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FIGS. 1–9, DECEMBER, 1968

RECENT ALGAL MATS OF A PERSIAN GULF LAGOON[1]

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ABSTRACT

Extensive laminated mats of algae are forming on the protected intertidal and supratidal flats of a highly saline lagoon, the Khor al Bazam, Abu Dhabi, southwest Persian Gulf. At the east end of the lagoon, the largest algal flat parallels the coast for 42 kilometers, and to the west another smaller one parallels the coast for nine kilometers. These flats, part of the seaward edge of a prograding coastal flat, have an average width of approximately two kilometers and a thickness of at least thirty centimeters. In some areas they extend landward in the subsurface for more than two kilometers, beneath a thin cover of evaporites and wind blown and storm washover sediments. Smaller flats occur in the shelter of islands, headlands, and swash bars.

The larger algal flats are divided on the basis of surface morphology, into four geographical belts. From the high-water mark seaward these are: (1) Flat zone—firm, smooth algal mat, with no topographic relief, overlying quartz-rich carbonate sand and evaporites; (2) Crinkle zone—leathery algal skin forming a blistered surface over gypsum and carbonate mush; (3) Polygonal zone—algal mat separated into desiccation polygons a few centimeters to two meters in diameter, which cover laminated algal peat; carbonate sand and mud fills the cracks between the polygons. (4) Cinder zone—a warty black algal surface, the color and size of the raised bumps resembling a weathered volcanic cinder layer. These bumps, shaped like small pustules two to three centimeters in diameter, cap an unlaminated algal and sediment peat.

The algal growth and structures appear to be determined by the frequency and duration of subaerial exposure and the salinity of the tidal waters; they are only related to wave energy when limited by wave and tidal scour at the edge of the Cinder zone and along ebb channels.

INTRODUCTION

Laminated algal mats resembling stromatolites are found growing on intertidal areas and in salt lakes in many parts of the world; for example, the Bahamas (Black, 1933), Florida (Ginsburg, Isham, Bein and Kuperberg, 1954), the west coast of Mexico (Phleger and Ewing, 1962), the south coast of Texas (Fisk, 1959 and Dalrymple, 1965), Great Salt Lake, Utah (Carozzi, 1962), Australian Salt Lakes (Clarke and Teichert, 1946), Shark Bay on the west coast of Australia (Logan, 1961), and the Persian Gulf (Kinsman, 1964b, and Illing, Wells, and Taylor, 1965).

Along the Khor al Bazam and the rest of the abu Dhabi coastline, Recent marine algal mats form on intertidal and periodically inundated supratidal zones (fig. 1) in the protection of islands, sand bodies and wide shoals in Abu Dhabi. These algae withstand temperature variations of over 30°C. and tolerate salinities from 47 parts per thousand to 196 parts per thousand (Kinsman, 1964b). The algae secrete protective mucilagenous jackets which Douglas Shearman of Imperial College (pers. comm., 1965) believes enable the algae to withstand such rigorous conditions.

The algal mats are characterized by films and layers of intertwined filamentous and unicellular blue-green algae that bind and trap sand-, silt-, and clay-size sediment washed onto the mats (Logan, Rezak, and Ginsburg, 1964). Thus the composition of the laminae reflect that of the adjacent sediment, except that the sediment collecting here is usually much finer grained due to the low energy environment in which the algae are growing. The mats exhibit varied surface morphology as a result of the "interaction of the algal film, detrital sediment, and physical environment factors" (Logan and others, 1964).

Early classifications of algal Stromatolites which were essentially generic (Walcott, 1914; Pia, 1927) were criticized by Black (1933) who showed the morphological features were partly controlled by environment. Subsequent studies have led to a combination of generic and descriptive classifications emphasizing the importance of stromatolites as environmental indicators (Maslov, 1939; Anderson, 1950; Rezak, 1957; Robertson, 1960). In contrast Glaessner (1962) suggests that form is restricted stratigraphically and is not necessarily an environmental indicator.

Logan and others (1964) established the following three major classes of algal stromatolite based on geometric form:

1. Laterally-linked hemispheroids (LLH); subdivided into close-linked hemispheroids less than a diameter apart (LLH-C) and spaced hemispheroids (LLH-S).

2. Discrete, vertically-stacked hemispheroids (SH); subdivided into those which overlap

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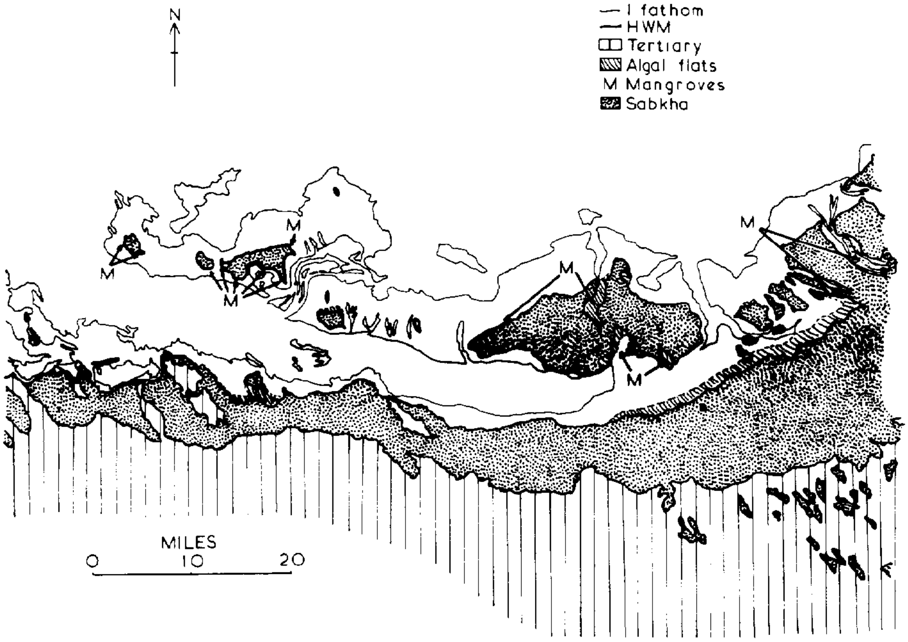

FIG. 1.—Location of algal flats and mangroves in the Khor al Bazam.

FIG. 2A.—Cross-section of algal polygons from the Abu Dhabi Sabkha. Overlying sediment contains gypsum and anhydrite. (G. P. Butler photo) upwards (SH-C) and those which do not expand vertically (SH-V).

3. Discrete spheroids (SS); subdivided into inverted-stacked (SS-R), and concentric spheroids (SS-C).

This classification cannot be applied to some common algal morphological types. These are the algal desiccation polygons found in the Bahamas (Black, 1933), Florida (Ginsburg and others, 1954), Qatar (Illing and others, 1965), the Trucial Coast (Kendall and Skipwith, 1966), and in the geologic record (Fischer, p. 118, 1964 and Aitken p. 1169, 1967). These polygons are formed as a result of desiccation of the algal mat surface. With continual algal growth, the margins of the polygons curl up and become rounded to form lips. Cross-sections through these structures reveal discrete stacks of polygonal saucers piled one upon the other (fig. 2A) rather than domed hemispheroids. Thus an addition is proposed to Logan and others' (1964) classification. This is inverted stacked hemispheroids (SH-I). The location and explanation of these features is given below.

GEOGRAPHICAL SETTING

The Khor al Bazam is situated on the Trucial Coast embayment. This embayment forms part of the southwestern coast of the Persian Gulf (fig. 3). Here a wide range of shallow water carbonate environments exist (fig. 4). These consist to the north of a line of reefs and barrier islands protecting a series of shallow lagoons. To the east deltas form between the islands where the ebb tide carries the lagoonal waters seawards. Oolites occur on most of these tidal deltas. In the protected waters of the eastern lagoons, carbonate muds and pellets form in conjunction with skeletal sands (Kinsman, 1964a; Evans, Kinsman, and Shearman, 1964). Westwards, where the lagoons are more open, aggregates of carbonate sand grains form (Kendall, 1966 and Skipwith, 1966). In both lagoonal areas black mangroves *Avicennia marina* and algal flats are developing. Tidal range is just over two meters on the open coast and drops to less than a meter in protected lagoons. The coastal sediments on both the islands and mainland are accreting seawards. The ground water of these sediments, though of marine origin, is being continually concentrated by the high evaporation rates of the area so that evaporite minerals form in the capillary zone and in the water table below. These minerals include gypsum, anhydrite, dolomite, and halite (Curtis, Evans, Kinsman, and Shearman, 1963; Butler, Kendall, Kinsman, Shearman, and Skipwith 1965), also celestine (Evans and Shearman, 1964), huntite, and magnesite (Kinsman, 1964a).

