THE HOLOCENE TIDAL FLAT COMPLEX OF THE ARABIAN GULF COAST OF ABU DHABI

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Abstract

Carbonate sand and mud of the offshore bank flanking the Khor Al Bazam lagoon, the lagoons of the western Abu Dhabi and the mainland coast are accreting and prograding. Seaward of the Khor Al Bazam lagoon the offshore bank is progressively extending its shoal and channel area, coral banks, tidal deltas, and nearshore coastal terraces. Where wave energy is minimal cyano-bacterial mats colonise protected intertidal sediments, building seaward, binding any sediment washed onto them and raising the sediment surface to the high water mark. here the cyano-bacterial mats are entrapped beneath prograding supratidal carbonate/evaporite coastal sabkhat. Mangroves flourish in tide-dominated areas protected from all but the smallest waves, and aid the entrapment of sediment later colonised by algal mats. Local beach ridges develop from spits that acquire beach faces, berms and dunes. These dunes are deflated as the beach line is stranded by coastal accretion. Landward of the beach ridges windblown and wind tide floodwater sediment has accumulated.

Traced landward from the middle intertidal zone of protected coasts the following are found: lime muds and sand flats in association with carbonate cemented hardgrounds passing to cyano-bacterial mat which exhibit a cindery mammillated character. and then polygons and algal crinkles. These latter are associated with a gypsum mush that thickens landward and is replaced by 20 cm thick anhydrite layer. Landward these sediments lie beneath a salt dominated crumpled polygonal surface and near surface interlayers of thin anhydrite and nodules that are flanked by stranded beach ridges of an earlier coastline. The cyano-bacterial materials are preserved as peats beneath the supratidal sabkhat. They have a high potential for being preserved in the geologic record.

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HOLOCENE FACIES TIDAL FLAT

Wide, long, cyano-bacterial tidal flats and coastal sabkha line the coastal lagoons of Abu Dhabi (Fig. 1) (Kendall & Skipwith 1968). At the east end of the Khor Al Bazam lagoon, the largest cyano-bacterial flat and the associated lower tidal flat sands and muds parallels the coast for 42 km and a smaller one parallels the coast for some 9 km. These flats, part of the seaward edge of the prograding coastal plain, have an average width of about two km.

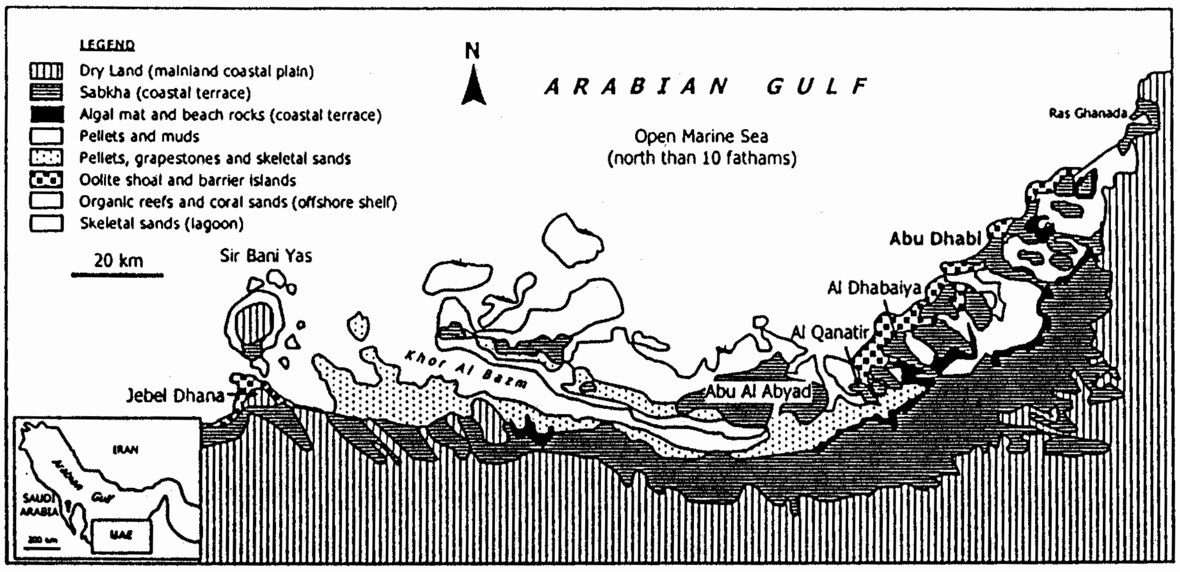


Figure 1. Map of the general marine facies of the coast of Abu Dhabi in the UAE.

The cyano-bacterial flats are underlain by compacted peat-like remains of living cyano-bacteria mat that landward reaches some 5-30 cm in thickness. This mat is prograding seawards, and commonly it extends landward in the subsurface beneath a layer of displacive evaporites and windblown and storm-wash-over sediment. Carbon dating suggests that locally the cyano-bacterial mat has prograded as much as 7 km in the last 4000 years (Kinsman 1964). Seaward of the mats are subtidal and mid intertidal accumulations of carbonate sediment. Landward of the cyano-bacterial mats are stranded beach ridges of an earlier shoreline subdividing the topography of the lower and upper sabkha. Traced from the present shoreline to the line of ancient beaches the character of the sediment surface reflects the topography and tidal range of the Holocene facies tidal flat (Butler 1969), (Fig. 2).

It should also be noted that similar wide tidal flats are located in the protected lee of islands, but here the middle tidal flat is marked by the growth of the mangroves (*Avicennia marina*) while landward lime muds, highly bioturbated by crabs, are accumulating. As with the more protected coasts with cyano-bacteria mats, a crinkled and crenulated mat extends over an accumulation of the gypsum mush of the upper tidal flat. In some places, this zonation of mangroves, crab-burrowed lime mud and gypsum mush is foreshortened so that mangroves abut against beach ridges of cerithids, or mangroves and lime muds adjoin the ridges.

