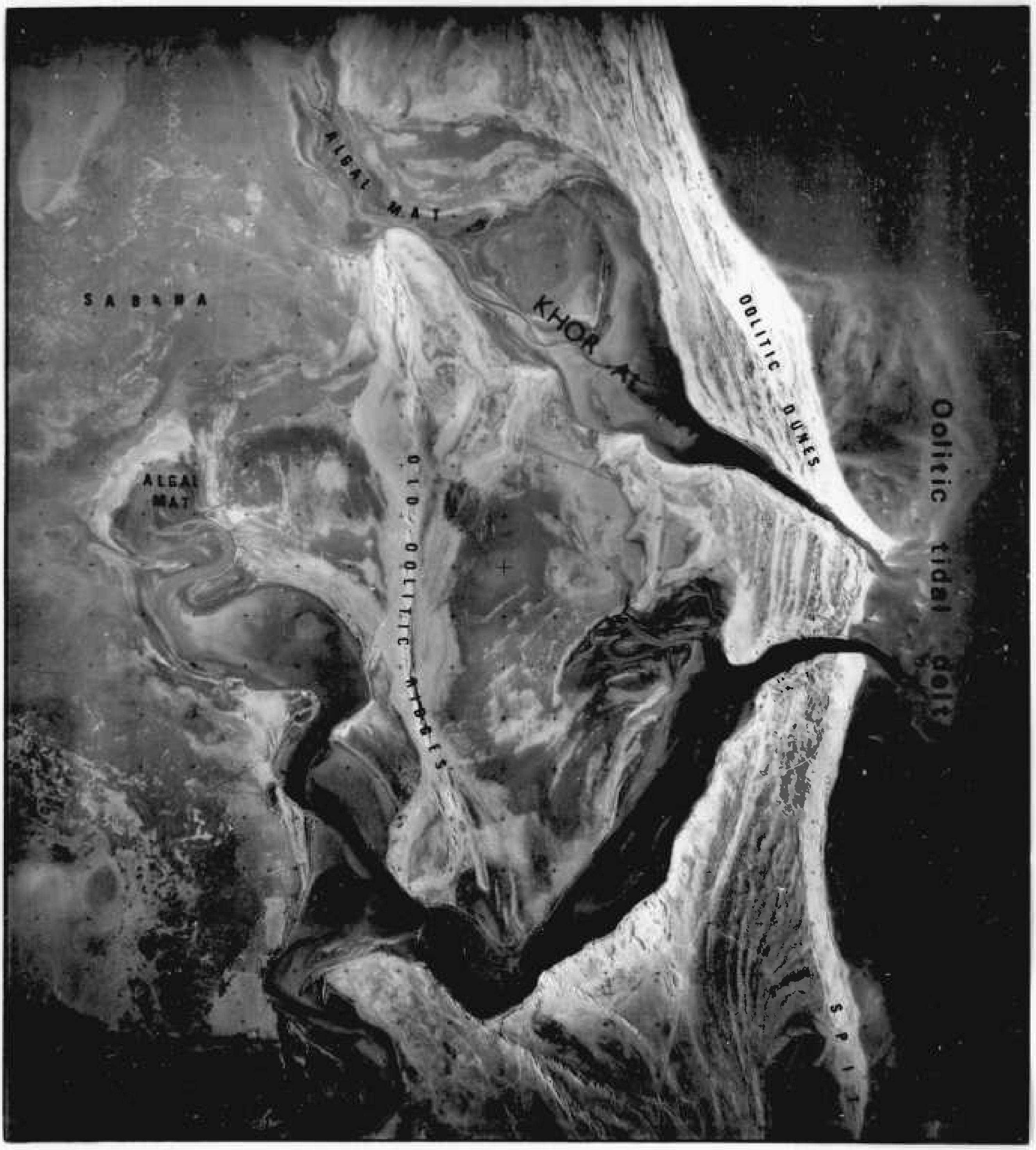
The sediments on the channel floors at the eastward side of the khors are mainly oolitic sands. The long bars or banks are also made of oolite sands with some skeletal debris, while the sediments in the landward parts of the channels are mostly carbonate muds.

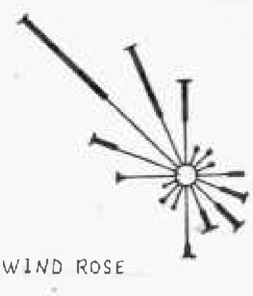
Cementation along the banks of the khors

Beachrocks along the banks of khors where the channels have cut through the barrier ridges are mainly cemented by aragonite. The morphology of the cement and degree of cement-

Plate 1.14.

Aerial photograph of the central part of the Al-Khiran area, showing tidal channels and tidal deltas.


ALGAL MAT
SABKHA
KHOR AL
OOLITIC DUNES
Oolitic tidal delta
ALGAL MAT
OLD OOLITIC RIDGES
SPIT



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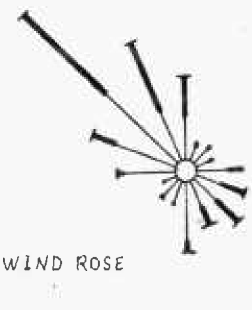

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ation varies from place to place. Thin sections of slightly cemented beachrocks near the mouths of tidal channels show that the cement comprises tiny needles of aragonite arrayed perpendicular to the surfaces of the grains. Individual crystals are acicular and average about 15 microns in length but vary considerably in size. They are usually in contact with one another only at their bases. In some cases this aragonitic fringe grows on a mciritic coating of aragonite or high Mg calcite which surrounds the carbonate grains.

In places where the channels have cut through the older barrier ridges, the beachrocks along the bank of the khors are very well cemented. The cement comprises prismatic crystals of aragonite which may reach up to 120 microns in length. The crystals are uniform in length; they are closely packed and are in contact with one other except at their tips: plate 1.15. They usually display square or acute terminations. The aragonitic cement almost completely fills the intergranular voids and also forms linings to the chambers of skeletal fragments. In some cases the aragonite cement displays a radial-fibrous fabric: plate 1.16.

Aragonite encrustations and fissure fillings

In many places along the banks of the khors, beachrocks in the lower zones are coated with a lustrous, light brown veneer of aragonite, while those in the upper zones, have dark grey to black highly irregular crusted surfaces. As seen in thin sections under the microscope these crusts consist of delicately laminar micritic aragonite.

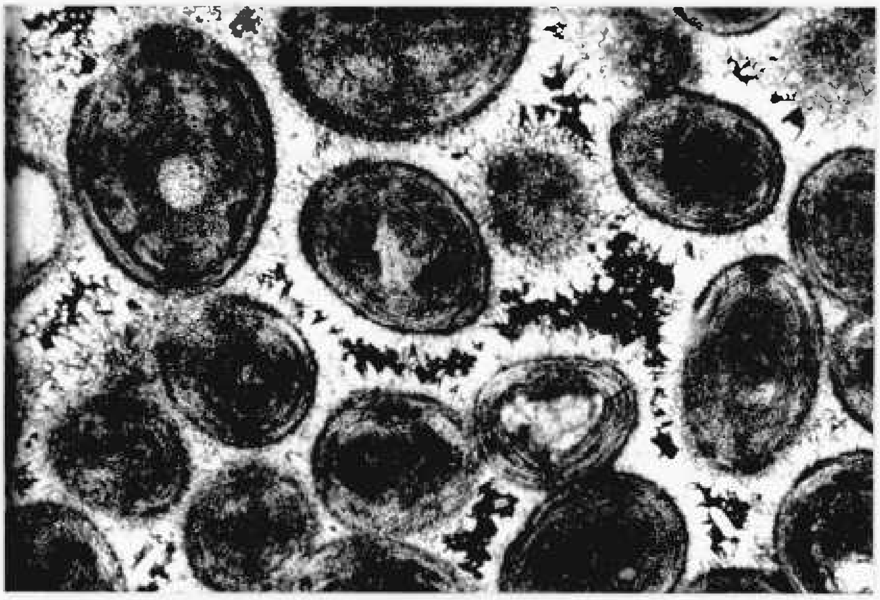


Plate 1.15.

Photomicrograph of beachrock, Khor Al-Mufatteh, showing aragonite cement with crystals arrayed normal to the surfaces of the ooids. Crossed polars, (x 80).

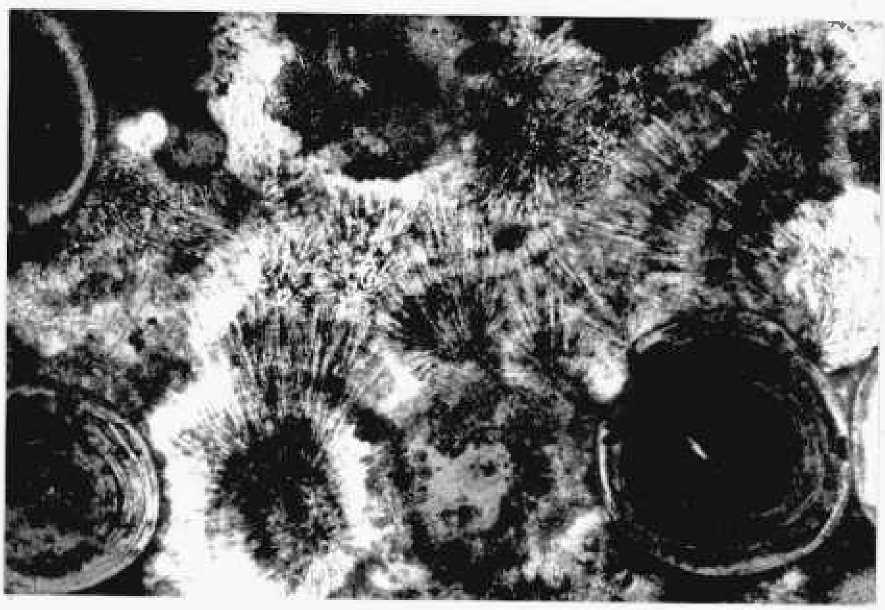


Plate 1.16.

Aragonite beachrock cement with radial fibrous fabric. Crossed polars, (x 80).

Laminar travertine - like aragonite crusts are also found lining the walls of vertical fissures and joints in the beach-rocks along the channel banks: plate 1.17. The fissures and joints offer easy access to tidal waters and are equally easily drained. It is thought therefore that the vertical crusts form by direct precipitation as the surface films of water dry out after the tide has fallen.

Stalactitic encrustations (dripstones)

The lower surfaces of beach rocks along the khors are characterized by the presence of columnar stalactitic structures which grow downward from overhangs. These columnar structures have an earthy appearance, they are grey in colour, and are generally about 5 mm in length. In a few instances they 'hang' downward for about 4 cm and are white and very hard. Some of the columns bifurcate downwards. Polished vertical sections through these dripstones, show that the laminae are concave - upwards: plate 1.18a. Seen in cross section the columns are crudely concentric: plate 1.18b. The columns have coalesced along their vertical lines of contact but otherwise they are separated by vertical pipes. The pipes are usually lined with crystals of fibrous aragonite. Gypsum may also be present and sometimes completely fills the hollows.

X-ray diffraction analyses indicate that the dripstone columns are composed entirely of aragonite. Thin section studies show that the aragonite is present as small accretionary or pelletoidal grains of problematic origin. The pelletoidal grains are ellipsoidal or cylindrical in shape and are arranged tangentially to the convex surfaces. They are not unlike the soft faecal pellets found in many places in the intertidal flats. The possibility that the lithified pellet-like grains which comprise the dripstones could have been produced by mud-feeding organisms appears to be remote. It is most likely that they were precipitated directly from droplets and films of tidal water or sea spray held on the undersides of the beachrocks. They are in a sense analogous to stalactites found hanging from the walls of caverns.

The morphologies of the dripstones as seen on polished surfaces closely resemble those of certain ancient stromatolites: e.g., figure 20 illustrated by Hofmann (1969) from the Proterozoic rocks of Northern Canada: plate 1.19. The important difference between them is, that in the stromatolites the laminae are convex upwards whereas in the dripstones they are convex downwards.

Tidal Flats

The tidal channels are flanked by tidal flats which are narrow at their seaward ends, but become wider inland towards the head of each Khor. The intertidal zone along the landward parts of the Khors can be divided into: lower, middle and upper flats on the basis of type and grain size of sediments and type of organisms which live there. All of these three subdivisions of the flats lie between mean low tide and mean high tide levels.

The sediments of the lower intertidal flats comprise carbonate sands, silts and sandy muds, and are characterised by the presence of burrowing crabs. The density of burrows

Plate 1.17.

Joints and vertical fissures in beachrock along the bank of Khor Al-Mufatteh. The fissures are filled with vertical laminar, travertine-like aragonite crusts.

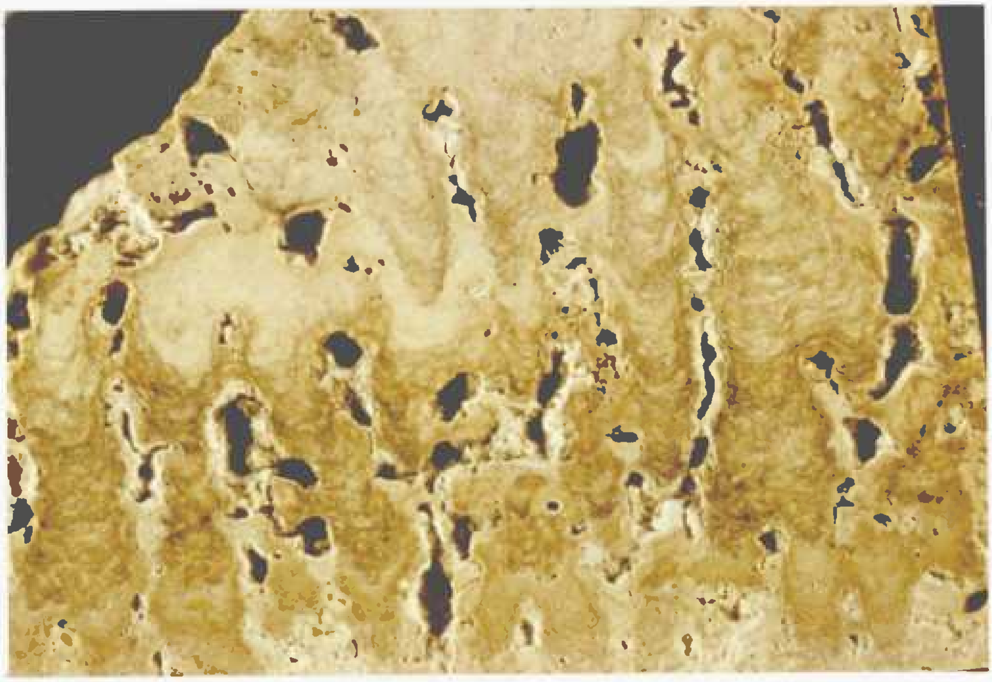


Plate 1.18a.

Dripstone: vertical section. Note the downward branching of the dripstone columns and the concave upward shape of the laminae. The irregular vertical voids between columns are lined with gypsum. Field approximately 4 cm.

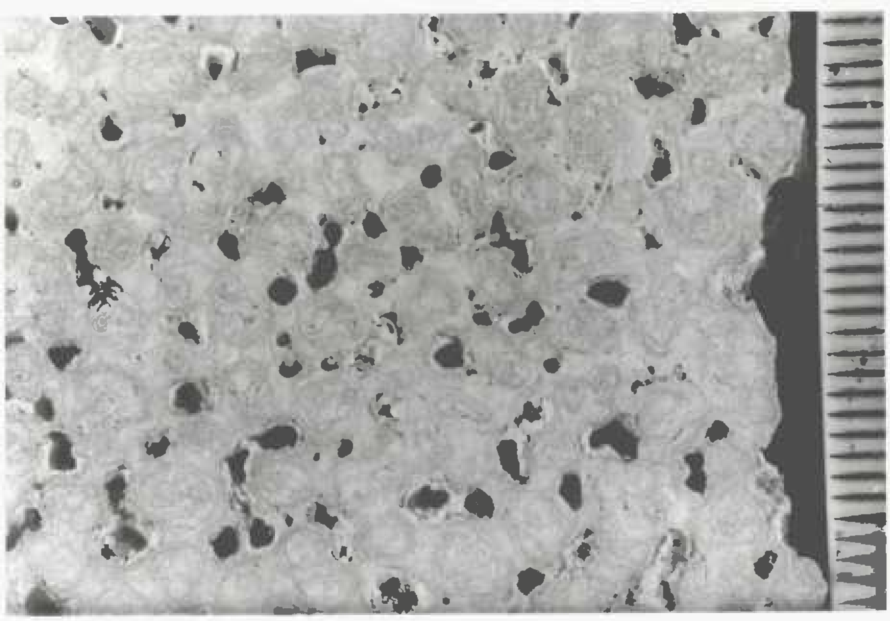


Plate 1.18b.

Dripstone: horizontal section. Note crude concentric structure of the columns. Field approximately 3.5 cm.

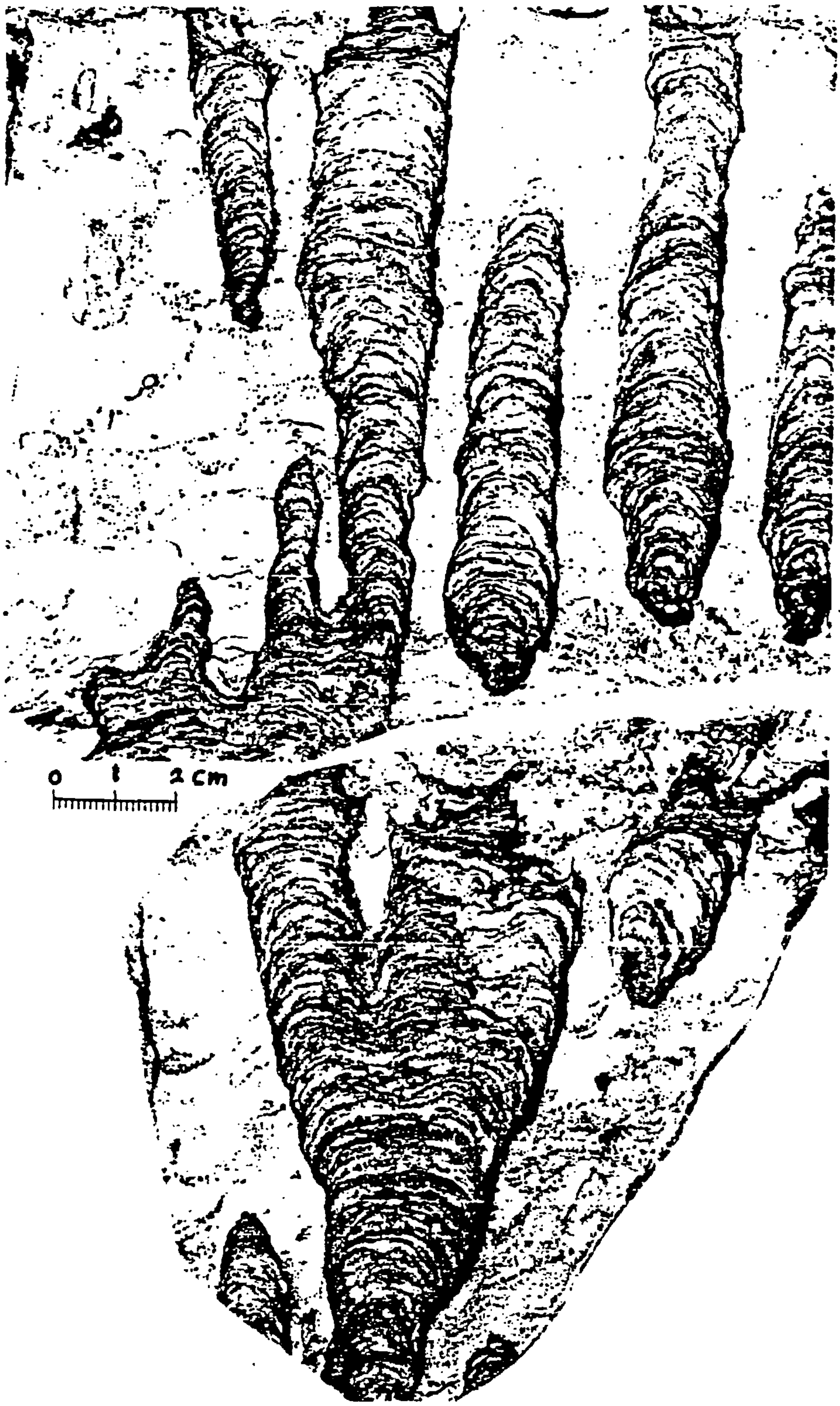


Plate 1.19.

Proterozoic stromatolites from the east coast of Hudson Bay, Canada. Note similarity of the branching nature of the stromatolitic columns with the branching of the dripstone columns shown in Plate 1.18.

Photograph by Hofmann (1969).

is in most places very considerable, and the burrowing activity has led to wholesale destruction of the original lamination of the sediment.

The middle intertidal flats are characterised by a complex of dendritic tidal channels, pools and ponds. Carbonate mud is the main sediment. These middle flats provide the most favourable environment for the development of algal mats. The upper intertidal flats are inundated for only short times during the highest spring tides, and they are perhaps the most muddy of all the areas under study. In places the muds are very deep and brine saturated. In consequence they are dangerous quagmires and camels are frequently lost in them: plate 1.20. At times the surface becomes salt-crusted, and polygonal pressure ridges due to growth of salt are common: plate 1.21. The salt crusts are ephemeral however and are removed when the area floods at high spring tide.

(4) Sabkhas

Beyond the intertidal flats there are extensive supratidal flats or sabkhas which stand only slightly above normal high spring tide level. Although these flats are flooded only when storms coincide with high tides, they are almost always under a marine influence by virtue of tidal ground waters. The sabkhas are more or less permanently saturated with brines which have salinities up to 560 parts per thousand. The surfaces of the sabkhas alongside tidal channels are mostly wet especially during early morning. In winter the ground-water table rises and floods slight depressions in the sabkha to form shallow saline pools, which leave thin veneers of halite crusts when they dry out. This halite is later removed by deflation. The sabkhas close to the inner margins of tidal channels are characterised by compressional ridges of salt and white halite flats: plate 1.21. This halite is ephemeral and is removed from time to time by marine flooding.

The sediments of the sabkhas consist of detrital and authigenic minerals. The detrital components are in part aeolian and in part carried in from the tidal channels during storm floodings. The aeolian materials include both locally derived coastal carbonate grains and grains derived from inland regions by the prevailing north-westerly (Shamal) wind. In consequence of the high evaporation rate the groundwater brines become concentrated by capillarity and evaporation, thus leading to the precipitation of the evaporite mineral gypsum. The gypsum crystals may occur singly (plate 1.22) or as mushes, and they are usually discoidal in overall shape.

The sabkhas of Al-Khiran are very similar to those along the coasts of Abu Dhabi and Qatar, but not so extensive (Evans et al, 1964, 1969; Kinsman, 1964, 1969; Illing et al, 1965; Shearman, 1963, 1966; Butler 1969 and Bush, 1973). However, the important difference is the absence of anhydrite from the Kuwait sabkhas.

1.6 Evolution of the Coastal Plain

The physiography and the distribution of sediment types in the coastal plain of the Al-Khiran area can be related to

Plate 1.20.

Young camel fatally trapped on muddy area around the inner margin of Khor Al-Mufatteh.

Plate 1.21.

Halite flat at the inner margin of Khor Al-Mufatteh, with bordering zone of polygonal compression ridges.

Plate 1.22.

Lenticular crystals of gypsum collected from the inner sabkhas.

two transgressive phases, which took place under different climatic conditions. During the Late Pleistocene, the first phase of marine transgression caused the development of barrier islands and lagoons which now form the inner barrier quartzose ridge and the inner sabkha. This transgressive phase may have been contemporaneous with deposition of the fluviatile Dibidibba Formation (Saleh 1975). This is suggested by the similarity in their heavy mineral assemblages. The quartz sand was subsequently reworked during and following the Late Pleistocene sea-level rise. Towards the end of the pluvial stage the influx of clastics gradually decreased. The fall in sea level which followed was accompanied by a change from clastic to carbonate sedimentation. This can be inferred from the presence of small oolites and superficial oolites in the upper aeolian parts of the inner quartz ridge. At the same time climate appears to have become more arid.

The rise in sea level of the Flandrian transgression, which started approximately 18,000 years B.P., was continued by the Holocene transgression which began 7,000 years ago. These led to the sea more or less achieving its present stand about 4,000 years ago. (A dated stratigraphic sequence for the coast of Abu Dhabi has shown that a rise of sea level occurred from between 7,000 years B.P. to 4,000 years B.P., Evans et al (1969).). The transgression at Abu Dhabi terminated in the formation of a shelly beach ridge near the present sea level. During this period when a hot and arid climate prevailed, the oolitic outer barrier ridges of Al-Khiran were formed.

The outer oolitic barrier ridges developed mainly by growth of spits which enclosed shallow lagoons. The latter were subsequently silted up with carbonate mud and sand and ultimately became sabkhas: plate 1.13 and fig. 1.3.

Samples collected from the oolitic barrier ridges were sent by the Department of Geology of Kuwait University to Teledyne Isotopes for radiocarbon age determination. The ages obtained were: 4820 ± 100 years B.P. to 3290 ± 95 years B.P. for the older oolitic ridges, and 2120 ± 105 years B.P. to 980 ± 80 years B.P. for the younger oolitic ridges. Bore-hole core samples and samples obtained from excavations in the oldest oolitic ridges, dug in the course of the search for construction materials, have shown the presence of shelly beach ridges approximately 1.5 m above the present sea level underlying the oolitic dunes. These and the presence of raised beaches along the cliffs west of Ras Al-Zor and Ras Al-Jlayah indicate that the sea level may have been slightly higher than that of the present day, about 1.5 metres, during the formation of the outer oolitic barrier ridges.

Tidal channels, i.e. the khors, appear to have influenced the development of the coastal plain of the Al-Khiran area. These tidal channels which trend roughly at right angles to the coastline may follow old drainage channels which formed during the Quaternary transgression. The khors are kept open and their positions are maintained by the scouring effects of tidal currents. They may have been guided by the Quaternary tectonic movements which affected the development of the inner barrier ridge (Saleh, 1975). However, there is no convincing evidence to suggest that the khors are fault guided.

It was suggested by Kinsman (1964) and others (Purser 1973) that tidal deltas are a favourable environment for ooid formation. The great accumulation of oolites in the areas of the tidal entrances to the khors seems to support this hypothesis. Elsewhere along the coast, where tidal channels are not present, oolites are less abundant. The production of oolites on the tidal deltas seems to be related to the hypersaline condition and the somewhat higher temperature of the waters of the tidal channels which drain the extensive protected tidal flats behind the barrier complex. Salinity measurements carried out during December 1974 (Saleh 1975) showed a gradual increase in salinity of the tidal water from 55 parts per thousand near the mouth of Khor Al-Mufatteh to 70 parts per thousand near the inner margin of the channel where algal mats are well developed. Groundwater salinities of the adjacent supratidal flats range from 170 parts per thousand to 560 parts per thousand. It is where these warm hypersaline waters flow out and meet the continuously wave agitated sea water over the shoals that the oolites appear to form.

Because of the production of large quantities of oolite sand on the tidal deltas and the direction of wave approach, oolites are continuously being swept onto the adjacent beaches. Some of the oolites are blown inland to form dunes, but the majority are affected by longshore currents which result in formation of megaripples, sand bars, submarine spits and barrier spits. Thus the barrier complex is being broadened by the development of tidal deltas at the mouths of the tidal channels which in turn provide sediment to the advancing coast. The accretion of the barrier complex is largely through the development of barrier spits in the direction of littoral drift.

The resulting beach ridges are covered later by blown sand from the intertidal platform during low tides, which are then stabilized by dune plants. The sheltered intertidal flats behind the barrier spits and along the inner margins of the khors , become the sites of development of algal mats. In this way sedimentation and coastal accretion has created, and still is creating protected environments favourable for the development of algal mats. The late Tertiary and Quaternary history of the Al-Khiran area is summarized in figure 1.4 and plate 1.23.

Plate 1.23.

Vertical sequence seen in the sea cliff at Ras Al-Himarah.

A. Chalky white oolitic limestone of the older oolitic ridge.

B. Brown wind-blown silty-sand.

C. Base of the inner quartzose barrier with herringbone cross-stratification.

D. Tertiary clayey sands and sandstones.


A
B
C
C
D
D
A
B

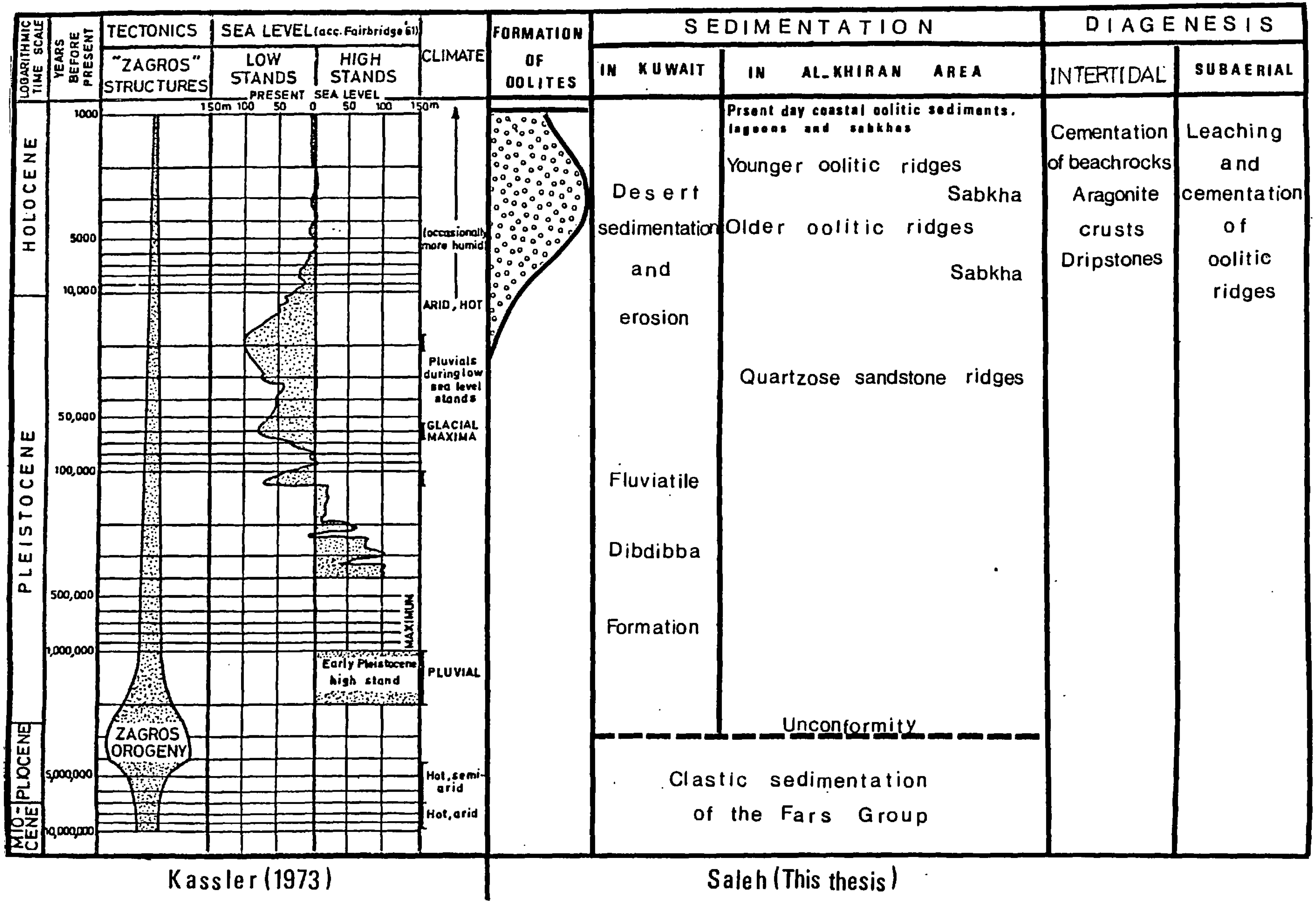



Figure 1.4.

