RECENT CARBONATE SEDIMENTS OF THE WESTERN KHOR AL BAZAM, ABU DHABI, TRUCIAL COAST

by

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ABSTRACT

The shallow water carbonate environment of the west Khor al Bazam is situated on the Trucial Coast of the southwest Persian Gulf. This region consists of a barrier protecting a lagoon. On the inshore side of the lagoon evaporite minerals dolomite, anhydrite, gypsum and halite form. The genetic history of the features that make up these major units is determined by comparison with similar features from non-carbonate regions.

The major components are distributed as follows: coral/coralline algae on the seaward side of the barrier; molluscan fragments in the lagoons; aggregates like those of the Bahamas in the lagoons and shoals; pellets and quartz on the shoals; mud in the lee of the barrier and in sheltered intertidal regions with stromatolite algal mats and mangroves.

Grapestones occur in both sublittoral and littoral zones and are initiated by beachrock cementation or by cementation induced by blue-green algae or both.

Detailed distribution patterns of the component particles of the intertidal embayment of Quala show that such component particles can be used to predict the relationship of a sedimentary body to the shore line without referring to such structures as current bedding. The patterns are seen to be clearly related to the agencies that acted on them.

Blue-green algae cause the diagenesis of carbonates contemporaneous with deposition by inducing the selective solution

and reprecipitation of calcium carbonate during photosynthesis and respiration. This converts calcium carbonate grains to microcrystalline aragonite. This is exemplified by the peneroplid foraminifera which are particularly susceptible to this process. The results of this process can be recognized in ancient limestones. Because these plants grow most vigorously in shallow water, they are a good environmental indicator.

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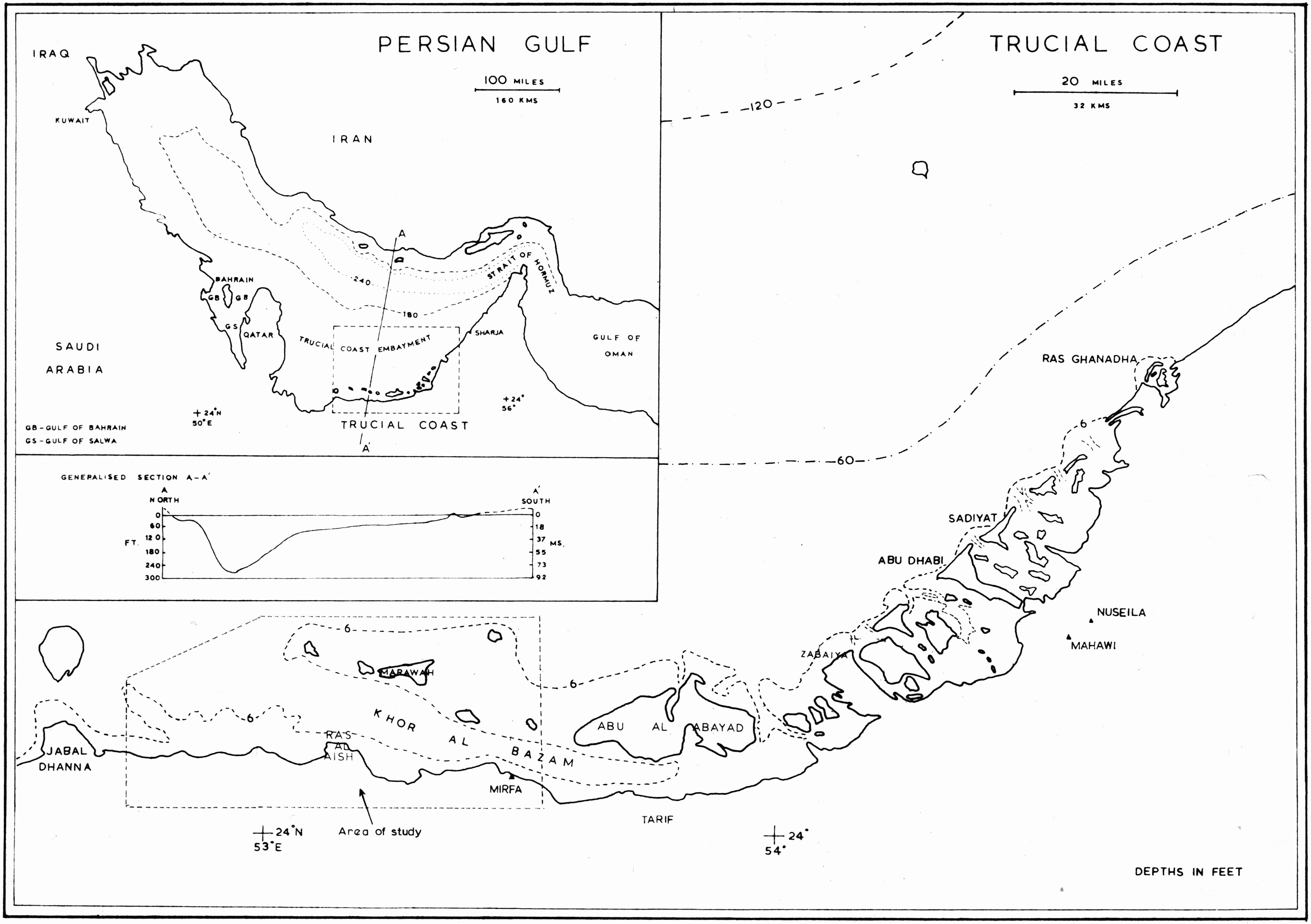
Top edge of all aerial photographs is north.

Figure 1


PERSIAN GULF
100 MILES
160 KMS
IRAQ
KUWAIT
IRAN
A
STRAIT OF HORMUZ
240
180
BAHRAIN
GB
GB
GS
QATAR
SAUDI ARABIA
TRUCIAL COAST EMBAYMENT
SHARJA
GULF OF OMAN
+ 24°N 50°E
+ 24° 56°
TRUCIAL COAST
A'
GB - GULF OF BAHRAIN
GS - GULF OF SALWA
GENERALISED SECTION A-A'
A NORTH
A' SOUTH
FT.
0
60
120
180
240
300
MS.
0
18
37
55
73
92
TRUCIAL COAST
20 MILES
32 KMS
120
60
6
RAS GHANADHA
SADIYAT
ABU DHABI
NUSEILA
MAHAWI
ZABAIYA
ABU AL ABAYAD
MARAWAH
KHOR AL BAZAM
RAS AL AISH
JABAL DHANNA
MIRFA
TARIF
Area of study
24°N 53°E
24° 54°
DEPTHS IN FEET

CHAPTER I

INTRODUCTION

1. PURPOSE OF STUDY

The general purpose of this investigation is to achieve a better understanding of the genesis and areal relationships of shallow water carbonate sediments. The area of study is confined to the west Khor al Bazam, which is located on the southwest coast of the Persian Gulf in the State of Abu Dhabi, some seventy miles west of the town of Abu Dhabi (Figure 1). With the results of the investigation it is hoped that ancient sediments of similar environment can be better understood and that predictions as to their areal distribution and relationships can be made.