Figure 1 shows the distribution of the algal flats in the Khor al Bazam. Two forms of mat occur: (1) open coast algal flats, and (2) enclosed algal flats. The open coast algal flats include that of the east Khor al Bazam (fig. 2B), Khusaifa, the south of Thimairaiyan, the west flank of Ras al Aish, the seaward side of Dagallah lagoon beach barrier (fig. 2C), the lee of Mahmeem, the north of Janana, and the coast of some of the islands of the east Khor al Bazam. Enclosed algal flats are found on parts of the island of Marawah, on the island of Hail, and parts of Abu al Abyad (fig. 2D). The latter are often protected by beaches and are closely associated with mangroves that line meandering drainage channels.

ZONATION OF THE KHOR AL BAZAM ALGAL MATS

The larger of the Khor al Bazam algal flats have been divided on the basis of surface morphology into four geographical zones (fig. 5).

From high-water mark seaward these are: (1) Flat zone—a firm, smooth algal mat surface with no relief, overlying quartz-rich carbonate sand and evaporites up to twenty centimeters thick (Logan and others, 1964, code LLH); (2) Crinkle zone—a leathery algal skin that forms a blistered surface over gypsum and carbonate mush (Logan and others, 1964, code

FIG. 2B.—Algal mat of the East Khor al Bazam with a) advancing lobes, b) beach ridges, c) flat flat, and d) sand flat.

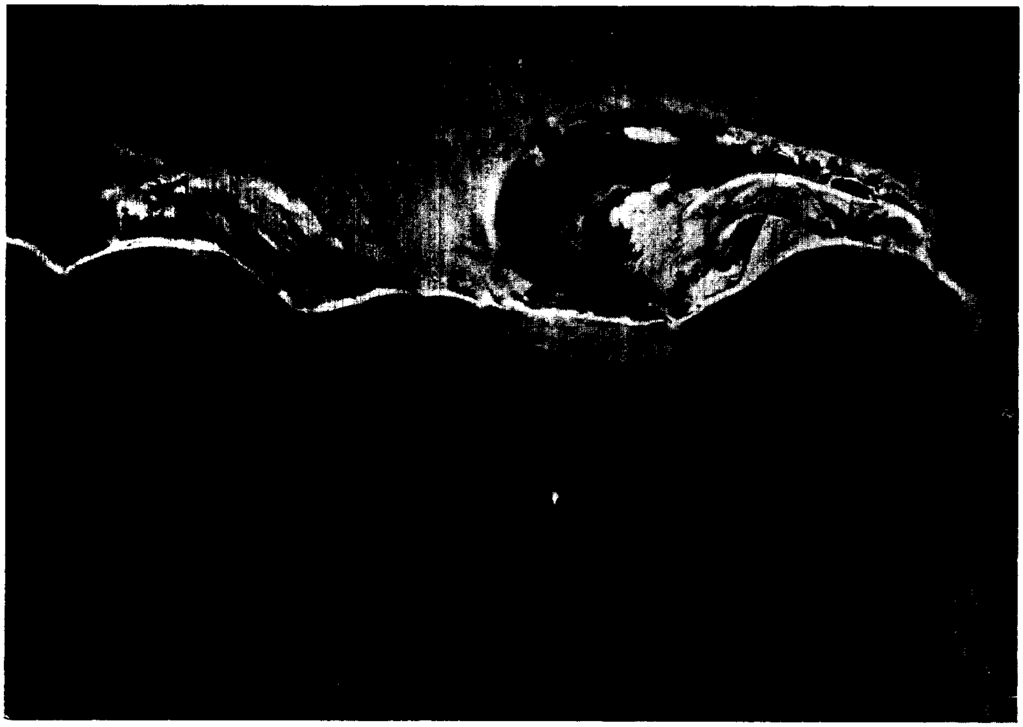

FIG. 2C.—Small algal flats north of beach barrier on the shoals west of Dagallah. (ADPC photo)

FIG. 2D.—Enclosed algal/mangrove complex on the south coast of Abu al Abyad. (ADPC photo)

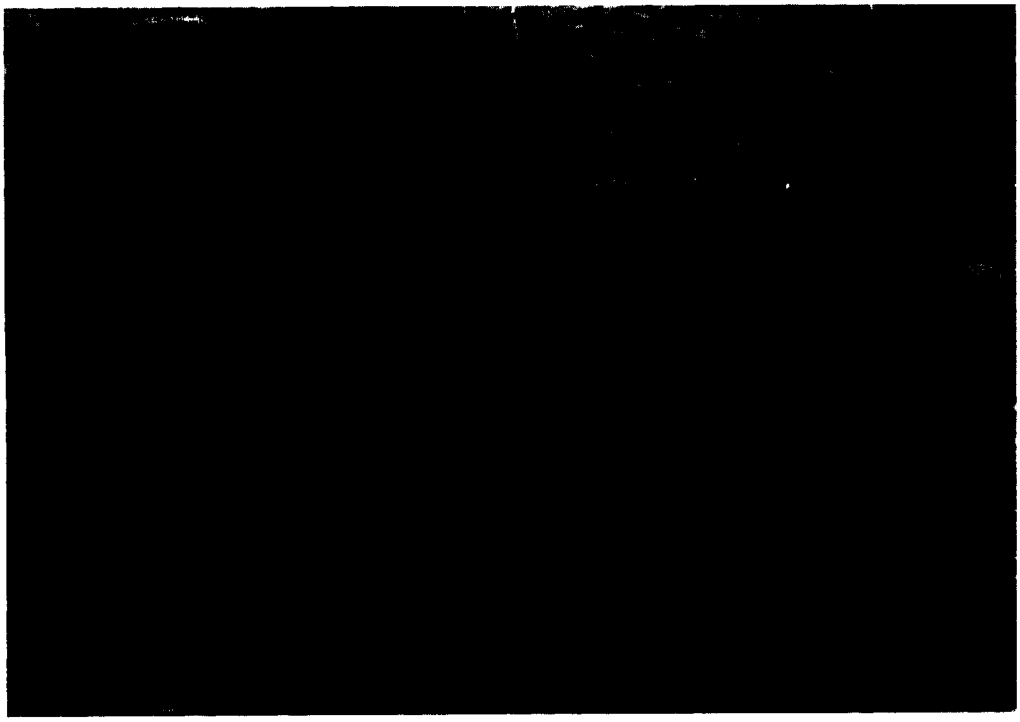

FIG. 2E.—Compressional ridges of salt crust at the top of the flat flat in the east Khor al Bazam.

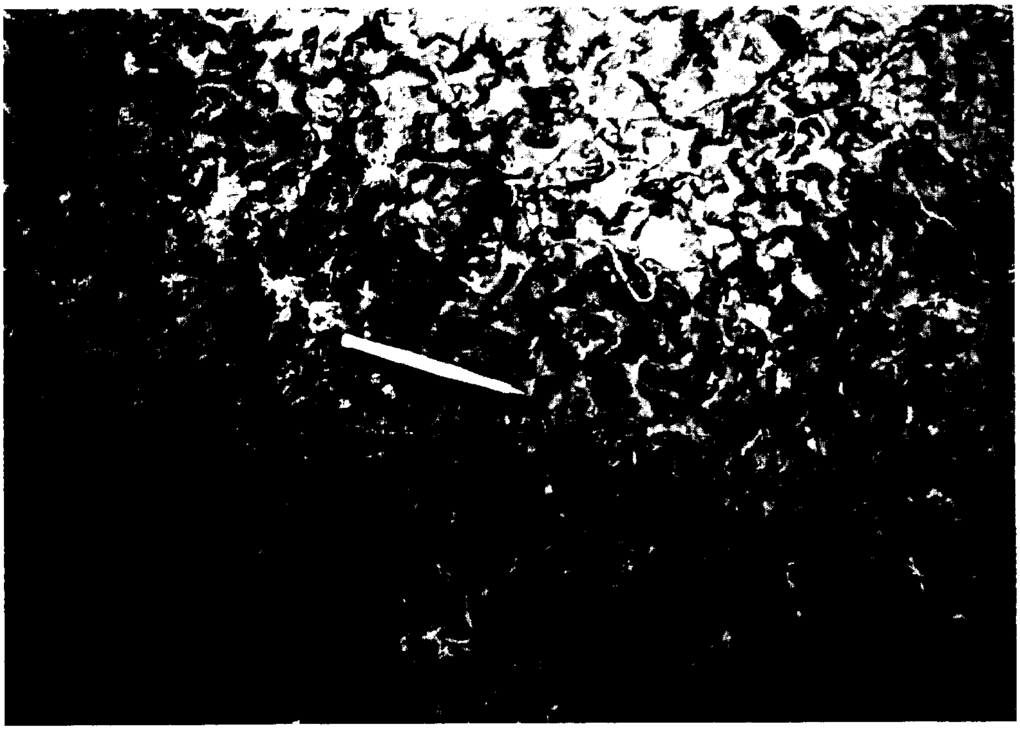

FIG. 2F.—Surface of the Crinkle zone.