Quaternary sedimentation in Kuwait with particular reference to Al-Khiran area.

CHAPTER 2.

Chapter 2

Algal mats and factors which influence their distribution and morphology

2.1 Algal mats: Introduction

Algal mats comprise a meshwork of intertwined filamentous and coccoid blue-green algae, embedded in mucilage, which form rubbery sheet-like deposits which can, and often do, trap and bind sediment particles. They are often laminated, with sediment rich layers alternating with layers rich in organic matter. Where they occur lithified in the fossil record, they are called stromatolites. Present day algal mats are mostly uncemented, but there are a few instances where they have undergone contemporaneous lithification. These latter can be termed Recent stromatolites. Although the fossilized algal mats, i.e. the ancient stromatolites, were clearly organic in origin, they seldom preserve remains of the organisms responsible for their formation. Thus in a sense stromatolites are neither organisms nor parts of organisms as it is only the trapped sediment which is characteristically preserved.

The algal mats in the study area are entirely intertidal in their distribution. They do not occur on all tidal flats, but are only present on those flats which are protected. They are extensively developed in the Al-Khiran area, but they are nearly completely absent from other places along the Kuwaitian coast and along most of the Saudi Arabian coast to the south. This is due to the presence of a sheltered environment behind the barrier complex in the study area.

The development of algal mats in the intertidal zones of Al-Khiran does not mean that ancient stromatolites or even other Recent algal mats elsewhere in the world, are necessarily restricted to intertidal settings. In some places, algal mats spread up into the supratidal zones, e.g. in the humid Bahamas - Florida region, and extend down into the subtidal zones in hypersaline environments, e.g. Hamelin Pool at Shark Bay, Western Australia.

Ancient stromatolites, particularly, during the Proterozoic, evidently developed in a wide range of environments. Some of which may have been fully subaquatic and normal marine.

2.2 Factors which influence the distribution and morphology of algal mats

By virtue of the fact that the Kuwait region is desert the upper limit of colonization of the coastal area by marine blue-green algae is clearly set by desiccation. Within the algal belt the distribution of algal mats, their morphologies and their internal structures depend on the interplay of numerous biological and environmental factors. The most important of these are: the presence or absence of grazing and burrowing organisms; the amount of wetting vis-a-vis desiccation; the strength of tidal scour, salinity, and the physical and chemical nature of the substrate.

(1) Role of grazing and burrowing animals

Recent algal mats around Al-Khiran are developed only on those intertidal flats which are most sheltered with respect to wave attack and tidal scour, such as the flats around the coastal lagoons which occur behind the southern barrier ridge and along the inner margins of the tidal channels: fig. 2.1. Even in these places the mats are limited to the uppermost parts of the intertidal zone. The reason for such a narrow range is that in the lower parts of the intertidal zone, invertebrate grazing organisms feed on and consume the algal mats as fast as they grow; while at the same time burrowing organisms are continuously disturbing the substrate so that the algae can never obtain a firm 'footing'.

The antipathetic relationship between the distribution of algal mats and grazing and burrowing organisms is well displayed at the following localities:-

(i) Lagoon A

There is a small tidal lagoon, here called lagoon A, behind a barrier spit at the north end of Khor An-Nhaim: fig. 2.1. The sides of the lagoon shelve very gently so that, although the lagoon is flooded at each high tide, a large part of the floor is uncovered during low tides. Algal mats occur around the lagoon but they are confined to the uppermost parts of the intertidal zone along the northern shore of the lagoon.

The lower limit of the algal mats is sharply defined at about mid-tide level. Below this level there are hosts of cerithid gastropods: plate 2.1. The latter cannot tolerate even mild desiccation, and if they stray into the upper part of the intertidal zone they die in consequence of exposure at low tide. The lower limit of the algal mats coincides with

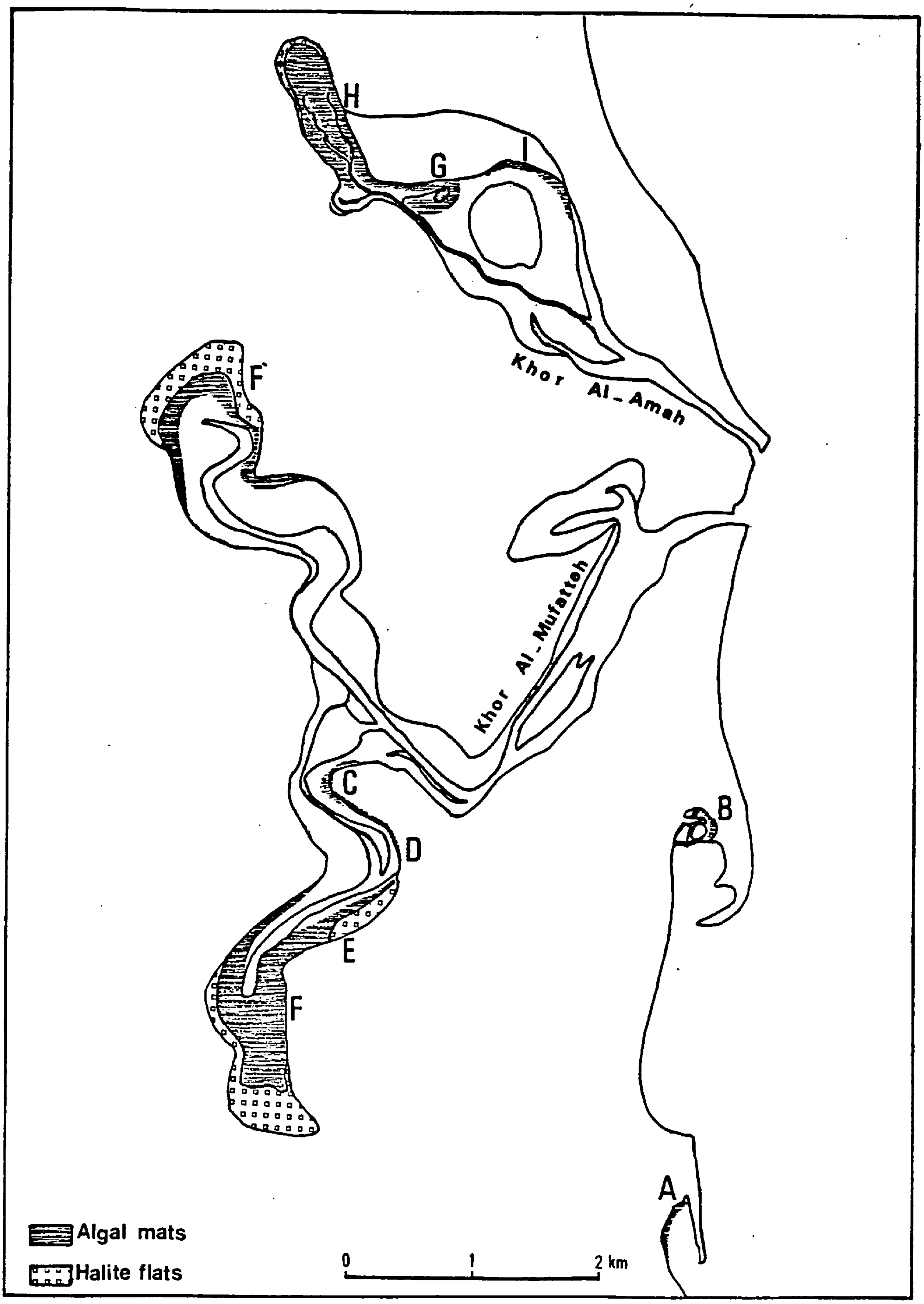


Figure 2.1.

Map prepared from air photographs showing the distribution of algal flats in the Al-Khiran area.

the upper limit of the distribution of the cerithid gastropods. Thus the inevitable conclusion is that the algal mats do not extend down below mid-tide level because there they are consumed by the gastropods as fast as they grow.

That the gastropdos do feed on the algae and thus prevent formation of algal mats is demonstrated by the following two observations:-

(a) In some places desiccation causes rupture of, or cracks in the algal mat, particularly on crests of blisters. Small hollows are thus produced where water remains after the tide runs out. Each of these tiny pool provides a mini-environment which becomes colonized by cerithids. Continuous grazing of the edges of the algal mats by the gastropods gradually increases the size of the hollows until ultimately relatively large mat-free patches are formed: plate 2.2.

(b) Where cars have crossed the algal flats, their tracks have made long linear depressions in the mats, some of these fill with water which remains as pools after the tide has ebbed. The water-filled ruts offer suitable living conditions for cerithid gastropods. In plate 2.3, it can be seen that gastropods have followed the car tracks along which they have completely eaten out the former algal mats. In places the gastropods have extended their activities laterally and have grazed out the mats for up to 20 cms on either side of the ruts.

These various lines of evidence leave no doubt that in many places it is the cerithid gastropods which are responsible for the absence of algal mat from the middle and lower parts of the intertidal zone.

Plate 2.1.

Close up view of the lower margin of the algal mat around lagoon A. The photograph shows the trails of cerithid gastropods feeding on the algal mat. The small step in the upper part of the photograph is the result of grazing activities of the gastropods.

Plate 2.2.

Ruptured blisters in algal mat caused by desiccation. These areas become the homes of cerithid gastropods, which by their continuous grazing eat away large patches of the surrounding mats.

Plate 2.3.

Cerithid gastropods living in shallow ruts made by the wheels of cars across an algal flat. The gastropods have completely grazed out the mats along the car tracks and they have spread laterally and are now grazing out the mats on either side.

Plate 2.4.

Cerithid gastropods living together with burrowing crabs in the middle of the intertidal zone of lagoon A. Note various sizes of feeding pellets produced by the different species of crabs.

Garret (1970) found a similar situation in parts of the Bahamas. There too, the algal mats and gastropods are mutually exclusive in their distribution: i.e. the cerithid gastropods live in the intertidal zone, whereas algal mats are mainly confined to the supratidal areas. By field experiments Garret was able to prove that cerithid gastropods prevented the build up of mats in the low intertidal areas by continuous grazing.

There is another factor which affects the distribution of algal mats in Lagoon A at Kuwait. Near the lower limit of the algal mats the surface of the sediment is covered with feeding pellets of various shapes and sizes (plate 2.4) produced by species of crabs which live in the same zone as the cerithid gastropods. The feeding activities of these crabs are also partly responsible for preventing the formation of algal mat, because they continuously disturb the sediment surface.

(ii) Lagoon B

Approximately 3 kms south of the mouth of Khor Al-Mufatteh there is a small subcircular pond close to a man-made fishing pool. This is marked as locality B on map fig. 2.1. The pond received tidal water via a narrow channel which connects with a larger lagoon to the south. Both the lagoon and the small pond differ from Lagoon A, which was described earlier, in that they are not drained completely during low tide.

Algal mats are only present in the upper intertidal zones of both the pond and the connecting lagoon.

The small pond presents an excellent example of ecologic zonation, and restriction of algal mats in consequence of the grazing and burrowing activities of animals. The pond is surrounded by three well-defined biologically distinct zones: fig. 2.2. These are: (a) a lower cerithid gastropod zone, (b) a middle crab zone, and (c) an upper algal mat zone.

The gradient of the intertidal zone around the pond is slightly steeper than that of Lagoon A. This affects the distribution of gastropods and crabs which are more sharply separated from one another than they are around lagoon A which is gently shelving.

(a) The cerithid gastropod zone

Cerithid gastropods occupy a narrow zone in the lowermost intertidal position: plate 2.5a. Because of the narrowness of the zone the gastropods are able to migrate back and forth with tidal rise and fall. Plate 2.5c shows the trails which they make as they hasten back towards the water as the tide ebbs in order to escape desiccation.

The gastropods are not only active as grazers, but they also disturb the surface of the sediment somewhat as they move and feed: plate 2.5b. The continuous movement of such a dense population of gastropods ploughs up the surface sediment and this disturbance also inhibits formation of mats.

Below low-water level, where the sediment is more muddy, there are few gastropods. Long burrowing worms were observed, and disturbance of the sediment by these worms does not favour the establishment of algal mat. The browsing activities of

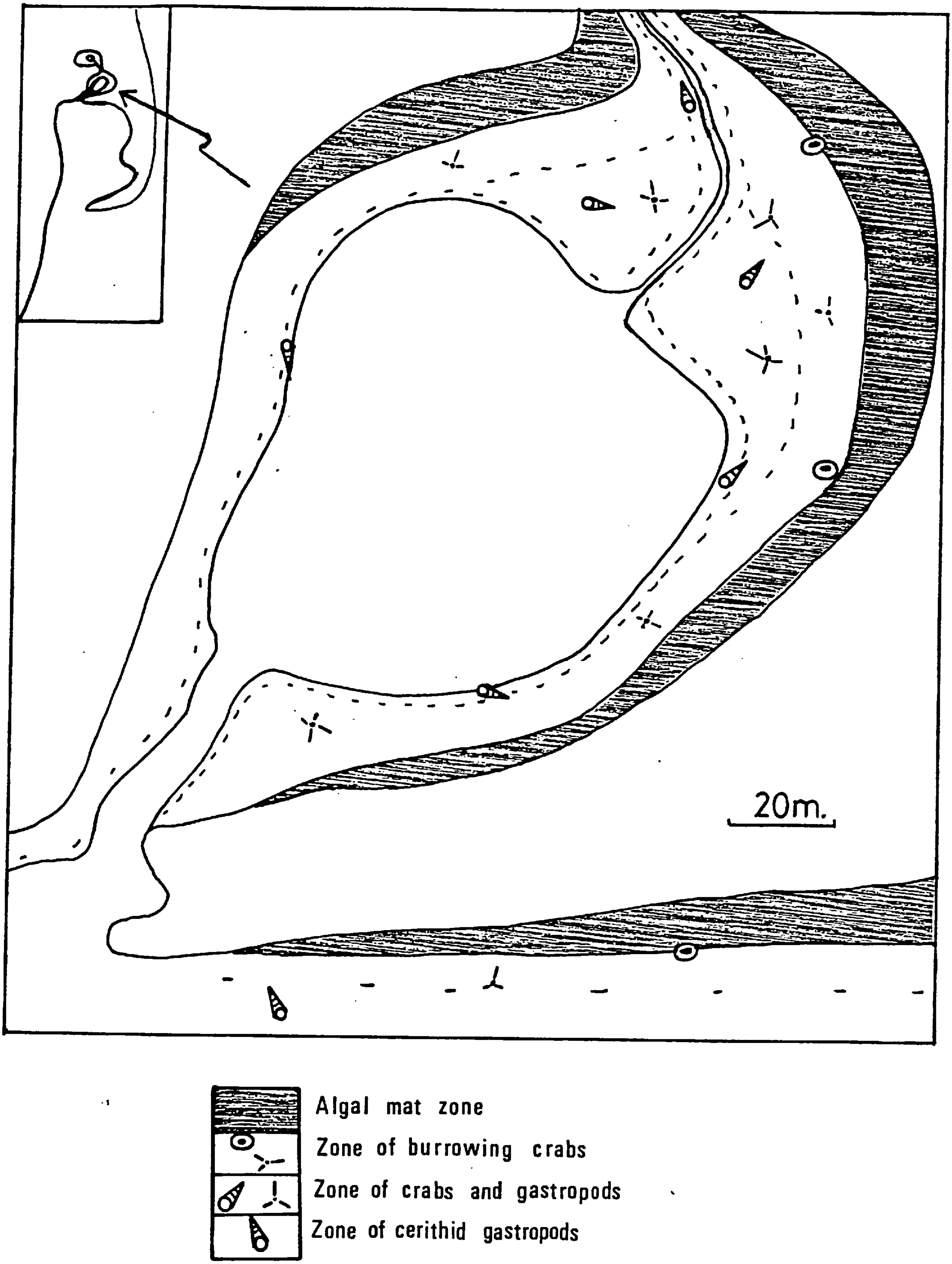


Figure 2.2.

Sketch map of a tidal pool along the coast south of Khor Al-Mufatteh, showing the ecological zonation seen in the intertidal zone around the pool. The pool is referred to as lagoon 'B' in the text.

Plate 2.5a.

Cerithid gastropods feeding around the wet margin of the pond in locality B, (lower intertidal zone).

Plate 2.5b.

Detail of plate 2.5a showing the gastropods and their trails. As they graze they also dig slightly into the surface sediment.

Plate 2.5c.

Gastropods moving down the tidal flats in order to escape desiccation as the tide ebbs. Note their nearly straight subparallel tracks towards the water.

small fishes may also be partly responsible for the absence of algal mat in the subtidal zone.

(b) The crab zone

The middle part of the intertidal zone around the pond is occupied by various species of crabs which seem to prefer a habitat intermediate between the two extremes: i.e. between the prolonged submersion of the low-intertidal gastropod zone and the high degree of desiccation of the high-intertidal algal mat zone: plate 2.6a.

The lower belt of this zone is populated by the small crab Scopimera, which lives there in large numbers. The crabs stay buried during high tide, but emerge from tiny burrows as the tide falls. They feed at the surface during low tide presumably on organic matter which coats the carbonate sand grains. In so doing they pellet the carbonate sand, and arrange the pellets geometrically around their burrows: plate 2.6b. They are so abundant that the entire zone where they live becomes pelleted in the course of one low tide. However, the pellets are not cemented and they disaggregate as the next tide rises and flood them. The effect of the feeding habits of these crabs on the sediment is to totally prohibit establishment of even the thinnest veneer of algal mat.

There is also another variety of organism, presumably a crab, which inhabits the upper part of mid-tide zone. This crab does not emerge from its burrow but periodically discharges sediment onto the surface. This discharge of sediment locally cover's and hence kills off the algal mats.

Plate 2.6a.

Crab burrows and pellets in the middle intertidal zone. The lower part of this zone (upper right of the photograph) is the feeding ground of tiny crabs. The burrows of larger crabs which live in the upper part of the zone can be seen in the foreground of the picture.

Plate 2.6b.

Detail of the lower portion of the crab zone showing the great abundance of feeding pellets produced by small crab, Scopimera in the course of a single low tide cycle.

(c) Algal mat zone

Algal mats are found in the highest parts of the inter-tidal zone: plate 2.7a, where the sediment is protected from grazing and burrowing organisms because the period of tidal wetting is too short for them to survive.

In contrast to lagoon A, the lower limit of the algal mat around Lagoon B is somewhat diffuse where it passes into the zone of burrowing crabs. Occasionally one can see that the lower part of the algal mat zone has only recently been torn up by the burrowing activities of the crabs: plate 2.7b.

The upper limit of the algal mats is clearly determined by extreme surface desiccation. In some places around the pool the algal mat is succeeded inland by a zone of halophytic plants, such as Salicornia, which in places overgrow the mats: plate 2.7c. Although the Salicornia zone is occasionally flooded by the sea, the likelihood is that the plants obtain most of their water from dew.

iii Inner margins of tidal channels

Disturbance of the sediment due to the activities of burrowing crabs appears to be the main factor which inhibits the establishment of mats in the inner margins of the tidal channels. The crabs live in large numbers in the lower inter-tidal zones in front of the algal flats, where they continuously bioturbate and rework the sediments. In all localities transition zones can be found where crab activity and algal colonisation occur patchily together. Cerithid gastropods

Plate 2.7a.

Lagoon B. Showing algal mats in the upper intertidal zone.

Plate 2.7b.

Lower margin of the algal mat zone. The right side of the photograph shows disturbance of the mats by burrowing crabs. The ruptured mats ultimately form small algal flakes.

Plate 2.7c.

The foreground shows the upper limit of the algal mat zone, where the mats are being destroyed by desiccation and growth of the halophytic plant *Salicornia*.

do not usually occur in these areas other than in a few pools in the lower reaches of the algal flat at locality E, see map fig. 2.1. These pools with gastropods are completely devoid of algal mat, and they contrast with similar pools at locality F which are floored by flat polygonal mats and have no gastropods. (These latter pools will be be described in detail in Chapter 3).

A: The Crab Field

Surface structures made by one particular group of burrowing crabs have the form of volcano-like mounds, each with a central vent: plate 2.8a. They are normally about 15 cms across and up to 5 cms high. They may occur isolated, or clustered together when they form small rounded or elongated highs: plates 2.8 b and c. The crabs appear to live wholly beneath the surface, and the mounds are built up by ejection of sediment from the entrances to the burrows. Different shapes of mounds may be formed by the same crab depending on the dampness of the substrate and the susceptibility of the excavated sediment to erosion.

In most crab fields along the inner margins of the tidal channels the sediments are always wet, and comprise a large proportion of mud and fine sand sized carbonate particles.

In area I, the sediment is coarser grained. It is of sand grade size, and is less wet. There, the crab mounds are presently being subjected to wind action, which winnows out much of the fine grained material leaving only the coarse grains such as skeletal debris.

The presence of crab fields, although inhibiting algal

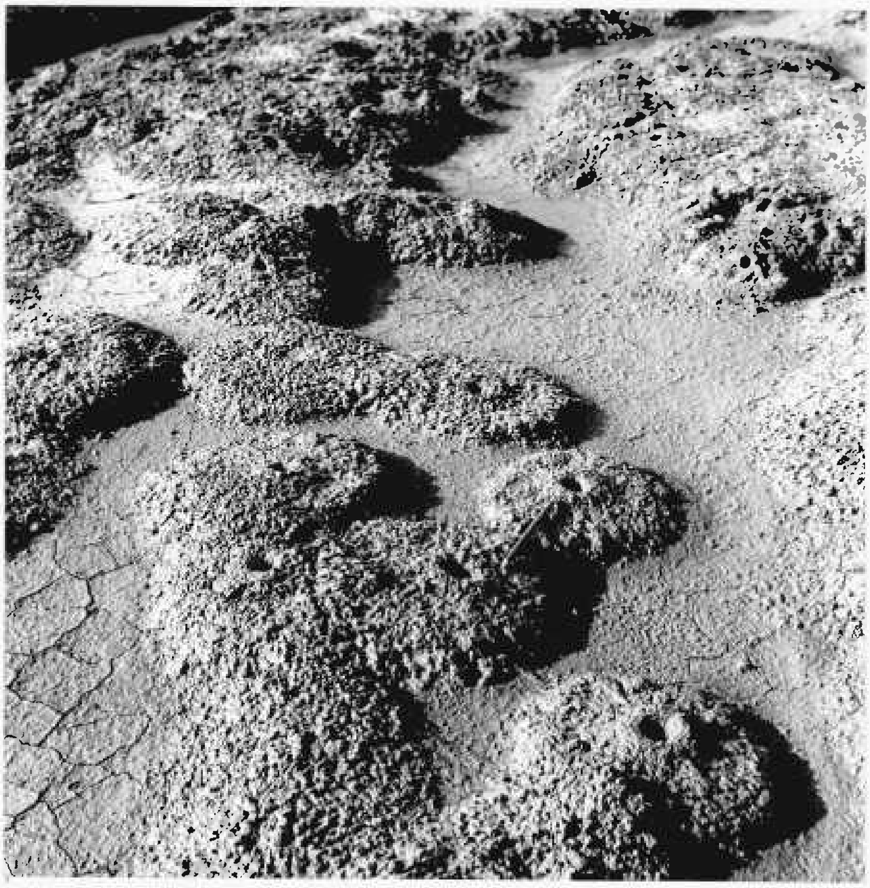


Plate 2.8a.

Isolated crab mounds in locality E.

Plate 2.8b.

Small ridges of coalesced crab mounds in locality E.

Plate 2.8c.

Rounded highs of coalesed crab mounds in locality F.

mat development in that zone, does appear to have exerted some influence upon the distribution of the algal mat zones behind. The relatively high structures built up by the burrowing crabs reduce the energy of the flood tide and obstruct run-off of the ebbing tide. This has two effects. Firstly it promotes deposition of sediments on the flats, and secondly, restriction of the ebb flow prolongs the duration of wetting in the upper intertidal areas. The net result is to encourage and extend the growth of algal mats behind the crab fields.

B: The transition zone between the crab fields and algal flats

There are always transition areas between the crab fields and the algal flats, where decrease in abundance of crab mounds is accompanied by algal colonisation of the spaces in between. In these areas the algal structures range widely in shape and size, and often form small discrete heads: plate 2.9. Ejection of sediment creates uneven surfaces around the burrow entrances and in adjacent intermound spaces. Algal colonisation of these surfaces results in formation of mats with irregular surfaces: plates 2.9 and 2.10. In some places, the high rate of algal colonisation gradually smoothes out these irregularities with time.

Locally the sediment ejected from burrows along the tidal channels serves as nuclei for the formation of spherical and subspherical oncolites up to 2 cm in diameter.

In area H, there are several small creeks which are migrating laterally by erosion of the outer sides of meanders, with concommitant depositions on the inner sides. Erosion is

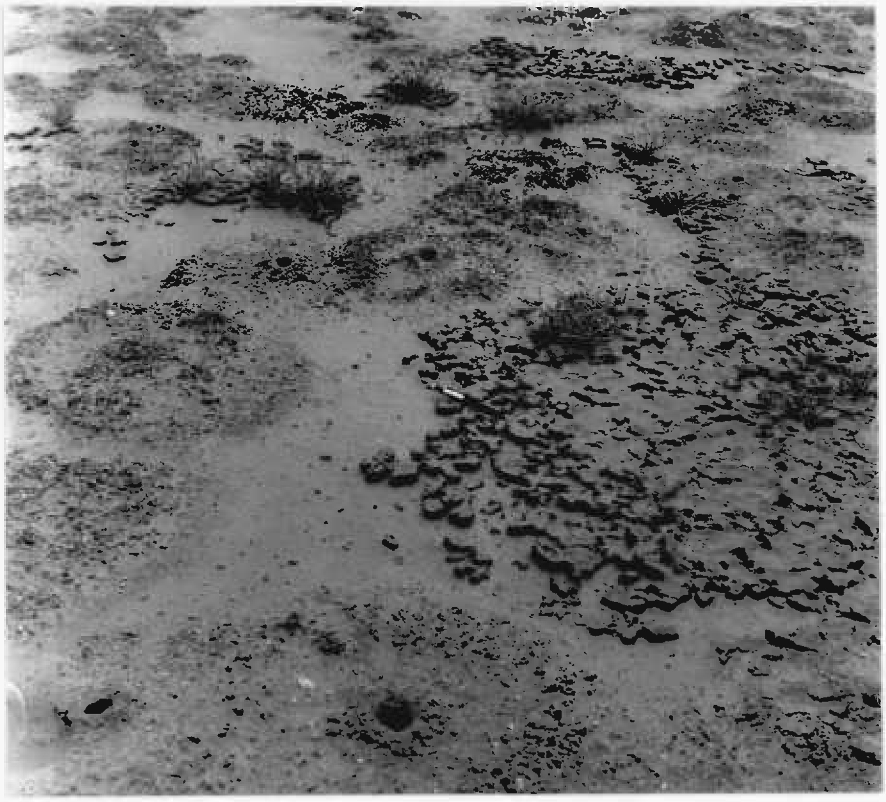


Plate 2.9.

Transition zones between crab fields and algal mat flats.

(a) Locality I: The sediment is sand-sized carbonate. Erosion of the surface leave relics of former crab mounds. Note the irregular pattern of the algal patches in the areas between crab mounds.

(b) Patches of irregularly shaped algal mat in depressions between well-developed crab mounds in more muddy sediments at locality E.

Plate 2.10.

Algal colomisation of abandoned crab-mounds in locality F. The irregularities on the mat surface are due to the irregularities on the substrate of the earlier crab burrows.

particularly active along the partially lithified, north-facing banks, where it is accelerated by the activities of burrowing crabs: plate 3.27. As a consequence of the lateral migration of the shallow tidal creeks, changes in the drainage pattern take place. These in turn have important effects in the critical area between algal flats and crab zones. Depending on which direction the frequency of wetting increases or decreases, the crab fields either migrate landwards or channelwards. In the latter case, the abandoned crab burrows soon become blanketed by algal mat: plate 2.10.

C: The algal mat zone

Along the inland reaches of the tidal channels and the intertidal strips on either side where there are no 'grazers' or 'burrowers', the blue-green algae flourish and produce extensive spreads of mats with a variety of growth forms. The algal flats in these areas pass back inland into supratidal salt flats and sabkhas.