2. REVIEW OF PREVIOUS WORK

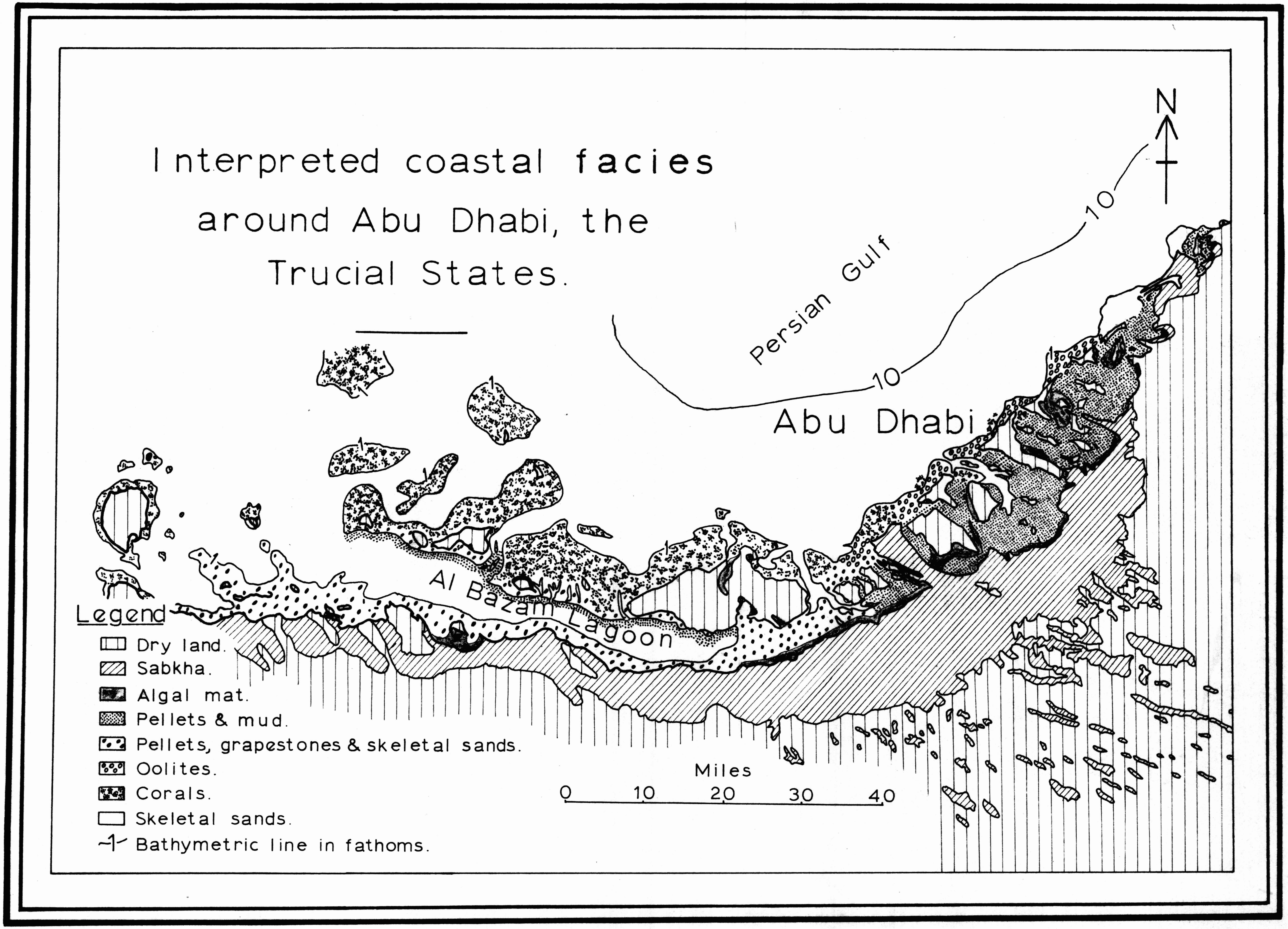
The sediments of the area of the west Khor al Bazam form part of a larger complex of shallow water carbonate sediments that fringes the western side of the Persian Gulf. This carbonate complex has been the site of intensive research since Bramkamp and Powers (1955) studied a series of carbonate and evaporitic sediments forming west of Qatar. Emery (1956) then gave a general description of the area and indicated that carbonate sands are found in the shallower water to the west whilst carbonate muds tend to be confined to deeper water and terriginous material to the east and north. Houbolt (1957) confirmed and expanded Emery's findings in detail east of Qatar.

Wells (1962) extended Bramkamp and Powers' work and found Recent dolomite in the coastal sediments of Qatar. Sugden (1963 a & b) gave further details of the sediments of the shallow water of the Gulf of Salwa and the Trucial Coast, also adding to Emery's original salinity maps. Curtis, Evans, Kinsman and Shearman (1963) extended the study of evaporites to the Trucial Coast, discovering an association of Recent dolomite and anhydrite. Since then papers by Evans, Kinsman and Shearman (1964), Kinsman (1964), and Evans and Shearman (1964) have all contributed further detail to the carbonate and evaporite environment of the Trucial Coast. In other contributions Wells and Illing (1964) made a study of the origin of 'whitings' in the southwestern Persian Gulf; Butler (1965) extended Kinsman's work on evaporites with detailed chemical analyses of the sabkha waters; Illing, Wells and Taylor (1965) carried out similar work on the west coast of the Qatar peninsula; and Shearman and Skipwith (1965) suggest that the mucilage secreted by the blue-green algae of the region may play an important role in later diagenesis of calcium carbonate grains.

3. REGIONAL GEOLOGY

The above cited publications indicate that almost the full range of shallow water carbonate environments exist on the Trucial Coast embayment. The broad pattern can be seen on the map (Figure 2). This shows a line of reefs and barrier islands protecting a series of shallow lagoons. Deltas develop between the islands where the ebb tide carries the lagoonal waters

Figure 2


Interpreted coastal facies around Abu Dhabi, the Trucial States.
N
Persian Gulf
10
Abu Dhabi
Al Bazam Lagoon
1
Legend
Dry land.
Sabkha.
Algal mat.
Pellets & mud.
Pellets, grapestones & skeletal sands.
Oolites.
Corals.
Skeletal sands.
Bathymetric line in fathoms.
Miles
0
10
20
30
40

seawards. Oolites form on most of these deltas. In the protected waters of the eastern lagoons carbonate muds and pellets form in conjunction with skeletal sands. Westwards, where the lagoons are more open, aggregates of carbonate sand grains form. In both the lagoonal areas mangroves and stromatolite-like algal flats are developing. The coastal sediments both on the islands and mainland are accreting seawards. The ground water of these sediments is of marine origin and is being continually concentrated by the high net rates of evaporation in the region. This results in the development of evaporite minerals in the capillary zone and the water table below. These minerals include gypsum, anhydrite, dolomite and halite.

Emery (1956) compared the Persian Gulf, a narrow shallow arm of the sea, to the geosynclinal basins of the past. His comparison was based on regional structure and the sedimentary and igneous character of the area.

Tectonically the Persian Gulf consists of a downwarp underlain by gently folded rocks. It is bounded to the southwest by the stable craton of Arabia, and to the northeast by the Tertiary fold belt of the Zagros mountains.

In cross-section, the Gulf is asymmetrical. It descends abruptly from the Persian shore to a depth of about 50 fathoms along the axis of the trough. On the Arabian side a gentle gradient has given rise to a broad shelf which seldom exceeds 20 fathoms, (Figure 1).

In the east terriginous material is carried into the sea by seasonal streams: the coarser material is restricted to the narrow shelf and the finer sediment is carried into the axial trough to mix with carbonate muds to form marls. To the north-west a fluvio-marine delta accumulates at the mouths of the Karun and Shatt al Arab. To the southwest carbonates form on the Arabian shelf. Just adjacent to the H.W.M. (high water mark) of most of the west Gulf coast, where the influx of fresh water is scarce, diagenetic evaporites form within marine-derived groundwaters. Away from the coast, desert sediments dominate the land areas. Emery (1956) and Kinsman (1964) both remarked on the similarity of the sedimentary pattern shown by the rocks underlying the Persian Gulf to those accumulating in it today. This, coupled with the fact that some of the world's largest oil fields are located in these underlying sediments, emphasises the economic importance of studying the Recent sediments to understand the stratigraphy of these older deposits.

4. FIELD TECHNIQUES

During the research programme two field seasons were spent on the Trucial Coast. In the first season, some two months were spent helping in field work for the Imperial College project round Abu Dhabi, two weeks helping Sir Patrick Skipwith with his field work and two weeks working in the west Khor al Bazam on the theses area. The second field season was of three months duration, but due to difficulties with equipment and weather only two weeks were devoted to field work.

As time for field work was so short it was largely devoted to the collection of sediment samples. At sea, these were collected from a 17 foot launch using a Deitz-La Fonde grab. Samples were located at approximately $\frac{3}{4}$ of a mile intervals along spaced traverses, (Sheets 1, 2 and 3). A continuous echo-sounding trace was made of traverses using a Bendix echo - sounder. Readings of temperature, pH and Eh were taken for each sediment sample, and temperature and pH recorded for the surface water at each locality. Separate samples for Foraminifera identification were collected at every third or fourth station and preserved in alcohol. Sample locations were positioned on the sample locality maps (Sheets 1, 2 and 3) by dead reckoning and the use of the echo traces; topographic control being non-existent.

On the mainland coast sampling traverses were made at intervals of approximately every two miles. Samples were collected from all the geomorphologically distinct environments that could be waded, (Sheets 1, 2 and 3). Where the sediments were not covered by the tide representative cross-sections were dug and some cores were collected.

5. CONCLUSIONS

The region was found to consist of the major geomorphological units of offshore bank, lagoon, coastal terrace and coastal strip. The features that comprise these units are comparable to features from non-carbonate shallow water environments. Their genesis is similar and so are the effects of tidal currents and waves. Aerial photographs can be used to establish the Recent history of the area almost independently of field control.

The general distribution of the major component grains of the sediments of the area has been found to be: coral/coralline algal fragments on the seaward side of the offshore bank; molluscan skeletal particles in the lagoon; aggregates, similar in appearance to those of the Bahamas (Illing, 1954), in the lagoons and shoal areas; aragonite pellets and quartz grains in shoal regions; and mud in the lee of the bank and sheltered intertidal regions with stromatolite algal mats and mangroves.

A study of Quala Bay showed that detailed grain size and component analyses can be used to interpret the history of sediments on a local scale. The distribution patterns of the components at different grain sizes suggests the direction of the shoreline and also conforms with such geomorphological features as angled bars.

The importance of blue-green algae in some carbonate provinces is indicated by the role they play in the west Khor al Bazam. Here, by the dual processes of photosynthesis and respiration, they aid carbonate precipitation and cause the texture of many of the carbonate grains to be modified. Peneroplid foraminifera have been found particularly susceptible to alteration by blue-green algae and can be used to study the role of the algae in the region.