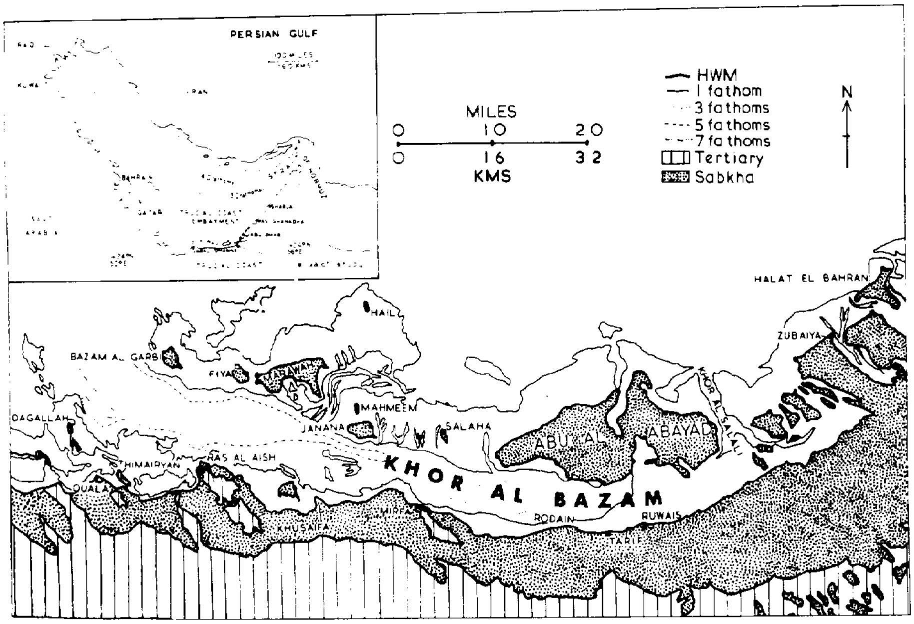

FIG. 3.—Location map of the Khor al Bazam.

LLH); (3) Polygonal zone—algal mat separated into desiccation polygons a few centimeters to two meters in diameter covering laminated algal peat. Carbonate sediment fills in under the curled-up polygons and into the vertical cracks (new code SH-I). (4) Cinder zone—a warty black algal surface, the color and texture of the bumpy surface resembling a volcanic cinder layer. The bumps, shaped like small pustules, are from two to three centimeters in diameter. This surface caps an unlaminated algal and sediment peat (Logan and others, 1964, code LLH). Zone boundaries are transitional. The two larger flats, the one south of Abu al Abyad at the east end of the lagoon and the other behind Khusaifa at the west end of the lagoon, show

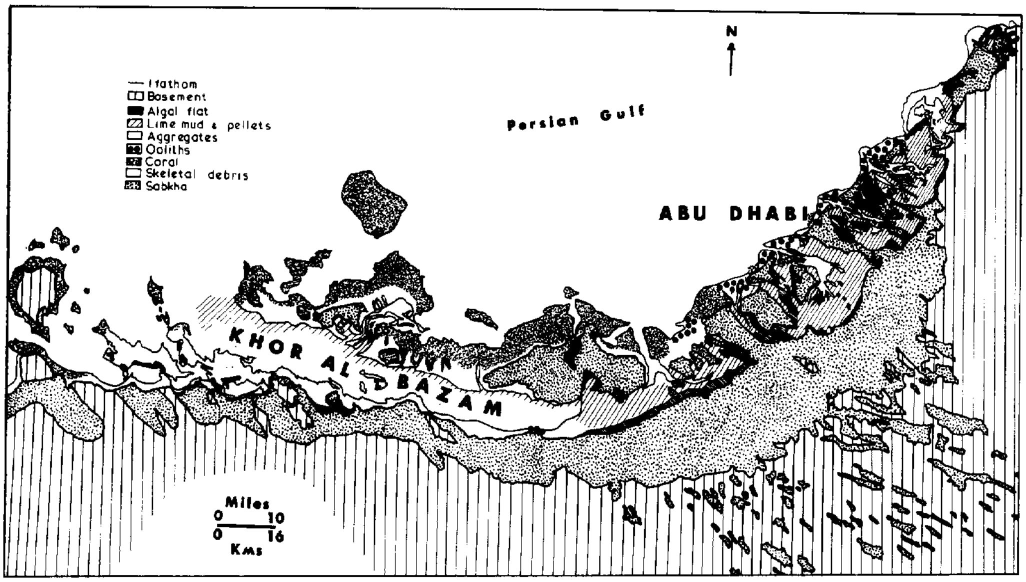

FIG. 4.—Interpreted lithofacies distribution in Abu Dhabi.

the best developed zonation. On all the smaller mats the zones are narrower, and on some there are no Polygonal and Cinder zones.

The algal zones are bounded landwards by a prograding supratidal coastal flat, the Sabkha (Evans, Kendall, and Skipwith, 1965; Illing and others, 1965), and seaward by intertidal sand or mud flats (fig. 4). The Sabkha surface is composed largely of calcium carbonate with a low percentage of quartz. The sediments were transported to their present position, mainly from the intertidal area, by waves during storm induced flooding and by winds. The Sabkha surface covers intertidal sands, muds, and algal flats and is the site of evaporite formation. The Sabkha can be up to thirty kilometers wide.

Flat zone

Landward, the Flat zone is bounded by either the salt-encrusted surface of the Sabkha or by beach ridges. Seaward it is bounded by the Crinkle zone (fig. 5). The landward edge of the Flat zone is taken as the line marking the first appearance of algal laminae at the air-sediment interface. The Flat zone is of variable width. On the large mats of the east Khor al Bazam and Khusaifa it fluctuates between half a kilometer and two kilometers. On the smaller flats it can be as narrow as a few meters or in some enclosed flats may not exist at all. In the latter case, as on the Marawah flats, the zone is replaced by a sand flat burrowed by the small crab *Scopimera* (fig. 6).

Where the Flat zone does occur, the Sabkha adjacent to it is usually characterized by wind blown storm washover sediments covered by a salt encrusted surface (as in Khusaifa and the southeast Khor al Bazam). The salt crust can be as much as two centimeters thick. Lateral expansion of the halite crystals commonly buckles the crust into a series of compressional ridges (fig. 2E). These are interlocked into polygonal saucers which can be up to three meters in diameter.

These salt-encrusted sediments can be absent, as for instance on the Khusaifa and Marawah flats where the beach ridges adjoin the Flat zone. At Marawah the beach ridges are often covered by dunes up to two meters high on which halophytes grow (fig. 6).

The commonest of these plants is *Arthrocnemum glaucum*. Phleger and Ewing (1962) found a similar association of *Salicornia* and algal mats in the lagoons of Baja California.

The Flat zone is divisible into an upper gray-colored Dry Flat sub-zone, covered by water only at high spring tide, and a lower pink Wet Flat sub-zone, covered every high tide. The former has a covering layer of salt. The algal skin of the Flat zone is usually about three millimeters thick and though the surface has a pink hue, the undersurface is a pale or green color. The sediment beneath the surface may be a brown quartz-rich carbonate sand or gray-white mud identified by X-ray analysis as calcium sulphate hemi-hydrate. Both types of sediment contain high percentages of small lenticular gypsum crystals. The thickness of this horizon can be as much as twenty centimeters (fig. 2A). At the inner edge of the zone at Khusaifa, anhydrite is forming as discontinuous blebs and layers above the gypsum and calcium sulphate hemi-hydrate.

There is little surface relief in mats in this area, and in cross-section the laminated sediments are seen to have only small undulations (LLH) due to irregularities in the underlying sediments and desiccation (fig. 8, Cores XIII and XIV). Sometimes the surface is marked by faint polygonal desiccation cracks that often extend downwards as much as twenty centimeters. This form of mat is also found as the initial mats in intertidal areas where moderately high energy conditions prevail. Flat layering of this type is similar to Black's type A (1933). In areas of initial mat, however, tidal scour around fixed patches of sediment could produce sinuous forms of stromatolite vaguely similar to those found in Shark Bay (Logan 1961).

Transition

The transition area between the Flat zone and the Crinkle zone is marked by both blisters and smooth algal surfaces. The first appearance of blisters on the smooth surface of the Flat zone marks the inner edge of the transition, and the absence of the smooth pink surface between the blisters delimits the seaward edge. Clarke and Teichert (1946, p. 273) described a similar transition in a Western Australian Salt Lake.