On the lower parts of the intertidal zones, algal flats are usually separated from the tidal channels by a narrow strip, populated by burrowing crabs where the sediments are intensely bioturbated. It is obvious that even a slight rise of sea level would cause the crab zone to shift towards the algal flat where, because the mats are not lithified, the mats would be easily destroyed by bioturbation: plate 2.11. Such destruction of mats by crabs due to shifting in the positions of crab fields, although not common now must be considered as being one of the most important destructive processes in

Plate 2.11a.

Destruction of algal mat by burrowing crabs at locality E.

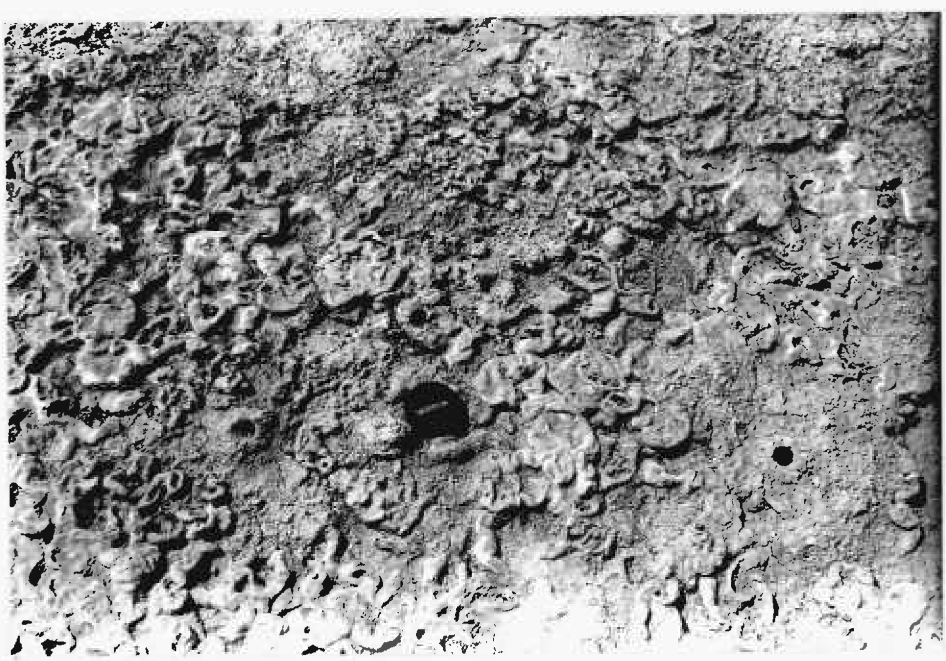


Plate 2.11b.

Close up of plate 2.11a.

this and indeed many other recent and ancient algal flats. Conversely when the crab fields shift channelwards or seawards, then mats are quickly restablished.

As a consequence of the high salinity along the inner-most reaches of the tidal channels, both grazers and burrowers are completely absent. Algal mats grow actively in all places and colonise almost the entire intertidal range including pools and ponded parts of channels. The algal mat in these areas is characterised by lobate advancing fronts: plate 2.12. The thick lips with dense beard like growth of filaments displayed by the mat front is clear indication of a high rate of growth.

In summary, the activities of grazing organisms, mainly cerithid gastropods, and intensive reworking by crabs, prevent establishment of algal mat in lower zones of the tidal flats. Mats are only developed in those places where environmental conditions exclude grazing and burrowing animals. The environmental factors include: desiccation in the uppermost intertidal zones, and high salinity in pools and ponds in the inner margins of tidal channels. In the latter areas where the growth of mats is not inhibited by grazers or burrowers, the mats advance with a lobate front: Fig. 2.3c. In contrast, where the lower margins of the algal mats are in direct contact with cerithid gastropods or burrowing crabs the leading edges of the mats are eroded and the boundaries show a variety of different patterns: fig. 2.3a and 2.3b.

(2) Wetting

The frequency and duration of wetting and drying appears

Plate 2.12.

Advancing growth front of algal mat at locality F. Note the lobate shape of the advancing front. Compare this with the biologically eroded front shown in Plate 2.1.

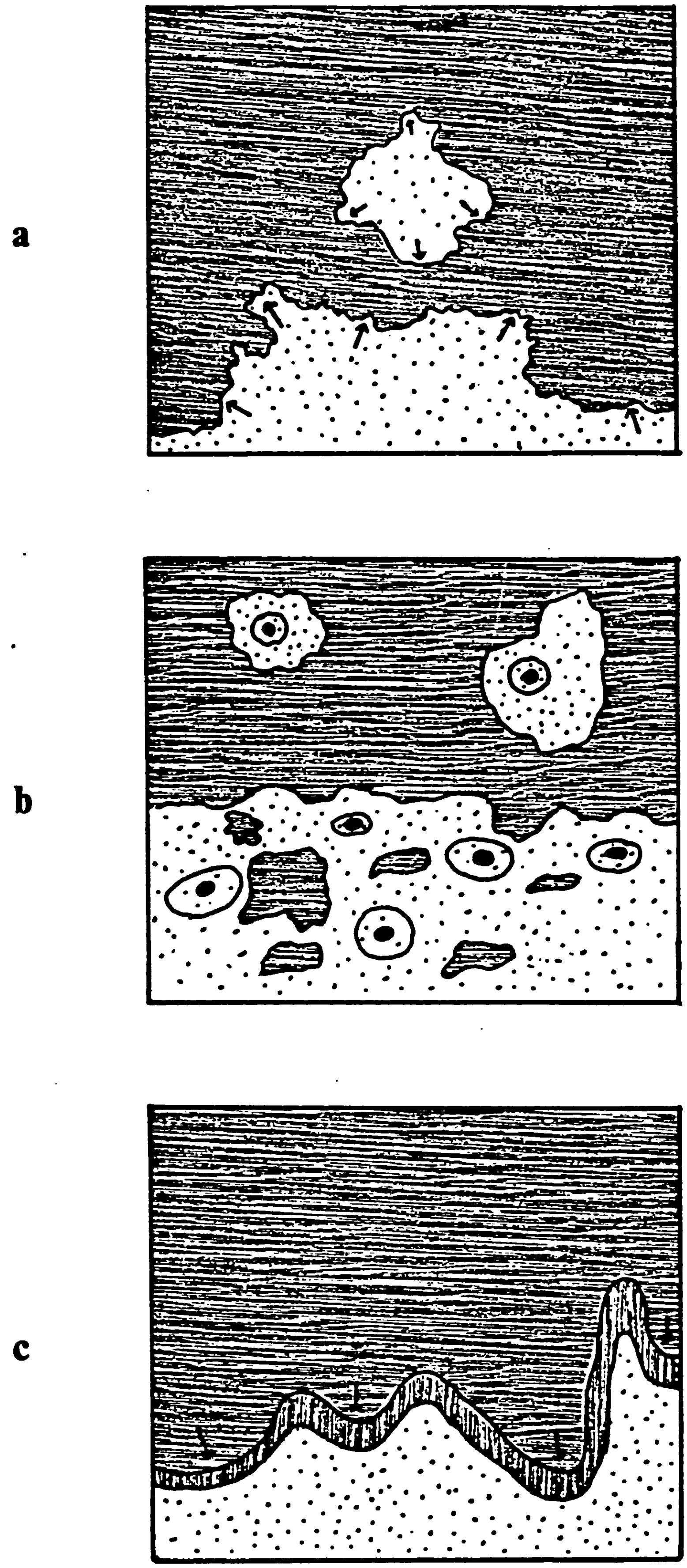


Figure 2.3.

Sketches to show erosional and growth margins of algal mat.

(a) Erosional front caused by cerithid gastropods.

(b) Erosional front due to the activities of burrowing crabs.

(c) Normal growing front: Note the lobate, undisturbed raised margin or lip.

to be the most important environmental factor which influences algal mat morphology. Certain mat forms develop only under conditions of continuous submergence, other types are found in moist poorly drained settings, while some forms only occur in areas of alternating flooding and subaerial exposure.

An example of the influence of duration of wetting is found in the development of the flat polygonal mat seen in poorly drained pools in area F. Vertical sections of mat from different pools reveal that the shapes of the internal laminae change from slightly convex upwards in the lower parts, to planar and concave upward shapes at the top: plate 3.13. It is suggested here that the earliest mats in these pools grew as small mound-shaped structures in which the laminae were slightly convex upwards. As the mat built up to the low tide water level of the pool, upward growth ceased but lateral growth continued to form a sheet of mutually interfering polygons. Growth around the edges of the polygons caused the lips to become raised. Such active growth around the edges of mat in all pools, most probably results from prolonged contact with water. In other words the water left behind in the pools during low tide surrounds the patches of flat polygonal mat and keeps their edges moist for longer periods than their centres. Thus, the change from convex to concave laminae and the formation of saucer-shaped polygons in later periods of mat growth reflects the changes in duration of wetting as the mat built up to standing water level. It is probable that growth in the centres of the saucer-shaped polygons is restricted by high salinity which develops in the thin veneer of water which is left in the depression of each polygon.

But this restriction may play only a minor role in the formation of upward concave laminations. Most important is the active growth around the edges.

Logan et al (1964) argued that growth of algal mat is inhibited by prolonged wetting. However, in the Al-Khiran area of Kuwait algal mats were found growing actively in many ponds and pools under conditions of continuous submergence.

Where mats have built up to the level of the water surface of poorly drained pools, the surfaces of the mats become subjected to alternations of flooding and subaerial exposure. At this stage a totally different growth form, the 'crinkle mat', starts to develop. A similar change is found in the subaqueous algal mounds of locality H. These latter become colonised by crinkle mat when their tops reach the water surface of the permanent ponds. These examples clearly demonstrate the importance of duration of wetting in determining the mat form.

Variations in the amount and duration of wetting over different parts of the itertidal zone result from several factors., These are discussed under the following headings:-

(i) Elevation

Generally speaking the frequency of tidal flooding at any one place is largely dependant upon its elevation and location in the intertidal zone with respect to spring and neap tide ranges. The higher areas on the tidal flats are flooded only at high spring tides, and they are in consequence less frequently inundated than the lower areas. However, the presence of numerous pools and ponds of permanently standing water in higher areas indicate that local irregularities in relief are important factors which have to be considered. Most of the 'lows' on the higher parts of the tidal flats, even those which are well drained surface-wise, are permanently damp because the groundwater table is at, or very near to the surface. Some of these lows, and also ponds, pools and channels, are conducive to development of thick algal mat. The relatively higher surrounding areas, which are subject to periods of desiccation are however covered only by relatively thin mats. The differences in elevation are of course very small, being only a matter of centimetres, but their effects are profound.

(ii) Modification of drainage by algal mat

In area F, most of the pools on the higher parts of the algal flat are floored with flat polygonal mat and are poorly drained. The present badly drained nature of these pools has resulted from the daming caused by algal growth across their exits. One of the results of the daming by algal mats is that although these pools are not frequently replenished with sea water, they dry out less often than pools on lower parts of the flats which are better drained. The effect of 'crinkle mat' in daming pools, and in consequence ponding up water at low tide, is shown, schematically, in figure 3.2. The relief and surface irregularities created by the growth of crinkle mat causes further minor local modification of the drainage which in turn promotes development of new mat forms.

In the area H, intense desiccation has cracked the crinkle mat to produce a flaky curled-type of mat. Some of the flakes have been blown away by the wind, and the parts of the substrate which were left exposed have become small hollows or lows which retain water and are only poorly drained during low tides. As a result they have become the site of colonization by 'tufted mat': plate 3.20.

(iii) The effect of tidal oscilation on frequency and duration of wetting

The frequency of flooding for a given location in the intertidal zone is variable throughout each synodic month. Figure 2.4 shows the tidal oscilation curve at Mena Saud on the open coast based on tidal data recorded for the year 1976. The diurnal oscilation pattern is asymmetric. There are normally four peaks in each 24 hour period during spring tides. These are:- LLW, HLW, HHW, and LHW. During neap tides the diurnal oscillations tend to have two peaks: one high water peak and one low water peak. Tidal ranges during maximum spring tides is about 2.3 m and approximately 1 m during neap tides. The diurnal tidal variations or the daily rise and fall of sea and the bi-monthly neap and spring cycles are mainly the results of interaction of the solar and lunar gravitational effects combined with the Earth's rotation. Tides of maximum range, i.e. spring tides, occur when the moon is either full or new; whereas the lowest tidal range, i.e. at neap tide, occurs in the first and third quarters of Moon's phases. The roughly two-fold increase in tidal range from neaps to springs results from the combined tide-generating effect of the Moon and the Sun as they fall along the same straight line with the Earth.

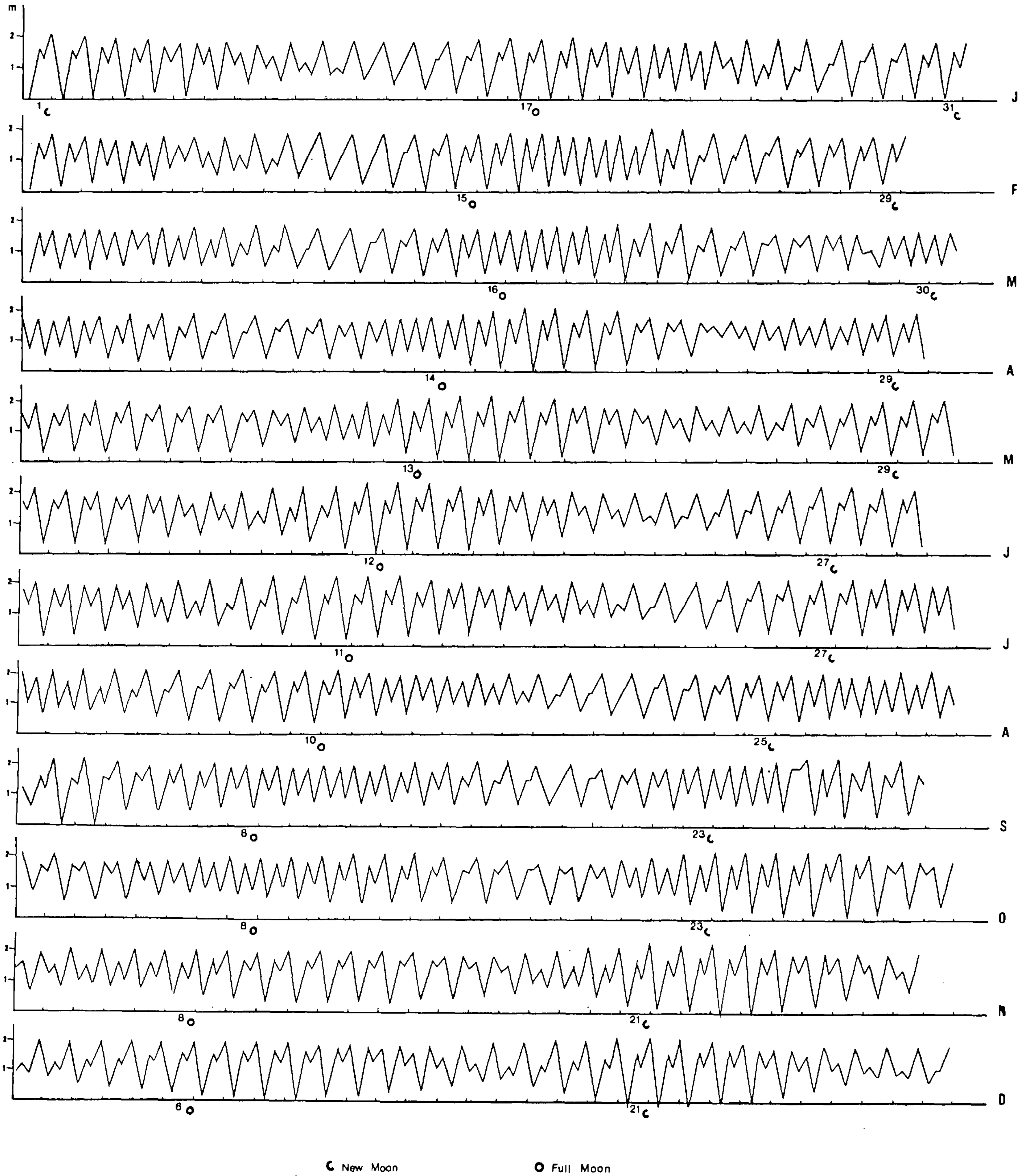


Figure 2.4 Heights of high and low waters at Mina Saud during 1976 (based on Admiralty Tide Tables).

In the Kuwait region, at the head of the Gulf, the tidal range decreases from 2.3 m along the open coast to approximately 1 - 0.5 m in the more restricted waters of the innermost tidal channels. In the latter places the tide is dampened and delayed. In the first instance the rising tide is delayed as a result of coastal configuration. When the water reaches the tidal channels and tidal flats its freedom is further restricted by the presence of numerous pools and minor channels, and even minor surface irregularities such as crab mounds and algal growth structures.

The intertidal zone is that area which lies between mean low tide and mean high tide levels. Above mean high tide level come the supratidal flats, which are only inundated by the highest spring tides or by storm conditions.

The strong prevailing northerly winds, (Fig. 2.5), known as the Shamal, have a profound effect on the spread of water over the tidal flats. As the tide rises in the Khors and spills over onto the flats, the Shamal blows the water far across the flats on the south side and at the same time holds the water back from the flats to the north. The effect of this is well seen in the distribution of the algal mats on the flats around Khor Al-Mufatteh. The Khor bifurcates: one arm trends to the south and the other to the north. The greatest spread of algal mats anywhere in the region lies around the southern arm of the creek; and this contrasts markedly with the limited extent of mats around the northern arm. Thus distribution of the mats relates directly to the effects of the Shamal. Further the types of mat are different on the two sides, presumably because of the differences in duration

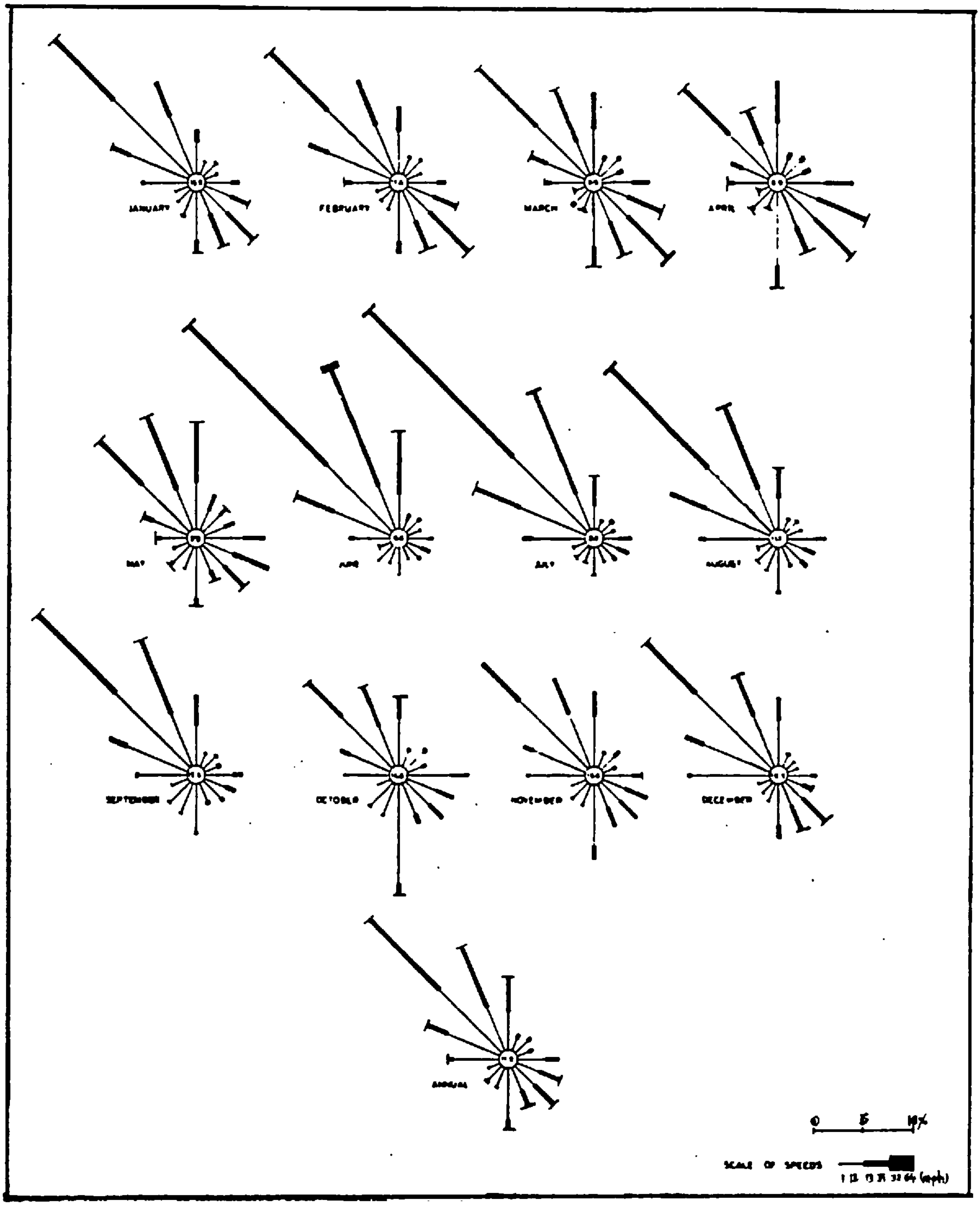


Figure 2.5.

Frequency of wind speed and direction at Kuwait International Airport, based on the record of 17 years (1947-1973).

of flooding which are again related to wind direction.

Tidal effects are important in several respects. Besides being the main source of wetting or water supply necessary for the growth of algal mats, tidal range in conjunction with the gradient of the tidal flats, has a major influence upon the thickness of the mats and the width of the zone which they occupy. The width increases on gentle gradients but decreases on steep gradients. Tidal range is also an important factor in determining the strength of tidal currents which in turn influence erosion and transport.

Other sources of water which play an ancillary role in the development and distribution of algal mats are: tidal groundwaters, rainfall and dew.

Tidal Groundwaters

The tidal groundwater table is found to be very close to the surface throughout most of the intertidal and supratidal areas. Thus, moisture resulting from capillary rise causes the surface of the sediments to be damp most of the time. In the upper reaches of the intertidal zone, capillary groundwaters play an important role in algal mat ecology. The high groundwater table prevents destruction of the mats by desiccation and further, it extends the upper limit of colonization beyond the range of high tides. The degree of dampness of the surface of the flats is also influenced by the type of substrate. This relationship is well demonstrated in Khor Al-Ama. There, on the lower parts of the algal flats where the host sediment is sandy, the mats are flaky and apparently desiccated. Further inland on the same flats, where the sediment is a carbonate mud, the mats are smooth and flat and lack any desiccation features despite the fact that they are less frequently flooded by the sea.

Rainfall

Rainfall in Kuwait is very low, approximately 112 mm per year, but it is variable from year to year. Because of its small amount and its irregularity, rain water only rarely wets the supratidal flats which remains parched for most of the year. For this reason algal mats cannot become established beyond high tide level. Elsewhere in the world, where rainfall and surface run off are considerably higher, as for example in the Bahamas and parts of Florida, algal mats extend up on to the supratidal zones. In Kuwait, the rainy seasons are winter and spring (from November to April), while the other months are almost rainless: Fig. 2.6. Surface runoff rarely occurs because most of the rainwater percolates down through the sands and gravels which cover large areas of the State and the neighbouring countries. Even following very heavy rainstorms the surface dries out quickly, except where water has collected in local depressions. There it forms pools which may stand for several weeks. Some of these seasonal, ephemeral ponds in the supratidal zone are floored with thin carpet of algal mat, though the ponds have no direct connection with the sea.

Dew

Records of relative humidity at Kuwait International

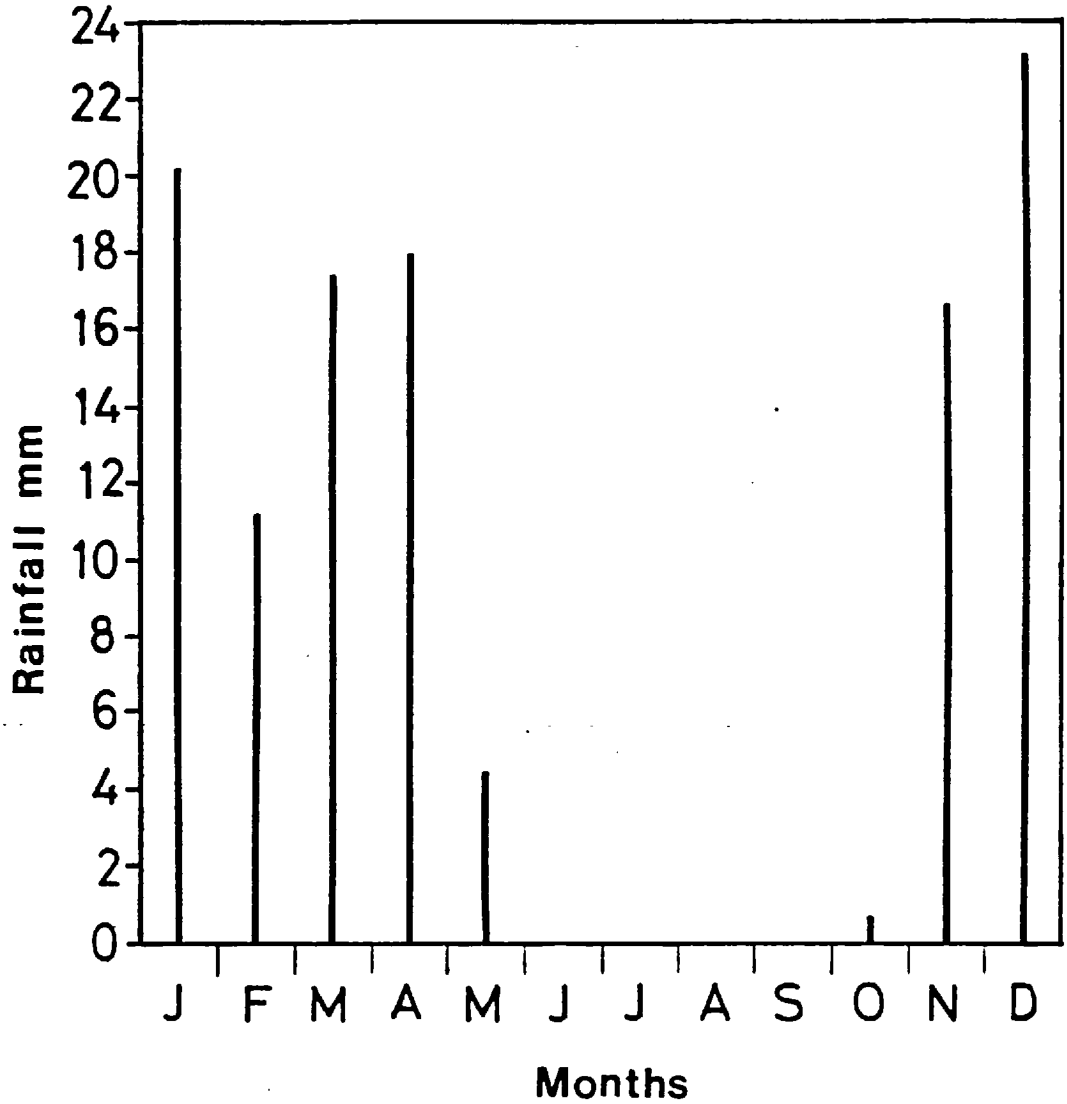


Figure 2.6.

Mean monthly rainfall at Ahmadi: based on 27 years, (1947-1973)

Airport (1974) show a large variation of the mean monthly values: Fig. 2.7. The maximum values usually occur during winter, with an average of about 95%, while the minimum values are mostly obtained during summer, especially in June and July due to hot dry shamal winds. The mean maximum humidity during summer is around 30%. However, exteme values of 100% can occur at almost any time of the year, and the same is true for the extreme low values which may fall to 2% or less. In the coastal areas, with which we are concerned, relative humidity is presumably much higher than at the airport which is some distance inland.

During maximum relative humidity, heavy dews can form, and the dew may be regarded as an important source of water which, combined with the capillary rise of groundwater, can cause wetting of large areas beyond the high water mark. Such a regular supply of mositure provided by dew is important in ensuring the continuing existance of algal mats on higher levels of the tidal flats.

In summary, the main source of water is that supplied by the tidal cycle. The drainage pattern, frequency of flooding and amount of wetting of the surface are modified locally by the presence of numerous pools and channels as well as surface relief created by growth of algal mats. It is these local effects which influence the amount of wetting of any area, and this in turn controls the development and detail of the character of the mats.