6. ACKNOWLEDGEMENTS

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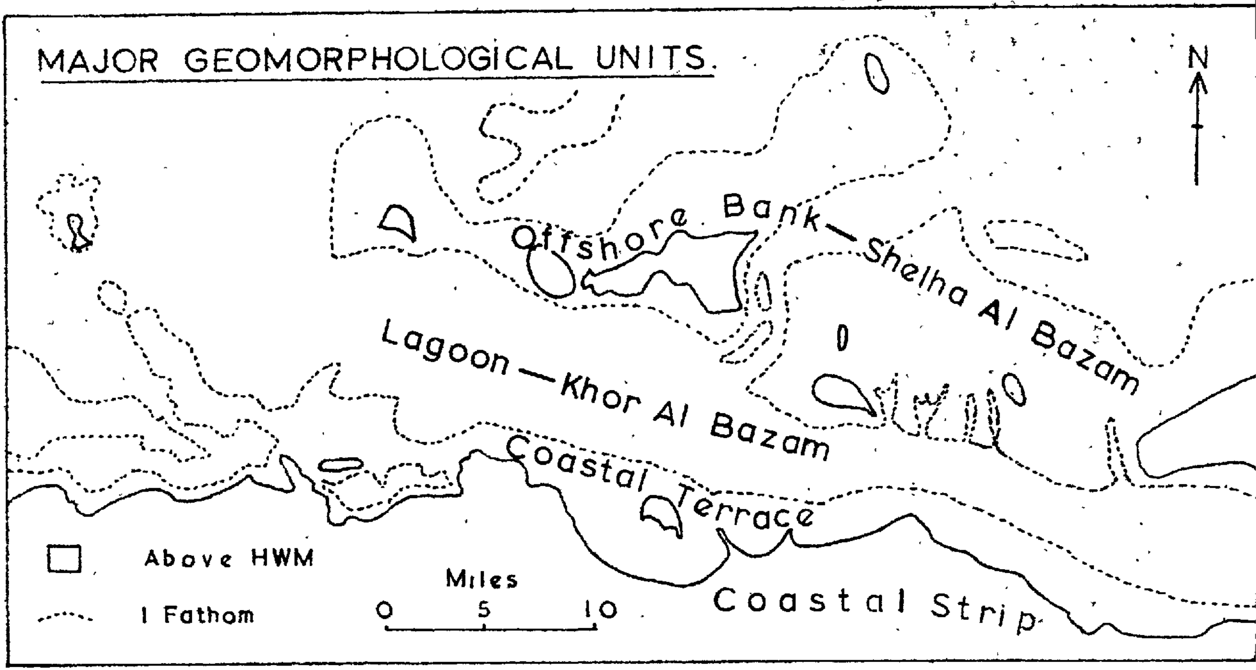
Finally I would like to thank Sir Patrick Skipwith, who has been my constant companion in the field and laboratory.

Figure 3


MAJOR GEOMORPHOLOGICAL UNITS.
N
Offshore Bank — Shelha Al Bazam
Lagoon — Khor Al Bazam
Coastal Terrace
Coastal Strip
Above HWM
1 Fathom
Miles
0 5 10

CHAPTER II

GEOMORPHOLOGY

1. INTRODUCTION

The area can be divided into four main geomorphological units: an offshore bank (Shelha al Bazam), a lagoon (Khor al Bazam), a coastal terrace and a mainland coastal strip (Figure 3). Each of these units is composed of a complex of minor geomorphological features, which include megaripples, spits and mangrove clumps. The geomorphological character of the area is the result of the interplay of the tide, wind, insolation, precipitation and original bedrock structure.

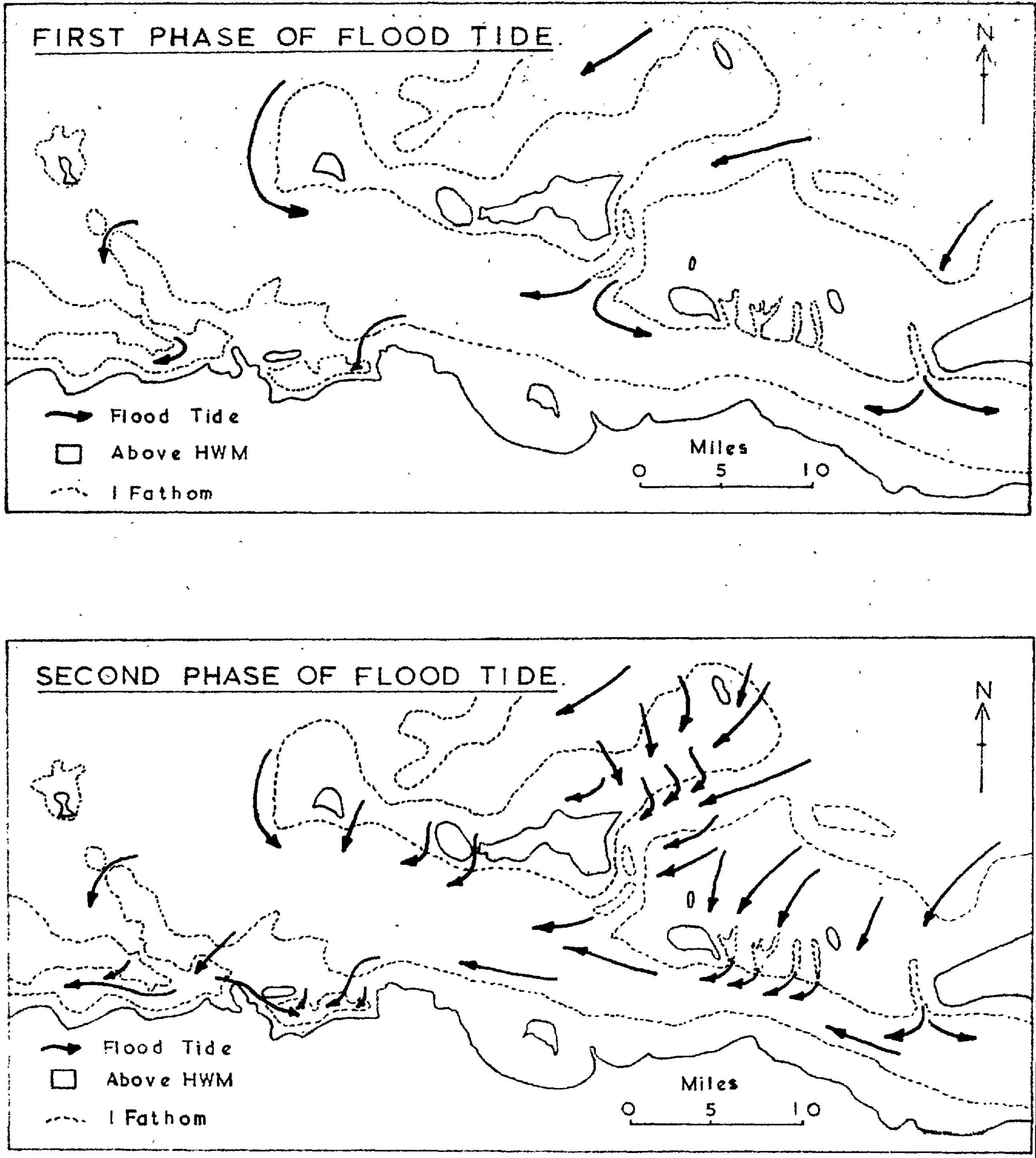
Tidal and weather data are limited, as records have only recently been kept by the Abu Dhabi Petroleum Company (A.D.P.C.). Even now stations are too far apart to provide an adequate picture. Consequently the determination of tidal directions has been in part inferred from the orientations of geomorphological features such as ripples, bars, channels and weed lineations shown by aerial photographs, and in part based on direct field observations. The relationships of these features to tidal currents, and hence the validity of this approach, has been shown by Van Veen (1953) and Stride (1963). Although it can reasonably be inferred that current movement has taken place in a particular direction, whether it was an ebb or flow current is conjectural in an area of such variable topography as Khor al Bazam.

The only tidal data available for the Khor al Bazam were recorded at Jabal Dhana. When compared with records from Zubaiya and Abu Dhabi this shows that the tidal flood wave progresses from northeast to southwest along this part of the Trucial Coast. Except for the major tidal channels, most of the offshore bank is exposed at low tide. Thus, during the earlier part of the flood tide, the flow of water into the lagoon is carried by these channels. (Top of Figure 4). Owing to this restriction of tidal movement, a head of water builds up seawards until eventually it surmounts the bank and flows over it into the lagoon as a series of 'jet streams' that downcut into the bank. Where those jet streams debouch into the lagoon they create deltas. The initial damming effect of the bank leads to local reversals in the direction of the flood tide along its inner edge where it is cut by major channels. The same effect is produced at the western end of the lagoon, (Figure 4). When the bank is flooded, however, the dominant east to west flow is resumed. This same direction of flood tide movement is to be found on the southern side of the lagoon and on the coastal shelf, with local reversals in the complex of small lagoons of the western coastal terrace.

This westerly movenent of flood can be inferred from aerial photographs. The orientation of mud streaks stirred up by bottom turbulence and the asymmetry of most of the tidal deltas which occur along the inner edge of the offshore bank show that the flood tide moves from east to west.