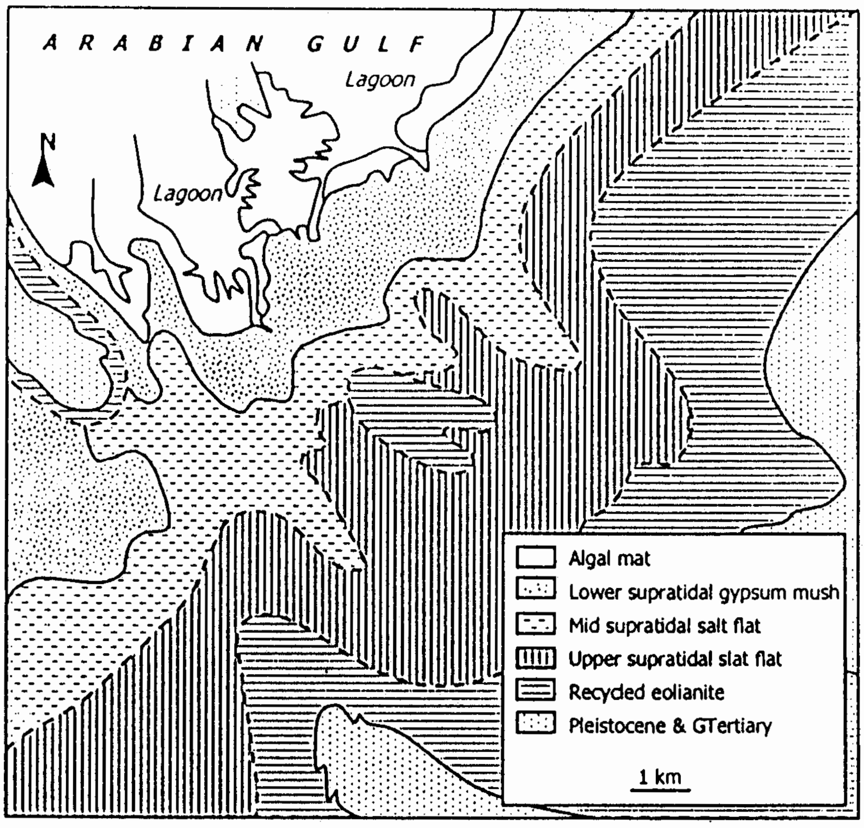


Figure 2. Sabkha sedimentary facies distribution along the southern Arabian Gulf coast (modified from Butler et al., 1982). Location of this section to the southwest of Abu Dhabi island (see Figure 3).

Lower intertidal carbonate flats

Traced seaward to landward across the protected tidal flats, particularly those flanked by cyano-bacterial or "algal" mats, the seaward subtidal to intertidal sediments are composed of foraminiferal-gastropod sands and/or muds and are often overlain by intertidal hardgrounds (Tab. 1). These hardgrounds are discontinuous and are capped by either "peat-like" layers of cyano-bacterial flat sediment adjacent to open lagoons or are capped by intertidal burrowed muds adjacent to the protected lagoons. Both these peats and burrowed muds are capped landward by supratidal evaporites. The hardground is cemented by a calcium carbonate and/or locally by later gypsum. This cemented layer tends to form a seal between the underlying more marine sediments with their marine waters and the overlying supratidal salt flats with their saline brines. This hardground is not present everywhere and seldom overlies the cyano-bacterial-peat layer. This latter occurs where the stranded shoals and coastal spits lie almost perpendicular to the shore and are elevated above the adjacent tidal flats. Here the hardground extends above the peat layer to be on-lapped by a layer of gypsum mush with a surface of cyano-bacterial mat.

Table 1. Sedimentary facies and diagenetic facies in Holocene tidal flat of UAE.

Sedimentary facies	**Thick-ness (cm)**	**Main components**	**Diagenetic facies**
Lower intertidal carbonate flats	30 - 120	Fragments of corals, skeletal sands, ooid and stabilised by the grass Halodule sp., bioclastic and peloidal carbonate sand and mud, cerithid and small shelled bivalves.	Isopach calcite cement, miniscus cement, leaching, skeletal and bioclastic carbonate sand
Middle to upper intertidal algal flats	10 - 55	Laminated cyano-bacterial mats intercalated with aragonite mud, this may be replaced by mangroves swamp and crab-burrowed lime mud. In upper intertidal gypsum crystals and protodolomite.	Gypsum mush, celestite, protodolomite, calcite
Lower supratidal salt flats	10 - 30	Gypsum mush forms a layer which is composed of a mass of loose but separate grain-supported gypsum crystals, with interspersed aragonite or dolomitised aragonite mud.	Gypsum mush, bassonite, dolomite ($MgCO_3 \cdot 3H_2O$)
Mid-supratidal salt flats	20 - 60	Crumpled surface of halite, capped polygonal anhydrite layer, and carbonate wash-over sands.	Pockets of gypsum crystals and anhydrite. The anhydrite partially replaces the gypsum mush and is accompanied by the partial replacement of aragonite muds with protodolomite
Upper supratidal salt flats	5 - 65	Near-surface modular anhydrite in a matrix of carbonate mud. Layer of chicken-wire anhydrite, represent the complete replacement of the gypsum mush	Anhydrite nodules, large gypsum disks, proto-dolomite, magnesite, hunite [$Mg_3Ca(CO_3)_2$], halite, polyhalite and the filling of intertidal molds in gastropods shells by anhydrite
Continental salt flat and recycled aeolian sands	15 - 45	Pre-Holocene eolianites, re-cycled Holocene eolianite, wash-over Tertiary sediments and bedded storm wash-over skeletal debris.	Anhydrite layer, secondary gypsum, dolomite and anhydrite are secondary. Anhydrite can rehydrate to gypsum

The cyano-bacterial facies of the mid intertidal to lower supratidal

Cyano-bacterial mats accrete and prograde on intertidal and periodically inundated supratidal zones where they are protected by islands, sand bodies, wide shoals, and wide intertidal sand flats (Fig. 1). The seaward edge of the cyano-bacterial flats, and where they line ebb channels, is limited by wave and/or tidal scour that erode the surface mats. These cyano-bacteria tolerate temperature variations of over 43 °C and tolerate salinities from 0 to 196 PPT (Kinsman 1964).