(3) Desiccation

The main control on the upper limit of colonization by

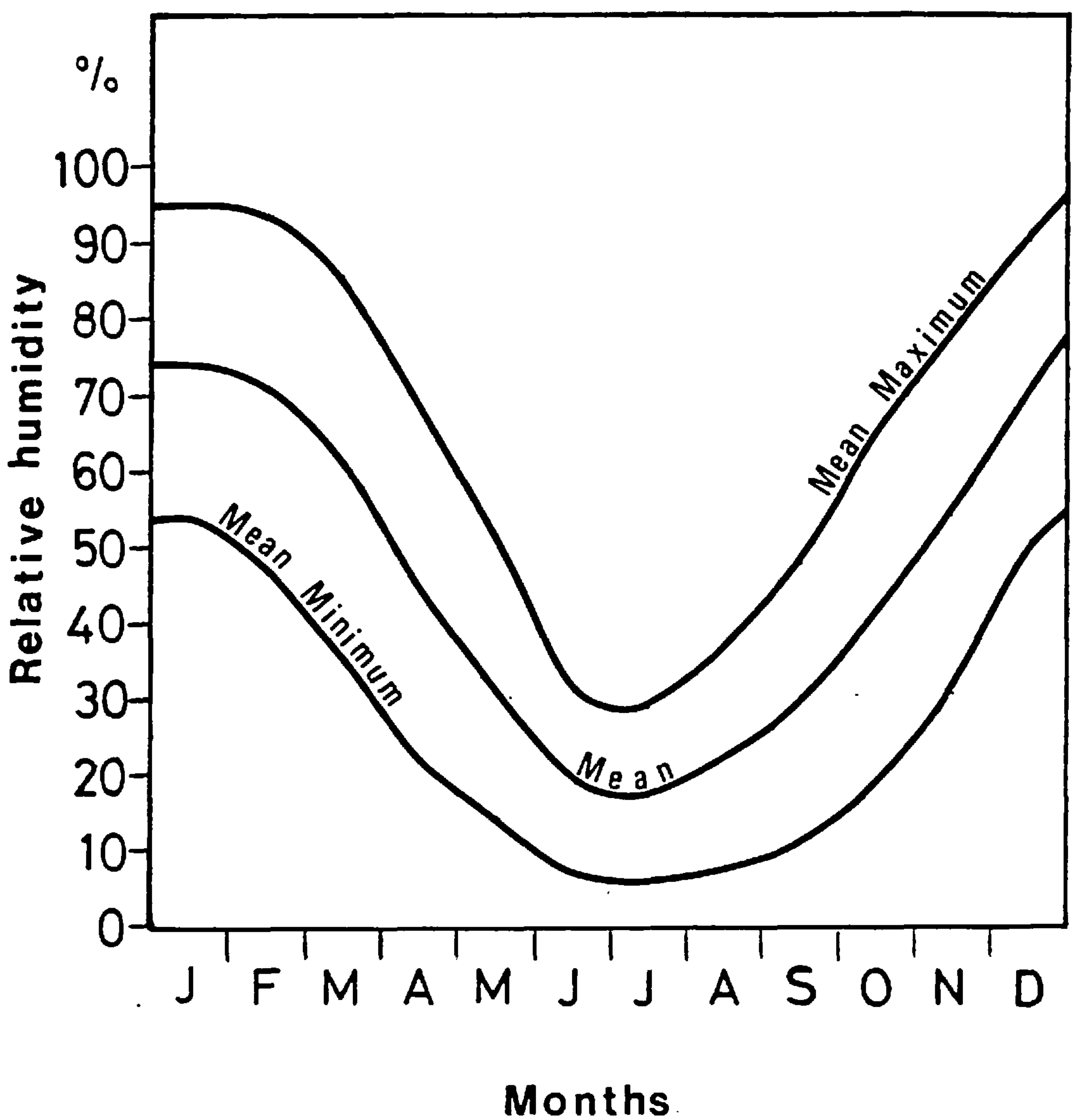


Figure 2.7.

Relative humidity: monthly averages at Kuwait International Airport (1974).

algal mats in Kuwait State is desiccation. The effects of desiccation on algal mats varies from place to place, depending on the lengths of time for which the mat is subject to drying out. The latter are dependent mainly on elevation and type of substrate. Mats in the higher parts of the algal flats, where flooding frequency is least, are subject to the most extreme conditions of desiccation. However, even on these higher flats where the substrate is muddy or where the water table is very close to the surface, the effects of desiccation by sun and wind on the mats are ameliorated.

On the high parts where conditions of high desiccation prevail, the thin veneer of algal mat is shrunken and exhibits desiccation cracks. Where completely dry, the mat has lost its rubbery flexible nature and has become brittle, and the surface aquires a grey colour. In certain areas, particularly where the substrate is less muddy, as in the highest and driest areas of the tidal flats between creeks in locality H, the mats are brittle and highly wrinkled. There, as a result of extreme desiccation the mat cracks and shrinks into concave - upward flakes which easily peel off surface and are blown around by the wind. The mats on highs are normally damp during the winter months but during the long periods of desiccation in summer algal growth becomes inhibited by desiccation and dehydration. Because growth of algal mats can take place only at the surface, either upward or laterally, mats on all of the highs are very thin. In contrast, algal mats in low areas have less restrictions upon their vertical growth than mats in other settings and consequently they develop the thickest accumulations. In the lows the underlying parts of the mats are black evidently reflecting reducing condition, and they are usually underlain by laminated peaty sections. However, as the low areas become filled as a result of continued algal growth, the mat surface ultimately builds up to a level where it becomes prone to intermittent periods of drying out and it then develops desiccation cracks.

(4) Substrate

The algal mats in Al-Khiran appear to be able to grow on almost all types of sediments, provided that the substrate has some sort of stability. Mats can be found colonizing loose skeletal sands, intraclastic sands, aragonite muds, cemented intertidal sediments, gypsum mushes and other algal mats. There are interesting relationships between the characteristics and modes of development of algal mat and types of the substrate on which they have grown.

(a) Sandy substrates

Algal mats which have grown on loose sands, such as those around the areas designated A and B, are usually present only as relatively thin veneers. This appears to result from the fact that the substrate drains rapidly during low tides and frequently dries out, so that the mats there are periodically affected by desiccation. Similarly, the surfaces of most of the highs between creeks in the area H are only covered with thin, highly wrinkled and desiccated mat. In many other places where the substrates are mostly mixtures of skeletal and other carbonate sands with varying amount of fine carbonate muds, such as in area I and along Khor Al-Mufatteh at locality C, only thin ephemeral sheets of algal mats are present. The poor development of mats in some of the above mentioned areas can also be attributed in part to the lack of complete stability of the substrate due to tidal currents and/or the activities of burrowing crabs.

(b) Muddy substrates

The fine-grained muddy sediments at the protected inner ends of the tidal channels seem to provide the most favourable substrate for algal mat colonisation. The main reason for this is believed to be the ability of muds to retain moisture during low tides. In addition, the presence of depressions in these flats where the groundwater table is only a few centimetres below the surface ensures permanent dampness. These conditions, together with the continuous supply of 'fines' leads to in the thickest accumulation of algal mat.

In all of the areas where wide spreads of algal mats cover muddy substrates, there is no sign of lithification of the mats.

(c) Rocky substrates

Partially and completely lithified stromatolites and oncolites are found on the rocky shores along tidal channels in localities D and G. These are the only lithified stromatolites so far found in the area studied, and they all occur on beach rock substrates. The beach rocks comprise coarse to medium grained carbonate sands partly cemented by aragonite. They are porous and permeable, and being along the shores of tidal channels, they drain freely and retain relatively little moisture at low tide. Thus, the mats which colonize them are similarly intermittently exposed and dried out. This leads to the precipitation of aragonite and penecontemporaneous lithification of the mats.

(5) Scour and erosion by tidal currents

Algal mats are restricted to the most sheltered parts of the intertidal flats, and are completely absent from the high-energy environments such as the open sandy shores and seaward parts of the channels. Their absence from these places is due to wave and tidal scour which keeps the sediments continuously in movement: i.e. the substrate is unstable. Tidal channels which cross the algal mat zone are also free from mats, and it is evident that the strong scour by ebb and flow currents militates against establishment of mats. In the shallow creeks of the upper reaches of the tidal flats where the strength of tidal scour has fallen off, the channels become gradually floored with continuous spreads of algal mats.

In general, the thickest developments of algal mats are found in depressions and pools in places with the weakest tidal scour and poorest drainage. Such pools are usually cut off from the main tidal channels because of the daming effect of algal growth across their shallow and narrow outlets. In contrast, minor channels and some pools in the lower reaches of the main tidal channels are usually directly connected to the main channel and in consequence they are subject to high tidal scour which inhibits any algal growth in their floors: Plate 3.9a. On the small scale, tidal ebb and flow currents also may scour the areas between discrete algal heads and hence continue to keep these heads separate from one another (see Chapter 3).

The effects of tidal scour on shapes of some algal structures can be seen by comparing the shapes of discrete algal heads from different localities. Algal heads which occur along banks of Khor Al-Ama in locality H are commonly strongly eroded around their bases: plate 3.28. Such undercutting of the heads is due to high scour by tidal flow and ebb currents, aided by abrasion caused by the presence of sand. Ultimately they become almost completely undercut and topple over where become the nucleii for oncolites. Elsewhere in the same area, where the heads are less influenced by tidal scour they are less undercut. In area E, where the sediment are much more muddy and, where tidal scour is less vigorous, the algal heads show much less erosion at their bases. The heads which are found far from the main tidal channel in locality E, where tidal scour is weak, show little or no undercutting.

Another obvious example of the effect of the tidal currents on the shape of algal structures is demonstrated by the elongation of subaqueous mounds: plate 3.5, and the preferred orientation of lithified stromatolitic structures on rocky beaches or banks (Chapter 4). The elongation of the algal structures is in the direction of water flow. Examples of the effect of the current regimen on the shape and orientation of old and modern stromatolites has been reported by several workers, including Hoffman (1967); Gebelein (1969); Hoffman et al (1969) and many others. The occurrences in Kuwait State support these earlier observations.

(6) Salinity

Salinities in the region under study were measured earlier by the writer in the course of M.Sc. research: Saleh (1975). Salinities of the intertidal waters in the shallow coastal areas along the open coast and in the lagoons behind barrier spits are generally higher than that of normal sea-water. They reach values of approximately 55 parts per thousand: i.e. they are metahaline. Salinities gradually increase from the entrances of the tidal channels and reach 70 parts per thousand, and are hypersaline, near the lower reaches of the algal flats (e.g. near locality D). Further inland, salinity may reach more than twice the latter value in many of the hypersaline pools at the very head of some of the tidal channels. In these pools salinities may vary seasonally and diurnally. During summer, after the tide has fallen, salinities in some pools reach that of halite saturation for part of the day. As a result, algal mat surfaces in these areas are encrusted by thin surface layers of salt. These thin salt crusts are usually dissolved by the heavy overnight dew, but the salt reprecipitates in the course of the following day. Salinities of tidal groundwater in the upper intertidal to lower supratidal zones may reach as high as 500 parts per thousand.

The hypersaline concentrations achieved by tidal waters entering the khors is the net result of: a very high evaporation rate with restricted exchange, in an area where fresh water input is almost negligable. The high evaporation rate is due to the extremely arid conditions, especially during summer when the average maximum temperature reaches 45°C: Fig. 2.8. Such high temperatures on long days with a clear and cloudless sky result in evaporation rates as high as 52.8 mm per day. Such a value was recorded on 5th July, 1973 at Kuwait Airport during hot and dry northwesterly gale-force winds. The amount of annual evaporation is about 600 cm, as computed from mean daily readings taken at Kuwait International Airport. The amount of evaporation along the coast is likely to be slightly lower due to higher humidity nearer the sea. The annual evaporation rate greatly exceeds the rainfall which is only about 11 cm per year.

The hypersalinity in the innermost parts of the tidal channels inhibits the voraceous grazing and burrowing organisms, so that algal mats can grow unimpeded over the entire range of the tidal environment. Thus salinity has an important indirect influence on the distribution of algal mats because of its role in restricting those organisms which would eat or otherwise destroy the mats.

The effect of salinity upon the biota of the intertidal flats can be clearly seen by comparing the types of organisms which inhabit tidal flats at different localities along the coast of Kuwait. In the low salinity tidal flats along the northern coast of the State, as for example near Khor Al-Sabbiyah and in Sulaibikhat Bay where the bulk of sediments is derived from the fluviatile muds of the Shatt

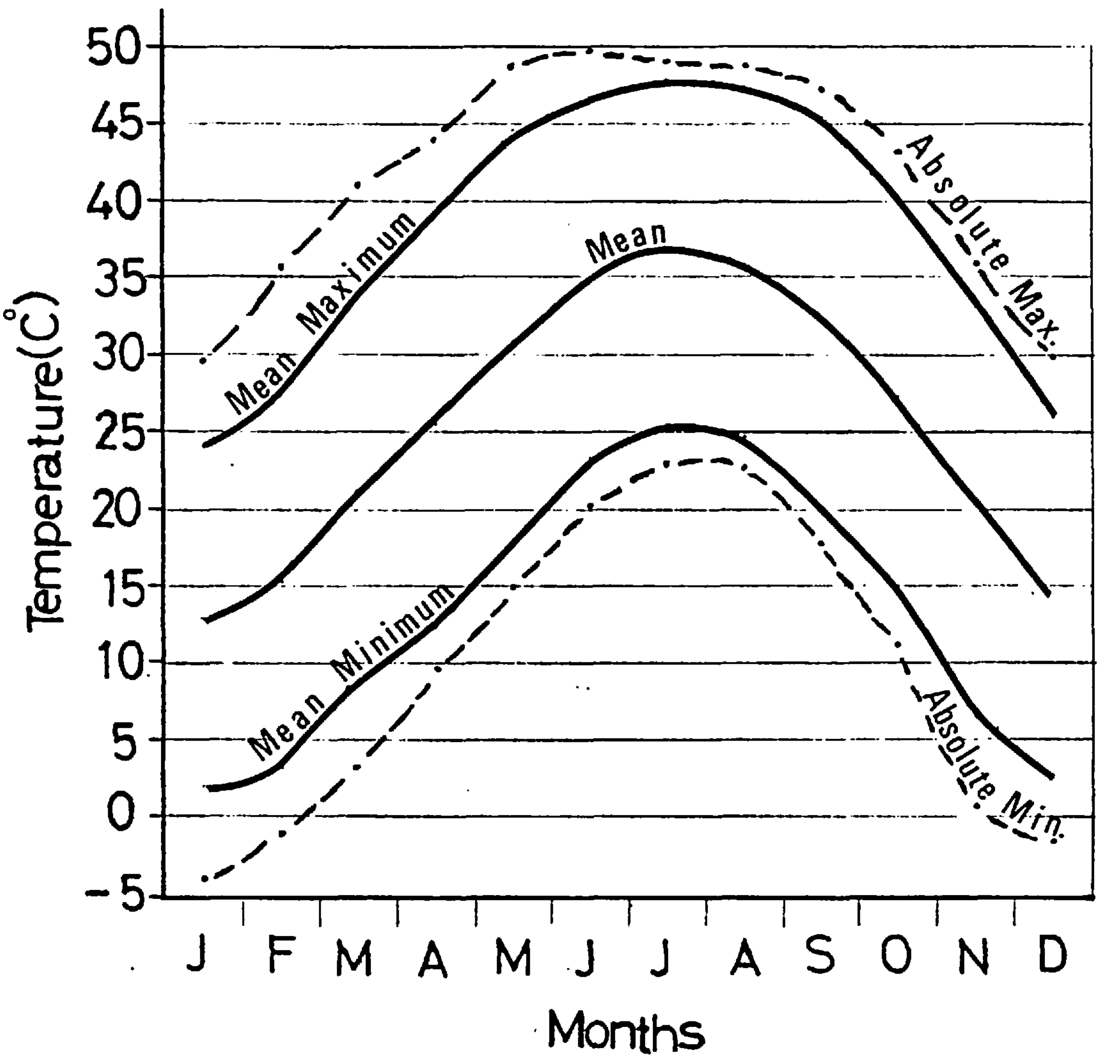


Figure 2.8 Temperature at Kuwait International Airport (1958 _ 1972)

Al-Arab, oysters and mud skippers live in abundance. In the higher salinity areas of the south, the coastal intertidal sand flats are inhabited mainly by bivalves and gastropods; whereas in more protected carbonate mud areas such as the coastal lagoons behind barrier spits cerithid gastropods are dominant. On the highest part of the intertidal flats and in the more restricted hypersaline areas such as the innermost margins of the tidal channels of Al-Khiran , the biota is limited to blue-green algae.

The role of high salinity in restricting the distribution of grazing cerithid gastropods which, in turn limit the development of algal mats has been described from Hamelin Pool, along the coast of Western Australia: Logan (1961); Hoffman et al (1969); Logan et al (1974); Playford and Cockbain (1976), and Hoffman (1976).

Hypersalinity and the concentration of interstitial waters by evaporation in Al-Kharan is of local importance in promoting aragonite precipitation and penecontemporaneous lithification of algal structures along the banks of Al-Khiran: see Chapter 4. It is also of importance because it leads to diagenetic interstitial growth of gypsum which can disturb or even destroy the laminations of algal mats.

CHAPTER 3.

CHAPTER 3

Morphology and Distribution of Algal Mats

The best development of algal mats in the area of Al-Khiran is found on the upper intertidal flats around the extreme inner margins of the tidal channels: Fig. 2.1. Less extensive algal flats are present around the protected coastal lagoons south of Khor Al-Mufatteh.

As a result of the interplay between the blue-green algae and physical environmental factors, including availability of sediment, a variety of growth forms are developed by the mats. Six basic growth forms are recognised, mainly on the basis of the surface morphology and internal lamination. They are given in an order based on the mode of occurrence with respect to extent of wetting and exposure: starting with those which have the longest duration of wetting and ending with those which are the most subaerially exposed. They are as follows:-

1. Subaqueous mounds
2. Flat polygonal mat
3. Tufted mat
4. Discrete algal heads and oncolites
5. Crinkle mat
6. Curled mat

In studying the distribution and morphological variations of these various forms in the field, the nature of transition from one type to another was traced laterally parallel to, as well as normal to the tidal channels.

3.1 Subaqueous mounds

The growth form termed 'subaqueous mounds' occurs as discrete heads up to 12 cm in height and may be as much as 40 cm across. They are found in a limited number of small tidal creeks in the area of the upper tidal flats of Khor Al-Ama. (Area H of Fig. 2.1). These flats are flooded at high tide by sea water which moves in along numerous small creeks, but the flats dry out on the ebb tide so that most of the area is dry for part of each day. However, for one reason or another, such as changes in the drainage pattern, residual water stays in depressions creating small 'permanent' ponds. These ponded parts of the tidal creeks measure 2-3 metres in width and may reach tens of metres in length: plate 3.1. Due to the high salinity of the ponded water, invertebrate grazers and burrowers are almost absent, and the ponded parts of the creeks, therefore, offer optimum conditions for the underwater build up and preservation of algal growth structures.

The surfaces of the mounds, i.e. the living parts, are olive green; but when cut open the internal parts are dark grey and show only faint lamination. However, samples which had been cut in half and left for a day or so were found to change colour, presumably by oxidation, from dark grey to buff. In consequence of this change, the laminae became much more obvious. (Compare plates 3.2 and 3.3).

The most distinctive feature of these mounds is the persistance of the laminae which continue unbroken across the structure. The laminae can be seen in hand specimen, and

Plate 3.1.

Ponded part of a tidal channel in area H. Photograph was taken during low tide.

Plate 3.2.

Freshly sectioned subaqueous algal mound from locality H; showing dark grey to black internal surface with faint lamination. The upper surface is olive green in colour.

Plate 3.3.

The same sample photographed the next day. Note the change in colour, due to oxidation, which inhances the laminar structure. The samll rounded pit in the lower right of photograph is where the mound was formerly rooted.

comprise a series of pale and light brown layers. They range in thickness from less than 0.5 mm to 1.5 mm. Each lamina can be traced easily across the mound, and commonly shows marked convex undulations. The surfaces of the mounds are domal or knobbly. It can be seen from plate 3.4 that this knobbly character of the surface is a growth feature, because it is moulded on the internal undulations. Once the structure has been initiated with lightly undulatory laminations, the convexities persist and are enhanced by upward growth, and are expressed at the surface as small domal protrusions.

Being under continuously submerged conditions, the mounds show no destruction or distortion of laminae; since they are neither desiccated nor disturbed by growth of gypsum crystals. There is occasional evidence of minor destruction of lamination by boring and burrowing organisms.

The mounds usually increase in diameter as they grow upwards. Some tend to be elongated in the direction of tidal flow: plate 3.5. It is obvious that such an orientation minimizes resistance to tidal current. The lower parts of the mounds extend a few centimetres below the surface of the surrounding sediment. This is probably a result of accumulation of sediment around the bases of the mounds so that they became firmly attached to the substrate by laminated 'roots' (Fig. 3.1 and plate 3.3).

Most of the mounds attain their maximum relief - about 12 cm - by reaching to within a centimetre or so from the water surface of the pond where their upward growth is terminated. They are constantly submerged and at high tide

Plate 3.4.

Close up of vertical section through one of the subaqueous algal mounds showing convex wavy lamination. Note the persistence of crenulations up through the mound, which ultimately express themselves on the surface as small protrusions.

Plate 3.5.

Subaqueous algal mounds showing elongation in the direction of ebb and flow along the channels, photograph during ebb. N.B. Stream-lines on the surface of the water.

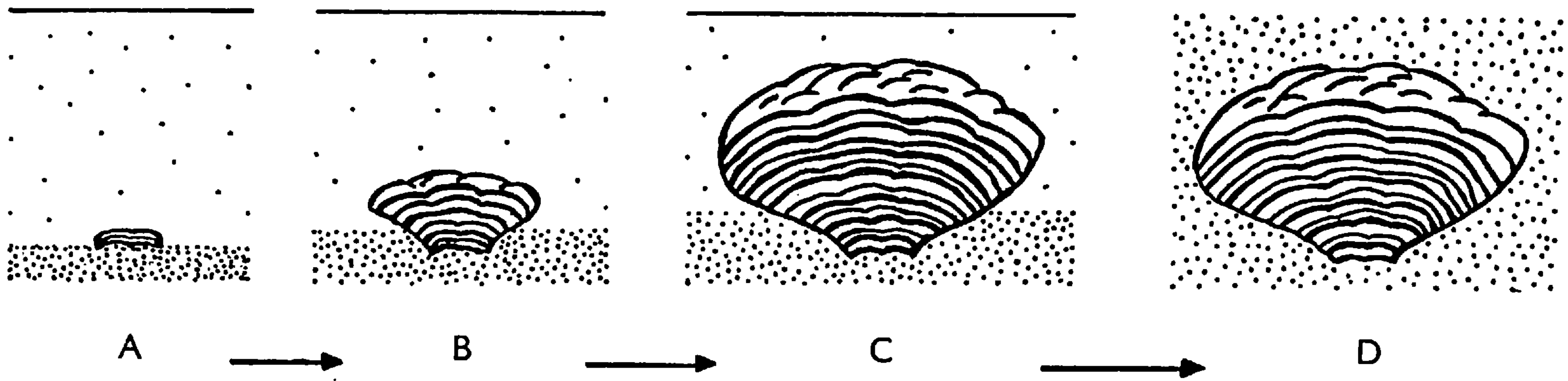


Figure 3.1.

Sketch illustrating stages in the accumulation of sediment around base of a growing subaqueous algal mound. This results in a root-like structure which holds the mound firmly attached to its substrate (stage C). Further accumulation of sediment as the pond silts up leads to preservation of the mound (stage D).

their tops may be under 30 centimetres of water. In shallower ponded channels the mat form can only develop low profiles but they spread laterally and coalesce to give rise to a continuous humocky mat: plate 3.6. Where, however, mounds have reached the pond surface, they become intermittently exposed and a new type of algal mat, whose growth form and internal structure differ considerably from the subaqueous mounds develops on top. This is best seen along the margins of the ponds: plate 3.7.

In some instances along channel margins, laminae of this form 'hang down' following the slope of the channel side. This feature was termed 'drap-over' by Gebelein (1976). In some places as many as three mat forms can be seen one on top of the other: plate 3.8.

The Recent subtidal algal biscuits in the Bermuda Islands and other places in the Caribbean region, described by Gebelein (1969) and Golubic and Focke (1978) may perhaps be the closest analogues. They do have some features in common, mainly in terms of size and orientation with respect to currents, but they differ considerably in their internal structure and lamination. The Bermuda algal biscuits show smooth laminations, largely lacking any crenulation. Other than this the subaqueous mounds of Al-Khiran contain very large amounts of organic matter and their sediment content is mostly fine lime mud. In consequence of this the cohesiveness of the mounds is very high.

Structures similar to subaqueous mounds are well known in ancient limestones, particularly in the Proterozoic, and the occurences found in the Kuwait State appear to be the first recorded present day examples.

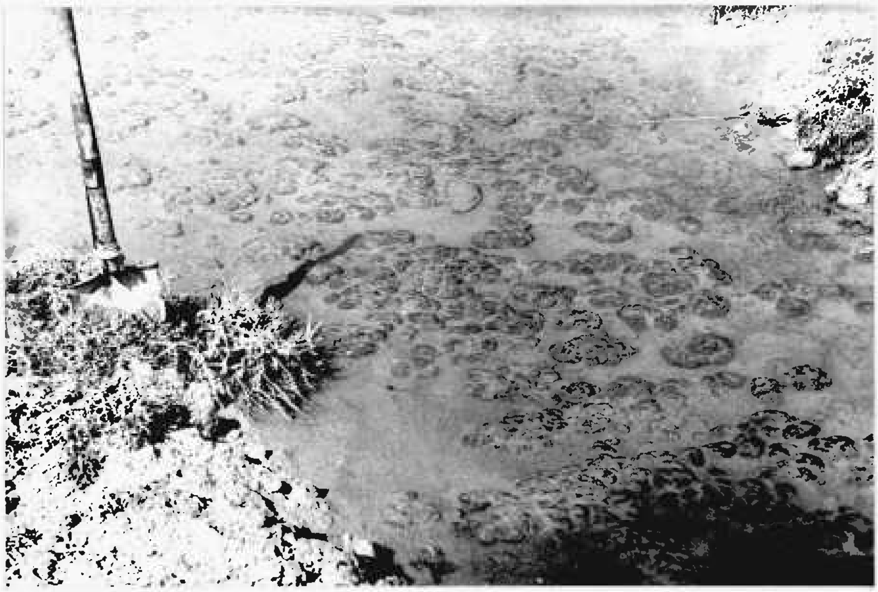


Plate 3.6.

Subaqueous mounds in a shallow ponded part of a tidal channel. Upward growth of the mat has ceased and has given way to lateral growth, so that in places the mounds have coalesced.

Plate 3.7.

Gas blisters on crinkle mat. The crinkle mat has grown on the tops of subaqueous mounds located close to the margin of the pond.

Plate 3.8.

Three mat forms resting one on top of the other, draped over a steeply dipping channel side. From top to bottom these are:

i. Crinkle mat
ii. Tufted mat
iii. Subaqueous mat.

On applying the geometric classification scheme proposed by Logan et al (1964), the mounds can be described as discrete, vertically stacked hemispheroids of variable basal radius composed of close-linked hemispheroidal laminae. They may be designated $\frac{\text{SH-V}}{\text{LLH-C}}$.

3.2 Flat polygonal mat

Flat polygonal mat is characterised by a smooth surface which lacks almost any relief and has high cohesion. It appears to be equivalent to the mats in the "polygonal zone" of Kendal and Skipwith (1968), the flat mat of Park (1973) and the gelatinous mat of Logan et al (1974). This type of mat is well developed in poorly drained pools within continuous crinkle mat terrains. It is best seen in locality F (Fig. 2.1), where the southern side of the main tidal channel of Khor Al-Mufatteh comprises a complex of small pools and channels: plate 3.9. It is those pools which occur in the uppermost parts of the intertidal area which appear to provide the optimum conditions for development of the mat in question. The various pools show all possible ranges and variety of stages of mat development. The mat can be found as a narrow rim around pools and along the margins of narrow channels, or, it may colonise the floors of pools either in isolated patches or as continuous carpets which usually display a polygonal pattern: plate 3.10. There appears to be a relationship between the extent to which this type of mat developed and the drainage characteristics of the pools. In the initial stages growth commences around the margins

Plate 3.9.

Complex of pools and channels at locality F.

(a) Relatively well drained pools and channels close to the main tidal channel. The highs are covered with crinkle mat but the pools are barren.

(b) Poorly drained pools in the upper parts of locality F, landward of photograph a. In the pool at the bottom of the photograph flat polygonal mat can be seen around the margin. In the pool, lower centre, the mat has spread from the margins to near the centre of the pool. The third pool, upper left centre, is well drained at low tides and has no algal development.

Plate 3.10.

Flat polygonal mats in poorly drained pools.

(a) The pool in the foreground shows patches of mat. The areas between the patches will gradually disappear and give way to a continuous spread of flat polygonal mat, as has already taken place in that part of the pool at the bottom of the photograph. The polygonal patches each have green unpraised rims. Note that the mats around the margins of these pools occur at two levels. Former exits from the pools have been dammed by growth of crinkle mat.

(b) A poorly drained pool completely floored with flat polygonal mat. Photographed at low tide.

of pools and along adjoining narrow channel ways or exists. In these latter areas, as the exists become constricted the pools become poorly drained. The newly formed flat mats along these passages are themselves then overgrown by the neighbouring crinkle mat which forms dams across them. Thus, growth of flat mat along the channelways is doubly important both in narrowing exist passages and in creating a suitable substrate for later crinkle mat colonisation. This results in partial blocking of the drainage and the creation of shallow ponds which only drain slowly on the ebb tide. They contrast markedly with the well drained pools and channel downstream where such damming is absent: plate 3.9 (a).

By ponding semipermanent water the pools thus establish conditions suitable for flat mat growth. As a result growth rate increases and gradually proceeds toward the centre of the pool. In some cases tongues spread across the floor of a pool dividing it into smaller entities: plate 3.11. This further aids water retention when the tide goes out and accelerates the growth. Thus, the growth of this mat form can be hastened by minor morphological changes in the pool brought about by the mat itself.

In other pools growth of the mat starts at isolated spots in the pool itself as well as around the margin: plate 3.10 a. With time, as those isolated patches spread the intervening spaces gradually disappear creating a complete continuous carpet as shown diagrammatically in Fig. 3.2.

In most pools it was found that the mat in all stages of its development is usually outlined by upraised rounded margins. These actively growing margins or lips are green in colour compared with the beige colour of the mat

Plate 3.11.

Growth of flat mat in a pool. The mat has spread out gradually from the margins of the pool, thus creating smaller pools. The edge of the mat is outlined by upraised rims which are olive green and contrast with the rest of the surface of the mat which is beige to brown.