Crinkle Zone

The Crinkle zone is seaward of the Flat zone (fig. 5). Algae form a continuous crinkled or blistered leathery skin (fig. 2F) that is only loosely attached to the underlying sediment. On the large flats of the east Khor al Bazam and Khusaifa, the zone varies in width about one kilometer, but on the smaller flats, as at Thimairaiyna, the zone is only a few meters wide. The crinkle surface is analagous to Logan and others (1964) laterally-linked hemispheroids (LLH) (both type C and type S) and is similar to some of the algal mats of Laguna Madre (Fisk, 1959) and the Dohat Faishakh, Qatar (Illing and others, 1965). The simplest type of blister occurs in the transition area between the Flat zone and the crinkle zone and shows growth structures up to five centimeters in diameter, comparable with Black's Type B algal heads.

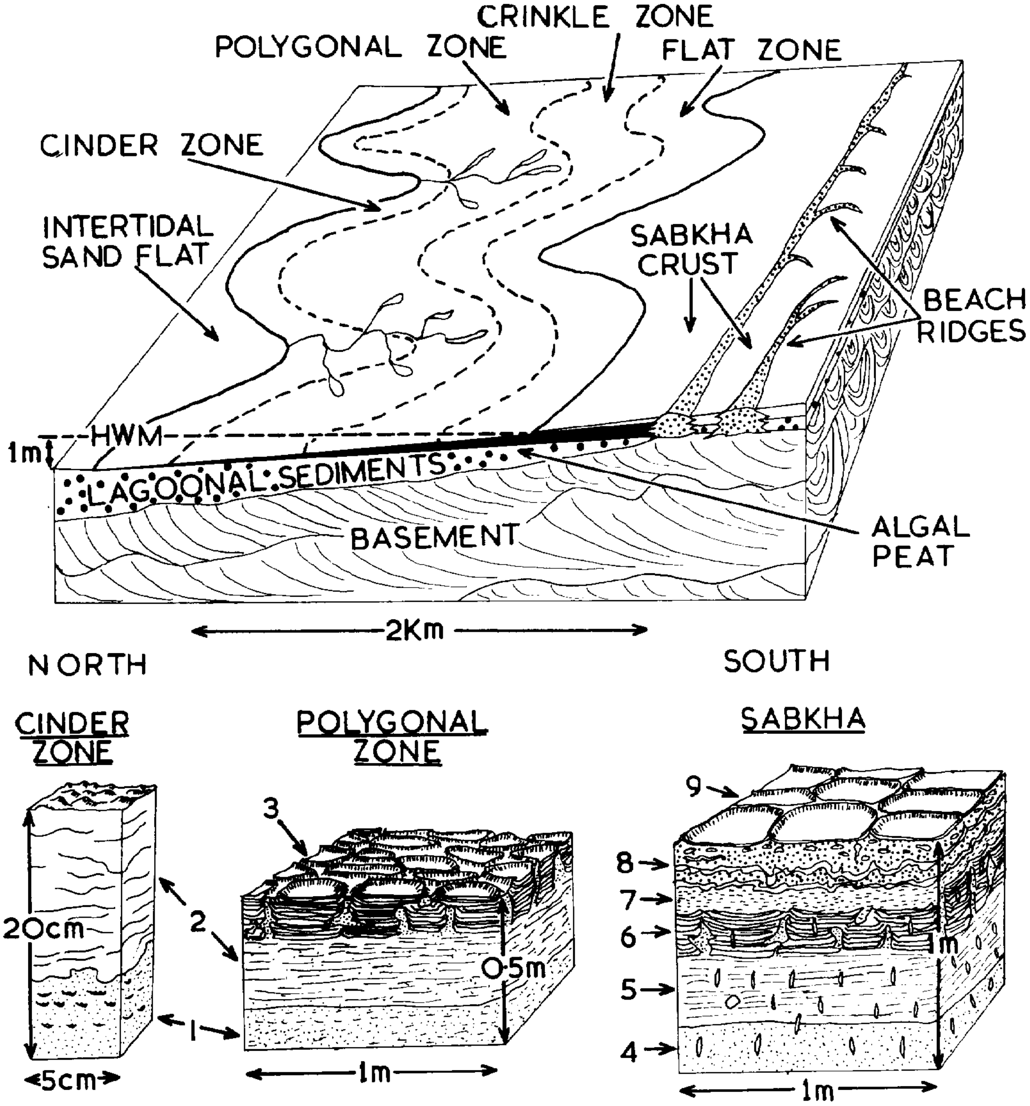

FIG. 5.—Zonation of algal morphology.

1. Lagoonal carbonate sands and (or) muds.
2. Poorly laminated carbonate rich algal peat.
3. Algal mat formed into polygons.
4. Lagoonal sediments with gypsum crystals.
5. Cinder zone algal peat with gypsum crystals.
7. Mush of gypsum crystals and algal peat.
6. Polygonal zone algal peat with gypsum crystals.
8. Anhydrite nodules and layers in a matrix of windblown carbonate and quartz.
9. Halite crust formed into compressional polygons.

Ancient analogues of the crinkled and blistered algal mat occur in Precambrian rocks of Australia (Robertson, 1960, Plate 14, fig. 2), in Permian Dolomites along the coast of County Durham, England, in Portlandian limestones exposed in the Bugle pit near Aylesbury, Buckinghamshire, England and in the Permian dolomites of the Guadalupe mountains of New Mexico.

Hollow blisters and crinkles show a variety of shapes and sizes (Clarke and Teichert, 1946). They have a basic polygonal pattern superimposed on the crinkle surface that is only apparent when the area is partially covered by tide. The

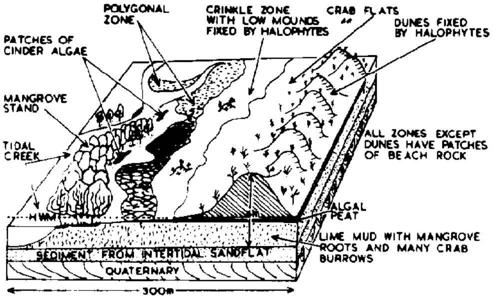

FIG. 6.—Mangrove creek.

sediments of the crinkle zone vary from aragonitic mud on the seaward to a mush of lenticular gypsum crystals on the landward. In other areas where the Flat zone is missing, as in some of the mats of Marawah, the sediment under the crinkles is only aragonitic. The muds or mush are commonly full of small horizontally oriented irregular vugs, one to three centimeters in diameter, similar in shape to the vugs of birdseye limestone. They are probably produced by a combination of desiccation and the movement of air trapped beneath the semi-permeable algal sediment by the incoming tide (Cloud, 1960; Hoyt and Vernon, 1963). The gypsum crystals associated with the crinkles form from the evaporation of capillary water beneath the algal flat at low tide. The algal mat acts as a membrane which prevents tidal water from flushing the ground water. It is reasoned gypsum does not produce the crinkles because crinkles exist where no gypsum is present, and in the higher flats horizontal layers of algae overlie gypsum with no apparent effect. On enclosed algal flats *Arthrocnemum glaucum* occurs on small hummocks in the middle of the Crinkle zone (fig. 6).

Transition

Between the Crinkle zone and the Polygonal zone, which lies to seaward, there is a transition zone in which the polygonal pattern of the Crinkle zone is more clearly demarcated. Here lines of blisters coalesce along the outlines of the polygons. Seaward the polygons become smaller, their boundaries more clearly defined, and the blisters disappear from their centers. Further into the polygonal zone, cracks outlining each polygon open vertically (figure 7A) so that each polygon ultimately becomes a discrete structure.

Polygonal zone

On the larger mats, as in the east Khor al Bazam and Khusaifa, the Polygonal zone fluctuates around one kilometer in width. On smaller mats it often is not present. The zone is characterized by algal mat broken into discrete polygons, normally hexagonal in plan, and separated from each other by cracks filled with sediment. Margins of the polygons curl up, but as the algae continue to grow, the edges become rounded and act as lips, trapping water when the tide goes out. Sediment is washed under the curled edge of the saucer (figure 2A). Mud cracks can show similar infillings (Shrock, 1948, p. 190). Growth forms of the Polygonal zone show a variety of polygonal structure. Mats on higher, better-drained ground have small polygonal saucers that range from three centimeters to more than 20 centimeters across. These inverted hemispheroids have prominent raised lips. Mats on lower, poorly-drained ground form into large polygons that tend to have no lips (figure 7B). These polygons can be as much as three meters across in ponded ebb creeks with restricted drainage. The edges of these polygons are sometimes separated by small deeper channels (twenty centimeters deep and from fifty centimeters to two meters across). The edges often form a curved overhand and closely resemble half of a vertically-stacked hemispheroid, type C (SH-C).