The cyano-bacterial mats of the upper intertidal to low supratidal zones of the restricted and protected tidal flat areas of the Abu Dhabi coast are dominated by *Microcoleus* and *Schizothrix*. These microbial mats of Golubic, (1992) are characterised by surface morphologies related to frequency of exposure to the atmosphere above the tidal waters, the salinity of these waters, and the resulting cyano-bacterial community (Fig. 3, 4 and 5), (Kendall & Skipwith 1968, Golubic 1992). The surface of the cyano-bacterial flats can be informally divided from seaward to landward on the basis of surface morphology into: 1) cinder zone of the low to mid-intertidal zone; 2) polygonal zone where there are shallow pools and channel areas with a high flood frequency in the higher intertidal zone; 3) pinnacle mat in the more elevated well-drained tidal flat areas; 4) crinkle zone from the highest intertidal area; and 5) flat mat of the low supratidal zone (Kendall & Skipwith 1968), (Fig. 4).

The most seaward cyano-bacterial mat forms the cinder mat of Kendall & Skipwith (1968). Here at the seaward edge of the algal flats, the surface is pustular or mamillated (Golubic 1992), and has the appearance of an irregular surface of small black cinders. As the cinder zone of cyano-bacteria is traced landward, the surface becomes smoother and is covered by desiccation polygons from 15-30 cm across which are coated by leather-like, dark-green layers of cyano-bacteria. The edges of the polygons upturn, and provide a small scale niche for pinnacled mat algae. The pinnacles of this mat are abundant in areas with low tide exposure, and occur with several environmental modifications nearer the shore. Where tidal creeks drain the algal flat, these meandering bodies of water are obstructed by further growths of cyano-bacteria forming dammed ponds. The ponds may be up to 10 m across, but are usually no more than 2-3 m in diameter. Here, pink surfaced layers of peat collect, broken into huge lily pad-like bodies measuring several meters across, which themselves may be desiccated into large polygons 0.5 to 1 m in diameter. These polygons are preserved and can be identified well landward of the present algal flat beneath the sabkha surface in trenches cut in the supratidal salt flats.

The algal-peat of the polygonal zone varies in composition from nearly 100% organic material to a very sandy organic material (Kendall et al. 1991, Schreiber et al. 2001). The peat richest in organics is associated with the ponds formed where the tidal creeks are dammed. These peat-filled creeks extend from the middle of the intertidal cinder zone to well back into the upper intertidal crinkle zone. The most common occurrence of the algal mat peat is associated with the polygonal zone and is represented by the stacked saucer-like structures of this zone. The cracked, unturned margins of the polygons are filled by carbonate sand. The peats of the ponds and polygonal zone are 30-45 cm thick at their seaward edge, but compress beneath the sabkha surface landward to some 25 cm.