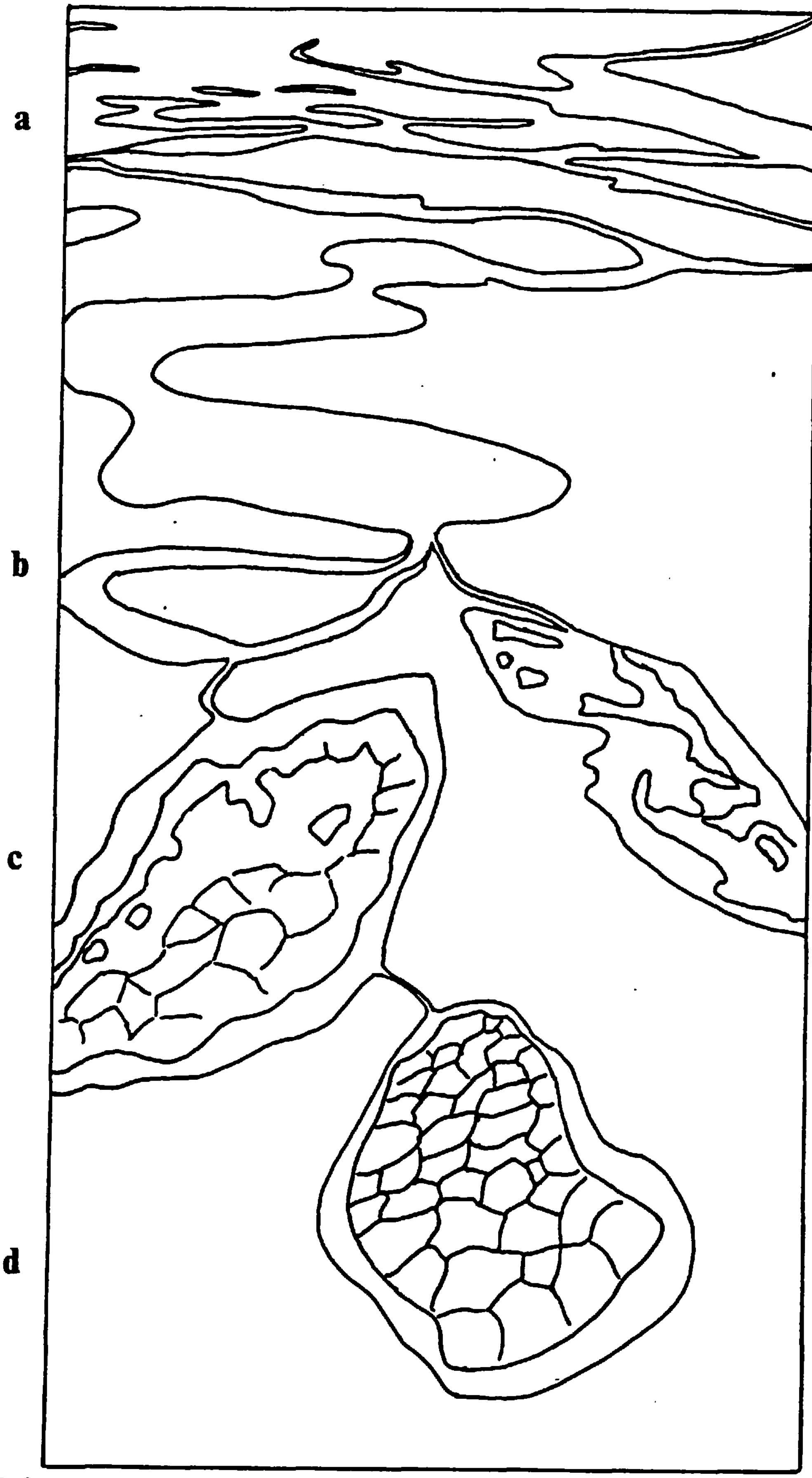


Figure 3.2.

Diagram illustrating the succession of atages in the evolution of poorly drained pools and ultimately the development of flat polygonal mat.

(a) Well drained pools and channels devoid of mat.

(b) Pools with partially blocked exits. Mats only fringe the pool margins.

(c) Poorly drained pools with narrower exits and patchy colonization.

(d) A poorly drained pool fully colonized by flat polygonal mat.

Plate 3.12.

Flat polygonal mat in vertical section. The pit shows discrete polygonal structures underlain by laminated organic rich mud. The dark colour is indicative of the reducing conditions which develop below the surface of the mat.

Plate 3.13.

Section of one of the discrete polygonal structures showing thickness of laminae. The top comprises slightly concave-up laminae due to active growth around the margin of the polygon.

surface. In cases where continuous flat mat originated from laterally coalesced patches, it is those upraised margins around the original patches which give the polygonal appearance of the mat. The polygonal pattern is thus the result of interference, and is not caused by shrinkage due to dessication.

Where the spaces between polygonal patches become filled with sediment, this leads to the formation of discrete polygonal structures: plate 3.12. Vertical sections through these structures exhibit changes in lamination from domal at the base to concave-up at the top of the mat: plate 3.13.

The latter change in configuration of the laminae results from growth of the marginal lip which leads ultimately to the formation of polygonal saucers, i.e. structures with raised edges and depressed centres similar to the inverted hemishperoids (SH-I) of Kendal and Skipwith (1968). The laminae appear very thick in hand specimen compared with the laminae of the mounds previously described. They reach as much as 0.4 cm in thickness and the average total thickness of the mat is about 6 cm. The strongly cohesive nature of the mat is due to its high organic content. In most places the flat polygonal mat was found to overlie black laminated organic mud.

3.3 Tufted mat

Tufted mat differs from all other mat forms, which tend to have smooth surfaces, in being made of closely spaced vertical bunches of algal filaments. These sometimes vaguely resemble the shape of sharks' fins. This variety of mat is also characterised by a dark green to black colour. It is equivalent to the tufted mat of Shark Bay, Davies (1970) and Logan et. al (1974) ; similar to the pinnacle mat of the Trucial Coast, Park (1973); and to the Lyngbya mats of Baja California, Horodyski (1977). The mat building alga is predominantly the filamentous cyanophyte Lyngbya aestuarii, whereas the other mat forms are dominated by the cyanophyte Microcoleus chthonoplastes. (The biology of the mat will be discussed in Chapter 5).

Tufted mat is very common in almost all localities in middle to upper intertidal settings along Khor Al-Ama, where the frequency of wetting is relatively high. However, the optimum conditions for its development appear to exist in a small circular pond in locality G which is completely floored by it. The pond is a few hundred square metres in area and is permanently covered by a thin sheet of water which ranges in depth from few centimetres during low tide to a few decimetres at high tide. The pond is connected to the main tidal channel by a narrow passage which runs east-west (Fig. 2.1). The water of the pond is supplied both through this passage and directly by flooding from the main tidal channel during high tide. Variations in frequency of wetting in the different parts of the pond results in the formation of morphologically different varieties of tufted structures. At the centre of the pond where the mat grows in conditions of permanent standing water, the mat is olive green in colour, and it forms round-topped mounds which have star-shaped pattern: plate 3.14. The mounds are connected by low ridges to form an overall reticulate pattern. Away from the centre of the pond towards the intermittently emergent conditions, small tufts with acute tips are found arranged in a polygonal pattern (plate 3.15).

Plate 3.14.

Star-shaped mounds of tufted mat in the middle of a pond, locality G, where the mats are continuously submerged. Note that the tops of the mounds are slightly rounded: compare with Plate 3.16.

Plate 3.15.

Tufted mat in partly submerged conditions close to the margin of the same pond as Plate 3.14. Tufts with acute tips are arranged in a polygonal pattern. The water ponded by these polygonal shapes is normally less than 5 mm but it is sufficient to create semipermanent submerged conditions. Inside these polygons, small round knots of filaments are visible.

This is best seen when the area is partially covered by the tide and each polygon acts as a small ephemeral pool. Small round-topped mounds can be seen developing inside the polygons. It seems as if the polygonal pattern results from growth of closely spaced tufts, which retain films of water during ebb tide. However there is the possibility that they might be moulded on the outlines of pre-existing desiccation polygons which may have been formed if the area was subaerially exposed for a relatively long period at some earlier time.

Closest to the margin of the pond, that is in more frequently aerially exposed settings, the tufts are dark green to black. They have a much more peaked shape, and may be as much as 2.5 cm high but only 1.2 cm wide at the base: plate 3.16.

In the area between the pond and the main tidal channel, the mat takes on a different shape and mode of occurrence. It forms rounded domal masses about 2-6 cm across and up to 3 cm high: plate 3.17. These are situated between mounds of crab burrows and halophytic plants such as <u>Salicornia</u>. The domal structures result from growth of tufted mat over the partially lithified crab burrow mounds. In some places the rounded masses have coalesced to form a continuous carpet of tufted mat: plate 3.18.

In the area H, tufted mat occurs on the tidal flood plain between branching creeks. There, it has three modes of occurrence: (a) As a continuous carpet of pinnacles: plate 3.19. (b) As small isolated patches of tufted mat within crinkle and curled mats: plate 3.20. (c) As fine tufts colonising other mat forms such as discrete algal heads: plate 3.21 and crinkle mat: plate 3.22. In the latter cases,

Plate 3.16.

Close up of tufted mat on the margin of a pond which intermittently dries out. Note the high peaked nature of the dark green pinnacle shaped tufts.

Plate 3.17a. Aligned clusters of mounds of tufted mat in the area between G and the main tidal channel. Crab burrows and halophytic plants occur between the clusters, (see also Plate 3.17b).

Plate 3.17b.

Detail of photograph 3.17a. The algal tufts form over partially lithified crab-pelleted sediment.

Plate 3.18.

Carpet of tufted mat produced by the coalescence of domal structures similar to those shown in Plate 3.17.

Plate 3.19.

Carpet of pinnacle-like tufts in area H. The tufts are uniform in size and display strong preferred orientation.

Plate 3.20.

Small patchy development of tufted mat in a zone of crinkle mat and curled.

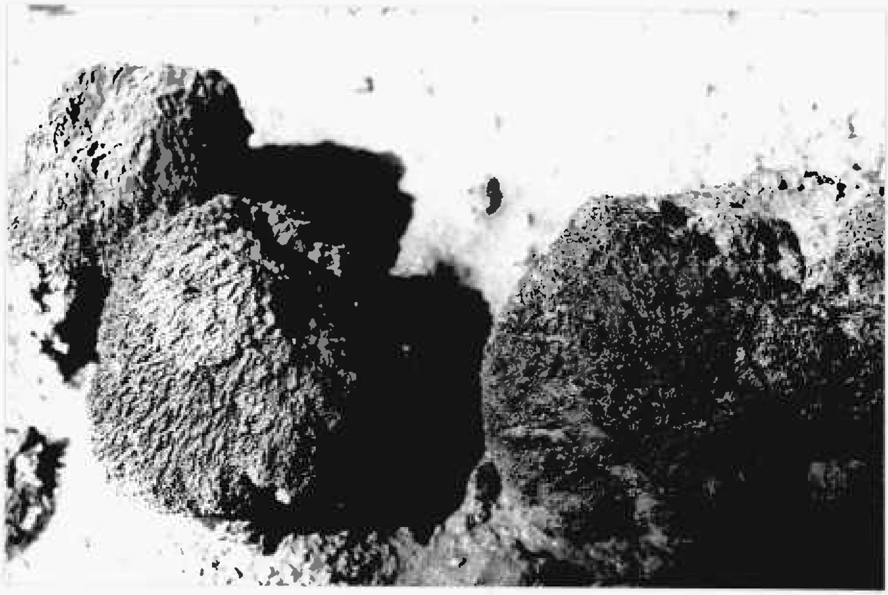


Plate 3.21.

Tufted algal filaments colonising discrete algal heads.

Plate 3.22.

Tufted algal filaments colonising the crests on crinkle mat.

Plate 3.23.

Coalesced tufts forming sharp-crested ridges with rectilinear arrangement.

Plate 3.24.

Tufted mat in the form of small knots of algal filaments, carpeting a shallow drainage channel in locality H. The mat has a net-like arrangement and overlies widely spaced gas blisters on crinkle mat.

overgrowths of fine pinnacles are commonly restricted to crests of crinkle mat.

The pinnacle-like projections 1-2 cm in height, usually display strong orientation which appears to be constant for each locality, and depends mostly on the direction of water movement (plates 3.18 and 3.19). In many instances, the pinnacles coalesce laterally to form sharp-crested ridges. The ridges may appear either, as subparallel lines, or, in a rectangular pattern: plate 3.23.

At the extreme end of the upper intertidal algal flat at locality H, it is common to find this type of mat carpeting the shallow drainage courses that flow towards the salt flat: plate 3.24. There it appears as a network of small knots of tufts covering widely spaced gas blisters of crinkle mat which floor most of the drainage creeks.

In summary it becomes clear that variations in the detail of the growth morphology of the tufted mat reflect differences in the degree of wetting to which they are subjected. Pinnacle-like tufts with acute tips as well as sharp crested ridges occur in intermittently emergent settings, while round-topped knobs develop under permanently moist conditions.

The tufts by themselves are almost entirely organic but they may act as sediment traps by collecting transported particles in depressions between tufts.

3.4 Discrete algal heads and oncolites

Discrete algal heads are isolated structures with considerable diversity in shape and size. They are found in locations where mechanical energy of tidal scour is relatively high, and they also usually occur in close proximity to certain types of crab burrows. They are developed either singly or in clusters in transition areas between algal flats and the crab zones which lie in the lower, seaward portion of the tidal flats.

In the area E, discrete heads are present as small domes characterized by rounded smooth surfaces. They are sited in the spaces between small crab mounds: plate 3.25. Sections cut across individual heads show that they are mostly hollow, but some are not. The latter are composed of superimposed convex-up laminae.

The heads or clusters of heads are kept separate by a combination of the scouring action of ebb and flow tidal currents, and, the activities of burrowing crabs. Where burrows are less frequent and as tidal scour decreases, the algal heads coalesce and develop into patches of crinkle mat: plate 3.26. Passing further inland along the shore of Khor Al-Mufatteh, crab burrows disappear completely and the whole surface is then colonised by continuous crinkle mat. In contrast, seaward of the zone of discrete algal heads, where burrowing crabs increases in abundance and the effects of scour become stronger, the area is devoid of any algal growth. However, small spherical algal balls or oncolites are found in some places bordering the main tidal channels of Khor Al-Mufatteh and Khor Al-Ama where energy conditions are relatively high. Small pelletoidal grains and shell fragments are subjected to intermittent agitation and serve as nuclei around which concentric algal laminae develop and ultimately give rise to oncolites. The average diameter of these oncolites does not usually exceed 1.2 cm and they are very

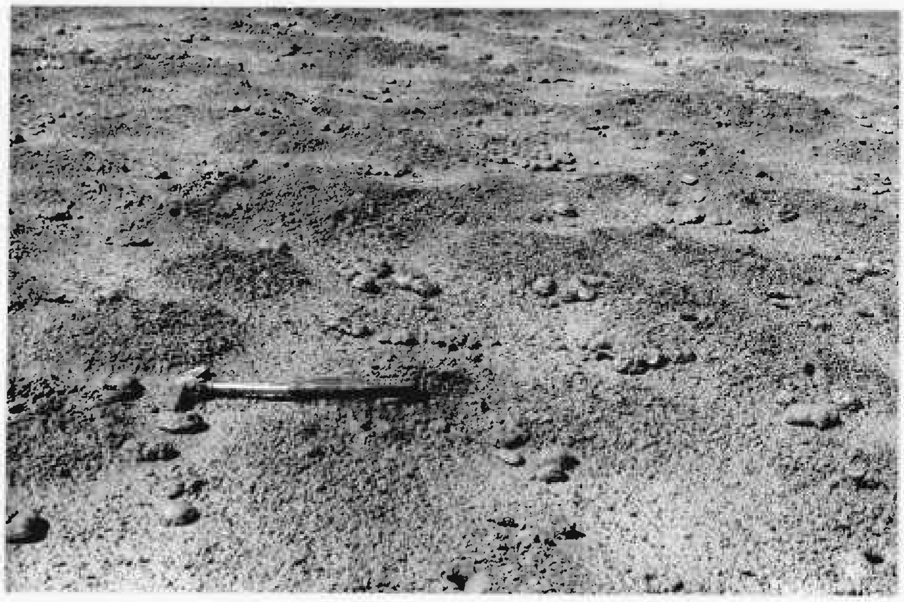


Plate 3.25.

Discrete algal heads with smooth rounded surfaces at locality E. The heads are located between mounds of crab burrows.

Plate 3.26.

The upper part of the zone of discrete algal heads, showing gradual transition into a continuous spread of crinkle mat.

well rounded.

In area H, where scouring and channelling are much more intense than at locality E and, where the sediments are of sand grain size, the discrete algal heads exhibit different characteristics.

In many places, the banks of the main tidal channels are partially cemented and are coated with a thin semi-lithified algal cover. These banks are subjected to the mechanical scouring of tidal currents as well as the activities of burrowing crabs. The banks become undercut leading to the formation of pebble size debris: plate 3.27. Some of these intraclasts become the sities of further algal growth. It appears that active algal growth is limited to the pebbles, and does not take place on the surrounding interareas, presumably because of the abrasive action of tidal scour. Such discrete heads are illustrated in plate 3.28.

Algal colonisation and doming over pre-existing relief features and irregularities is also noticeable in many shallow creeks which run close to the main tidal channel of Khor Al-Ama. This relationship indicates that mechanical scouring played a role in preventing algal development in the intervening spaces, and resulted in development of discrete algal heads, i.e. growth is upward rather than lateral. The average diameter of the heads is about 6 cm and they are mostly hemispherical in shape. Many of them are undercut at the base: plate 3.28. This latter feature can be interpreted as an expression of scouring.

Cross sections of some of these heads show that two types of laminae occur. Following the nomenclature of Logan

Plate 3.27.

A partially cemented channel bank at locality H. Scouring effects of tidal current accompanied by the activities of burrowing crabs have undercut and weakened the outer bank causing it to collapse and give pebble size clasts.

Plate 3.28.

Discrete algal heads along the bank of Khor Al-Ama in area H. The algal heads have been undercut by tidal scour which has also inhibited algal growth between the heads.

and others (1964), these are: (i) Discrete, vertically stacked hemispheroids with constant basal radius (SH-Ċ). (ii) Vertically stacked hemispheroids with variable basal radius (SH-V).

The surfaces of most of the heads are usually ornamented with tufted mat: a feature best displayed in algal heads found in the interareas between crab-burrow mounds: plate 3.21. Their equivalents in area E do not show such marked ornamentation because of the absence of tufted mat.

It is interesting to note that some of the algal heads, particularly those along the channel margins from locality H, show signs of branching: plate 3.29. It seems that many of the above mentioned controls on the formation of discrete algal heads also apply in development of branching heads. Branching may result from active growth on raised parts which enhances irregularities of substrate. In other instances successive laminae may smooth out irregularities. Thus, it appears that sizes and shapes of heads are often dependent on those of the bases or nucleii, although it is clear that abrasive action of tidal scour also plays a role.

These algal heads which can be regarded as SH (stacked hemispheroids) structures following Logan et al (1964) are relatively small compared with the cryptozoon structures at Shark Bay, which reach a maximum height of 2.5 ft; Logan (1961).

In contrast to the subaqueous mounds, which are organic rich structures with only very fine grained trapped sediments, discrete heads are generally sediment rich and contain coarser sediment grains.

Plate 3.29.

Discrete algal heads along the bank of the main tidal channel at locality H. Note the tendency of the heads to branch.

It is worthy of mention, that some of the algal heads , especially those which have a roughly cylindrical shape can be easily detached from the substrate by tidal scour. This leads to the formation of oncolites.

3.5 Crinkle mat

Crinkle mat is characterized by a leathery appearance and blistered skin: plate 3.30. It is the most abundant mat form in Al-Khiran area, where it covers most of the protected intertidal mud flats. Crinkling of the mat produces a variety of hollow domal structures some of which are hemispherical. The surface is usually very smooth and its colour ranges from olive green in areas of more frequent wetting to beige or brown in drier locations. It sometimes appears whitish-grey, especially during summer, due to the presence of a thin salt crust.

This mat form is equivalent to mats in the "Crinkle Zone" of Kendal and Skipwith (1968) and resemble "convoluted mat" of Davies (1970). The average thickness of the mat is about 1 cm. The lamination is varied, and depends mainly on the type and amount of sediment which is introduced by tidal flooding (detailed discussion of lamination will be dealt with in Chapter 5). The maximum thickness of the mat occurs adjacent to the main tidal channel in area F, where it may reach up to 6 cm: plate 3.31. It is there too, that the hemispherical blisters reach their largest size. Most of the mat has an average relief in the order of 2.5 cm. Landward away from the tidal channels the mat shows progressive decrease in relief and passes gradually into curled mat. In

Plate 3.30.

Close up view of crinkle mat, showing large closely spaced blisters.

Plate 3.31.

Crinkle mat along the margin of the main tidal channel in area F. Note the high relief of the mat and the large size of the blisters.

some places the crinkle mat may be seen to pass laterally into a flat non-crinkled skin, without any relief (similar to 'Flat zone' of Kendal and Skipwith (1968).

In localities F and H, the dome-shaped structures or hemispheroids which are adjacent to the tidal channels are slightly more widely spaced; i.e., the spaces between blisters is greater than their diameters. They are similar to the laterally-linked hemispheroids, types (LLH-S), of Logan et al (1964) except that they are hollow. Inland from these areas, the hemispherical blisters of the crinkle mat become contiguous, and thus resemble the closely linked hemispheroids (mode LLH-C) (Logan et. al. 1964). It is most likely however, that because of the hollow structure of this type of mat form it would flatten after burial.

Crinkle mat grows in intermittently emergent conditions, where it is uncovered diurnally at low tides, but because of the high water content of the underlying muddy substrate, the mat remains moist even during low tides.

Higher up the tidal channels towards the upper intertidal mud flats, tidal creeks become very shallow and the relief of the surrounding crinkle mat decreases gradually: Plate 3.32. Closer to the salt flats, crinkle mats become restricted to the banks of small tidal creeks where they drape over the steeply sloping sides: Plate 3.33. Low relief crinkle mat to nearly flat mat is also a characteristic feature of the algal flats in the protected coastal lagoons (localities A and B).

Near the landward margin of the crinkle mat, particularly along the main tidal channel in the area F, it is not uncommon to observe gas bubbles escaping (with an audible noise) through

Plate 3.32.

Low relief crinkle mat surrounding a shallow tidal creek with local dams of crinkle mat cutting across the creek.

Plate 3.33.

Growth of crinkle mat along the bank of a small tidal creek in area F.

the pitted, low relief mat surface as it becomes covered by the rising tide: Plate 3.34. In this may lie the clue to the origin of the blistered surface of the crinkle mat. It is most likely that as the tide rises, trapped air or gases of organic origin are forced to migrate beneath the semi-permeable algal skin. As a result the mat is uplifted and becomes only loosely attached to the sediment below, leading to the formation of blisters. Gases driven by the advancing tide may finally escape by locally disrupting the surface.

According to Cloud (1960), gases of organic origin can be evolved by bacterial decay of organic matter. They comprise mainly carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S) and hydrogen (H_2). That entrapment of evolved gases may be a factor in the development of blisters was also suggested by Ginsburg et al (1954, reference in Davies, 1970) and Davies (1970). Alternatively a high rate of lateral growth by itself may lead to lateral pressure in the mat and consequently gives rise to crinkling.

It is possible in some instances that uplift or doming of the mat was aided by the growth of displacive gypsum crystals within the mat. This cannot be considered as a prime factor because, crinkling can be seen in many places where there are no gypsum crystals. Further, little or no crinkling is seen in many places where gypsum is found both in the mat and in the sediment beneath.

In summary, blistering of the crinkle mat in the Al-Khiran area is probably caused both by movement of trapped gases beneath the relatively impervious algal skin and the lateral expansion of the mat surface due to high rate of algal growth.

Plate 3.34.

Low relief crinkle mat covered with thin film of flood water. Note the gas bubbles escaping through small pits in the mat surface.

3.6 Curled Mat

Curled mat is found in the uppermost parts of the algal flats which are flooded for the shortest period of time. It is considered to be a modification of the crinkle mat due to high desiccation. The mat is characterized by low relief, small thickness, pale brown to grey colour and its concavely curled surface.

In the highest parts of the interchannel areas of locality H, intense desiccation has caused the mat to crack and curl upwards forming flakes up to 3 cms across. As desiccation proceeds, the flakes continue to curl and roll up, (Plate 3.35) and become entirely detached from the underlying sediment. These algal flakes are analogous in shape and genesis to the hollow algal balls of Davies (1970). Once the flakes become detached from the sediment, they are easily transported by wind.

It has been found that these hollow 'oncolites' are usually formed in close proximity to patches of tufted mat: Plate 3.20. In some cases they are overgrown by fine tufts of Lyngbya aestuarii, whose presence may have aided the development of the flakes.

In the area F, where tufted mat is absent, desiccation of the uppermost part of the crinkle mat causes the blisters of the mat to rupture and collapse without formation of concave upward flakes. It is suggested therefore, that modification of the crinkle mat due to desiccation is dependent among other factors, on the amount and type of algal species in the mat.

Plate 3.35.

Curled mat, locality H. Curling resulting from extreme desiccation has produced hollow spheroidal flakes. Most of these flakes are detached from the underlying sediment and form hollow oncolitic-like structures.

Plate 3.36.

Low relief algal mat in locality A, where extreme desiccation at the landward margin of the mat has caused overfolding of large sheets of mat. Lagoonward is to upper right of photograph.

Algal mats along the coastal lagoons (localities A and B), differ from the mats in other areas in their behaviour during desiccation. There, desiccation has cracked the mats into roughly polygonal shapes, which sometimes curl upwards at their edges. This is due mainly to their relative flatness, coarser sediment content, low organic content and sandy substrate. In locality A, at the landward margin of the mat where it is subject to the highest desiccation, the landward edges of the mat dry out and start to roll up in large sheets: Plate 3.36. The rolling-up or overfolding is directed lagoonward, i.e. with convex sides of the folds pointing landward. This behaviour of the mat is different from that found by Davies (1970) where the overfolding is directed landward as a result of onshore, flood-tide forces.

It appears therefore, that the response of crinkle mat to desiccation is varied, and depends on several factors: viz (a) duration of subaerial exposure; (b) relief of the mat and its thickness; (c) size of incorporated sediment particles; (d) proportion of organic matter and types of algal species, and (e) the type of substrate.

3.7 Areal zonation of the morphological types of algal mat

The distribution of algal mats and the regional zonation of the various growth forms are largely governed by frequency of flooding and frequency of wetting or desiccation. Flooding frequency refers to the frequency with which any location in the intertidal flat may be covered with sea water by tidal flooding. This frequency is a function of the elevation of any point in the intertidal zone, relative to the low tide level. Wetting frequency is the duration in which a surface may be kept wet by any mechanism. It is in part a function of micro-relief, i.e. local differences in relative elevation.

In general terms there is a regional zonation of mat forms, but irregularities of surface relief, and the presence of pools and channels, lead to local variations which sometimes mask the simple picture. Broadly speaking the zonal distribution of mat forms is influenced by the general slope of the tidal flat and the local irregularities. Obvious zonation of mat forms can be seen on tidal flats with gentle slopes. Where the gradients is steep, the mat forms are condensed to the extent that three or four types can be seen resting one on top of the other in the one place : plate 3.8.

The algal flats along the tidal channels of Al-Khiran can be divided into three main zones. These are:

(i) The lower algal flats

In the lower parts of the algal belt, the sediment are intensely bioturbated by large populations of burrowing crabs. This disturbance of the sediment and the scouring action of the tidal waters are the main factors which prevent the establishment of mats in the lower part of this zone. Small patches of mats and a few small discrete algal heads are found in the upper part of the zone where the crabs are less abundant. There are some pools in this zone; and all of these are devoid of algal mat because of the grazing activity of the many cerithid gastropods which live in them. The pools also have a population of very small fishes which may also feed on the algae.

(ii) The middle algal flats

The middle belt of the algal flats is characterized by the numerous pools and channels. Algal mats occur not only on the flats but also in the pools and channels. The presence of algal mats in these pools contrasts markedly with the absence of mats in the pools lower down on the same flats. The difference is accountable by the fact that cerithid gastropods and burrowing animals are absent from the higher pools. Salinity may be the controlling factor.

Most of the various type of mat forms are present in this zone, which appear to correspond with the 'polygonal' and crinkle zones of Kendal and Skipwith (1968).

(iii) The upper algal flats

The upper parts of the algal flats are characterized by low relief mats which are often coated with a veneer of salt which persists throughout much of the neap tide interval. In places the mats desiccate and curl up and in consequence are torn off their substrate and blows away by the wind. This zone may correspond to 'flat zone' of Kendal and Skipwith (1968).

The long period of evaporation result in diagenetic interstitial growth of gypsum in the mats and in the underlying substrate. In extreme cases this growth of gypsum causes destruction of lamination of the mats.

The ecologic zonation around the coastal lagoons has been described in Chapter 2. Cores taken through the algal flats around lagcons A and B show that the algal mats overlay bioturbated carbonate sediments, and these in turn overlay muddy carbonate sediments in which cerithid gastropod shells are abundant. This succession records a regressive cycle, which comprises the upward passage from a lower intertidal subenvironment through middle to high intertidal settings.

Intertidal flats along the inner margins of tidal channels locally show similar regressive sequences in the lower part of the algal belt. However, the algal mat units are much thicker than those around the coastal lagoons.

CHAPTER 4.

CHAPTER 4

LITHIFIED STROMATOLITES AND ONCOLITES

4.1 Occurrence

Lithified stromatolites and oncolites in Kuwait State differ from all other algal mats of the region in that they are highly indurated, and are characterised by lack of particulate texture and the relative scarcity of algal remains. It is interesting to note that they closely resemble certain inorganic concretionary structures.

The lithified algal mats, i.e. stromatolites, are only found on porous 'beachrocks' along the sides of tidal channels: Plate 4.1. The beachrocks are restricted to those shores that face north or northwest; Fig. 2.1. These areas are exposed to waves and spray caused by the prevailing northwest Shamal wind.

4.2 Morphology

The lithified stromatolites display several varieties of surface morphology, such as: flat sheets which grade into crinkled or laterally-linked hemispheroids, discrete vertically-stacked hemispheroids and various irregular shapes. A similar crust also develops around all types of beachrock fragments forming oncolitic structures of various sizes and shapes.

The thickness of the stromatolitic crust ranges from several millimetres to about 3 cm. The outer surface is buff, beige or greenish-grey to black in colour. The crust is often broken into polygonal slabs due perhaps to desiccation, or repeated expansion and contraction due to wetting and drying and aragonite crystallization: plate 4.1. The topmost part of the crust may also crack and exfoliate, probably as a result of diurnal temperature changes. The surface of the stromatolitic crust is generally smooth, but in some cases it may be pitted. Some of these pits may have been formed before lithification commenced. This possibility is supported by the presence of similar pits on the adjacent non-lithified algal mats (compare Plate 4.2a with Plate 4.2b). There are places, however, where organism of one sort or another have clearly bored into the stromatolites after lithification.