In cross-section more sediment can be seen trapped around and under edges of the small polygonal saucers of the raised areas than in the larger polygons of depressions. The polygonal inverted hemispheroids exhibit distinct horizontal laminae (new code SH-I) which are formed by the alternation of sediment deposition and algal growth (Black, 1933). Algal accumulation may be by alternation of two types of algal cell. One layer may consist of globular cells and the next one of filaments. Monty (1963) ascribes similar laminae, in Recent algal stromatolites of the windward lagoon of Andros island, to the noctidiurnal metabolic cycle of algae. In the Khor al Bazam the laminae have a more complex origin owing to the effect of tidal water and storms.

The algal peat of the Polygonal zone can be as much as twenty centimeters thick. Cross-sections show that the edge of the inverted hemispheroid (figure 2A) grows upwards similar to Black's (1933) Type C. There is a similarity between the algal polygons and the beginning stages of the ancient stromatolite *Collenia symmetrica* (Rezak, pers. comm., 1967).

There are often other morphological features superimposed on the surfaces of these polygons. These usually take the form of Logan and others (1964) laterally-linked hemispheroids (LLH-S). They are formed when algae grow over pieces of flotsam washed onto the flat. This flotsam includes calcareous algal colonies, seaweed, or pieces of driftwood, and each produces different varieties of doming. Seaweed drifted onto the

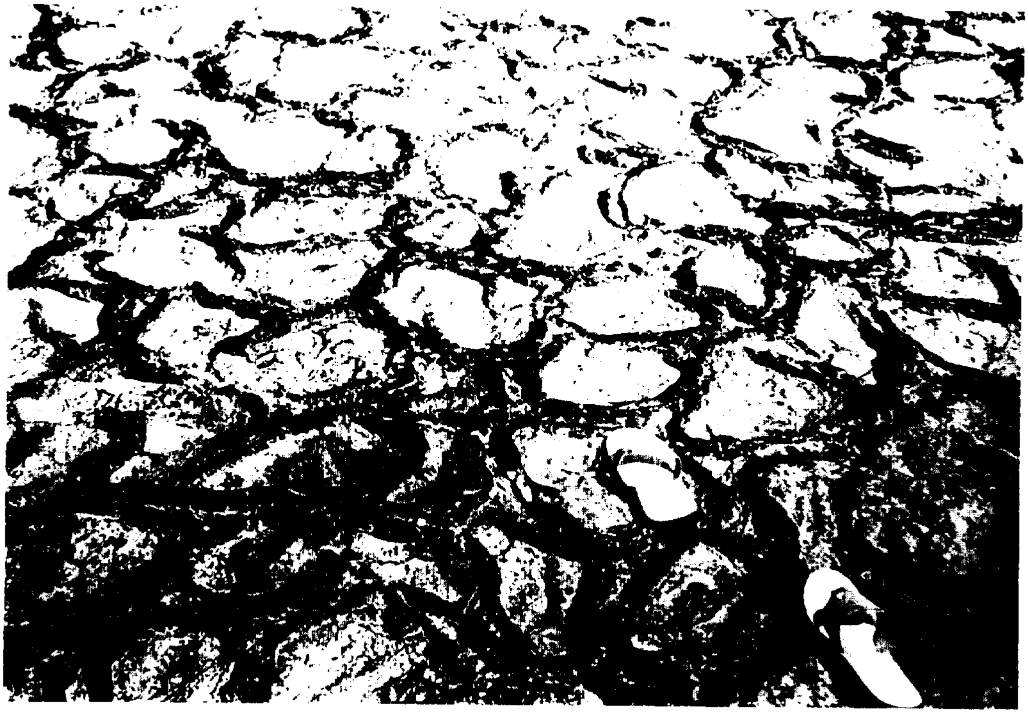

Fig. 7A.—Polygons of algal mat.

Fig. 7B.—Pools and channels with lily-pad type algal mat.

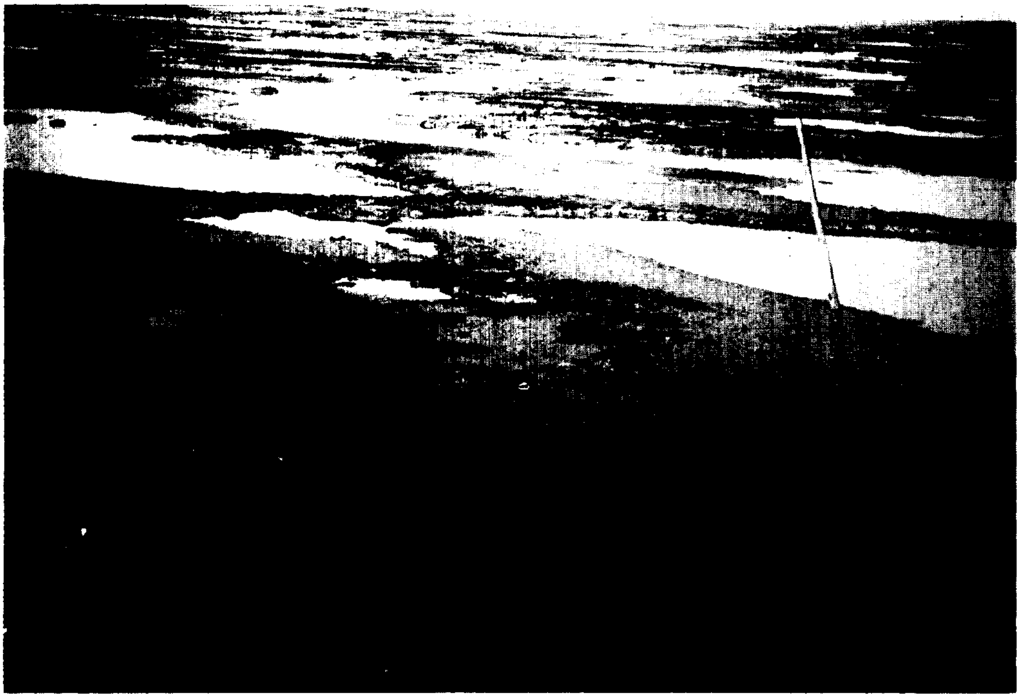

FIG. 7C.—Cinder algal mat.

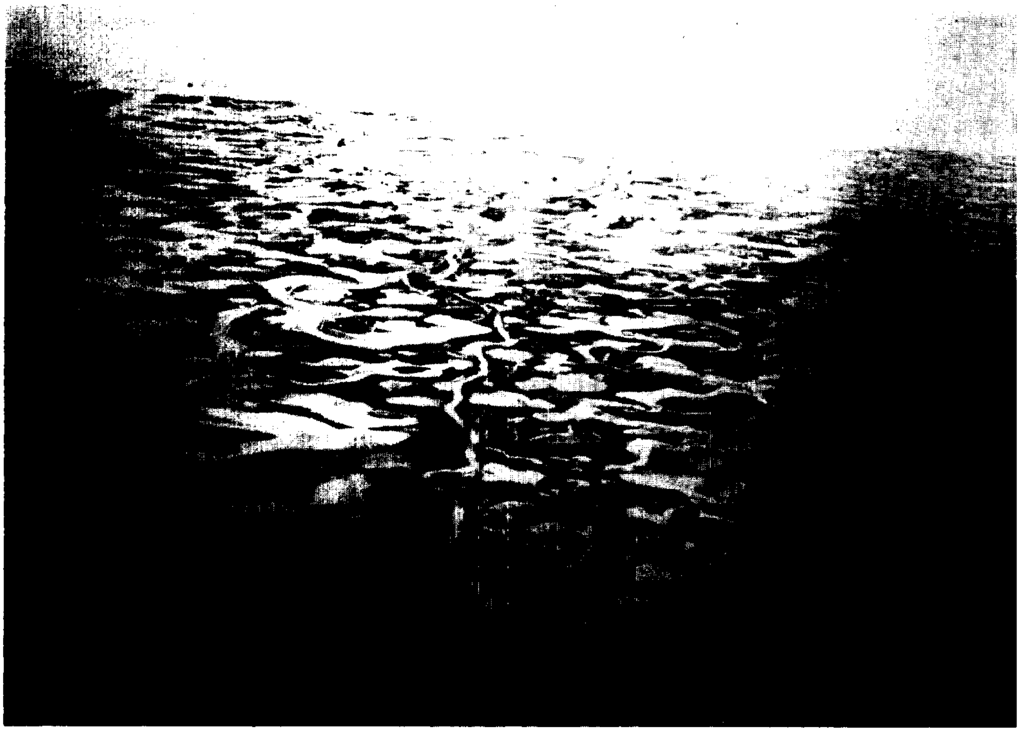

FIG. 7D.—Oblique of algal flats of East Khor al Bazam with pools and channels.