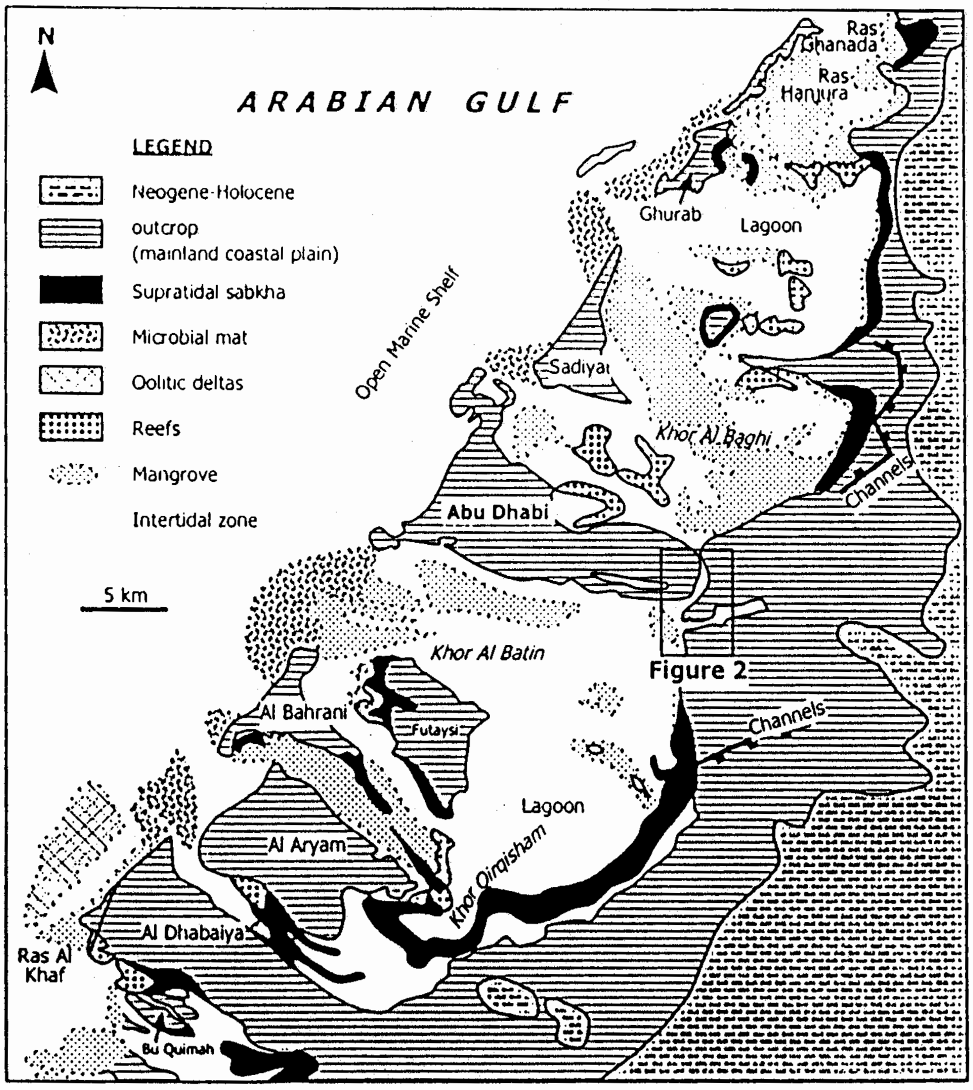


Figure 3. Holocene tidal flat facies distribution of the Abu Dhabi coastal carbonate environment (modified from Kenig et al., 1991).

The upper intertidal zone, which is flooded during middle-to high tide, is commonly covered with a crenulated or crinkled green to black cyano-bacterial mat (Kendall & Skipwith 1968). This is the convoluted mat of Golubic (1992) and the crenulations are probably formed by the rapid lateral growth of its surface. A mush of gypsum crystals begins to accumulate beneath the surface of this mat in the upper intertidal zone. The crenulated mat is a leathery, wrinkled organic layer, blackened on the upper surfaces of the folds in response to air-exposure, but commonly retaining the pinkish-beige colour on lower less exposed surfaces. The crenulated folds trap air and gases (probably methane) that are expelled when walked upon. A common morphological variation of these mats includes the formation of "tufts" on the upper more aerated surface of the crenulated mat, usually in the mid-intertidal zone at transitions between the pinnacle and polygonal mats with the crenulated mat. Occasionally in the upper-most intertidal zone, the crenulated mat can desiccate and shrivel to form a dried crust at low tide. In the lower supratidal zone there is a thin layer of microbial material (less than a centimeter) at the surface in this zone, and the sediment surface becomes horizontal, probably because the cyano-bacteria do not grow vigorously and the pink cyano-bacterial surface no longer expands laterally. Gypsum continues to actively precipitate beneath a centimeter or less of the surface sediment. The sediment is moist, but dewaters where footsteps and vehicle tracks have compressed it and anhydrite can form in the resulting depressions. A surface of carbonate wash-over sediment may contain halite, but it does not form a crust at the surface.

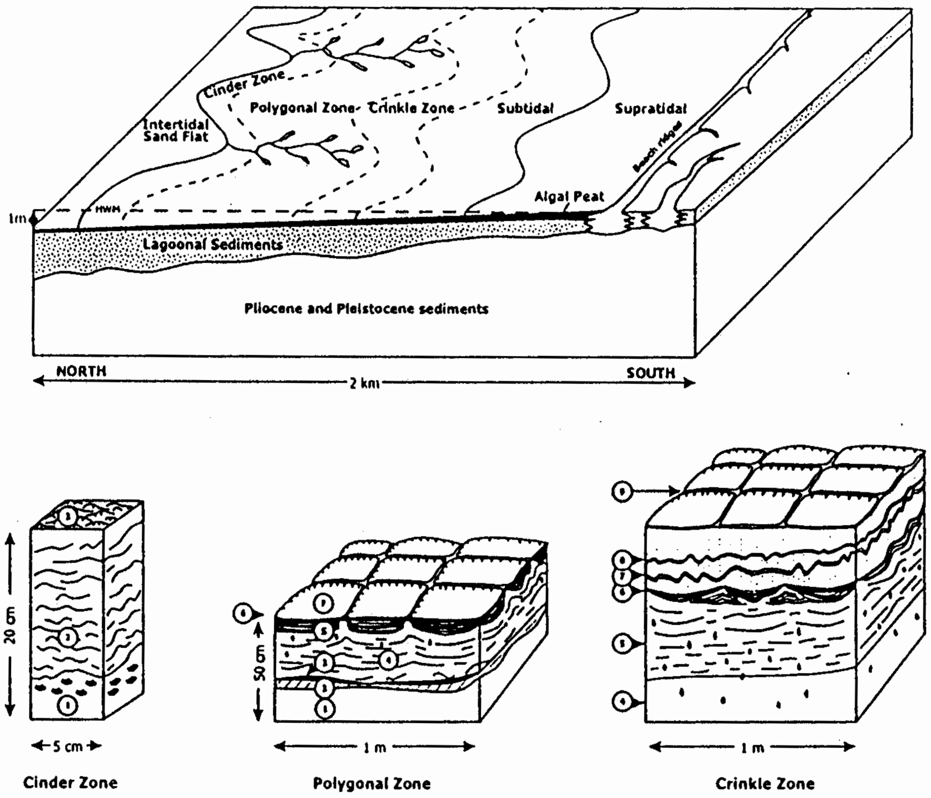


Figure 4. Composite idealized model showing distribution of sabkha sediments based on the barrier island – lagoon sabkhat of Abu Dhabi region (modified from Butler et al. 1982). (1) Lagoonal carbonate sands and/or muds with carbonate hardgrounds, (2) Vaguely laminated lower tidal-flat cyano-bacterial peat, (3) Upper tidal-flat algal mat; commonly laminated and cross-cut by desiccation polygons, (4) Large gypsum crystals (prismatic or lenticular), (5) Cemented carbonate layer, (6) Hightidal flat to supratidal mush of gypsarenite and carbonate, (7) Supratidal anhydrite polygons with windblown carbonate and quartz, (8) Anhydrite layer replacing gypsum mush and forming diapiric structures, (9) Halite crust formed into compressional polygons.