The small hemispheroidal structures may be initiated by algal growth over pre-existing irregularities on the substrate. This preferential growth enhances the raised parts of the substrate while the adjacent depressions remain free or much less encrusted; plate 4.3. Development of these small hemispheroidal structures is often confined to banks around the channel bends, where energy conditions are strongest. In those places, algal growth, which starts as encrustations on surface irregularities on the beachrocks, continues to build on the crests, but growth in the intervening depressions is inhibited by erosion due to tidal and wave scour. The height of the structures is generally about 3 cms, but in slightly lower positions (a distance not more than 1.5 metres channelwards) the semi-lithified hemispheroidal algal heads may reach up to 7 cms in height. The height of the structures therefore, seems to be related to the amplitude of the tidal range over the various parts of the channel sides. The hemi-

Plate 4.1 (a). View of the bank of Khor Al-Mufatteh at locality D: showing beachrock encrusted with lithified stromatolite. The flat and crinkled stromatolitic crust are broken into polygonal slabs.

(b) Close-up photograph of the lithified stromatolitic crust showing several surface morphologies. The crests of the growth forms are beige or buff, while other parts are blue black. Elongation of the small heads is parallel to the tidal channel

Plate 4.2a.

Extensively bored surface of nonlithified leathery algal mat on the surface of the lowest part of the beachrock. (bedding plane view)

Plate 4.2b.

Lithified stromatolitic crust with an extensively bored surface. The two photographs 4.2a and 4.2b were taken only 60 cm. apart. (bedding plane view)

Plate 4.3.

Close-up photograph of a cemented stromatolitic crust, showing small hemispheroidal structures. The heads are elongate parallel to the channel side.

Plate 4.4.

Nonlithified, living mat (darker buff patches) overlying an indurated crust. The leathery algal mat is draped over the beachrock margin.

spheres are beige in colour while their sides are dark blue to black. The latter may result from heavy infestation by boring algae.

In many places in the lower zones of the lithified crust, the beachrock is covered with non-lithified algal mat; plate 4.4. These tend to occur along the margin of a tidal channel. In some lower positions of beachrocks, active algal growth may build up individual isolated heads, some as high as 7 cms. The living topmost parts of these algal mats and semilithified stromatolites were found to be pervaded by filamentous and coccoid blue-green algae.

4.3 Shapes and orientations of the lithified hemispheroidal algal structures

Observations show that there is a tendency for the small ellipsoidal 'hemispherical' algal structures to be arranged in rows and to be elongate subparallel to the tidal channel; i.e. in the direction of water movement. In many cases they exhibit a distinct elongation which trends at an angle of about 25° to the direction of the local shoreline of the channel. The structures tend to widen upward and where closely spaced the heads sometimes coalesce; plate 4.5.

On applying the geometric classification scheme proposed by Logan et al (1964), the structures can be described as discrete, vertically stacked hemispheroids which pass into laterally-linked hemispheroids as a result of upward growth expansion. Thus the compound structure may be designated SH - LLH.

In almost all cases the domal hemispheroids are tilted channelward, and if they are cut in half vertically, their constituent laminae show a similar asymmetry; plate 4.6. This inclination towards the channels is probably due to the fact that this is the direction from which both water, sediment and nutrients reach them. Hoffman (1967) has used such asymmetrical growth forms as paleocurrent indicators.

Domal or hemispheroidal structures are particularly common in settings where currents and wave action are relatively strong. Such places are generally found at bends along channels, particularly those which face the prevailing shamal wind. In other settings where currents and wave action are relatively weaker, only flat sheets of stromatolitic crust are formed.

The lithified stromatolitic structures of Al-Khiran bear some resemblance to those described from Hamelin Pool in Western Australia, especially in terms of morphology and environmental setting. The only real differences is that the domal structures of Al-Khiran are much smaller and are more indurated. In Hamelin Pool, the best previously known examples of modern stromatolites occur on rocky headlands in the intertidal zone where they have become lithified as a result of subaerial exposure. In the intervening bays only flat unlithified algal mats occur, (Logan 1961; Hoffman 1976). The lithified stromatolitic crust of Al-Khiran may also be analogous to the subfossilized, indurated stromatolites of Marion Lake, South Australia described by Von Der Borch et al (1977).

Plate 4.5.

Cross-section of small laterally-linked hemispheroids. Note the creation of large primary voids as the heads coalese.

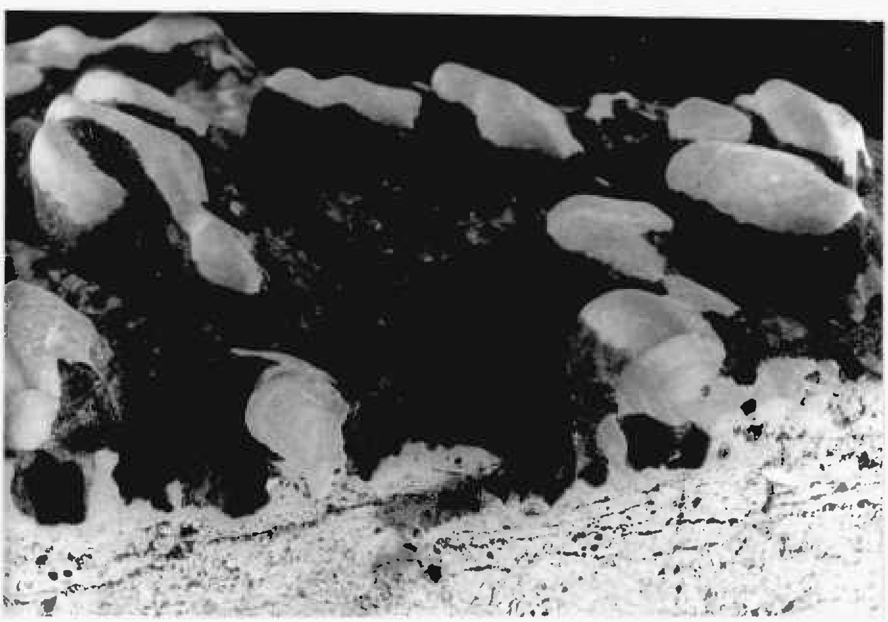


Plate 4.6.

Vertical section through lithified stromatolitic heads and the underlying beachrock. The section is perpendicular to the direction of the channel which lies towards the left of the photograph. The hemispheroids are tilted or inclined channelward. The convex up laminations display marked asymmetrical growth leaning into the on-shore waves. Note the horizontal or sheet cracks in the substrate. Height of structure is about 3 cm.

4.4 Internal structure and lamination

Vertical cross-sections through the lithified algal mats show an asymmetrical convex-upward arrangement of distinct alternations of dark and light brown laminae: plate 4.6. The laminae which can be seen in hand specimen vary from 1 mm to 0.2 mm in thickness. The thicker laminae are usually characterised by an alignment of pores which gives them a porous appearance: plate 4.7. The pore spaces are usually elongate and lie perpendicular to the laminae. The alignment imparts a palisade-like appearance to the otherwise concentric laminae: plate 4.7. Similar structures have been termed: fenestrae, unsupported voids, loferites, bird's eye structure or open space structures by various authors. The term fenestrae will be used in this thesis to describe the structures.

Examination of thin sections shows that the laminae structure is produced by alternations of dark and light brown micritic carbonate layers. The dark brown laminae are very thin with a few if any fenestrae. The dark colour suggests that these layers are rich in organic matter. The light coloured layers are much thicker, with an abundance of elongate tubular fenestrae. Some of the latter are extremely small and can only be properly studied under the optical microscope, where they can be seen to enclose algal remains and/or pigmented organic matter: plates 4.8 and 4.9. In any one zone, the fenestrae are all of the same order of size, but the sizes vary from zone to zone: plate 4.9.

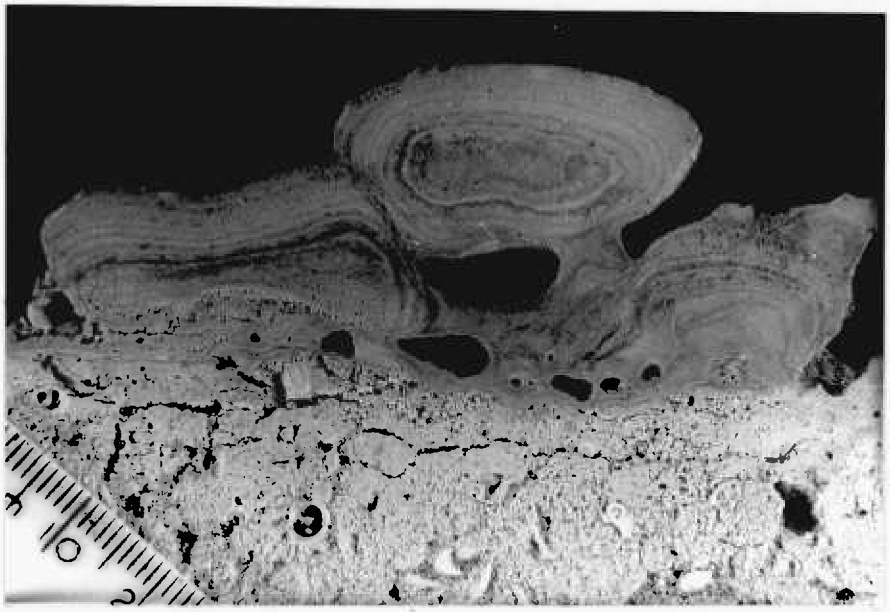


Plate 4.7.

Cross-section of lithified hemispheroidal stromatolitic structures showing both concentric and radial fabrics. The radial or pallisade fabric is due to alignment of vertical fenestrae which are readily visible to the naked eye, especially at right hand side of the photograph. The oncolitic structure at the top of the photograph is part of asymmetrically growing hemispheroidal structure cut parallel to its elongation. Note the porous oolitic substrate and the horizontal cracking.

Comparison of the lithified stromatolitic crust with the nonlithified algal mats which lie on top of it, shows that the laminae in both are almost identical (compare plates 4.9 and 4.10). Thin section examination of living algal mats reveals the presence of thin, dark and dense algal rich horizontal layers which alternate with thicker layers composed of vertically oriented algal filament molds surrouding pelletal grains: plate 4.10. Such vertical algal growths play an important role in the mechanisms of trapping and binding of sediment particles which in turn leads on to the construction of the organo-sedimentary layered structures. It therefore appears that the vertically oriented fenestrae in the lithified stromatolites originated as a result of decay of algal filaments which formerly stood vertically. However, they appear to have been enlarged, probably as a result of the activities of coccoid algae which promoted dissolution of the carbonate of the walls. Logan (1974) in his description of similar vertical features in the 'Intertidal Veneer' of Shark Bay, suggested that they were root moulds after higher plants such as halophytes and mangroves. This is not possible in the occurrences in Kuwait State because no higher plants, not even Salicornia live along the rocky shores of the Khors.

The fenestrae must not be confused with larger voids in the stromatolitic crust which were formed as a result of the coalescence of the heads of adjacent domal structures. Often where the heads of domes have coalesced, individual lamiane in the top parts of the structures can be followed from one to another forming bridges over the underlying interdomal voids: plates 4.5 and 4.6. Large carbonate grains,

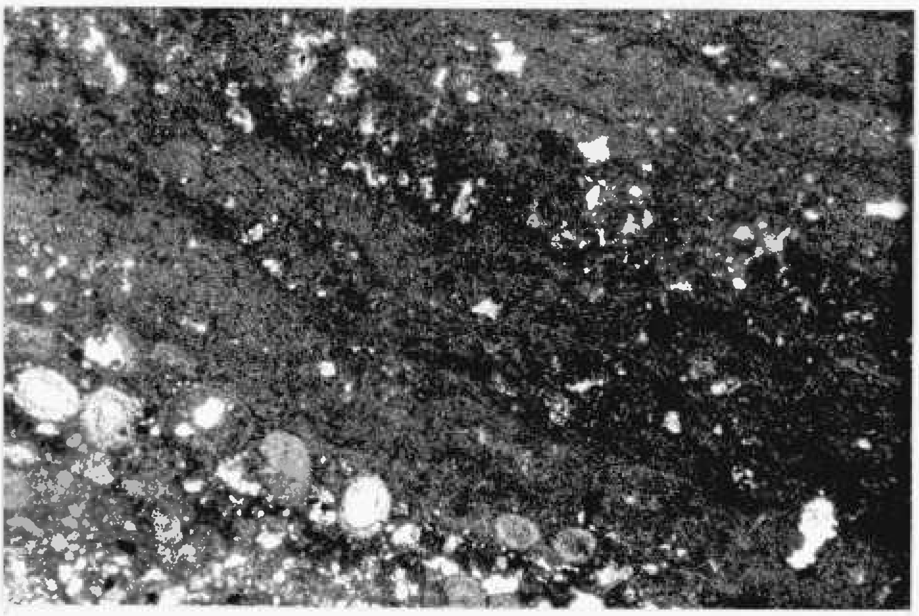


Plate 4.8.

Photomicrograph of a lithified stromatolitic crust: showing alternations of dark and light brown laminae of micritic aragonite. Note the alteration of grains near base of the stromatolitic crust. The lower left of the photograph is part of the underlying substrate, (x 30).

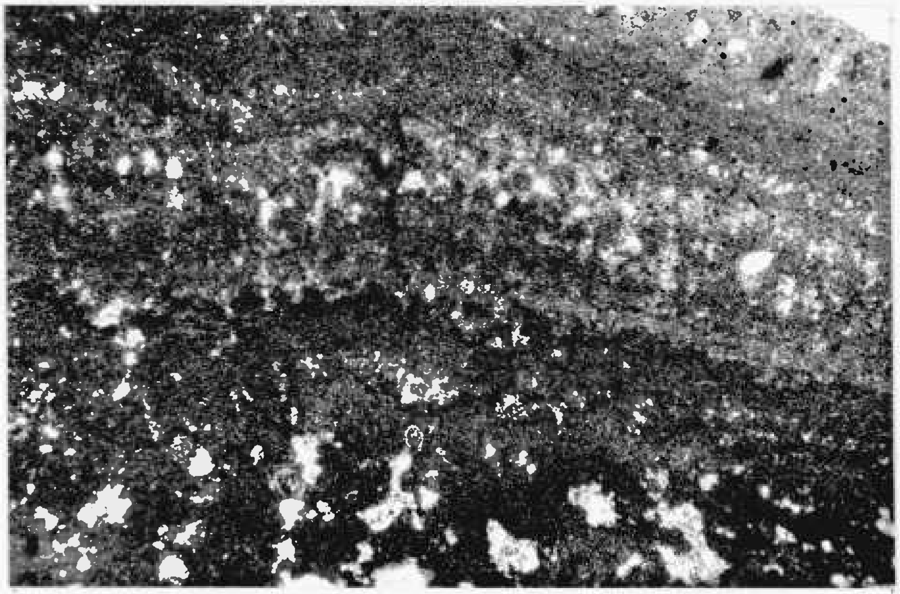


Plate 4.9.

Photomicrograph of an indurated stromatolite showing alternate dense and porous laminae with little sign of any entrapment of sediments. In any one of the porous laminae the fenestrae tend to be uniform in size and shape. Some are extremely fine while others are large and orientated normal to laminae, (x 13).

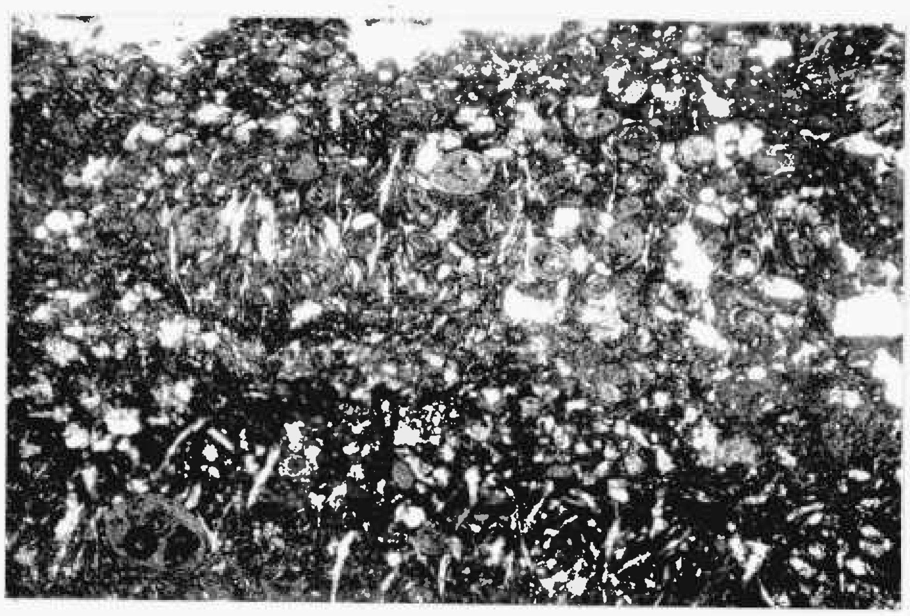


Plate 4.10.

Photomicrograph of living algal mat, showing alternations of sediment-rich and organic-rich layers. Note entrapment of pelletal grains between vertically orientated algal filament molds. These laminae and the vertical orientation of algal molds are similar to the laminae and fenestral fabrics shown in plate 4.9, (x 30).

such as skeletal fragments are often washed up onto the banks of the Khors, and some of them fall into the depressions between algal domes. When the algal heads coalesce the exotic grains become permanently trapped. In some instances a lodged skeletal fragment may become the substrate for algal encrustation and thus facilitate the lateral linkage between adjacent domes.

In addition to the above mentioned primary voids, there are other voids which result from later boring by molluscs etc. They vary in size depending upon the type of organism. Some of these borings may have been created prior to complete lithification.

Many of the primary voids and most of the later bores are partially filled with fine grained carbonate sediments, silts and/or muds which were washed in during storms. This introduced sediment often has a geopetal arrangement. The geopetal fillings are accompanied in many cases by diagenetic growth of lenticular gypsum crystals. Some of the fenestrae, primary voids and bores are lined with fibrous aragonite, while others are filled with gypsum crystals.

4.5 Oncolites

The stromatolitic crusts are commonly associated with intraclasts which are completely coated with laminated crusts which are identical to those which encrust the beachrocks. These oncolitic structures have a wide range of size and shape. They vary in size from coarse sand up to pebble grade, and the larger ones are generally tabular in shape, while the smaller ones tend to be subspherical. The stromatolitic crusts around these intraclasts vary in thickness, from few mm to about 2 cm, depending in part on the size of the nuclei. The surfaces of the oncolites are usually smooth and their overall shapes tend to be determined by the shapes of the nuclei.

Sections through the oncolites show that their nuclei are mainly intraclasts derived from the underlying beachrocks, plate 4.11, but some are mollusk shells, plate 4.12, or fragments of former laminated crust. Many of the oncolites were in fact pre-existing domal stromatolitic structures which became detached. Where these latter fragments were overturned a new algal coating developed on their former undersides, thus producing complex, compound oncolites: plate 4.13. Complete coating of large intraclasts does not seem to require continuous rolling about. The larger immobile polygonal slabs, commonly exhibit coatings on their upper surfaces only: but, if by chance a slab has been turned over, it will become coated. The abundance of coated intraclasts in close association with the polygonaly cracked stromatolitic crust, indicates that formation of the intraclasts was aided by both the vertical polygonal cracks and the horizontal sheet cracks. The large slabs often have smaller, second order polygonal cracks along which they may break later, and become further coated to produce discoidal or biscuit-like shapes: plate 4.11a. The oncolites can be transported for short distances either landwards or channelwards. In some instances, oncolites which occur along the bank of the tidal channel are carried to the upper intertidal and supratidal zones by waves during storms

Plate 4.11a.

Tabular oncolitic grains or "biscuits" with smooth surfaces.

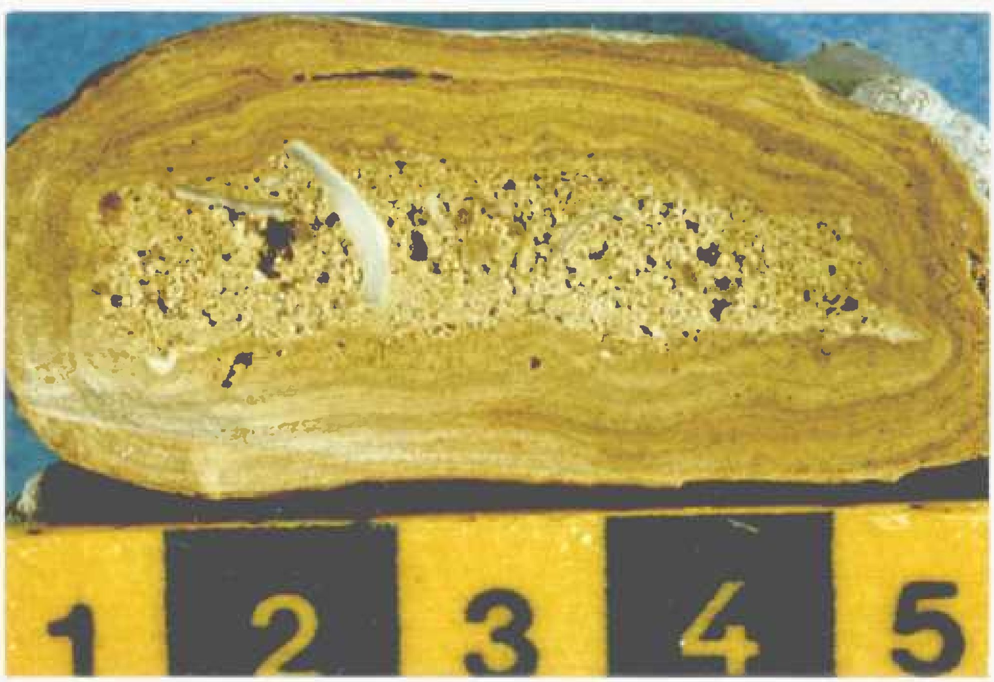


Plate 4.11b.

Polished cross-section through one of the tabular oncolites.
Note the finely laminated structure of the stromatolitic coating.

Plate 4.12.

Thin aragonitic encrustations coating mollusc valves.

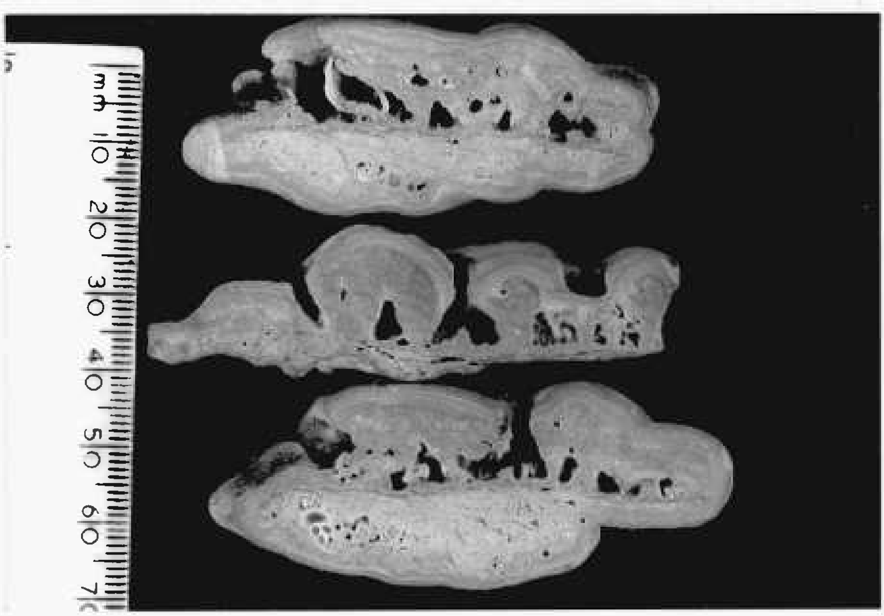


Plate 4.13.

Cross-section through oncolite-like structures formed after detachment from pre-existing stromatolites. Note the development of new coatings on their undersides.

at high tide flooding. Other oncolites however slide down the slope of the channel side, aided by the ebbing tide. In both cases the oncolitic grains become sorted: the smaller ones are generally carried for longer distances away from their place of origin. One can see how, by these mechanisms of transport, accumulations of oncolites may show both normal and inverse types of grading, such as are found in ancient pisolitic rocks: for example the Permian pisolites from the Capitan Reef of Guadalupe Mountain of New Mexico, (Dunham, 1969).

Unlike the above mentioned mobile oncolitic structures which always have a nucleus, vertical sections through the fixed or attached stromatolitic structures sometimes reveal concentrically laminated structures which have no foreign nucleus: plate 4.7. Such a concentric appearance is formed in situ as a result of asymmetrical growth of stromatolitic heads.

4.6 Processes of lithification

A satisfactory explanation for the local lithification of the stromatolites is not easy to obtain. However, it seems likely that the processes were the same as those which lead to beachrock cementation. This is suggested by the fact that the lithified stromatolites sit on beachrock, and the cement is continuous from one to the other. However, the stromatolites are more strongly cemented than the underlying beachrock.

The lithification takes place in a narrow zone along the banks of the channels. In this position the sediments drain readily each time the tide falls. The beach rock is in fact highly permeable so that the algal mats which overlie them drain out rapidly. Thus the small amount of water which remains in the mats evaporates quickly and immediately precipitates aragonite. Such rapid precipitation of aragonite could account for the cryptocrystalline texture. It may explain why algal mats found on muddy substrates are unlithified, because they are always wet due to the moisture retention of their substrate even at low tide.

In some places along the tidal channel banks, all stages can be found from nonlithified living algal mats to fully cemented ones. The partially lithified mats are only found immediately adjacent to the banks of the channels where they either, overlie the beachrock directly, or, have grown on top of pre-existing lithified stromatolitic encrustations. The lithified stromatolitic structures undoubtedly originated as algal mats. This is demonstrated by the following relationships: (1) The existance of uncemented algal mats and oncolites similar to the cemented ones. (2) All intermediates can be found between unlithified and lithified mats: sometimes even in the one hand specimen. (3) Identical growth forms can be found in both living and fully lithified mats.

There are differences in microstructure between the living and lithified mats, but these are all attributable to diagenetic modifications which accompanies lithification. The differences include: the presence of well developed fenestrae, absence of particulate texture and the scarcity of algal remains in the lithified material;

4.7 Possible role of blue-green algae in lithification

Generally speaking, algal mat structures lithified by contemporaneous in situ precipitation of calcium carbonate are very rare in marine environments but, they are not uncommon in fresh or brackish waters (Monty 1967, 1972; Golubic 1973). The precipitation of calcium carbonate occurs within or on the surface of algal sheaths, either, as a result of algal photosynthesis, or, of bacterial decomposition of the sheath (Gebelein 1974). In these cases the resulting stromatolites are strongly lithified. They usually lack particulate texture but molds of the algal filaments are often well preserved.

However, Recent stromatolites which formed by in situ precipitation of aragonite have been described by Horodyski and Vonder Haar (1975) from hypersaline ponds at laguna Mormona, Baja California, Mexico. These authors have shown that the coccoid cyanophyte, Entophysalis, "permineralized within an aragonitic crust". They also mention that the algae may cause the precipitation of aragonite in the ponds. Logan (1974) described hard pelletoid rinds in the supratidal zone of Shark Bay, Western Australia, where the coatings consist of layers of coccoid algae. These occurrences are fair evidence that blue green algae may play a role in lithification of stromatolites. It is likely therefore, that the coccoid algae which occur along the porous rocky banks of the tidal channels in Al-Khiran could similarly have participated in lithification. Although lithification by precipitation of aragonite in such settings can be induced inorganically, by the beachrock and surf spray process, utilization of CO_2 by blue green algae in the course of photosynthesis would accelerate the precipitation.

4.8 Scarcity of algal remains in the lithified crusts

The scarcity of remains of both filamentous and coccoid cyanophytes in the fully cemented stromatolitic structures is inevitable, because of the extent of diagenetic alteration. The fenestral fabrics in the lithified stromatolites are at least partly attributed to the destruction or decay of bundles of algal filaments.

Studies of modern and ancient stromatolites in carbonate sediments have shown that they contain little or no cellular material, despite the fact that algae were responsible for their development (for exceptions, see Awramik, 1976). For this reason the origin of stromatolites remained in doubt for a long time. It was only Black's studies in the Bahamas (1933) which confirmed their algal origin. The second most important discovery by Logan (1961) of well developed modern lithified seromatolites in Shark Bay, Western Australia, removed all doubt that they are organosedimentary structures of algal origin.

However, in spite of their ephemeral nature these primative microorganisms have been found completely preserved in cherts back into the Pre Cambrian. The oldest occurrences of blue-green algae (both coccoid and filamentous) known to date were found in the Fig Tree Chert of Rhodesia (about 3100 million years old) and in the Gunflint Cherts on the northern shore of Lake Superior in Canada (2,000 million years old) (see Awramik 1976).

4.9 Lack of particulate texture

The unlithified algal mats along the banks of the Khors in Kuwait State usually follow the contours of the substrate and drape over the edge or margin of the beachrock: plate 4.4. As seen under the microscope the laminae in these draped algal mats and semi-lithified stromatolites are vertical or near vertical, with the trapped carbonate sediment grains also arranged vertically. Such a vertical disposition of detrital grains may give the clue to the algal origin of those ancient structures, which have lost all their organic matter.