The offshore bank acts as a barrier to the Khor al Bazam which channels the ebb and flood tidal movements and increases

Figure 4


FIRST PHASE OF FLOOD TIDE.
N
Flood Tide
Above HWM
1 Fathom
Miles
0
5
10
SECOND PHASE OF FLOOD TIDE.
N
Flood Tide
Above HWM
1 Fathom
Miles
0
5
10

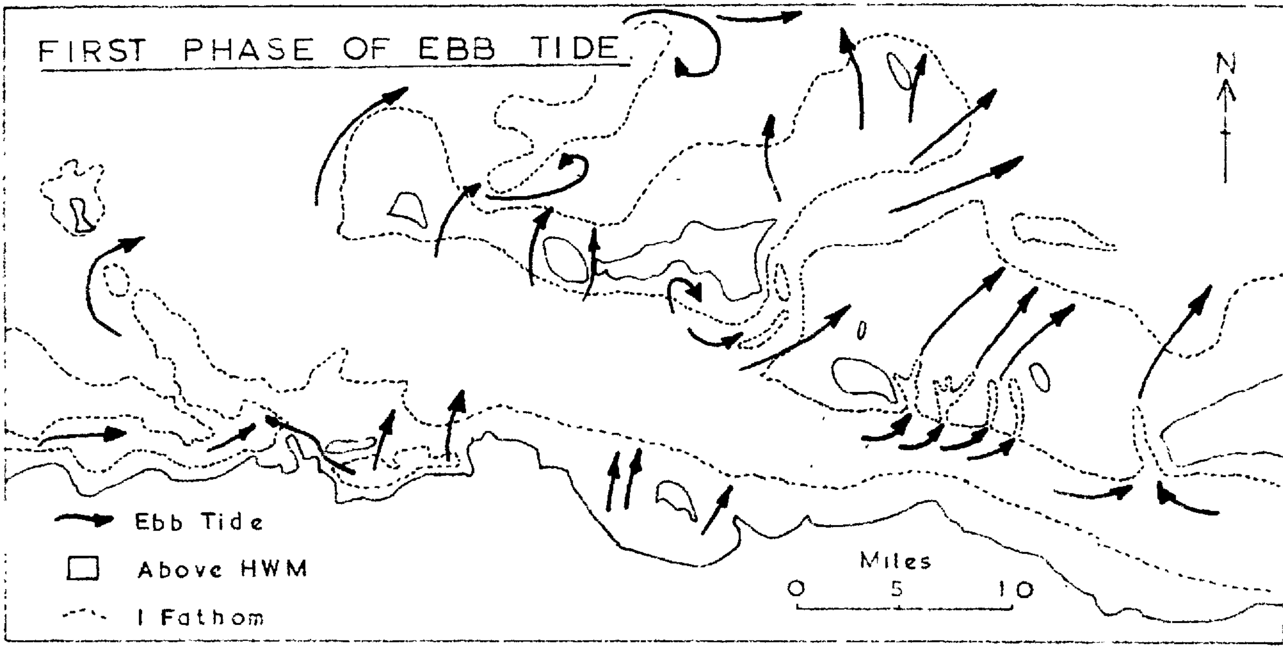
their speed. A similar channelling of the tides occurs between the offshore bank and the large coral patch-reefs to the north, and in the coastal complex of lagoons of the west Khor al Bazam. The direction of this channelling shows itself in the orientation of megaripples and spits. For example, in the large channel that cuts across the offshore bank, the spits are orientated towards the lagoon along the direction of the flood tide.

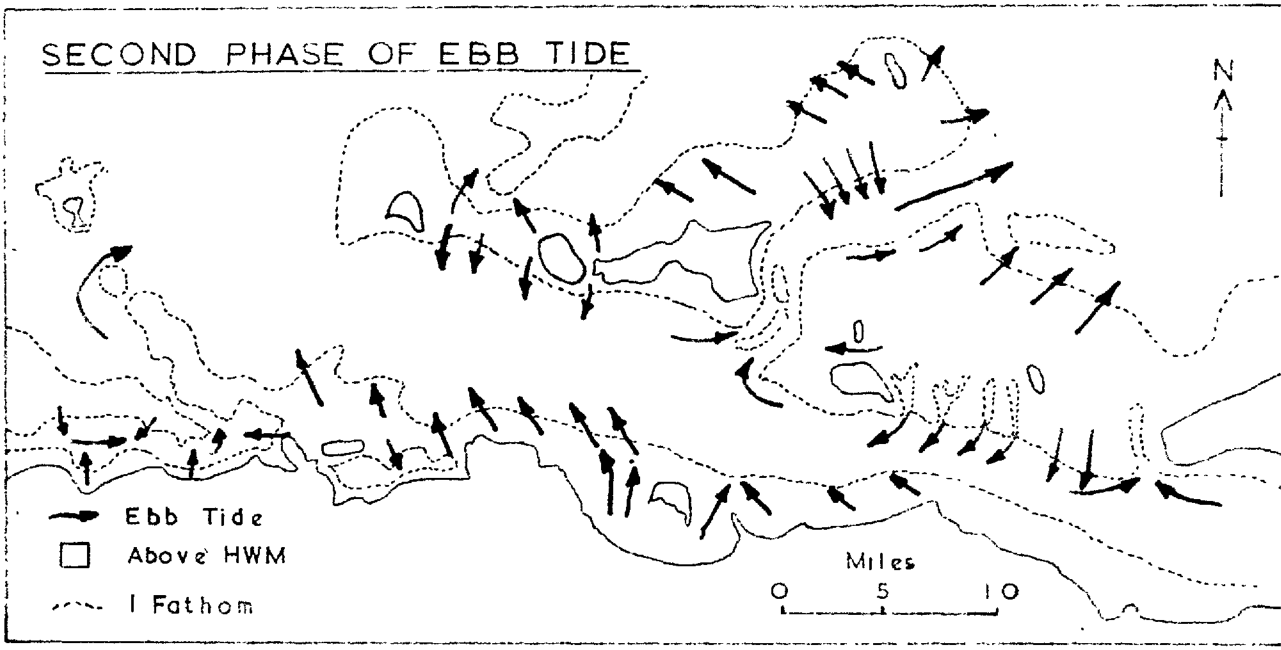
At the onset of the ebb tide there is a general movement of water towards the east. This flows out over the banks until they are exposed. The ebb then flows radially off the banks and along the major channels, (Figure 5).

During the ebb tide there is a flow of water out of the Khor al Bazam under the influence of gravity. This is a general movement towards the greatest low in the open sea to the north-east, with local movements along the lines of least resistance. The lineations produced by these local movements are seen as longitudinal megaripples and the orientation of ebb gullies.

The importance of the ebb and flood tides can be gauged when it is realised that they generate so many of the geomorphological features of the area. Unlike the lagoonal areas adjacent to Abu Dhabi (Kinsman, 1964c) the flood tide plays the greater role in the Khor al Bazam. Possibly because the flood attains higher velocity than the ebb tide. Similar differences in speed between flood and ebb tides is discussed fully by Phleger for Recent Mexican lagoons, (Phleger et al, 1962). The causes of these differences in tidal speeds in the Khor al Bazam are difficult to unravel because of the complicated relief of the sea