The crystals of gypsum vary in size from a few millimeters to a centimeter in diameter and form a layer that ranges in thickness from a few centimeters to as much as ten centimeters. Lime muds overlain by and caught up in this crystal mush show evidence of dolomitisation. The crystals overlie a cyano-bacterial·peat, commonly forming a transition zone of organic-rich gypsum layers. This facies overlies discontinuous hardgrounds of carbonate sand that are often cemented by both carbonate and/or gypsum.

The preservation of the peat-like remains of the cyanobacteria probably can be linked to the "pickling" effects from the high salinities of the area and the reducing environment in which the cyano-bacteria are accumulating. The presence of stranded beach ridges landward of the cyano-bacterial flats suggests that the cyano-bacterial-peats are not the first Holocene sediments to accumulate here. In fact, during the early stages of the Holocene, the western Abu Dhabi (Khor Al Bazam area) and portions of the lagoons behind the Abu Dhabi island were undoubtedly open bodies of water, subject to higher wave energies than today. The result is that chenier-like beach ridges, formed of cerithid gastropod debris, line the coasts. Subsequently, the lagoon margins filled, shallowed, became more restricted, and the beach ridges ceased to develop. On the coasts of the Khor Al Bazam lagoon, intertidal cyano-bacterial mats began to form while offshore carbonate sands or muds accumulated. These cyano-bacterial stromatolites have since prograded five to six kilometres seaward, and close to Abu Dhabi City reach seven kilometres.

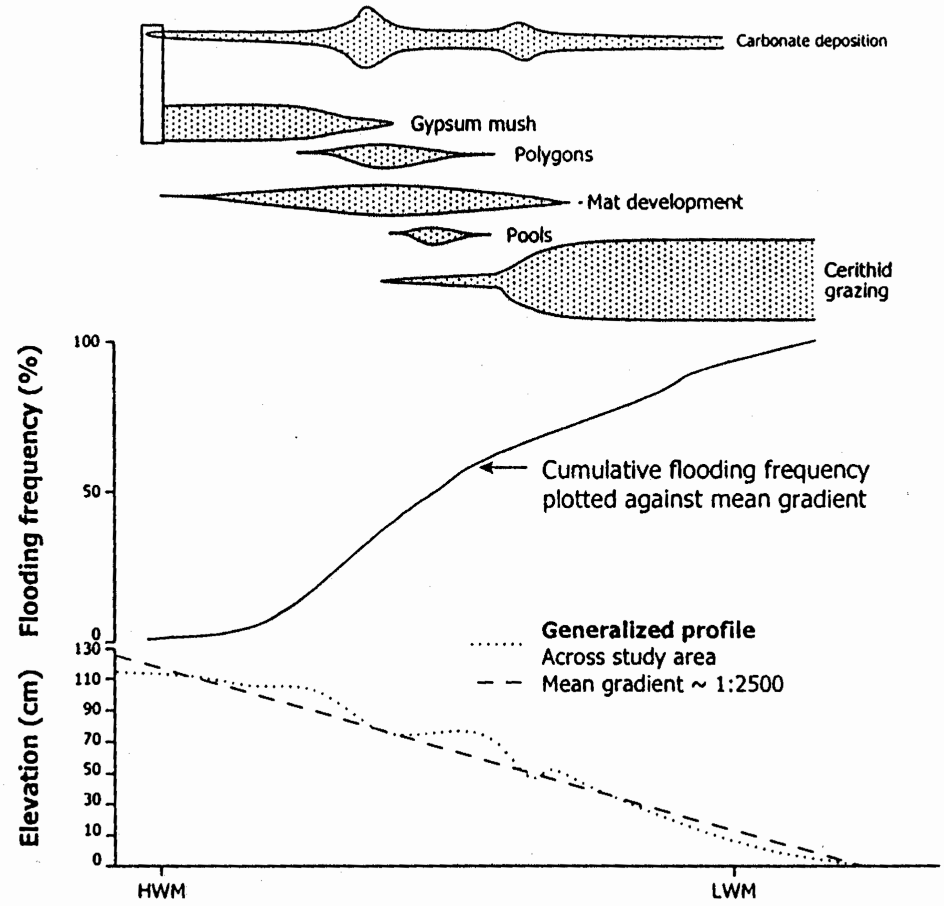


Figure 5. Distribution of microbial mat types and sedimentary features across the Abu Dhabi tidal flats (modified after Park, 1977).

Mid to upper supratidal evaporites

As the buried layer of gypsum mush is traced landward from flat zone of the cyano-bacterial flats or from the crab-burrowed muds of the mangrove swamps, the surface of this gypsum mush becomes oxidised and is replaced by an initially thin layer of anhydrite (1-2 cm thick) which is interlayered with storm wash-over carbonate sediment. Over a distance of tens of meters the layer of gypsum mush becomes completely replaced by a 20 cm thick upper sequence of anhydrite that lies beneath a polygonally to convoluted and cracked surface crust of halite. The underlying anhydrite is finely crystalline and has the consistency of cream cheese. It is thixotropic and contains pseudomorphs after discoidal gypsum, which ranges from 0.05 mm to 30 cm in diameter (Butler 1969, Butler et al. 1982, Warren & Kendall 1985). This anhydrite is a predominantly secondary mineral that replaces gypsum. Locally it replaces carbonates or occurs as a direct precipitate into voids. This anhydrite-rich layer and the underlying peat disappear close to the line of stranded beach ridges. The beach ridges overlie laminated and burrowed lime muds. At some localities, these burrows remain open. The cyano-bacterial-peat usually occurs seaward beneath the surface evaporite layer, although in local areas protected by islands, a lime mud replaces this peat as it does close to the beach ridges.