In the lithified stromatolites it is also common to find the laminae similarly draping over the edge of an individual head or over the edge of the beachrock. But, these occurrences apparently enclose no trapped sediment. Two possibilities arise: either, all trapped detrital sediment particles were diagenetically altered during lithification, or, that the stromatolitic encrustations were formed by in situ precipitation processes and not by the normal trapping and binding mechanism. These two possibilities will be discussed under the following headings:

(a) Role of blue green algae in destruction of particulate texture

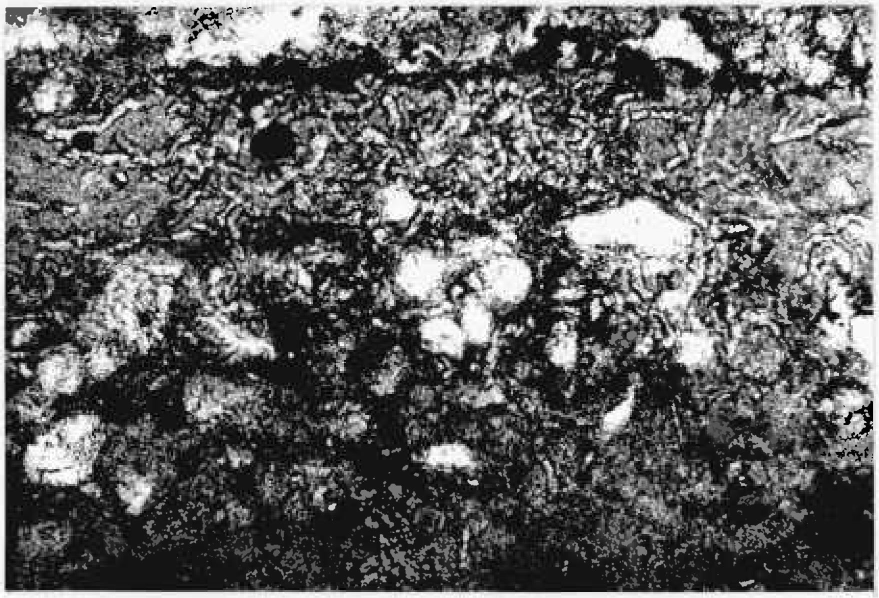
In order to understand the possible diagenetic effect of the endolithic coccoid algae it is necessary first to discuss briefly the findings of some previous workers. Bathurst (1966) has termed the repeated boring of carbonate grains by endolithic algae and the subsequent precipitation of micrite in the vacated algal bores as "micritization". The role of the micrite envelopes formed around skeletal grains by this process in the preservation of moulds of skeletal grains during subaerial, fresh water diagenesis was also described by Bathurst (1975). Kendall et al (1966) and Shearman and Skipwith (1965) emphasized the importance of algal mucilage which could act as a template in the course of diagenesis. Micrite envelopes similar to those described by Bathurst are found surrounding carbonate particles in many places along the intertidal zones of Al-Khiran area. The envelopes vary in thickness and their inward extensions are often seen to cut across the fabric of the skeletal grain.

Kendall and Skipwith (1969) found that all types of carbonate grains in Khor Al Bazam, along the Persian Gulf, have been altered to some extent to microcrystalline aragonite apparently as a result of the activities of blue-green algae. The alteration of cryptocrystalline aragonite takes place irrespective of whether a grain is made up of calcite or aragonite , and the grain ultimately becomes pellet-like with an internal cryptocrystalline fabric which retains little or no evidence of its original nature. Taylor and Illing (1969) also commented on the activity of boring algae in the alteration of carbonate particles to form pelletoidal grains in the Recent sediments around Qatar Peninsula. They showed that algal borings can penetrate about 0.2 mm below the surface of the grains. Such activity creates a dense , creamy to white, cryptocrystalline aragonitic crust which sometimes measure several mm in thickness. Logan (1974) showed that pellets and pelletoid rinds can form by alteration of carbonate grains of any type, irrespective of whether they were originally aragonitic or calcitic, by destruction of primary microstructure and filling of internal voids. These smooth pelletoid rinds are developed on pebble-to-cobble size intraclasts, on the surface of lithified pavements, and on stromatolite structures at Shark Bay, Western Australia. Logan also attributed the formation of such pellets and pelletoid rinds to precipitation of aragonite in multiple voids created by algal borings, similar to the micritization process of Bathurst (1966). The intragranular voids are also obliterated by, either, alteration of void-filling carbonate, or precipitation of cyrptocrystalline aragonite in open voids. The surfaces of the rinds are smooth or finely pitted and they are up to 5 mm thick. Logan et al (1974) and Logan (1974) reported the presence of 'film mat' on indurated substrates in the supratidal zone. This mat is a dark greenish to black coating which comprises layers of coccoid algae, living in a 1-2 mm thick pelletoid rind. It is evident therefore, that the penecontemporaneous lithification of such rinds and the progressive alteration of grains to crptocrystalline aragonite as a result of algal boring, will generate a rock that retains little evidence of its original particulate texture. Thus, lack of particulate texture in many ancient stromatolites is not in itself enough to rule out the possibility of a sediment-binding origin, especially after later diagenetic alteration of aragonite to calcite: Hoffman (1973).

There seem to be some similarities between the hard pelletoid rinds and the associated film mat of Logan (1974) and Logan et al (1974), and the lithified and semilithified stromatolitic crusts and oncolites of Al-Khiran. The similarities are notably in the algal assemblages, the style of lithification and environmental settings. However, the cemented stromatolitic crusts of Al-Khiran show neither, evidence of sediment binding by algae, nor, alteration of grains by micritizations except near base of the crust: plate 4.8. The carbonate grains at the top of the substrate are altered to cryptocrystalline aragonite and their outlines merge into the surrounding micrite. It is likely therefore that even if trapped grains were originally present, intense infestation of the surfaces by communities of coccoid endolithic algae would cause wholesale obliteration of the particulate texture. This is also suggested by the existance of many altered grains in the unlithified and partially lithified algal mats which overly the lithified stromatolites. There, the detrital sediment particles have been pervaded by numerous tiny near vertical algal borings: plate 4.14. These may ultimately lead to complete obliteration of the original particulate texture.

(b) In situ precipitation of microcrystalline aragonite

A second possible process in the formation of the lithified aragonitic crusts could be that of in situ precipitation of cryptocrystalline aragonite. The process of in situ precipitation is most probably controlled or initiated by



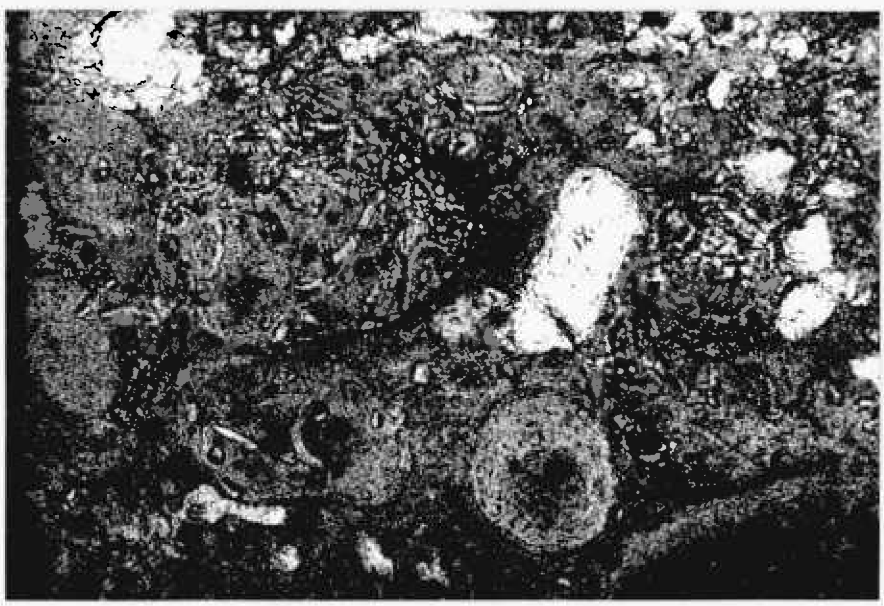


Plate 4.14.

Photomicrographs of semilithified algal mats (locality D) showing carbonate particles pervaded by algal borings, (x 130).

the algae, rather than being a simple inorganic precipitate from sea spray. This is evidenced by the crinkled nature, presence of discrete heads, orientation of heads and numerous other features which cannot be explained in terms of mere physico-chemical precipitation. However, it should be borne in mind that while the trapping and binding mechanism is the main, or probably the only mode operating in the algal mats in Al-Khiran and in most other modern shallow marine environments, it is the in situ precipitation process which is the dominant one in modern freshwater stromatolites. Both processes appeared to be equally important in the formation of ancient marine stromatolites, and Monty (1976) therefore suggested that some of the earlier blue green algae had the ability to precipitate calcium carbonate from sea water.

In conclusion the precise mode of lithification of stromatolites and oncolites remains uncertain, but there can be no doubt about their algal origin.

4.10 Discussion

(A) Organic origin of lithified stromatolitic structures:

In spite of lack of particulate texture and scarcity of algal remains in the lithified stromatolitic encrustations of Al-Khiran, their algal origin can be inferred by the following features:

(1) The presence of hemispheroidal structures with marked channelward inclinations. The orientated growth or asymmetrical lamination suggests that they were formed

by organisms which grew towards the source of supply of nutrient supply.

(2) The similarity in range of external morphologies with the nearby living algal mats and the semilithified algal stromatolites: plate 4.2. Likewise the similarity in microstructure, with vertical fenestrae or pallisade fabrics which may indicate an origin similar to that of the algal filament molds in the non-lithified algal mats: plates 4.9 and 4.10.

(3) The laminations in lithified stromatolites are rich in organic matter. This can be seen when thin sections of the crust are immersed in very dilute hydrochloric acid (about 2%) with malachite green for about four hours. The carbonate dissolves and leaves laminae of blue-stained organic matter.

(4) The presence of intermediate stages in lithification of the algal mats indicates conclusively that the lithified stromatolitic encrustations were initially algal mats.

(B) <u>Similarities and differences between lithified stromatolites and laminar calcretes</u>

Laminar calcretes which occur in many parts of the world have much in common appearance-wise with the lithified stromatolites of Al-Khiran. Calcrete crusts result from processes which operate in the vadose zone, associated with soil development in non-marine environments. Their formation involves dissolution and reprecipitation of calcium carbonate, and often produces sheet-like or small domal laminar structures: Multer and Hoffmeister (1968), Read (1974 and 1976), Robbin and Stipp (1979) and H. Hassouba (personal communication). These finely laminar calcrete structures could in some cases easily be mistaken for algal stromatolites. The main criteria which may help in distinguishing between the two can be summarised as follows:

(1) The stromatolitic encrustations of Al-Khiran tend to grow convex upward and to thicken over highs. Laminar caliche on the other hand tends to fill depressions, line sinkholes and subvertical fissures. Laminar calcretes can also be found flooring voids in sediments beneath a laminar horizon to form stromatactis-like structures.

(2) Although in some cases laminar calcretes may thicken over highs, it seems very unlikely that they could produce oriented, asymmetrical hemispheroidal structures like those shown in plate 4.6.

(3) Stromatolitic crusts exhibit fenestral fabrics in the form of pallisade or radial structure. Calcretes do not. However, tubular molds of root hairs have been found in some calcretes but these do not form a pallisade or radial fabric.

(4) Stromatolitic crust often have polygonal cracks commonly associated with formation of oncolitic grains. Calcretes may show in situ brecciation which also includes fracturing of pisolites, but the resulting fissures may be lined or floored with laminar calcrete.

(C) Comparisons between lithified oncolitic structures and nonlithified oncolites , calcrete pisolites and other coated grains

The oncolitic grains shown in plates 4.11, 4.12 and 4.13 are much different from the small nonlithified oncolites described in Chapter 3, (page 149). The latter which range in size from 0.5 to 1.2 cms show evidence of overturning and rolling during the formation. This is seen in the presence of discontinuous laminae and microunconformities. The presence of concentrically arranged fine-grained detrital particles in the small algal oncolites implies adhesion or trapping while the oncolites were in movement. The more continuous laminae of the lithified oncolites are characterized by the presence of vertical fenestrae with little evidence of particulate texture.

Calcrete pisolites have been described from modern and ancient vadose environments by numerous authors: e.g. Swineford et al, 1958; Dunham 1969 and Read 1974. The characteristic features of these calcrete pisolites include: (a) reverse grading, (b) In-place downward thickening of envelopes, and (c) repeated in situ brecciation during growth.

The Al-Khiran cemented oncolites are locally transported either landwards or channelwards, and could conceivably be deposited with reverse or normal grading. Calcrete pisolites are mainly calcitic in mineralogy, but, Scholle and Kinsman (1974) described pisolites and caliche from the Persian Gulf which comprised aragonite and high-Mg calcite. In many places along the seaward position of Khor Al-Mufatteh and Khor Al-Ama, laminated, lacy and pisolitic carbonate crusts are present: these are similar to those reported by Scholle and Kinsman (1974).

Other aragonite-coated grains, which have much in common with the indurated oncolitic grains of Al-Khiran have been described by Purser and Loreau (1973) from some intertidal and supratidal localities in the Persian Gulf.

(D) Preservation and recognition of lithified algal mats in the fossil record

An important result of early lithification is the potential preservation of growth structures. In this respect lithified algal mats stand in marked contrast to the non-lithified ones in which growth forms are obliterated by compaction.

Criteria for recognition of penecontemporaneously lithified algal mats in the fossil record would include:-

(1) Association with beachrock substrates rather than muddy ones.
(2) Association with coated intraclasts derived from the underlying beachrocks.
(3) Entrapment of detrital sediment, including large marine skeletal fragments between stromatolitic structures.
(4) Association with skeletal grains with oncolitic coatings.
(5) The presence of borings, as opposed to burrows.
(6) The presence of polygonal cracks, microstalactitic and dripstone fabrics on the undersides of some of the polygonal slabs.

CHAPTER 5.

CHAPTER 5

Biological and Sedimentological Aspects of Algal Mats

Because algal mats are organo-sedimentary structures constructed as a result of interactions between blue-green algae and sediment, it is necessary to discuss both, the biological and sedimentological factors which influence the build up of mats.

Most of the environmental parameters which affect the distribution and development of morpholotical types of algal mats also have an influence upon the transport of sediments and the chemical precipitation of carbonate and sulphate minerals. This chapter therefore, deals with these various aspects under the following headings:

(1) The mat-building algae

(2) Trapping and binding processes

(3) Role of algal mats in the protection of underlying sediment

(4) Rates of mat development

(5) Laminations in algal mats

(6) Dolomitization

5.1 The mat-building algae

The most important cyanophytes which form the algal mats of Al-Khiran are: *Microcoleus chthonoplastes* and *Lyngbya aestuarii*. These are both filamentous. Unicellular or coccoid algae also occur in some places, particularly in those mats found on rocky substrates.

The main role of the algae in the growth of mats is their ability to trap and bind sediment particles. In all of the various types of algal mats, with the exception of the tufted mats, it was found that Microcoleus chthonoplastes species is the dominant alga and in some instances it seems to be the only one present, especially where environmental conditions are very harsh due to desiccation. In the tufted mats, the tufts themselves are built by Lyngbya aestuarii.

The present study has shown that the same algae can produce different mat forms under different environmental conditions. This indicates that in most instances the algal mat morphology is unrelated to the algal community. However, different algal communities produce different algal mat morphologies even under the same environmental conditions. It becomes evident therefore, that algal mats morphology in Al-Khiran area is partly environmentally controlled and partly biotic.

The question of whether the ancient algal stromatolites were environmentally controlled or biologically controlled has long been a matter of debate. The influence of the physical environmental conditions on present day algal mat morphology and microstructure was first recognized by Black (1933) in his pioneer work on the algal mats of the Bahamas. His work was subsequently extended to tidal flats in Florida and elsewhere in the Bahamas by: Ginsburg et al, 1954; Ginsburg, 1955; Ginsburg and Lowestam, 1958; and to the Persian Gulf by Kinsman 1964; Kendall and Skipwith, 1966, 1968, 1969; Park 1973; and to Western Australia by Logan (1961); Davies, 1970, etc. Logan, Rezak and Ginsburg (1964) showed that stromatolites are produced by complex microbial assemblages and cannot therefore reflect biological properties of any particular species. They concluded that the differences in morphologies reflect different environmental conditions.

At the opposite extreme, the Russian school emphasised the biotic influence, rather than purely environmental factors, in shaping or determining the morphological and microstructural features of stromatolites. The influence of environmental factors on the morphology of ancient stromatolites was either not accepted or denied by the Soviet workers for a long while (Semikhatov, 1976). They introduced a system of form-genera and form-species nomenclature which they applied to the Precambrian occurrences (reviewed by Semikhatov, 1976).

Evidence has been accumulating in recent years which has led many authors to call for a combined approach: considering both biotic and environmental influences. It is argued that macrostructure is influenced by physical environmental factors, while in many cases the microstructure seems to be controlled by biological processes (Gebelein, 1974). Even in the extreme Russian school there is now a tendency towards accepting the influence of environmental factors in determining the morphology of stromatolites (Serebryakov, 1976) and (Semikhatov, 1976).

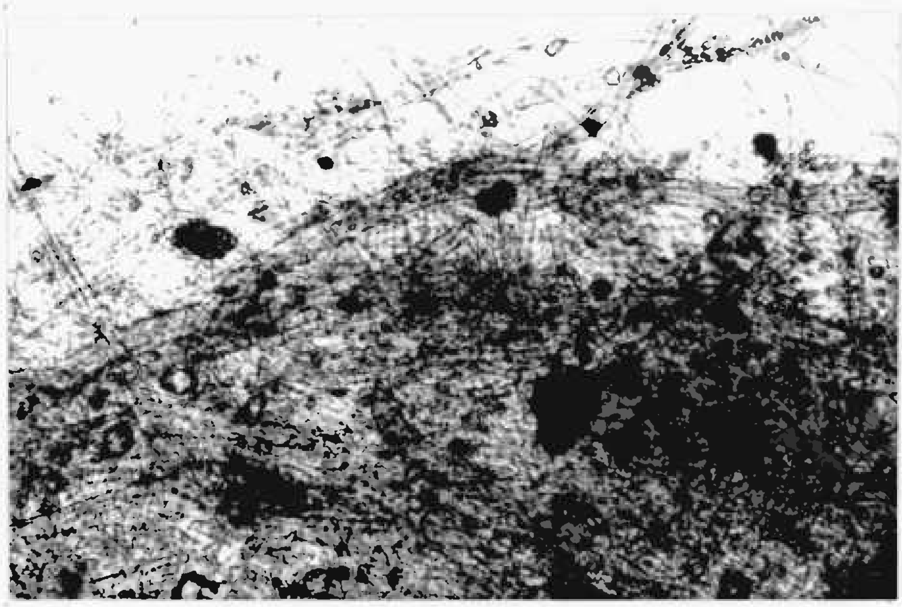
Microcoleus chthonoplastes

The filamentous blue-green alga Microcoleus chthonoplastes is the dominant species in the algal mats of the Al-Khiran area. The trichomes of Microcoleus occur in twisted bundles which are enclosed within a common sheath: plates 5.1 and 5.2.

Each trichome is a filament about 3 micron wide divided into a chain of small cells. Individual trichomes grow out from the communal mucilaginous sheath and secrete a new sheath as they advance. The tip of each thichome, i.e. the terminal cell is generally conical in shape.

The trichomes of many of the blue green algae including Microcoleus appear to have the ability to glide through their mucilaginous sheaths and so change their positions. Because of this mobility the mats can build up both by normal upward growth of the trichomes and by upward gliding of trichomes. The latter ability allows the algae to move upwards quickly and escape burial if sediment is suddenly deposited on the surfaces of living mats. As the trichomes glide upwards they leave empty mucilaginous sheaths behind them. Living trichomes can be found only in the upper few mms of the mats i.e. down to levels where sufficient light is able to penetrate. Below this depth, any trichomes which have not migrated upwards begin to disintegrate, apparently by bacterial decay but their mucilaginous sheaths persist. Bacterial decay of trichomes is most intense in the layers immediately below the living surface of the mats and may extend down for a centimetre or more. Trichomes are rare below this depth and the few which do occur are in advanced states of decay.

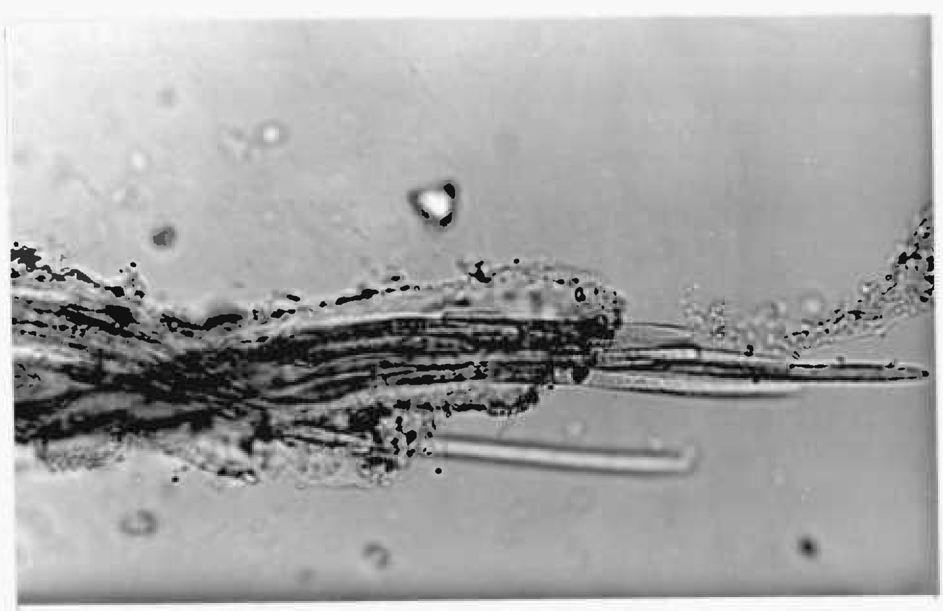
Comparisons of living algae at the mat surface with algal remains at depth were made by Horodyski et al (1977) on Microcoleus mats of Laguna Mormona, Mexico. These workers measured the diameters of trichomes at the mat surface and at various depths. They found that the average diameter of the trichome decreased by about 60% at depth of one cm below



100µm

Plate 5.1.

Living filaments of Microcoleus chthonoplastes from the surface of algal mat. Note the interwoven bundles of filaments and the entrapped sediment particles.



15µm

Plate 5.2.

Close-up of Microcoleus sp. showing several filaments sharing a single common sheath. Note the conical habit of the terminal cells of the trichomes.

the mat surface.

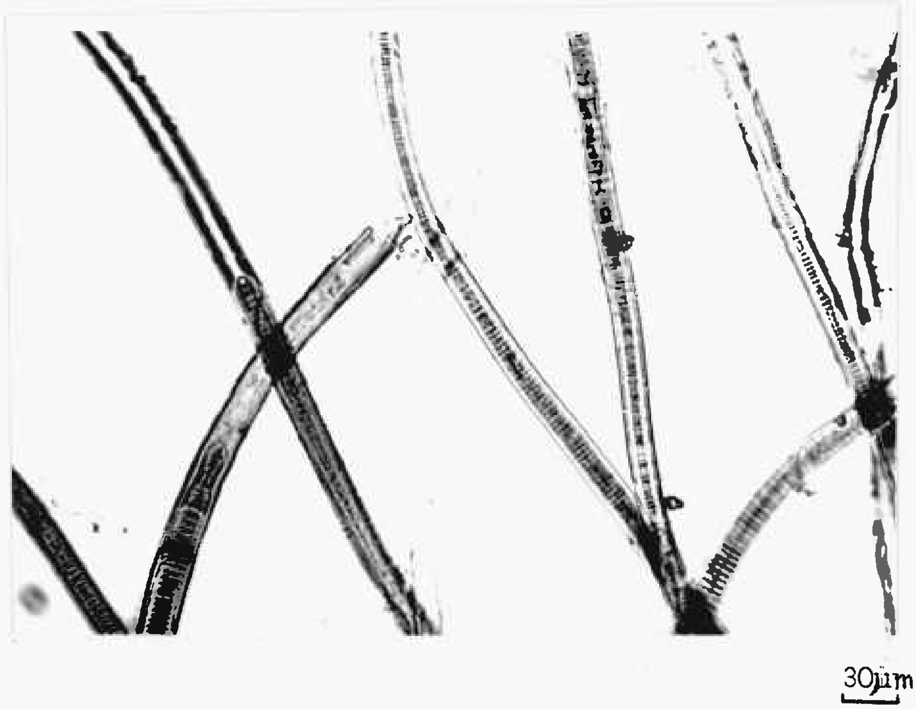
Mention has already been made of the fact that Microcoleus chthonoplastes appears to be the alga most resistant to desiccation. Its tenacity probably results from protection afforded by the thick mucilaginous sheath which surrounds it. The sheath appears to be both resistant to long periods of intense desiccation and at the same time appears to have antibiotic properties which inhibit bacterial attack.

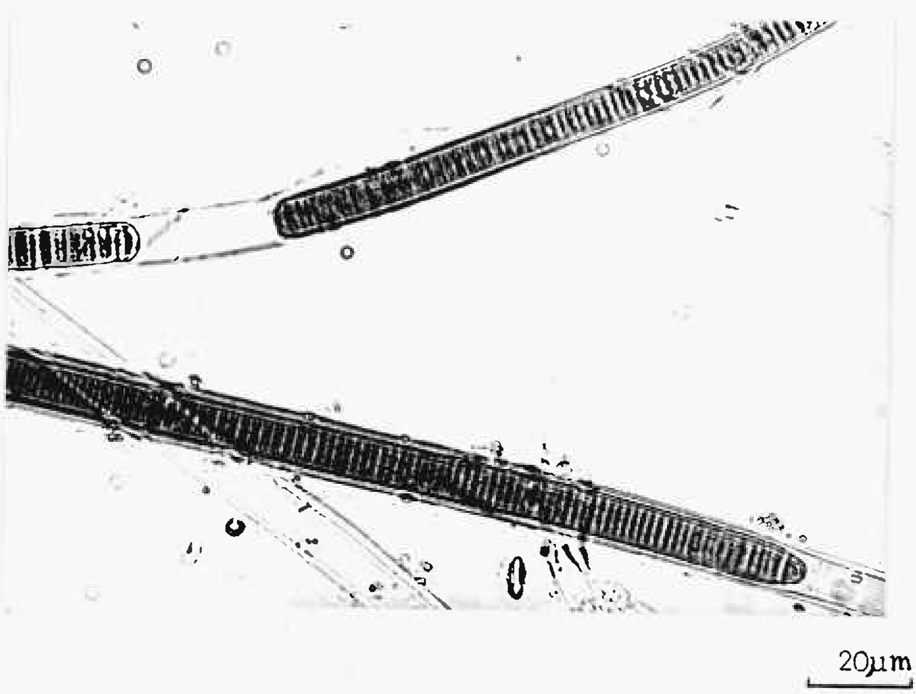
Lyngbya aestuarii

Lyngbya aestuarii is the next most abundant filamentous cyanophyte in the algal mat of Al-Khiran. It is characterized by large trichomes which range from 10-20 micron in width and individual filaments may reach 5 mm in length. In contrast to Microcoleus, each trichome of Lyngbya produces its own individual sheath of mucilage which is usually relatively thick and sometimes exhibits a layered structure: plates 5.3 and 5.4. The tips of the end cells are usually rounded, but sometimes they exhibit 'contraction' features similar to those described by Horodyski (1977) who attributed the contraction to desiccation.

The firm thick sheaths and their relatively large size give a rigidity to the filaments. It is probably this which allows the tufts of the tufted algal mats to stand erect without the aid of supporting sediment: plate 3.16.

The processes involved in the development of tufted mats in Al-Khiran may be similar to those which give rise to the formation of tufted algal structures in hot springs at Yellowstone National Park, Wyoming (Walter, et al, 1976).





Plates 5.3 and 5.4.

Filaments of Lyngbya aestuarii. Each filament consists of large-diameter trichome enclosed in a thick, rigid sheath. Note the "contraction" features displayed by the terminal cells of the trichomes.

There, individual tufts are initiated by development of local knots of filaments which result from the tangling of the filaments as they glide over the substrate. Later filaments are then deflected upwards over these knots , where they stand erect due to phototaxis. These vertical filaments cohere and become pointed during low tide like hairs of wet 'paint-brush'. Such clustering of the filaments possibly helps in retaining mositure when the mats are exposed during low tides.

The directions of gliding of the filaments are perhaps not entirely random. This is suggested by the fact that in some places the tufts coalesce to form sharp crested ridges of various shapes: plate 2.23. The distribution of tufted mats suggests that the environmental factor which most influences their development is the frequency of wetting i.e. the flooding history. Acutely tipped cones and sharp crested ridges occur in intermittently emergent settings , whilst small round-topped knobs develop under permanently moist conditions. The tufts in the intermittently emergent settings tend to become more pointed as they increase in height and deviate from the vertical by leaning towards the source of flood water.

5.2 Trapping and binding processes

Where there is a supply of sediment, the algae play an important role in trapping and binding the sediment particles.

The blue-green algae which live at the surface of any mat comprise a mass of densly intertiwined filaments and mucilage. Any detrital particles, whether they be coarse sand, silt or mud which are washed onto the mats by the tide, storm waves or winds, become trapped by the mass of algal filaments and mucilage. If an algal mat becomes buried by a sudden influx of new sediment, the algae move up through the sediment as a phototaxial response, either by normal growth or by gliding to spread out over the new surface. In moving upwards through the sediment the mucilaginous sheaths bind the sedimentary particles so that they become firmly incorporated into the body of the mat. Thus each mat becomes a complex of organic and sedimentary materials.

Depending upon the rate and nature of the supply of sediment, the structures of the mats may range from randomly incorporated sediment at one extreme to delicately laminar alternations of sediment and organic matter at the other.

The ability of filaments of Microcoleus chthonoplastes to trap sediment particles is not limited to any particular grain size. They can trap very fine grained particles as well as relatively large shell fragments. On the other hand, the tufts of the tufted mat formed by Lyngbya aestuarii appear to lack the capacity to bind sediment, but sediment particles can be trapped in depressions between adjacent tufts.

The part played by other blue green algae in the entrapment of sediment has been discussed in detail by many authors, including Monty, 1965; Gebelein, 1969 and Neumann et al 1970.

5.3 Role of algal mats in the protection of underlying sediment

The role of algal mats in protecting the sediment of the underlying substrates from erosion, especially in subtidal environments, has been studied by several researchers including Ginsburg and Lowenstam, 1958; Bathurst (1967); Gebelein (1969) and Neuman et al 1970. Bathurst found that in some areas of the Bahama Bank, calcarenite grains on the floors of lagoons were bound together by a gelatinous substance which immobilized the sand even in the presence of tidal current scour. He concluded that "where ancient limestones have textures which would conventionally be interpreted as indicating low energy deposition, they may in fact have been laid down in high energy environments where the floor was immobilized by a mat". These observations on subtidal mats can be extended to the intertidal mats of Al-Khiran which similarly stabilise the underlying sediments and protect them from erosion.