Figure 5


FIRST PHASE OF EBB TIDE
N
Ebb Tide
Above HWM
I Fathom
Miles
0
5
10

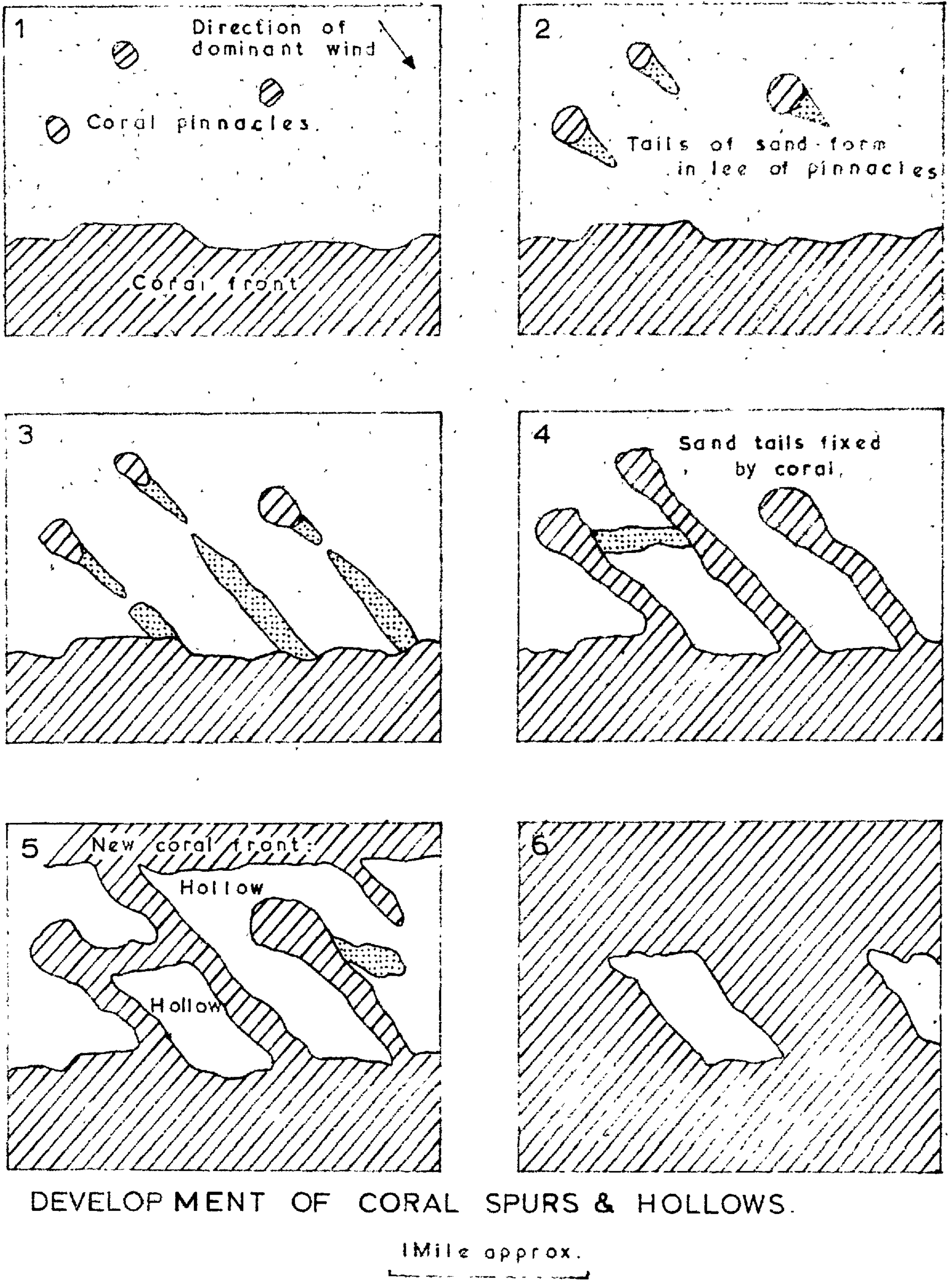

SECOND PHASE OF EBB TIDE
N
Ebb Tide
Above HWM
I Fathom
Miles
0
5
10

bottom in and adjacent to the area.

Kinsman (1964c) compiled a complete synthesis of weather and wave data for the Abu Dhabi area. He showed that winds blow predominantly from the northwest, (Sheets 1 - 3, cf. wind rose), the direction of greatest fetch, so that the largest waves also come from this quarter. The full force of these waves is broken by the coral shoals north of the Shelha al Bazam and by the Shelha itself and areas of most profuse coral growth appear to be directly related to the heaviest wave action. The orientation of major reef fronts is perpendicular to the direction of maximum wave approach, whilst most coral spurs and grooves are parallel to the direction of greatest wave action, (Figure 6). In contrast directly in the lee of the coral shoals on the shallow offshore bank and in the lagoon, wave activity is much reduced.

Large waves break on the outer edge of the offshore bank. Small waves pass over the edge moving across the bank in company with other small waves generated by the breaking of the larger waves. The depth of the bank is approximately constant for several miles with few or no shoals. When waves touch bottom in the shallowest water, they create angled bars, beach ridges and beach spits characteristic of the intertidal zone. In the lagoon onshore winds can produce only small waves. These do not affect the lagoon floor but do affect the shoal area of the coastal terrace. Because the winds generally blow across it rather than down its long axis wave effects in the lagoon are limited. Instead tidal currents dominate the lagoon and those

Figure 6



DEVELOPMENT OF CORAL SPURS & HOLLOWS.

parts of the shelf beyond heavy wave action.

The dominant onshore wind has an important effect on the sediments of the intertidal areas and supratidal areas. When the surface layers of these dry out and are no longer bound by interstitial moisture, the wind transports them inland. G. Evans (Personal communication 1964) collected samples of desert sand thirty and forty miles inshore, which contained small percentages of carbonate of coastal origin.

Insolation and the resulting temperatures and humidity were also discussed by Kinsman (1964c). Because of the low rainfall, less than two inches a year, and because of the high net rate of evaporation the water table in the supratidal areas is of marine origin. Thus many of the islands on the Shelha al Bazam, and much of the mainland sabkhas, have entirely marine ground waters. Below the water table and in the capillary zone above, evaporation leads to concentration and precipitation of salts. The level of the water table plays an important role in determining the surface relief of the sabkhas, since only dry sand can be carried away by the wind. (Evans et al, 1964).

The surface upon which the present sediments started to accumulate is now obscured. Most certainly it is composed of a complex of Quaternary and Tertiary rocks and it would be of interest to know its relief.

2. CLASSIFICATION AND DESCRIPTION OF THE GEOMORPHOLOGICAL UNITS AND FEATURES OF THE WEST KHOR AL BAZAM

A classification of geomorphological features was based on field observation and interpretation of aerial photographs taken in 1958 by the R.A.F. and in 1963/64 by Huntings, (London). The results of this study are shown in the three geomorphological maps, Sheets 1, 2 and 3. Cross-sections exhibited beneath the maps were compiled from echo traces made by Bendix echo sounder. These were positioned by dead reckoning.

Footnote:

Localities described in the text can be identified on maps included with the thesis. These localities are given map references, which are obtained as follows:

Example: Quala:

a: Note the number of the sheet on which the locality occurs. For Quala, this is sheet 1.

b: Take the west edge of the square in which the locality lies, and read the number printed opposite this line on the north or south margins. For Quala, this is 4.

c: Take the south edge of the square in which the locality lies and read the letter opposite this line on the east or west margins. For Quala, this is H.

Map reference for Quala is thus: 1/4/H.

3. MAJOR GEOMORPHOLOGICAL UNITS

Since the origins of the major geomorphological units in the area are complex, the units are classified on the basis of their relationships to sea level and their geographical position. Each of the major geomorphological units of the west Khor al Bazam may be arbitrarly divided into major and minor geomorphological features. The three tables below summarise these features - Table 1 relates major geomorphological features to the major units; Table 2 relates major features and their genesis; whilst Table 3 relates the minor features of more universal occurrence to their genesis. Table 1 also shows how several of the major features occur in more than one of the major units.

TABLE I

The Classification of the Major Features in Relationship to Major Units

MAJOR UNITS	SUBDIVISION BASED ON RELATION TO LWM	MAJOR FEATURES
1: Offshore Bank	a) Features below L.W.M.	i: Coral Reefs ii: Tidal Channels & Deltas
	b) Features below & above L.W.M.	i: Weed Patches
	c) Intertidal features	i: Sand Flats ii: Mangrove Areas iii: Algal Flats
	d) Intermittently flooded features	i: Sabkha Barrier Islands
	e) Dry Land	i: Islands of Cemented rock
2: Lagoon	a) Features below L.W.M.	i: Open Lagoon with flat floor ii: Open Lagoon with dissected floor with weed patches
3: Coastal Shoal	a) Features below L.W.M.	i: Coral Reefs ii: Tidal Channels & Deltas
	b) Features below & above L.W.M.	i: Weed Patches
	c) Intertidal features	i: Sand Flats ii: Algal Flats
4: Mainland Coastal Strip	d) Intermittently flooded features	i: Sabkha Plain
	e) Dry Land	ii: Hills & Outwash

TABLE 2

The Classification of Major Features in Relation to Their Genesis

PRIMARY AGENTS OF GENESIS

1:	Marine	a)	Waves	i:	Intertidal Sand Flat
		b)	Currents	i:	Tidal Channels and Deltas
				ii:	Open Lagoon with Flat floor
				iii:	Open Lagoon with dissected floor.
		c)	Biological	i:	Coral Reefs
				ii:	Weed Patches
				iii:	Mangrove Areas
2:	Marine and Subaerial	a)	Wind, Waves & Currents	i:	Sabkha Barrier Islands
				ii:	Mainland Sabkha Plain
				iii:	Islands of cemented rock.
		b)	Wind, Fluvial	i:	Hills and Alluvial Fans.

TABLE 3

Classification of Minor Features that Occur in Two or More Major Features

	Origin:	Minor feature:	Occurrence:
1: MARINE	a) Waves	1: Break point bars	Lower part of the littoral zone to below L.W.M.
		2: Runnels & bars	Sand flats
		3: Intertidal spits and beaches	Upper part of littoral zone on sand flats
	b) Currents	1: Submarine spits	Variable
		2: Megaripples	Variable
		3: Rills and Gullies	Littoral zone
2: SUBAERIAL	a) Wind and Biological	1: Coastal Dunes	Above H.W.M. parallel to Coast.

A) Offshore Bank - Shelha al Bazam

The offshore bank is approximately seventy miles long and fr five to twenty miles wide. It rises fairly abruptly from a depth of between fifteen and sixty feet. It is dissected by numerous tidal channels and it is composed of shoals (seldom deeper than 6 feet), intertidal flats and islands. Its seaward edge is a coral reef, whilst its lee side is marked by tidal deltas where channels debouch into the lagoon. Table 1 lists these and other features which comprise the bank. They are described in more detail in later sections where they are considered in relation to their genesis rather than geographic location.

B) Lagoon - Khor al Bazam

The lagoon behind the bank is about seventy miles long and is five to twenty miles wide. Its floor slopes down gently westwards. The east Khor al Bazam, opposite the centre of Abu al Abayad, is exposed at low tide, whilst opposite Bazam al Garbi its floor lies at a depth of fifty feet. East of Janana the Khor al Bazam has a flat bottom. West of this point it is eroded into numerous flat topped ridges.

The depth of the lagoon, ignoring the eroded areas, ranges from twenty-four feet opposite Salaha to thirty-four feet opposite Bazam al Garbi: an increase of ten feet in fifty miles. This gradient continues back into the east Khor al Bazam. The depth of the eroded areas lies around thirty-five feet between Fiya and Ras al Aish, and reaches fifty feet opposite Bazam al

Garbi. The gradient of the eroded areas is ten feet in twenty miles.