Thus in the mid to upper supratidal zone halite polygons commonly overly, in descending order, a sequence of storm wash-over carbonates, anhydrite, minor gypsum, cyano-bacterial peat, and medium-to-very coarse carbonate sand. Large (5 to 10 cm across) gypsum crystals are common within or immediately below the lowest cyano-bacterial peat layer, often preserving original cyano-bacterial laminations. The buried cyano-bacterial peat commonly displays the desiccation polygons seen on the surface of the tidal flats in the upper intertidal zone and overlies discontinuous hardgrounds of lower tidal flat carbonate muds and sands, cemented by carbonates or gypsum. This vertical sabkha sequence, which extends from the cyano-bacterial flats to the beach ridges, reflects the previously described surface relationships for lateral sedimentary settings that can be traced from the land to the sea.

The major difference landward of the cerithid beach ridges is that the sediments overlying the gypsum and anhydrite being precipitated here are covered by an accumulation of thicker storm wash-over carbonates and clastics, which are derived from the tidal flat or are blown from inland. This wash-over sediment includes gypsum crystals that were eroded from the upper cyano-bacterial flats. These crystals now form the nucleus to the "cumulus cloud-like" nodules of anhydrite found just within and beneath the sabkha surface. Trenches dug landward of the beach ridges may expose shallow lagoonal sediments dominated by carbonate mud. Large gypsum rosettes are found in this mud. The waters associated with the ridges and adjacent landward are stained with iron which leaves a vivid red stain of hematite marking the top of the water table. Early Holocene aeolian carbonates and sediments washed out as fans from Tertiary outcrops have accumulated on the most landward side of the sabkha. Here, particularly within the sabkhat close to the Abu Dhabi Island, the anhydrite layers and nodules are replaced by gypsum. This replacement is a response to the influx of the fresher continental waters from the Arabian interior entering the coastal system (Patterson & Kinsman 1981). Meanwhile, to the landward side of the buried lagoon, the water takes on a milky appearance, probably a response to the presence of suspended carbonate mud as described by Swart et al. (1987) and Muller et al. (1991) from the Holocene sediments of Qatar and Abu Dhabi respectively.

ORGANIC MATTER IN A RECENT CARBONATE ENVIRONMENT

Cyano-bacterial material and associated carbonate sediments collected along the coast of western Abu Dhabi were investigated in terms of their: 1) surface conditions at deposition; 2) geometry and relationship to surrounding facies; and 3) organic chemical composition from whole rock, bitumen, and kerogen analysis.

Microscopic evidence shows that the solid organic matter is mostly highly fluorescent algal material that is relatively free of microbial maceration. This suggests that the organic matter is well enough preserved to become a source rock.

Total organic carbon (TOC) values in some samples are as high as 8.4%, with Rock-Eval pyrolysis yields as high as 564 mg of hydrocarbons per gram of TOC. Although TOC and Rock-Eval techniques were developed to assess petroleum source-rock potential for ancient rocks that have at least undergone organic diagenesis (a major loss of organic functional groups and condensation to a functionally more stable geopolymer), analyses of these recent cyano-bacterial sediments indicate significant organic enrichment, with potential to generate hydrocarbons upon thermal degradation. These results represent significant evidence that rocks of this type can be potential petroleum sources.

Laboratory studies indicate that concentrations of organics in these cyano-bacterial deposits meet productivity requirements based on TOC analyses (Fig. 6). Hydrocarbon generation potentials based on Rock-Eval pyrolysis (HI values) suggest that the organic matter is capable of generating oil and gas upon thermal maturation; however, these results also indicate that the organic matter may be more gas prone than oil prone. On the other hand, elemental analysis, which is usually more accurate than Rock-Eval pyrolysis, indicates that the organic matter is more oil prone than gas prone. Both Rock-Eval pyrolysis and elemental analysis show that the organic matter follows the Type II kerogen evolution pathway.

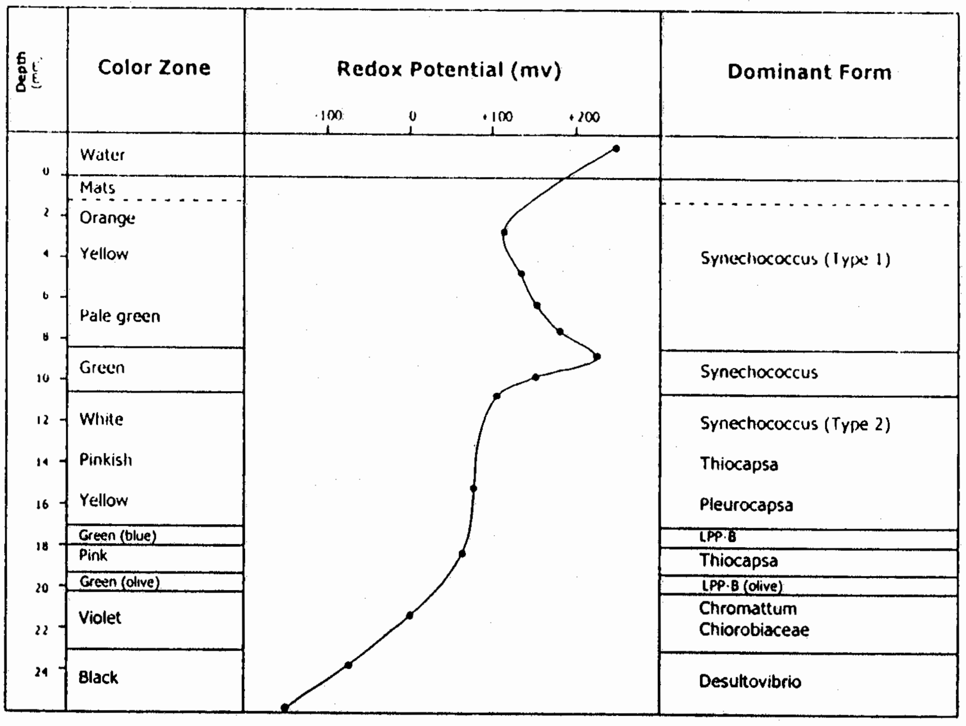


Figure 6. Chemical and physical details through a typical cyano-bacterial mat on a sabkha (composite). Thickness of mat (mm) is shown on the left, with color of the various 'sublayers'. Redox potential shows anoxic conditions below about 2 cm deep. Main microorganism groups at each depth are indicated on the right. (modified from Sheppard et al., 1992).