5.4 Rates of mat development

Although algal mats as such are only developed in a specific belt in the intertidal zone, the blue green algae do in fact live in the areas seawards and landwards of this belt. Seawards of the mats the surface of each sediment particle has its own small colony. In the lagoons these algae are continuously being grazed on by cerithid gastropods so that each sediment grains is alternately colonized and stripped bare. In consequence mats cannot develop. The cerithid gastropods are voraceous browsers and require a plentiful supply of food. The lagoons support dense populations, and their survival indicates that recolonization of the sediment by the algae must be very rapid. Along the landward limit of the mats, extreme desiccation during periods of neap tides causes the mats to flake and curl up. Ultimately they become detached from their substrate and are easily blown away by strong winds to leave a bare barren surface. However, when this surface is next wetted by high spring tides it is recolonized, and a thin veneer of mat develops very quickly. However, this can be destroyed and lost during the following neap tidal interval. Thus although no permenant mat is developed, algal colonization and incipient mat development must be very rapid.

In the central flats, low areas such as pools and ponded parts of channels provide the optimum conditions for accumulation of thick algal mat. This is in part because the lows are ideal sites for collecting detrital and suspended particles. The accumulation and preservation of mats in such pools is aided by the reduced activity of bacteria which results from the generation of anaerobic conditions. The anaerobic state is caused by the presence of permanent or near permanent saturation which, in the absence of drainage, generates stagnant conditions. Anaerobic bacteria then takes over. However, due to lack of drainage the waste products of the bacteria are not flushed out but accumulate in situ. Ultimately the waste products of the bacteria reach a concentration which renders the substrate toxic to them. The bacteria then die off, and the organic matter is left in state of arrested decay. This is similar to the process which leads to the formation of peat as described by Shearman (in Selley 1976). This state of arrested decay, allows preservation of the organic matter prior to burial, and it is an essential prerequisite for ultimate maturation of organic matter to hydrocarbons. If, as some authorities believe, algal mats may be source material for petroleum, then the algal mats of Al-Khiran and the adjacent porous barrier ridges could serve as a model for source rock and reservoir rock in some ancient limestone sequences.

The thick accumulation of algal mats which occurs in the lows is in contrast with the surrounding highs where the mats are well aerated and water circulation flushes them clean. There conditions promote bacterial activity and allow maximum decay of organic matter. Therefore, it seems that the rate of bacterial decay on higher parts of the central flats is in state of balance with the growth rate of algae.

In places with low flooding frequency and low wetting frequency, desiccation is severe and has a major influence upon both the algal and bacterial populations. In such places the mat becomes dry and brittle. It comprises mostly dead algae with a low bacterial population. In many of these places, the destruction of the mat is further aided by interstitial growth of gypsum which may cause the separation of the mat from the underlying substrate. In general therefore, growth rates of the algal mats seems to be very slow in most parts of the algal belt. This conclusion is supported by the following observations:

(a) In the algal mat zone of the area E, there are some places where algal mats were destroyed several years ago by cars which became stuck and had to be dug out. Such places were examined several times during the three-year period of this present research. It was found that in most instances these places show almost no observable colonization by algae and many of them are still devoid of algal mat.

(b) Camels sometimes get stuck in the muddy areas within the algal flats. As they struggle to free themselves, they destroy large areas of mat. In most cases the camels fail to escape from these muddy traps and die there: plate 1.20. Skeletons of camels which died in this zone are ultimately covered by algal mat, but only very slowly. Comparisons of photographs taken of one of these camels remains over a three-year period shows that very little or no observable recolonization has taken place over the exposed parts of the camels remains: plate 5.5.

However, in certain cases the rate of algal colonization can be relatively rapid. For instance in some of the slightly deep car tracks, where water remains as small pools after the tide has ebbed, tufted mats were observed to develop within less than a year.

At locality I, a small shallow pit (about 1000 m^2) was dug landward of the upper reaches of the algal belt (i.e. in the supratidal flat) in the search for construction materials. This pit which was open during the course of this study, was later filled with tidal water and

Plate 5.5a and b.

Remains of a camel which had been trapped in crinkle mat zone at locality F. The interval between the two photographs is about 3 years. Note that very little or no observable recolonization has taken place over the exposed parts of the camel's remains in the lower photograph.

transformed into a small pond. When this pond was revisited after about 11 months, it was found floored with continuous algal mat 3-6 mm in thickness: plate 5.6.

The rate of growth of mats depends on both the rate of growth of the algae and the rate of supply of sediment. Because both are intermittent, the algal mats do not grow at the same rate throughout the whole of the year. The algae may 'bloom' during certain periods or under certain conditions, and the mat may build up very quickly, while at other times algal growth may be very slow or cease completely.

The rate of particulate sedimentation also fluctuates, because of irregularities in flooding frequencies e.g. due to: normal, neap or spring tides; and storms and strong winds.

It is concluded from the above observations that the rates of mat development in the central parts of the flats in the Al-Khiran area are very slow. Most of the intermittently emergent mats seem to have reached a state of equilibrium, where growth is balanced by desiccation and bacterial decay.

Park (1976) was able to determine the growth rate of algal mats in the Trucial Coast by measuring the thickness of the mat which had colonized a discarded core lying on a Flat mat surface. He found that the core became overgrown by new algal mat 4.5 - 5.0 mm in thickness over a period of 22 months: i.e. a growth rate of 2.5 mm per annum. This value is approximately the same as that for the mat which developed within 11 months in the pit at locality I.

Plate 5.6.

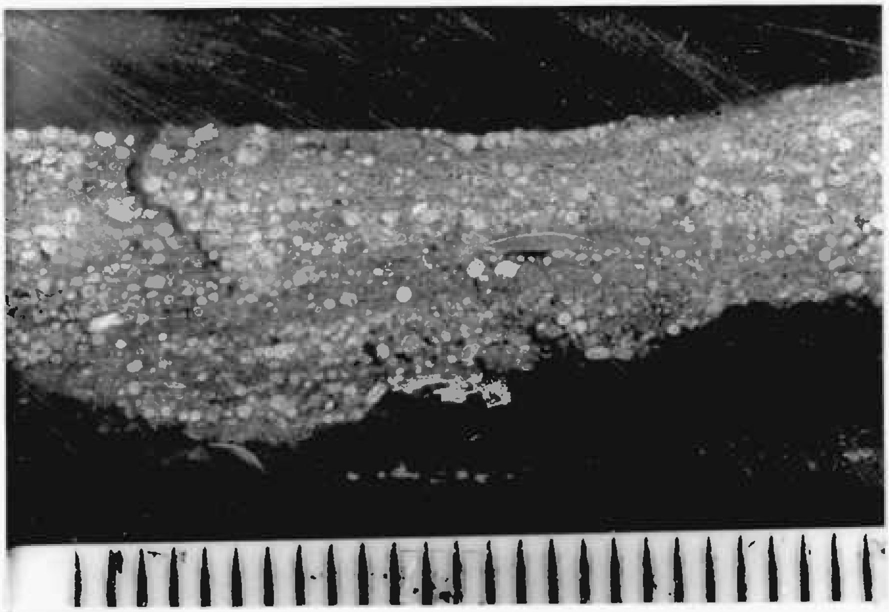
Artificial pond at locality I, floored with a continuous carpet of algal mat, when the pit was revisited after about 11 months.

The conditions under which these observations were made were anamolous and unnatural ones. There remains, therefore, the question of when and how quickly mats develop under natural conditions. Are the laminae in the mats produced daily, monthly or seasonally or are they the result of some other periodic event? This question still remains without a satisfactory answer.

5.5 Lamination in algal mats

Lamination is one of the essential characteristics of algal mats and stromatolites. The development of lamination is mainly due to the interaction of algal growth and particulate sedimentation. These two processes produce alternations of organic-rich and sediment-rich laminae. Laminations in algal mats of Al-Khiran are variable in content and thickness, depending on position of the mat in relation to tidal flats. Such variations of lamination in different localities are mainly due to different degrees of flooding and desiccation and differences in amount and type of sediment which are transported by tidal channels and deposited over the algal mats.

The laminae in the mats from localities A and B along the coastal lagoons are characterized by sediment layers which are not more than one sand grain in thickness. The sand grains are mostly oolites and pellets: plate 5.7. These sediment laminae alternate with algal rich layers which carry finer detrital carbonate particles of silt and mud grain size. Such simple alternations can also be seen in the algal mats on the rocky substrates at locality D.



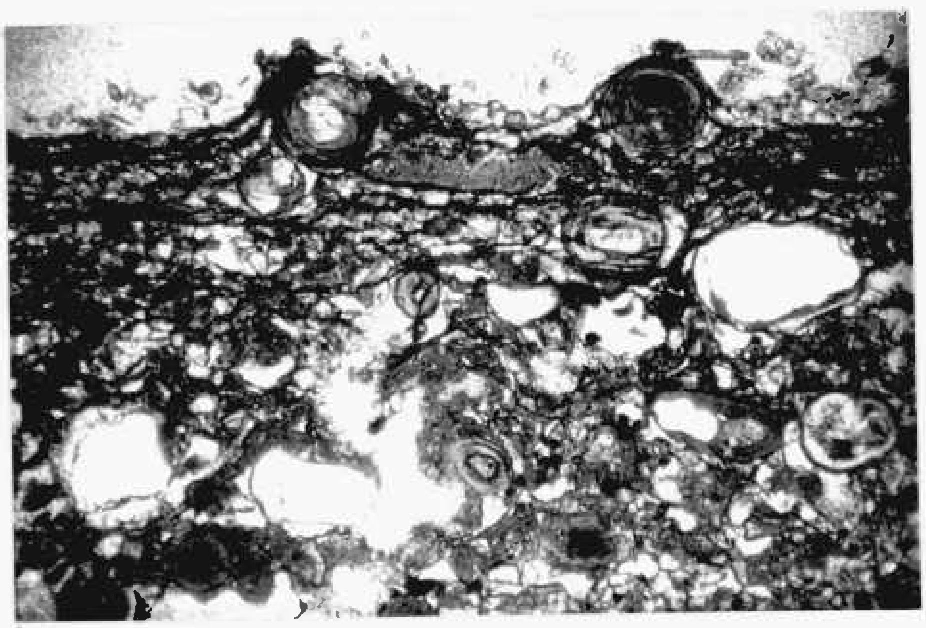


Plate 5.7a.

Vertical section of a piece of algal mat from locality A, showing thin lamination.

Plate 5.7b.

Photomicrograph from the uppermost part of the above algal mat showing sediment laminae, one sand grain thick, alternating with algal rich laminae with finer sediment, (x 40).

Elongate particles in the laminae align themselves with their long axis parallel to the growth surface of the mat, even where the mat undulates or drapes over the steep banks.

Algal mats in the intertidal flats around the extreme inner margins of the tidal channels are characterized by finer-grain sediment compared with the grains trapped in the mats around the coastal lagoons. Because of the irregular flooding and episodic influxes of detrital particles, the thickness, grain size and compsoition of the sediment layers in mats around the inner margins of tidal channels are very variable: plates 5.8; 5.9 and 5.10. The variations appear to depend on the type and strength of the agent which deposited the sediment layers: i.e. normal, neap or spring tides, storms or strong winds. Because these agents have different frequencies and capacities, they cause marked variations in the rate of sedimentation and the sizes of the introduced detrital sediment particles, from time to time even in the one place. If the sedimentation rate is very high, thick sediment layers form with only very thin and faint organic laminae between them. Such thick layers of sediment which are usually deposited during storm conditions, may alternate with dark purely organic laminae which by contrast contain very little or no detrital sediment: thus indicating that they were formed when the sedimentation rate was very low. In some cases, especially in areas where energy conditions are relatively high, and where the sediments are of sand grade size, the algal mats are very rich in sediment and the algal laminae are very faint indeed. This can be seen in the lower reaches of the algal belt along the bank of the

x 13

Plates 5.8a and b.

Photomicrographs showing the laminae in crinkle mat from the inner margin of a tidal channel. Note the alternation of dark organic laminae and light sediment-rich layers. Note also the destructive effect of gypsum crystals in modifying lamination. Growth of gypsum in certain preferred horizons give a palasade-like appearance.

x 30

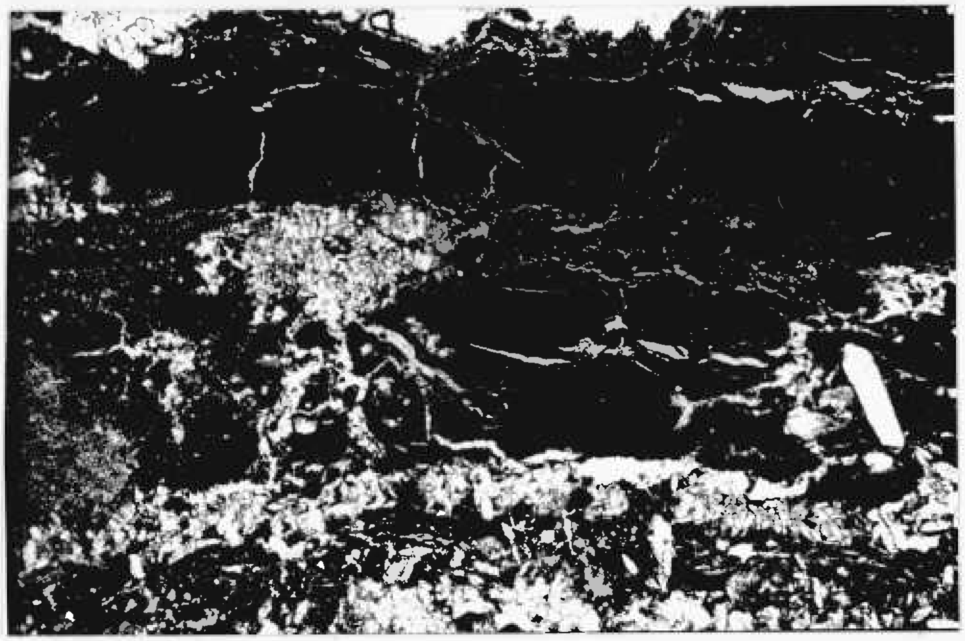


Plate 5.9.

Photomicrograph of crinkle mat at the inner margin of Khor Al-Ama showing development of small polygonal cracks in the fine grained laminae. Note also the destructive effect of gypsum crystals, (x 13).

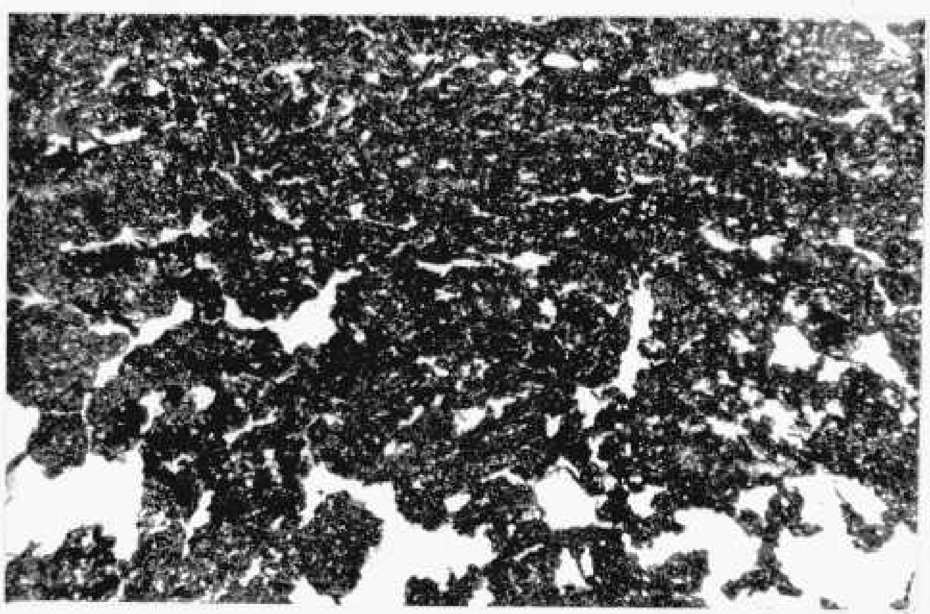


Plate 5.10. Photomicrograph of an algal head at locality E showing development of laminoid fenestral fabric, (x 13).

main tidal channel in locality H. In some other places the mats show discontinuous laminae which result from local factors, such as sediment ejected from time to time by burrowing animals, such as crabs.

From the above observations, it is obvious that lamination in intertidal zone algal mats, where they are intermittently flooded, may be the expression of: (a) alternations of well-defined individual laminae of different composition, such as purely sediment laminae or organic rich and sediment rich laminae; (b) successions of layers with different grain sizes, separated by faint or well defined organic laminae. Layering in some cases, may result from diagenetic changes which affect the mat during subaerial exposure. For instance, the development of laminoid fenestral fabric: plate 5.10, and the growth of gypsum crystals in certain layers to form palisade structures: plate 5.8a.

Mats under continuously submerged conditions, e.g. subaqueous mounds, and those in poorly drained pools, e.g. flat polygonal mats, show layering which is different from that described above. The organic content in these latter mats is very high and the sediment is much finer grained than in other mat types. Vertical sections cut through the mats show that the lamination is due to changes in colour: plates 3.2, 3.3 and 3.13. Thin section studies reveal that layering is not the expression of differences in grain size, but is mainly due to variations in the ratios between organic matter and sediment in the various laminae: plates 5.11 and 5.12.

Plate 5.11.

Photomicrograph in a subaqueous algal mound at locality H, showing lamination resulting from variations in the ratios between organic matter and fine grained sediment in the various laminae, (x 30).

Plate 5.12.

Photomicrograph in flat polygonal mat at locality F, showing the high organic content in the mat with fine grained mud, (x 13).

Although the different types of laminar fabrics described above record some degree of periodicity in the growth of the algal mat, it seems that the periodicity was far from being regular. In the intertidal environments, where sedimentation is not continuous, and algal growth is intermittent, growth of any mat may stop for long periods of time but resumes when suitable conditions prevail. Such interruption of growth would create microdiastems between some of the laminae. It is therefore, very difficult to determine the precise significance of individual laminae.

Diagenetic modifications of laminae

Algal mats can be affected by a variety of diagenetic processes some of which may completely obilterate the original fabric. These processes include: cracking and shrinkage due to desiccation, growth of gypsum, micritization of grains, cementation, compaction of mats during subsequent burial and dolomitization. Some of these diagenetic features are discussed separately as follows:

(a) Desiccation features

Mats in higher reaches of the algal belt and those overlying sandy substrates within the intertidal zone are strongly affected by desiccation during subaerial exposure. Structures resulting from desiccation have already been described in Chapter 3. The type of desiccation feature depends on the grain size of the sediment and the proportion of organic matter present. Laminae with fine-grained sediments respond to desiccation more readily than the coarser sandy ones. The mats not only develop polygonal shrinkage cracks at the surface, but other small cracks also develop internally in the muddy laminae: plate 5.9.

Shrinkage and drying of the mat can also produce fenestrae or spaces which have no apparent support in the framework which composes the mat: plate 5.10. Such fenstral fabrics are very common in the algal mats which are intermittently flooded and subjected to desiccation for prolonged periods. The most common type is the laminoid fenestral fabric. However, in few cases vertical tubular fenestrae may develop as a result of the decay of vertical bundles of filaments. Such types of fenestrae or molds after filaments are mainly found in mats which overlie hard substrates as described in Chapter 4. They occur as small tubules surrounding carbonate particles: plate 4.10. Parallel arrangement of the fenestrae can form palisade-type structure.

(b) Growth of gypsum crystals

In the higher reaches of the algal flats, the growth of gypsum plays an important role in modifying lamination and in extreme cases may lead to total destruction of the original structure. The growth of gypsum may commence and spread along certain preferred horizons and thus form palisade structure. In other cases the growth appears to be at random, and nests of gypsum crystals may form in hollows of crinkle mats or along planes of separation between organic and sediment laminae. As the gypsum crystals grow they deform and displace the overlying laminae which in turn may lead to buckling of the mat. The sharp edges of the crystals of gypsum can easily slice through the laminae so that the organic matter and sediment are displaced into the intercrystal area. In this way some of the lamiane are completely destroyed and only scattered remnants can be recognised.

The development of mushes of gypsum crystals beneath algal mats, causes the mats to separate from the underlying sediment. This ultimately leads to destruction of the mat by desiccation. It shrinks and flakes and the flakes are easily removed by wind.

(c) Compaction by burial

Although rapid burial of the leathery algal mats may actually aid their preservation (by protecting them against destruction by desiccation), the consequent compaction may have a significant effect upon the structure and lamination in the mat. When mats are buried, the overburden load causes flattening of many of the growth forms. Compaction also results in progressive dehydration of the organic laminae and reduction in their thickness.

In many instances the algal laminae are in fact made up of several much thinner laminae. On compaction by burial such thin laminae will certainly condense and appear as one layer.

The lithified stromatolites would not be expected to compact significantly, and penecontemporaneous lithification is thus an essential prerequisite for the preservation of growth forms.

(D) Micritization

The role of endolithic algae in the destruction of particulate texture in the mats has already been discussed in Chapter 4. Alteration of grains by micritization can best be seen in the semilithified algal mats at locality D along the right bank of Khor Al-Mufatteh. There, the mats become the site of intense colonization by endolithic algae. As seen under the microscope, the carbonate grains in some laminae are pervaded by numerous tiny, near vertical algal borings: plate 4.14, some of which are empty but others are filled with micrite. As the number of borings increases the extent of micritization also increases until ultimately the granular texture of the sediment is completely obliterated. In many of the fully lithified stromatolites, the laminae are wholly micritic. One possibility is that the micrite is secondary, and that the original material was a carbonate sand which became altered to micrite as a result of the activity of boring algae.

5.6 Dolomitization

Penecontemporaneous dolomitization of fine grained carbonate muds is common along the muddy banks of the tidal channels, where the sediments are periodically water saturated. In these areas, concentration of interstitial water by intense evaporation causes precipitation of aragonite, $CaCO_3$, and gypsum, $CaSO_4\ 2H_2O$. This leads to an increase in the ratio of magnesium to calcium in the marine derived intersitial waters. This change in the chemistry of the waters is believed to promote dolomitization of the very fine-grained calcium carbonate.

X-ray diffraction analysis of samples from various parts of the region show that the highest concentration of dolomite occurs in the mats around lagoon A. There, the proportion of dolomite is greatest in the uppermost part of the inter-tidal zone, where the mats are strongly desiccated: plate 3.36. The average thickness of the mats is less than 1 cm, and the maximum concentration of dolomite is found in the top few millimetres, where the mat is lightly cemented relative to the other parts which are uncemented. The sediment layers in these mats are only of one sand grain thick: plate 5.7, and may be composed of oolites, pellets, quartz and/or shell fragments. The organic rich laminae of the mats contain fine-grained carbonate mud. It is these latter which have the high dolomite content. Selective dolomitization of the algal rich layers may be enhanced by the fine grained nature of the sediment. Kahle (1965) suggested that dolomitization may also be promoted by the presence of clay minerals. No gypsum crystals were found in this area; however it is possible that the precipitation of aragonite may have increased the Mg^{++} content of the interstitial waters relative to Ca^{++}.

Photosynthesis and respiration of the blue green algae should affect the concentration of CO_2 and O_2, and also the pH and Eh of the interstitial waters. Such biologically induced changes in the microenvironment would be expected to promote diagenetic alterations and may be responsible for the precipitation of the cement.

Many ancient stromatolites are characterized by interlamination of dolomite and calcite on a centimetre or millimetre scale (Gelelein and Hoffman 1971 and 1973). The dolomite laminae appear to be equivalent to the algal-rich layers of the Recent mats, while the calcite laminae are equivalent to the non-algal layers of the modern occurrences.

Gebelein and Hoffman (1973) attributed the selective dolomitization of the algal-rich layers to the ability of the algal sheaths to preferentially absorb magnesium from the pore waters. They suggested that the magnesium ions are complexed with the organic matter, and that dolomitization takes place when the magnesium is released as the organic matter decomposes.

Complete dolomitization is rare in present day algal mats, and Gebelein and Hoffman explained this by suggesting that the algal sheaths, in which the magnesium is concentrated are very stable and do not decompose until long after deposition or even lithification. Thus the part of the dolomitization of ancient stromatolites could have been post depositional.

Penecontemporaneous dolomitization of the algal mats at locality A may thus have resulted from reactions between the fine-grained carbonate mud in the algal-rich layers and the magnesium ions released during decomposition of the organic matter in the same laminae. Mention has already been made of the fact that the algal mats in the landward limit are periodically destroyed by desiccation. Such complete decomposition of the algal material would release magnesium which could be stored in the interstitial waters.

CHAPTER 6.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The area of Al-Khiran on the southern coast of Kuwait is one of Recent carbonate sedimentation in a complex of barrier spits, ridges, lagoons, tidal channels, tidal flats and sabkhas. The physiography and development of the barrier complex is affected by winds, waves, tidal currents and the presence of tidal channels (khors) which contribute to the rapid coastal accretion and progradation of the outer barrier.

The barrier ridges are of two major types, which were formed during and following two transgressive phases in the Quaternary. The ridges are: the inner quartzose sandstone barrier ridges (Late Pleistocene) and the outer oolitic barrier complex (Holocene). The latter consist of a complex of beach and dune ridges which were mainly developed by growth of barrier spits in the direction of littoral drift. The barriers enclose shallow lagoons landward which were subsequently silted up with carbonate mud and sand and ultimately became sabkhas. The sediments of the sheltered intertidal and lagoonal environments are largely formed in situ as a result of various biological and chemical processes. On the supratidal flats or sabkhas, the main supply of detrital sediment is aeolian sand. This is intermixed with in situ interstitial gypsum and other chemically precipitated diagenetic minerals.

The accreting coast gives rise to protected intertidal environments behind the barrier ridges which are favourable for widespread development of algal mats. These occur around the margin of the lagoons and the tidal channels. The cover of rubbery mats in these sheltered intertidal settings gives some resistance to the erosion of these zones, which in turn aids the silting up of the lagoons and the progradation of the coast.

The algal mats of Al-Khiran area are entirely intertidal in their distribution, extending from approximately mid-tide level up to the level of highest spring tide. They are only present in those flats where environmental conditions, such as high salinity and desiccation exclude grazing and burrowing animals which would eat or otherwise destroy the algal mat. Thus, it is mainly the grazing activities of cerithid gastropods and the distrubance of sediment by burrowing crabs which inhibit the establishment of algal mats in lower intertidal zones. Mats cannot grow above the level of highest spring tides because of the intense desiccation in the desert hinterland. The width of the algal mat belt varies from place to place and appears to be related to the local gradient of the tidal flats and to their positions relative to the prevailing northerly winds.

Throughout the algal belt it is possible to recognise a number of algal mat growth forms, perhaps the most important of which are: subaqueous mounds, flat polygonal mats, tufted mats, discrete algal heads, crinkled and curled mats. The mat building algae are all blue-green algae. The commonest species is Microcoleus chthonoplastes which is found in most mat forms, but Lyngbya aestuarii is the most abundant alga in the tufted mats. The most important environmental factor which influences algal mat morphology appears to be the amount of wetting vis-a-vis desiccation. Certain mat forms develop only under conditions of continuous submergence e.g. subaqueous mounds. Other types are found in moist poorly drained settings, e.g. flat polygonal mats, while some others develop under conditions of alternating flooding and subaerial exposure, such as crinkled and curled mats. The amount of wetting of the surface is modified locally by the growth of the algal mat itself. It is these local effects which influence and controls the development and detail of the character of the mat. Broadly speaking there is a regional zonation of mat forms, but irregularities of surface relief, and the presence of pools and channels leads to local variations which mask the otherwise simple picture.

The thickest accumulation of mats is found in lows, e.g. pools and channels. These depressions form a natural site for sediment accumulation on the one hand and a low degree of bacterial activity on the other. The latter results from the toxic conditions which build up in anaerobic situations. The latter condition is a result of permanent or near permanent saturation and stagnant conditions due to lack of drainage. In the surrounding highs where more aerobic conditions prevail, the mats become subject to the effects of two main destructive elements namely; high desiccation and bacterial decay, and only a thin mat is developed. In such highs lateral rather than upward growth prevails. In response to the space problem which arises from lateral expansion, the rubbery mat is forced to buckle and become crinkled. Such crinkling is aided by the movement of trapped air and gases generated by bacterial activity beneath the mat.

The amazing variety of growth features of the mats would most certainly be lost on compaction, as most of them are in fact uncemented.

The high salinity leads to diagenetic interstitial growth of gypsum in some places which has a disruptive effect on lamination.

The physical properties of the sediment substrate are also important in influencing growth forms. Muddy sediments provide the most conducive substrate for widespread algal mat development. It was found that even in higher reaches of the tidal flats where the flooding frequency is very low, the amount of water held in the sediment is sufficient to prevent desiccation of the mats. On sandy substrates, the effects of desiccation are much more intense, even if the area has a relatively high flooding frequency. The mat becomes hard and brittle and often curled.

On porous cemented substrates, such as beachrocks along parts of the banks of tidal channels, lithified stromatolites are developed. Because of the porous and permeable nature of the rocky substrates, the beachrocks drain freely and retain little moisture during low tide. Thus, the mats which colonise them are similarly intermittently exposed and dried out. This leads to precipitation of aragonite and penecontemporaneous cementation of the mats. Locally, fragments of the cemented mats break off and become further coated ultimately to form oncolites. The stromatolites and oncolites are characterized by lack of particulate texture and scarcity of algal remains. They display several varieties of surface morphology. The most common are laterally linked hemispheroids. The hemispheroidal structures are usually arranged in rows and are elongate subparallel to the tidal channel; i.e. in the direction of water movement.

The presence of algal mats in the intertidal zones, especially where they are in a state of arrested decay (e.g. in some pools and channels) should allow preservation of the organic matter prior to burial. This is an essential prerequisite for ultimate maturation of organic matter to hydrocarbons. If, as some authorities believe, algal mats may be source material for petroleum, then the algal mats of Al-Khiran and the neighbouring porous barrier ridges could serve as a model for source rock and reservoir rock in some ancient limestone sequences.

The algal mats of Al-Khiran are features of great natural beauty, but they are vulnerable and could easily be destroyed. The writer trusts that the work presented in this thesis will urge the authorities in Kuwait to take measures to protect the Al-Khiran area, and preserve the algal mats for the pleasure and interest of scientists and others in the future.

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