FIG. 7E.—Incipient algal mat in the protection of angled bars. (ADPC photo)

flat in long streaks parallel to the shore may become fixed by algae to form low parallel ridges and shallow ponds common to some parts of the flat. Some of the baffles reported by Illing and others (1965) may have similar origin. These are similar to those formed in the Cinder algal zone. The rippled surface of sand washed onto the mat is also often covered by algae. Gas also produces doming of the semipermeable algal surface. The most perfect of the hemispheroids are formed by this mechanism. Examples occur on the Khusaifa flats. Cloud (1960) illustrates this type of gas doming in muds. Logan and others (1964) describe the same agencies illustrated here.

Transition

The boundary between the Polygonal zone and the outermost zone, the Cinder or Broken zone, may be transitional. Passing seaward, the mats at the centers of the polygons become sites for cinder-like growths, cracks between the polygons gradually disappear, and the polygonal outlines vanish. In this way the whole surface changes from the slimy smooth leathery surface of the polygonal zone to a nodular mat typical of the Cinder zone.

Cinder Zone

The Cinder or Broken zone is marked by the growth of a warty almost black mat superficially resembling a layer of cinders (fig. 7C). The bumps are two to three centimeters across. The Cinder zone forms only a small part of the width of the algal flats. It is seldom over half a kilometer wide. On the smaller mats the cinder zone is often missing. Most of the cinder type of algal growth typical of the larger mats is intermingled with skeletal sands that are associated with small swash bars. Algae grow mainly on the highest point of the bar and on its protected inner slope and less frequently on the raised edges of large desiccation cracks in the sediment seaward of the mat. Towards the algal flat algal colonies twenty to fifty centimeters high coalesce and form wave-resistant features that rise above uncemented, easily-eroded sand. This is particularly noticeable near shore, where small depressions retain water and form pools at low tide. The floors of the pools are covered by blebs of algae (one to ten millimeters diameter) broken from larger colonies. No samples were collected, but the blebs superficially resembled discrete spheroids (SS) (Logan and others, 1964).

The raised features resemble a poorly-formed version of Logan and others stacked hemispheroids (SH) and Cryptozoon. When examined in detail the surface often consists of small (one to ten millimeters), tight crenulations and blebs (laterally-linked hemispheroids type LLH-C). This cindery crenulated texture is confined to the outer algal zone and is a valuable criterion for zonation.

In some places, particularly on enclosed flats, parts of the surface of the Cinder Zone are made up of clumps of vertical-standing algal fibers. These clumps form a variety of features a centimeter high, some like serrated teeth, and others like clubs. Ginsburg and others (1954) reported similar vertical fibers from Florida.

In the northwest and northeast parts of the main Khusaifa flat areas, the Cinder zone is heavily scoured. Aerial photographs suggest similarities between scoured ridges and the Shark Bay hemispheroids (Logan, 1961).

On the smaller mats of the enclosed type where it is associated with mangroves, the Cinder zone is sparsely developed and is often cemented into beach rock. This beach rock, and other beach rock that forms in higher algal zones, does not show the fine laminae of the uncemented algae. Instead it forms thicker layers of cream colored limestone similar to that described by Newell and Rigby (1957, p. 50) in the Bahamas west of Andros island, and by Shinn and others (1965).

In cross-section the Cinder algal sediments of the larger mats contain large quantities of aragonite mud. They show little lamination (fig. 8) and are often full of anastomosing tubelike holes. This spongy texture is believed to form as rising tides force trapped air through the algal mats. A similar texture was observed in soft sand by Hoyt and Vernon (1963), and in laminated fine sand overlain by laminated algal mats in southern Texas by Dr. Peter B. Andrews (pers. comm., 1966). No worms or insects were found though Ginsburg and others (1954) found them in similar algal sediments from Florida.

Seaward of the Cinder zone, depending on the degree of protection from oncoming waves, skeletal and pelleted sands or muds accumulate. These sediments support far more algal growth than those farther seaward.

CONCLUSIONS CONCERNING ASPECTS OF STROMATOLITE FORMATION

Physical Parameters of Growth

The algal mats of the Khor al Bazam are found in the protected parts of the intertidal zone along the mainland coast behind shoals, in several island embayments, and in association with mangrove swamps.

It is concluded that in the Khor al Bazam region:

(a) Algae will not thrive as mats above a very definite upper limit of hydrodynamic conditions, and mats are co-incident with a rapid decrease in the erosive effect of waves landward.

(b) Algal mats grow best where they can obtain the maximum amount of sunlight and yet remain moist and in contact with water. Where the area is almost permanently under water, as at the lower edge of the intertidal zone, algae grow in profusion on the sediment components, but do not form mats. This is probably due to turbulence of the water. For example, Monty (1965) only found cryptozoon and collenia-like stromatolites of blue-green algae at a depth of two meters at low tide in the protected waters of the windward lagoon of Andros Island. In contrast the algae become dormant when exposed permanently to subaerial conditions, for here they are unable to grow over the cover of windblown sediment. The optimum conditions of growth are those experienced in the Polygonal zone, which produces the thickest algal peat layer. Here the algae are growing rapidly upwards to the high-water mark level of the Crinkle zone.

(c) The algae appear to be able to withstand very high salinity (Fritsch, 1952). Not only is gypsum and calcium sulphate hemi-hydrate precipitated immediately below the upper zone of the algal flat, but the dry flat sub-zone was found to be covered by at least 25 millimeters of salt. Similarly the algae are not limited by temperature in the intertidal environment. The Trucial Coast is one of the hottest areas in the world and the dark color of the algal mats absorbs this heat, yet they continue to have vigorous growth.

(d) Algal mats do not need a hard substrate on which to grow (Black, 1933) and on the Trucial Coast mats are found growing over other algal surfaces, skeletal sands, aragonite muds, and gypsum mushes.

Relation of Growth-Form Environment

Each of the morphological zones of the algal mats of the Khor al Bazam occurs within certain depth limits relative to the high-water mark (fig. 5). Thus some of the zones are covered by water more frequently than others and for longer periods of time (fig. 9 and table 1). This appears to control the growth form of the mats and is apparent in the zones. Here the least exposed and so little desiccated areas are the pools and channels. These exhibit lily pad polygons while the more frequently exposed channel sides are formed of small polygons. Where the channels and pools are deep, the floor may be covered with nodules similar to those of the Cinder zone. In the same way Polygonal zone can have similar nodules. The relation of growth form to water cover is further expressed where raised areas in the Polygonal zone tend to bear crinkle structures.