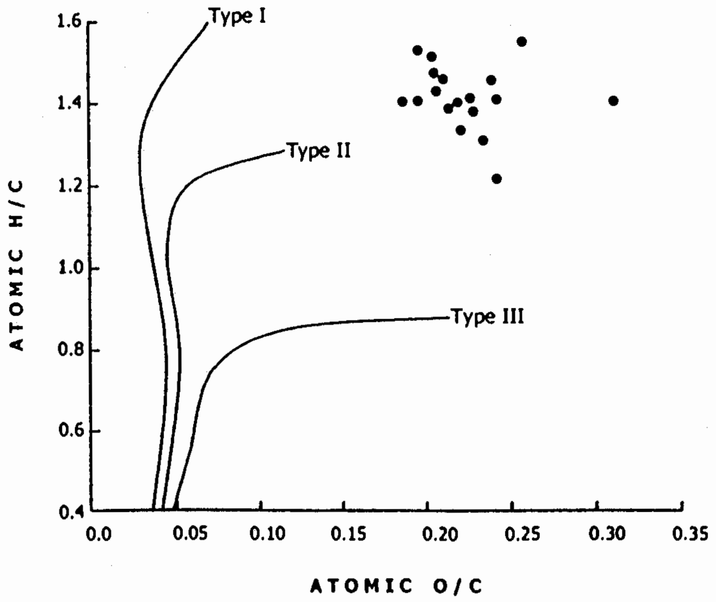


Figure 7. Modified van Krevelen diagram showing H/C to O/C relationships from elemental analyses of cyano-bacterial mat samples from Abu Dhabi, UAE.

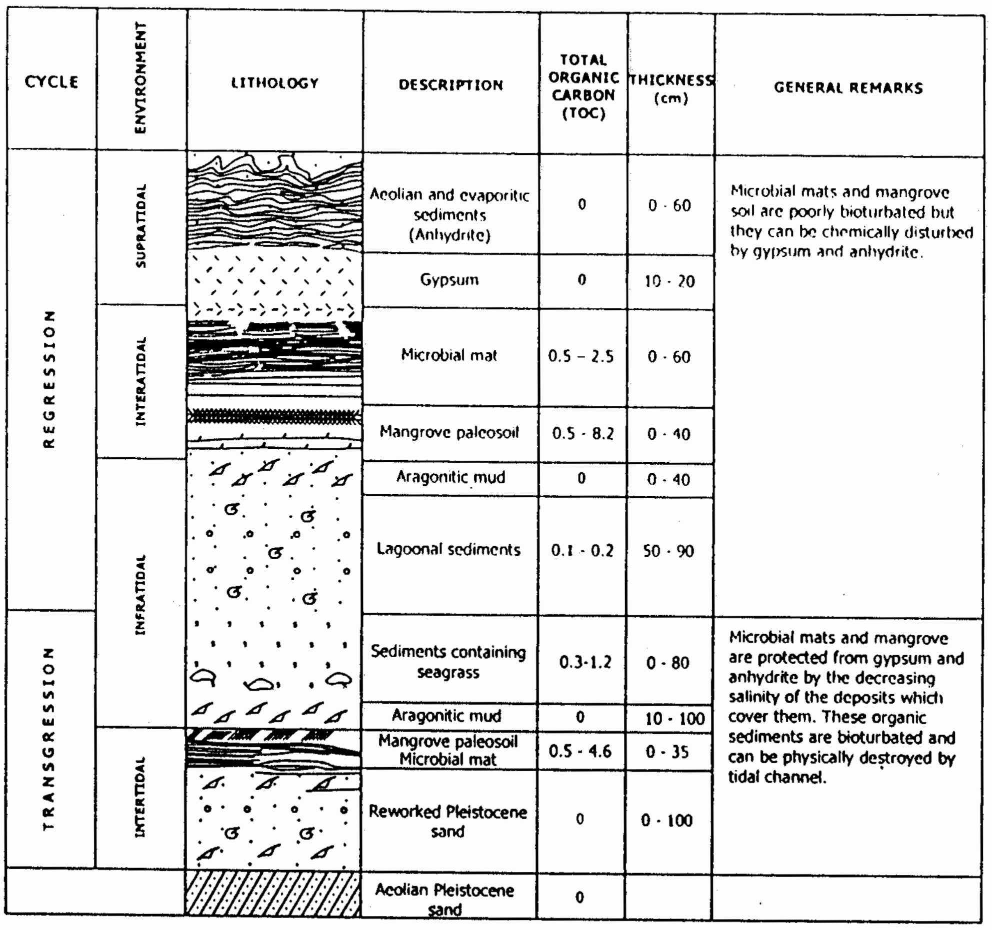
Analyses of mats collected from western Abu Dhabi are compared with those collected by Cardoso *et al.* (1978) and Kenig *et al.* (1990) from other areas of Abu Dhabi. TOC of the sediment in the field area has a wide range of organic enrichment (0.46-8.40% TOC). Whole rock pyrolysis yields moderately high Hydrogen Indices (HI) of 389-597, typical of marine Type II kerogens. These values (0.5-2.7% TOC and HI – 510 to 675) were published by Kenig *et al.* (1990). Elemental composition (C, H, N, O, S) of isolated solid organic material (Kerogen precursors) showed atomic hydrogen to carbon (H/C) ratios (1.20-1.54) that fall directly on the Type II evolutionary pathway, as shown in a modified van Krevelen diagram (Tissot & Welte, 1984). Stable carbon isotope ratios ranged from –8.41 to –10.78% (Fig. 7).