The agency by which the lagoon floor was eroded is not known. It may have been westward tidal flow from the large channel west of Ras al Sehama, or else fluvial erosion during low Pleistocene sea levels. At the present time the Khor al Bazam is being filled by sediment from three sources: from the offshore bank by deltaic accretion, from the east Khor al Bazam in the form of current deposited material, and from the coastal strip by the accretion of the coastal terrace. Kinsman (1964a) suggests that when the Khor al Bazam is eventually filled, the coastline will take on a north-south configuration as with the area east of Zubaiya (Figure 1).

Weed (brown algae) patches are the only major features of note occurring in the lagoon apart from the undissected and dissected floors.

C) Coastal Terrace

The coastal terrace is divided into two sections at Ras al Aish. To the east, it is a shoal of between a quarter to five miles wide, lying between the lagoon and the coastal strip. The terrace slopes gently seawards with a gradient of approximately 1:5,000. At its seaward edge it is a poorly maintained coral reef, which is still spurred. Landwards, the terrace is narrow round the peninsulas of Tertiary and Quaternary rocks, but wider across embayments. It is likely that the terrace represents, at the Tertiary headlands, an eroded step cut into the rock. Opposite bays it is an accreting reef flat, growing on a foundation of Quaternary rock. Evidence of this can be seen from the air.

To the west of Ras al Aish the coastal terrace is protected by small offshore banks and subsidiary lagoons. As with the major offshore bank bounding the Khor al Bazam, the small offshore banks have their edges limited by coral reef but, like that on the eastern terrace, this reef is poorly developed Behind the bank the subsidiary lagoons are progressively silting up and their southern edges are accreting seawards. The narrow coastal terrace is not unlike the terrace to the east, but has no recognisable coral development along its northern edge.

Both the east and west sections of the coastal terrace exhibit the major geomorphological features listed in Table 1.

D. Coastal Strip

The coastal strip extends along the whole of the west Khor al Bazam and into adjacent areas, with a width of between five to twenty miles. It consists of irregularly spaced hills of Tertiary and Quaternary rocks aligned approximately N.N.W.-S.S.E. Between these hills there are salt flats or sabkhas (Evans, Kendall and Skipwith, 1964). These are of marine and aeolian sediments accreting across and around a platform of cross bedded Quaternary rock. The hills seldom rise above fifty feet and are surrounded by outwash fans.

4. GEOMORPHOLOGICAL FEATURES FORMED BY THE SEA

A) Major Features Formed by Waves

(i) Intertidal Sand Flats

Intertidal sand flats are present on the eroded surface of ancient reef flats, or the wave cut benches of pre-Holocene rocks. They have a gradient of approximately 1:5,000, and vary in width from a quarter to five miles. They are generally covered by a variable thickness of unconsolidated sand, which may be underlain by several layers of poorly cemented limestone. These layers of rock have flat upper surfaces and irregular lower ones. Some layers are contemporaneous beach rock and are forming from the unconsolidated sediment of the sand flat. They are cemented by calcium carbonate precipitated from evaporating capillary water during low tide by the mechanism cited by Ginsburg (1953). This process is probably particularly active during the height of summer. Before further sediment accumulates the upper surface of the beach rock is truncated by storms.

Not all the layers are contemporaneous and some are of different composition to the loose sand above them. These particular horizons can extend from six feet below the L.W.M. to a few feet above the H.W.M. (In the latter case they are covered by beach and algal sediments). It is probable that these limestones represent sediments developed as the sea level rose across the Pre-Holocene platform. They were cemented to form beach rock contemporaneous with this change in sea level.

The surface may be divided, on the basis of fauna, into *Cerithium* (a small turreted gastropod) flats and crab flats. The *Cerithium* flats form the lower areas and the crab flats the upper areas of intertidal sand flats. The crab characteristic of the latter zone is *Scopimera* sp. It produces radial patterns of feeding halls. Kinsman (1964c) also refers to these zones.

The sediments of the intertidal sand flats are highly burrowed, probably by a combination of crabs and worms. Ginsburg (1957) noted a similar phenomenon in carbonate sediments of Florida.

B) Minor Features Formed by Waves

(i) Break Point Bars:

On the seaward edges of the offshore bank and coastal terrace, sand ridges lie parallel to the shore and are covered by the highest tides. These are similar to break point bars as defined by King (1959). She described these features from the Great Lakes of North America, California and the Baltic. She summarised the history of the controversy which has arisen about their origin. From the evidence of tank experiments she explained how they can form in relatively tideless seas at the break or plunge point of waves. If this is true, then the bars of the Khor al Bazam could have been produced by waves which break as they cross the edge of the offshore shoal areas and coastal terrace.

This feature is commonly referred to in the literature as an 'offshore bar', (Thornbury, 1959), and has been defined as a 'long shore bar' by Shepard (1952). Both these terms are confusing because they have general application to such a wide variety of phenomena. In this thesis the definition of King (1959) is used. The term 'bar', however, is applied in the way Shepard (1952) proposed for an elongate sand body submerged at some point of the tide.

Break point bars may take the following forms:-

a. Single break point bars
b. Crescentic bars
c. Multiple break point bars.

a. Single Break Point Bars:

Single break point bars are well developed along the eastern edge of the Ras al Aish coastal terrace (Plate No. 1), (Map Ref: 2/3/H), and also on the terrace just west of Mirfa (Map Ref: 3/3/H). They can also occur in front of the offshore bank where a coral reef has fixed the sediment. One location in front of the bank where they are found without coral is east of Bazam al Garbi. They can range from a quarter to one mile in length along their axes. At station 179 the bar has a height of four feet and lies in 14 feet of water (see cross-section sheet 2). The bar between stations 224 and 223 is in 10 feet of water and also has a height of 4 feet (see cross-section sheet 3). Both have widths of 180 feet.

Plate 1

Southeast of Ras al Aish (2/2/H) showing

(i) Break point bars to the seawards of the coastal terrace.

(ii) Transverse megaripples on the weed covered terrace front.

(iii) Rhomboid megaripples close to the shore.

(iv) The western edge of the Khusaifa algal flat with angled bars and scours.

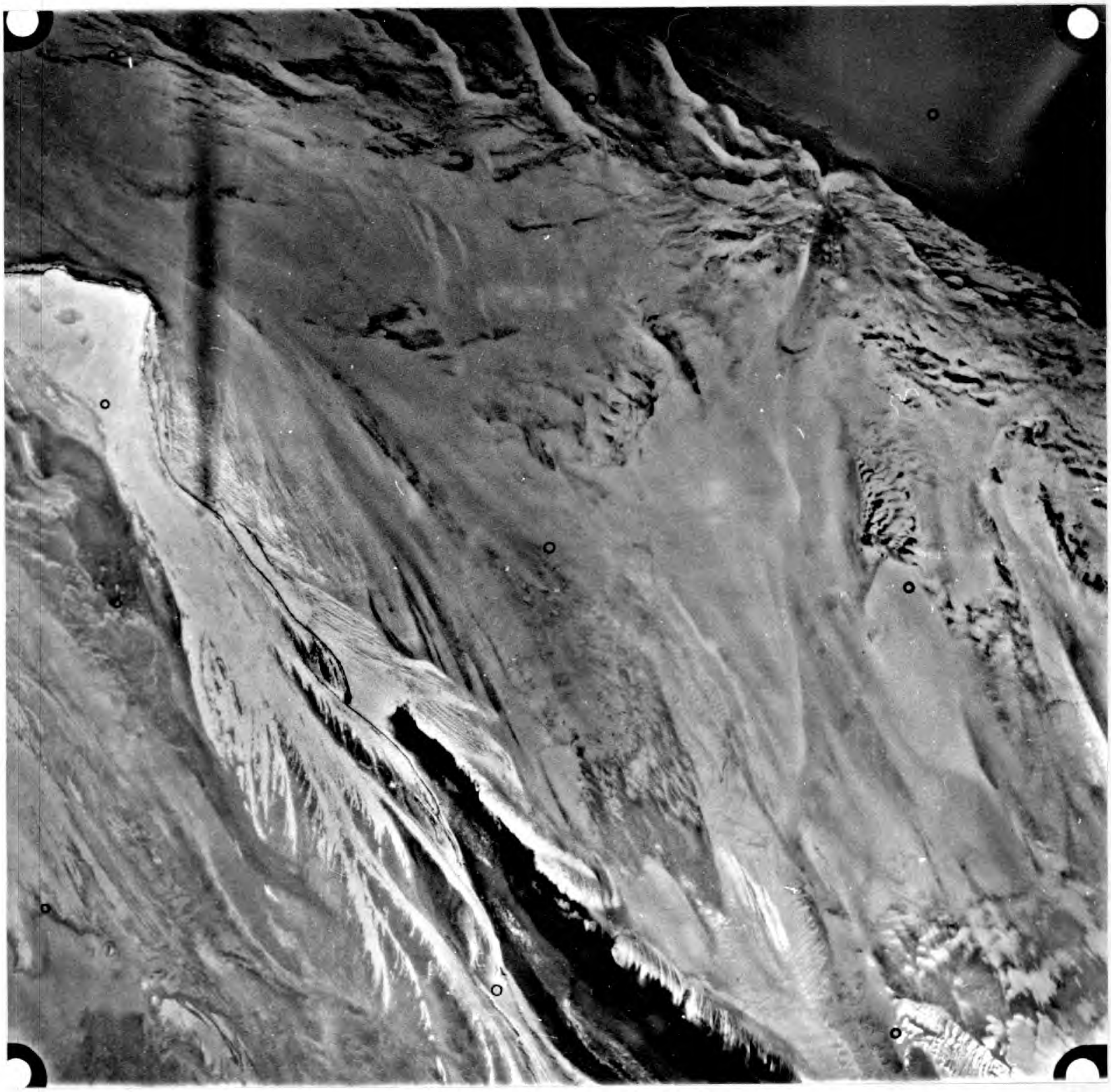
(v) Spit accretion formed against a rock headland.