Polygonal cracking of the algal mat is un-

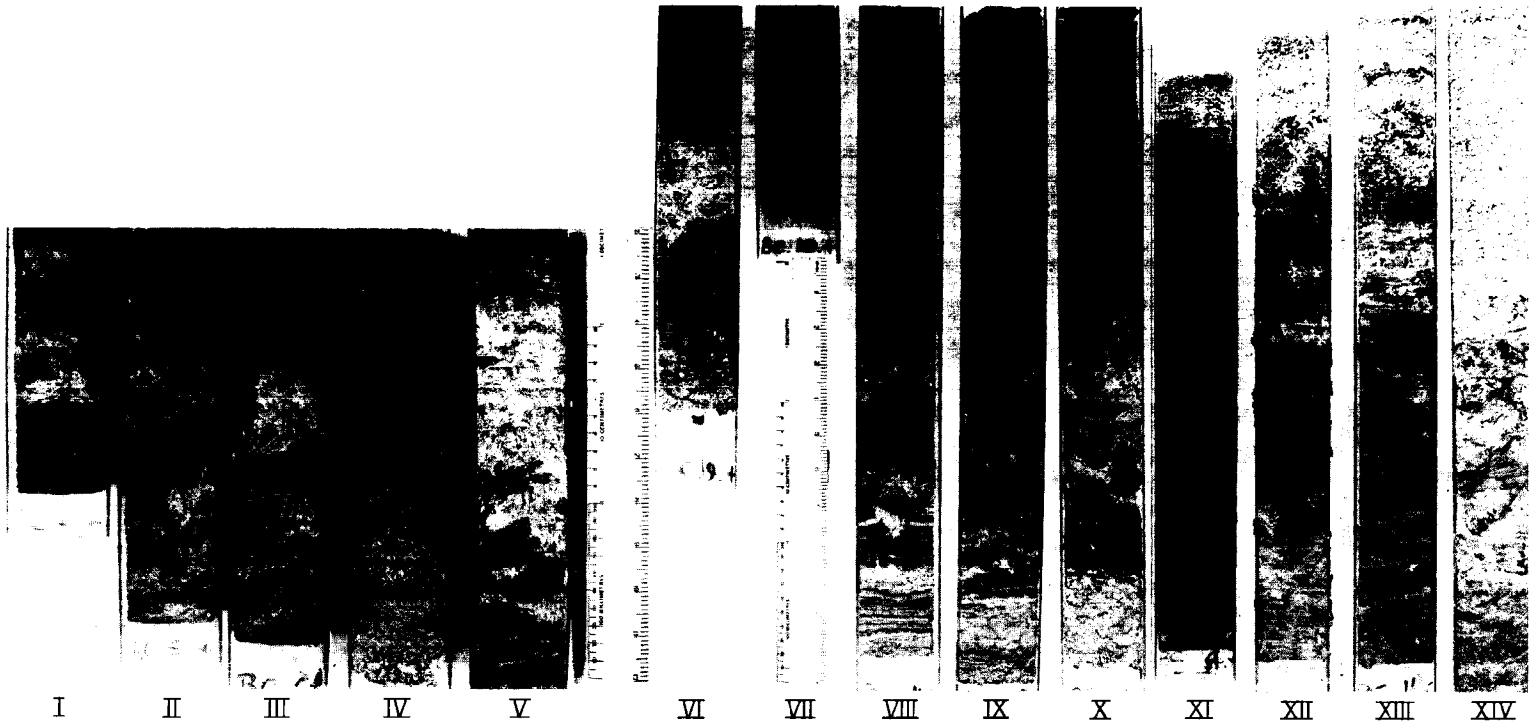

FIG. 8.—Series of cores from Khusaifa algal mat, Traverse 9.

Cores I, II—Algal flat front. Poorly laminated algae intermixed with high percentage of aragonite mud. Base of cores are of sand flat sediment.

Cores III, IV, V—Front of polygonal algal zone. Disturbed but laminated algae. Base of cores are of sand flat sediment.

Cores VI, VII—Polygonal algal zone. Well laminated at top of core. Algae at base of core represents front of algal flat at earlier stage of development. Base of cores is sand flat sediment.

Cores IX, X—Crinkle algal zone. Top of cores have a mixture of algae and gypsum crystals. Layers below represent earlier stages of algae flat.

Cores XI, XII, XIII, XIV—Flat algal zone. Tops of cores are very rich in gypsum. Periods of algal growth represented by dark crenulated line. Note voids similar to fenestrae.

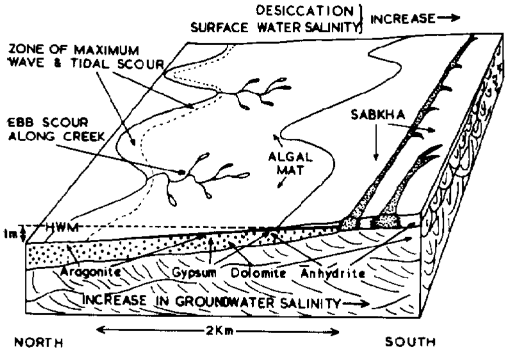

FIG. 9.—Limits of agents acting on the algal mats.

doubtedly the result of desiccation. The cracks are similar to those formed by the desiccation of mud. Kindle (1917) and Bradley (1933) showed that the curvature of mud-cracked layers was determined by (1) the vertical grain size distribution, (2) the presence of salt crystals, and (3) the rate of drying. Finer grained sediments tend to contract more completely during desiccation than coarser grained sediments. Thus contraction of fine grained material, underlying coarser sediments, produces a dome; if the grain-size distribution is reversed, a saucer results. Salt crystals in a mud increase the "effective grain-size." Bradley (1933) showed that the effect of the rate of drying is negligible except for fine clays; John Everette (pers. comm. 1966) confirms this. Anderson and Everette (1964) discovered that polygon size is a direct function of mud thickness and confirmed Kindle's (1933) conclusion on the effect of grain size and grain size distribution.

This same reasoning can be used to explain the small algal polygons of the raised areas and the large polygons of the depressions. In the high-relief areas where the small polygons occur, the mats are initially thin. During frequent drainage and desiccation the mats break into small polygons. The edges of these polygons tend to curl up because the upper surface dries more quickly than the base, resulting in differential capillary contraction that breaks the mat free of the substrate (Bradley, 1933, p. 58). Sediment is then washed into the cracks around and under the algal polygon. Desiccation of later algal growth causes the algal surface to pull away from the less cohesive sand. The polygons continue to be small because the sediments continue to be inhomogeneous and the algal mat never becomes firmly fixed to the substrate.

The process of initiation of the large algal polygons in depressions is not known. These polygons probably begin growth after a depression is dammed, either by sand bars or vigorous algal growth. Algal dams of this kind are to be seen at the front of the Khusaifa algal flat and the Dohat Faishakh, Qatar (Illing and others, 1965). The result is that depressed areas are less often exposed at low tides and so are less desiccated. Thus the algal mat becomes firmly fixed to the substrate and with the exception of drainage channels grows evenly over the bottom of the depression. The polygons are larger because the algal mat is not desiccated until it grows above the low tide water level of the ponds. By the time the mat reaches water level it is so thick that the polygons formed are large. The edges of these polygons show little curling because the algae are so firmly fixed to the substrate. The larger polygons are eventually overlain by small saucers (fig. 2A).

Desiccation also plays a part in the formation of the Crinkles of the Crinkle zone. Air, trapped in the sediment by the rising tide beneath the algal surface, lifts the semipermeable algal mat, thus producing the crinkles and disrupting the underlying sediments. After long periods of desiccation the blisters crack and collapse (Ginsburg and others, 1954). Where the crinkles are particularly desiccated they shrink and peel off the surface. Fisk (1959), Logan and others, (1964) and Illing and others, (1955) have noted this texture too. The flat zone has few crinkles because it is less often covered by any marked depth of water. In the polygonal zone any air trapped in the algae escapes through the permeable sediment-filled cracks. In the Cinder zone so few cracks are formed that the algal peat is disrupted. Other evidence of desiccation occurs in particularly mud rich algal sediments. Here desiccation causes the laminae to pull apart to form structures similar to those recorded by Tebbutt, Conley, and Boyd (1965) and Fischer (1964). They called this structure laminoid

TABLE 1.—*Physical processes acting across the algal flats*

I. Periodicity of desiccation increases landwards while periodicity of submergence falls.
   Effect landward. . a. Surface morphology changes from cindery to polygonal, to crinkled, to flat algal surface.
   b. Increase in salinity of water trapped on flat.
   c. Increase in salinity of groundwater.
   d. Change of algal species.
II. Wave scour falls rapidly from front of algal mat and ebb scour falls, too (except along ebb creeks).
   Effect. . . . . .a. Eroded algal front.
   b. Some erosion of ebb creeks.
   c. Very limited erosion of inner zones.

fenestral fabric and loferite, respectively (fig. 8, cores XIII and XIV).

Fisk (1959) believes that blisters and crinkles are formed by gas generated in sediment below the gypsum or carbonate mush which rises and becomes trapped in pockets in the leathery surface. However, in the Khor al Bazam, trenches cut in the innermost Flat zone, not the Crinkle zone, encountered the most trapped gas.

The effects of salinity on algae growth are not so obvious as effects of desiccation (fig. 9 and table 1.) However, the surface algae is colored pink only in the most highly saline regions of the algal flat, such as the centers of polygonal saucers (the raised lips remain green) on the large polygons in ponds and beneath the halite crust of the Flat Zone. In the winter months the pink surface of the polygonal saucers and the large "lily-pad" polygons become green, suggesting that when evaporation rates are lower and the water less saline the algal form alters.

Logan and others (1964) proposed that it is prolonged wetting that inhibits algal mat growth. However Monty (1965) has shown that blue-green algal mats can grow in two meters of water. It is proposed here that it is high salinities that inhibit rates of growth. For instance saline algal pools (fig. 7D) similar in shape to the salt pans of temperate marshes (Davies, 1962; and Evans, 1965) and well back from the erosive action of breaking waves, are being slowly overgrown while their edges grow upwards more rapidly. Also algal polygons that trap saline waters grow upward fastest on their edges. In the Flat zone where there is a salt crust, rate of algal growth is inhibited, too.

The change in color of the mat from pink in the saline zones, to green or brown on the open mat, to gray on parts of enclosed mats is probably due to the species of algae or bacteria that are favored by the local conditions. Ginsburg and others (1954) noted a similar sequence in the algal mats of Florida. The change from the slimy finely laminated algae of the polygonal zone to the poorly laminated crumbly algae of the cinder zone is probably a species change in response to increasing desiccation.