PRESERVATION POTENTIAL OF CYANO-BACTERIAL MAT

As the cyano-bacterial mat becomes buried more deeply, the gross morphologic structures are less well preserved (Fig. 8). For example, below the gypsum mush facies polygonal and mamillate mats are easily distinguishable in buried sections. Beneath the lower supratidal facies (further inland) only the polygonal mat was identified by field inspection. The crenulated cyano-bacterial mat subfacies was not evident in the subsurface at all. This mat may not be preserved because: 1) it forms more inland in a higher and a more oxidizing depositional setting and/or 2) it forms in a setting conducive to precipitation of post-depositional and displacive gypsum.

Previous studies of Abu Dhabi cyano-bacterial mats assessed relative "preservation potential" of mat types based on the preservation of gross structures (Park, 1977). Preservation of the mat is a function of the subsurface extent (thickness and distribution) of the mat and the assumption that the mat will not be altered physically beyond easy recognition of the gross structures. The first part of this assessment may not be correct since the distribution and thickness of buried mat types cannot be unequivocally assumed based on the present extent of living equivalents. For example, if conditions 500 years ago were not conducive to mamillate mat growth in this area, it cannot be assumed that lack of mamillate mat in sediment 500 year old means that the mat was not preserved.

The second assumption is that the buried mat should "look like" its living counterpart on the surface. Geometric associations of the mat with inorganic sediment, such as well-formed laminae and desiccation polygons of the flat mat are easily recognised. Therefore, the flat mat can, without a doubt, be recognised in the subsurface. The mamillate mat, on the other hand, does not have such distinctive features. Additionally, it is prone to compression. Consequently, the "occurrence", or rather recognition, of the mamillate mat in the subsurface may not be as common as that of flat mat. However, this is a function of the initial extent, condition, and composition of the mat, as well as the criteria used for identification, not a result of poor preservation potential.



CYCLE	ENVIRONMENT	LITHOLOGY	DESCRIPTION	TOTAL ORGANIC CARBON (TOC)	THICKNESS (cm)	GENERAL REMARKS
REGRESSION	SUPRATIDAL		Aeolian and evaporitic sediments (Anhydrite)	0	0 - 60	Microbial mats and mangrove soil are poorly bioturbated but they can be chemically disturbed by gypsum and anhydrite.
			Gypsum	0	10 - 20	
	INTERTIDAL		Microbial mat	0.5 – 2.5	0 - 60	
			Mangrove paleosoil	0.5 - 8.2	0 - 40	
	INFRATIDAL		Aragonitic mud	0	0 - 40	
			Lagoonal sediments	0.1 - 0.2	50 - 90	
TRANSGRESSION			Sediments containing seagrass	0.3-1.2	0 - 80	Microbial mats and mangrove are protected from gypsum and anhydrite by the decreasing salinity of the deposits which cover them. These organic sediments are bioturbated and can be physically destroyed by tidal channel.
			Aragonitic mud	0	10 - 100	
	INTERTIDAL		Mangrove paleosoil Microbial mat	0.5 - 4.6	0 - 35	
			Reworked Pleistocene sand	0	0 - 100	
			Aeolian Pleistocene sand	0		

Figure 8. Holocene organo-sedimentary sequence of the Abu Dhabi coastal carbonate environment (modified from Kenig et al., 1991).

Petrographic analysis provides an alternate means of recognising mat types in the subsurface. Additionally, study of microstructures can delineate subtle diagenetic changes in the mat as well as the degree of preservation of the cyano-bacterial constituents of the mat. Thus, the following observations of cellular and amorphous organic components of the mats are offered:

Coccoid species (or at least the cell walls of these organisms) are relatively well preserved, regardless of the mat type in which they are found. Literature citing fossil examples of cyano-bacteria emphasises this point, since many of the examples are coccoid species similar (or perhaps identical) to those collected from western Abu Dhabi (Golubic & Barghoom, 1977; Awramik, 1984; Golubic & Yun, 1985).

1. The amorphous organic material (sheath material and probably cell fluids) may degrade in a manner that destroys depositional microstructure. If or when this material is preserved, it will probably be preserved in an amorphous form, the origins of which are difficult or impossible to decipher.

2. The dissolution of inorganic components (e.g., pods of micritic carbonates) and subsequent compaction of the mats may alter the depositional structure of the mat.

CONCLUSIONS

The tidal flats with the seaward margin of the coastal plain or sabkha can divided into:

(a) Lower subtidal carbonate flats with muds, sands and hardgrounds
(b) Upper intertidal cyano-bacterial flats from seaward to landward of cinder like cyano-bacterial mat, polygonal mat (with local pinnacles and channels) and crenulated mat passing into flat mat
(c) Lower supratidal evaporites with gypsum mush
(d) Mid supratidal evaporites with gypsum being replaced by anhydrite and flanked to the landward by stranded beach ridges
(e) Upper supratidal evaporites trapped in storm wash-over, recycled aeolian and Tertiary sediments include gypsum and anhydrite

The potential for the preservation of this cyano-bacterial material in these intertidal and supratidal settings is still being investigated but it looks as if tidal flat settings similar to those of Abu Dhabi could be an important source of hydrocarbons in the future and have been in the past.

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