Scale approx. 1:30,000

(Top edge of all aerial photographs is North)

PLATE I


Break point bars
Transverse megaripples
COASTAL TERRACE
N
Spit
SABKHA
Rhomboid megaripples
Algal flat



b. Crescentic Bars:

Crescentic bars were found in only one part of the Khor al Bazam (Map Ref: 2/2/H, Figure 7). Similar structures have been described by King (1959), Williams (1960), and Shepard (1952). Shepard called them lunate bars. The precise nature of their origin is unknown but both Williams and King suggested they are formed by the intersection of two wave directions within small bays.

c. Multiple Break Point Bars:

Multiple break point bars are developed at the entrance of, and to the west of, the Dagallah lagoons, (Plate 2 and Plate 3), (Map Ref: 1/2/H). Shepard (1952) and King (1959) discussed similar features and suggested that they were formed by different sizes of wave. The deeper outermost line of bars being formed at the plunge line of large waves and the inner lines by smaller waves.

(ii) Runnels and Bars

Within the intertidal zone there are parallel ridges of sand separated by 'lows'. These correspond to the 'balls and lows' of Johnson (1919), the 'runnels and ridges' of King (1959) and the 'runnels and bars' of Williams (1960). This last term is used in this thesis.

In the Khor al Bazam these structures occur in three forms:

a) As runnels and bars with frequent cross-cutting channels.

Figure 7

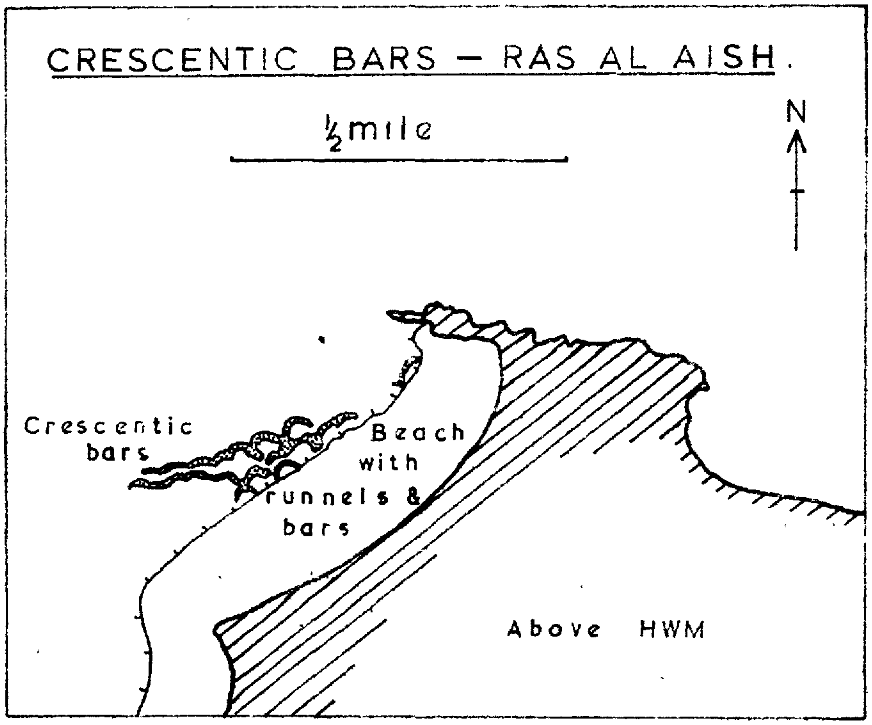

CRESCENTIC BARS – RAS AL AISH.
½ mile
N
Crescentic bars
Beach with runnels & bars
Above HWM

Plate 2

The western mouth of Dagallah lagoon
(1/1/H) showing:

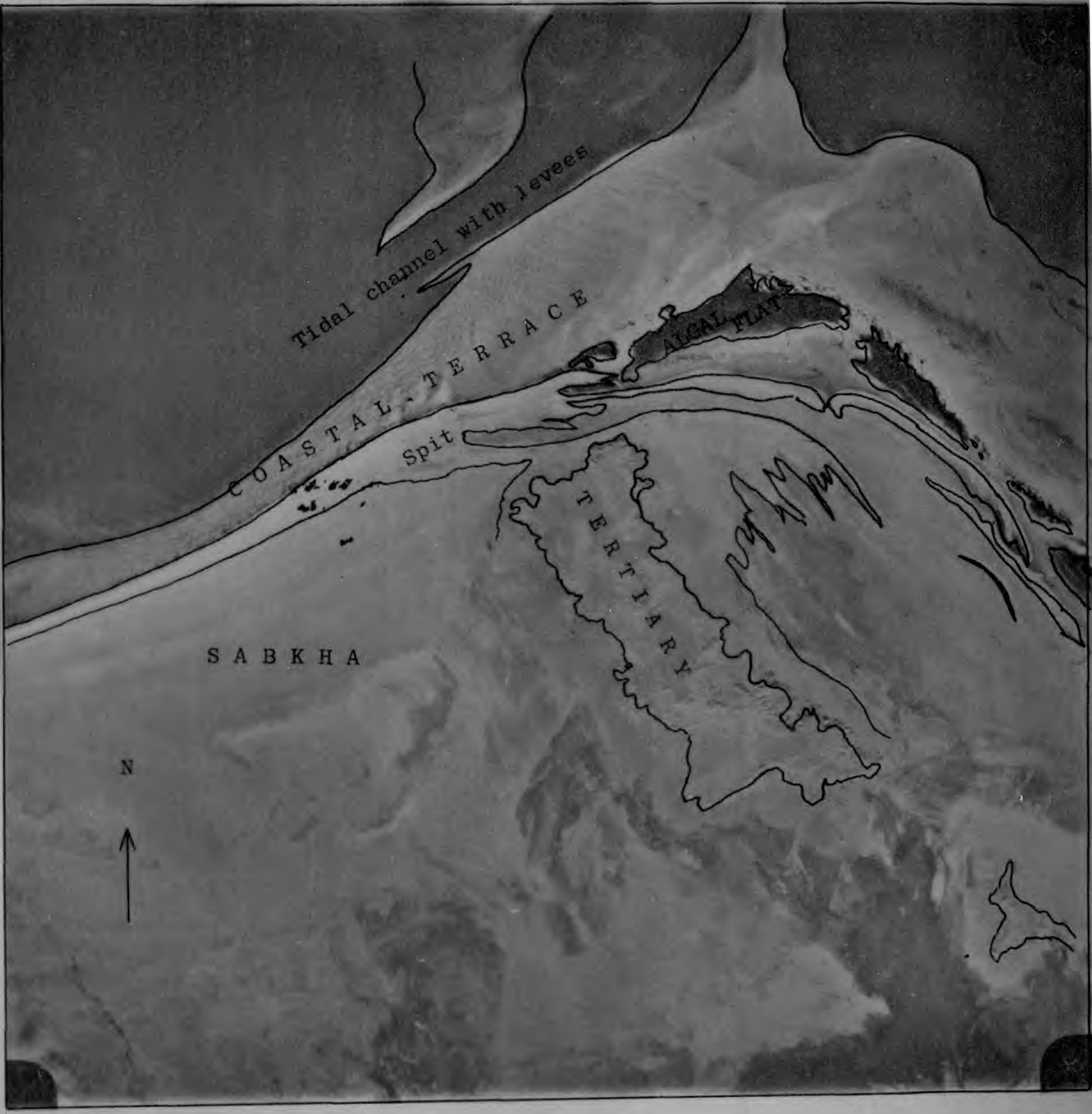
(i) Tidal channel with levees

(ii) Coastal terrace with break point bars and various forms of runnel and bar.

(iii) Algal flat and spit accretion moulded round a Tertiary headland.