On the larger algal mats, scouring and mechanical fragmentation by storms (Logan and others, 1964, p. 79) is largely confined to the seaward edge of the algal flats where the extension of the mat is limited by erosion (fig. 9 and table 1). However, exceptionally large storms do sometimes tear up the surface of the algal mat, even as far shorewards as the back of the Crinkle zone. This is of local importance only and seldom occurs, as is evidenced by the thickness of the mat even in the Cinder zone. Similarly, scouring and channelling by tidal run-off (Logan and others, 1964, p. 79) is largely confined to the Cinder zone and to small meander ebb channels that cross the Polygonal and Cinder zones. The effect of ebb scour in the channels is continually limited by damming produced by algal growth (Illing and others, 1965). The only noticeable effects are undercutting the banks of creeks, producing a rounded edge where the algae drape the overhand, and formation of levees along the channel bank due to higher rates of sedimentation.

Colonization of Sediment by Algal Mats and the Establishment of Zones

Colonization of the sediment by algal mat begins on an intertidal area where energy conditions fall to a limit tolerable for extensive algal growth. This is followed by the outward accretion of the mat over the sediments at its seaward edge.

(a) *Initiation of an algal mat.*—the initial formation of an algal mat in the intertidal zone is by a form of pink colored algal growth similar to that of the Flat zone with invariably no surface relief (fig. 7E).

An algal sequence across one of the large mats of the Khor al Bazam showed a Flat zone, and seaward an "incipient mat." This suggests the incipient mats are the initial form which develops over the sediment at inter-tidal depths normally associated with the Crinkle and Polygonal zones. As the accumulation of sediment seaward of the mat continues, water turbulence is reduced. Thus tracing the "incipient" mat seaward with time it is gradually replaced first by crinkled mat, then the polygonal mat, and lastly the cinder-like mat. Traverses in the east Khor al Bazam showed that the "incipient" algal mats sometimes even grow seaward from the Cinder zone, but an established mat normally colonizes its seaward edge with Cinder algae. The reasons why the cindery algal growth does not initiate the algal flats are probably that: (i) They may need more moisture than other other algal surfaces. (ii) Although individual cells can grow under all conditions they do not have enough cohesive power to combine as a mat except under very gentle hydrodynamic conditions. The "incipient" algal mat, on the other hand, is mainly formed of intertwined algal filaments which give it much greater strength.

(b) *Outward accretion.*—Cross-sections across established algal flats like those of the eastern Khor al Bazam and Khusaifa show that the zones are accreting outwards. The associated sediments of one zone are seen to overlie those typical of the zone immediately seaward of it (figs. 6 and 8). Thus the basal sediments are sands colonized by cindery algal growth. The algae themselves are similar to those which infest the oolitic pellets of the intertidal area west of Rodain, but are far more numerous. Such an algal population tends to "stabilize" the sand through the coalescence of the algae and the formation of a mat. As the algal surface of the Cinder zone grows upward, the surface eventually assumes polygonal form in response to the changed environmental surroundings. Continued upward growth will then change the polygonal surface to a crinkled one. Increased salinity of interstitial water causes precipitation first of calcium carbonate (Dalrymple, 1965) and then of calcium sulphate within the algal mat. Thus colonization of sediment by cindery algal growth extends the limits of the algal flats to seaward, while upward growths of the algae maintain the zonal sequence. When the upward growth of the flat zone reaches the H.W.M., windblown and storm washover sediments smother further algal growth, and a sabkha surface begins accumulating.

The outward growth of the algal mats can be a gentle and steady process, but the growth may be speeded up by catastrophic events. The zonal sequence of the algal flats described above was recorded in December, 1962. There had been no major storms or flooding during the preceding seven years. When the area was revisited in February 1964, however, there had been two periods of storm (March 1963, and January 1964) which had flooded the sabkha, broken through the coastal dunes, and locally torn the algal mat. After the last it was found that though the zones were essentially the same, the high water mark reached only as far as the Crinkle zone and not, as in the previous year, the Flat zone. This may merely have been due to neap and spring tidal fluctuation (there being no tidal data for this part of the coast) and the original system may have been re-established. On the other hand, the area above high water had been covered by a layer of carbonate silt and clay and blisters, and crinkles were cracked and deflated. In order to thrive, the algae would have to grow rapidly through this layer of sediment raising the surface of a large area of the algal mat, causing a rapid seaward advance of the supratidal area. A rate of accretion seaward of the algal mat of 8 km in 200 years was established by Dr. David Kinsman (pers. comm., 1965) from radio carbon dating of an algal sediment eight kilometers back in the sabkha at Abu Dhabi.

The algal zones are superimposed on large raised features. This is particularly noticeable in the west Khusaifa flat and parts of the east Khor al Bazam. Here the fronts of the algal flats project seaward in a series of lobes (fig. 2B). These lobes are growing on the landward extension of the ridges which divide the ebb channels of the sand flat from one another. Likewise, the embayments between the lobes are the landward extension of ebb channels. The lobes are thus the frontal expressions of high relief which extends seaward across the algal flat, and the embayments are expressions of lines of low relief. Kinsman (1958) noted this same development west of Abu Dhabi, and Evans (1965, p. 219) recorded similar ridges and depressions in marshes of the Wash Norfolk, England. The areas of higher relief are well drained (whereas those of low relief are poorly drained) and are easily recognizable from the small meandering ebb creeks that dissect them.

Fossilization of Algal Structures

It has already been shown that the growth forms of the intertidal algal mats are similar to those of ancient stromatolites. But are these likely to survive? Most of the algal peats preserved in the sabkha show a flattened bedding similar to that which Robertson (1960) called "wavy-laminae" form. This flattening is probably caused both by original growth and by expulsion of moisture from the algal mat on burial. Many laminated limestones and dolomites may be of this origin. Where the cracks between the polygonal structures of the algal flats become filled with sediment, discrete structures will be preserved as "cylindrical" forms of stromatolite (Robertson, 1960; Fischer, 1964 p. 118; Aitken, 1967). These too can be seen in the peats of the sabkha sediments (fig. 2A). Compaction is greatest in the peats so that sand fill produces domes.

In order for the surface structures of the Trucial Coast algal flats to be preserved as fossils the intertidal area may have to become permanently exposed and cemented. Cementation would be similar to that described by Logan (1961) in the clubshaped algal heads of Shark Bay and has been recorded near the middle of the Khusaifa flat. Here large parts of the crinkle zone form a beach rock covered by a thin layer of growing algae. In appearance this surface is not unlike the back of the Crinkle zone and is often cemented and itself incorporated into the cemented sediment. This cementation is probably due to the better drainage here than elsewhere on the flats.

Owing to the gentle slope of the intertidal platform and the very small tidal range of the Trucial Coast, the resultant 'stromatolites' will be small structures of the stacked saucer type (SH-I) and the laterally-linked hemispheroidal type (LLH) (Logan and others, 1964). The large discrete stromatolites that are described from the Pre-Cambrian and lower Palaeozoic rocks probably required a greater tidal range, a more steeply-sloping intertidal platform than that of the Khor al Bazam, and perhaps a eustatic rise in sea level. The first two criteria have been shown Logan (1961) to favor the growth of discrete structures. The final criterion remains a matter for conjecture. Alternatively the large areally ellipsoid domes are produced by more vigorous algal growth than is found today in the Khor al Bazam. Other structures may be the result of different rates of sedimentation or different variations in algal species.

CONCLUSIONS

Algal mats growing along the coast of the Khor al Bazam show a zonation based on their surface morphology. These zones form four geographical belts, progressing seawards; (1) Flat zone—characterized by smooth algal surface, with no relief, which overlies quartz-rich carbonate sand and evaporites (LLH). (2) Crinkle zone —charocterized by a leathery algal skin forming a blistered surface over gypsum and carbonate mush (LLH). The origin of these blisters is unknown but probably is a combination of desiccation and the movement of trapped air with the rising tide. Wave scour is restricted, even during large storms. (3) Polygonal zone—characterized by algal mat separated into desiccation polygons (New code SH-I). The smaller of these polygons have raised edges between and under which sediment collects. The growth of the laminae are limited by salinity. The size of the polygons is governed by frequency of exposure to desiccation. Wave scour is limited, even during large storms. (4) Cinder zone—characterized by a warty surface, in color and size not unlike a layer of weathered lava cinders, and showing few or no laminae in cross-section (code LLH). The seaward edge of the zone is restricted by wave and tidal scour.

The only factors that affect all four algal zones and their surface morphology are:

(1) The interrelated agencies of desiccation and tidal water.

(2) Landward increase in salinity across the mat.

Of these agencies desiccation is by far the most effective in controlling the surface morphology and salinity, and hence the rate of algal growth.

Two agencies that do not act over the whole mat and are thus of only local importance are:

(1) Wave scour.

(2) Tidal scour.

Wave scour is confined to the newly-initiated mat and the front edge of the mat and in small ebb creeks.

The algal mat morphology of the Khor al Bazam suggests that in environmental interpretation of other algal stromatolites, allowance should be made for the effects of desiccation as well as wave and tidal scour.

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