Scale approx. 1:30,000

PLATE 2


Tidal channel with levees
COASTAL TERRACE
ALGAL FLAT
Spit
TERTIARY
SABKHA
N

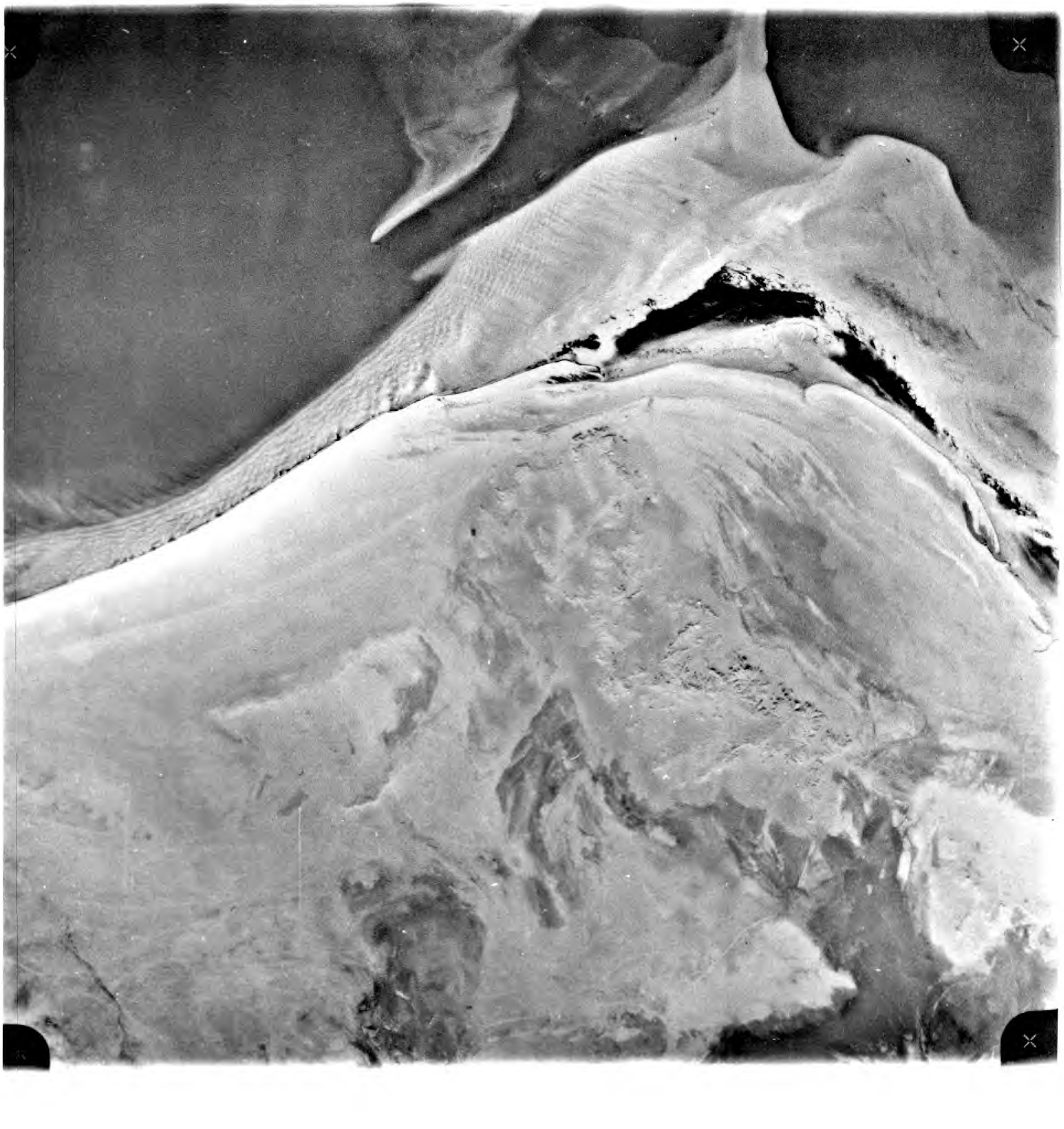


Plate 3

The coastal terrace west of Dagallah lagoon entrance showing:

(i) A poorly developed coral front along the seaward edge of the terrace.

(ii) Multiple break point bars.

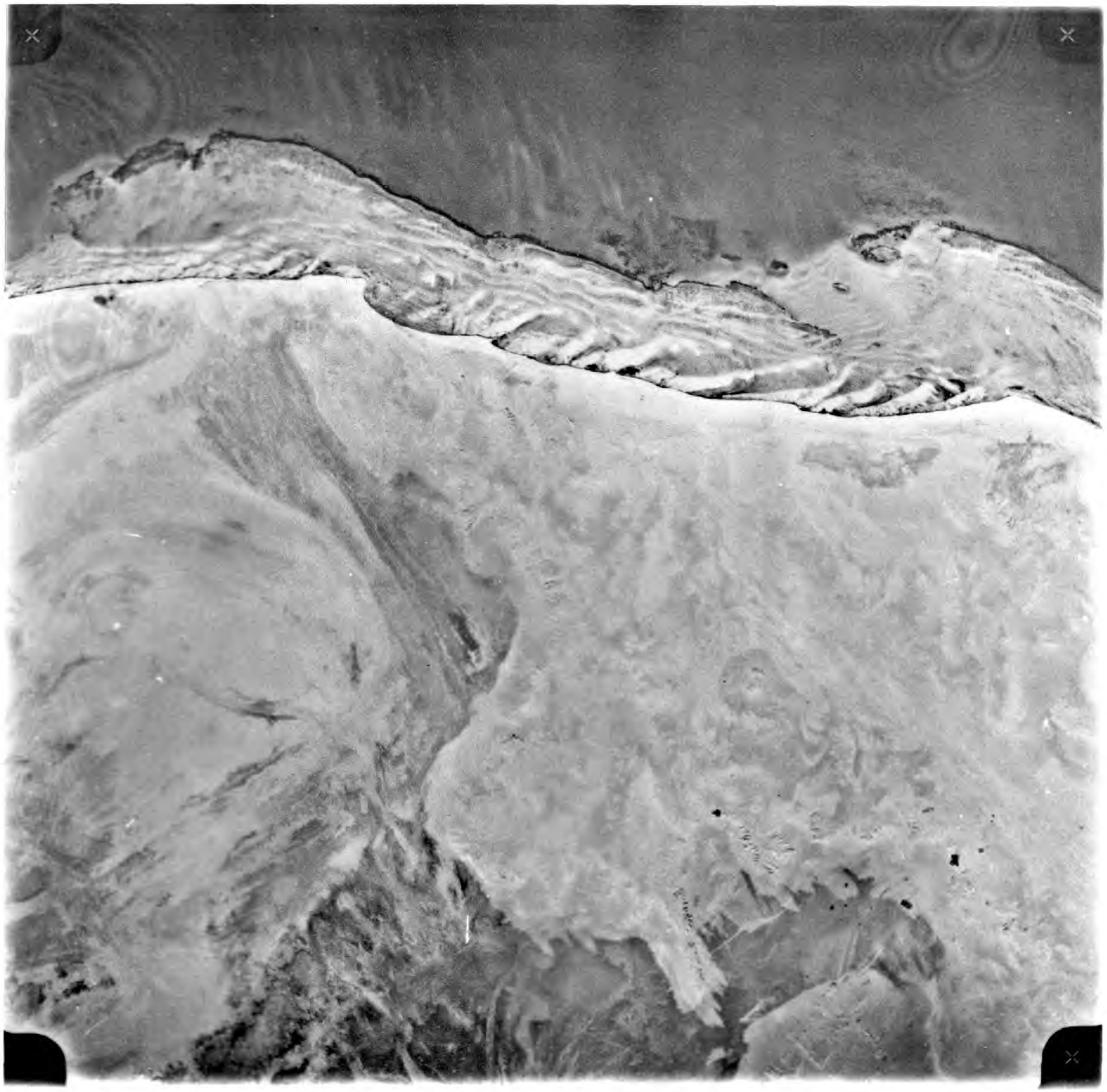
(iii) Angled bars.

(iv) Thin line of coastal dunes.

Scale Approx. 1:30,000

PLATE 3


CORAL FRONT
MULTIPLE BREAK
POINT BARS
ANGLEY BARS
DUNES
SABKHA
N



b) As runnels and bars with few cross-cutting channels.

c) As angled runnels and bars.

King (1959) believed that, in the first of these varieties the 'bars' were produced by the swash of breaking waves on an incoming tide and the runnels by the erosion of the ebb tide. Davies (1962) accepted this conclusion.

Williams (1960) suggested that all three varieties form by the same mechanism. The close proximity of these structures to one another in the Khor al Bazam supports the idea of consanguinity.

a) Runnels and Bars with Frequent Cross-Cutting Channels.

Runnels and bars with frequent cross-cutting channels are best seen in the Khor al Bazam just west of the Dagellah lagoon entrance, (Plate 2) and in the bay at the northern tip of Ras al Aish (Map Ref: 2/2/H). In cross-section, the front of the bars have a rounded slope and their landward face is steep. Their width is approximately 30 feet and their height is 6 inches to 1 foot. They have very variable wavelength. As defined, they lie parallel to the coast and are frequently cut by cross-cutting channels which are generally perpendicular to the coast.

b) Runnels and Bars with Few Cross-Cutting Channels:

In the Khor al Bazam, sand ridges of some 30 feet wavelength and between 4 to 6 inches amplitude are common on the upper and middle intertidal flats of the offshore barrier and coastal terraces. They form parallel to the shore in evenly spaced groups of from two to twelve individuals, as for example, west of Dagallah lagoon entrance (Map Ref: 1/4/H and Plates 2 and 4). Van Straaten (1953) compared similar features from the Wadden Sea to runnels and bars, but stated that the relationship is not proven. Plate 2 shows that they are related because they pass into each other. Van Straaten suggested that the fact that they are parallel to the shore, indicates an origin from 'surf', i.e. breaking waves. In the west Khor al Bazam these features are often cemented, or partially covered by other features. This suggests that the conditions necessary for their formation are only rarely developed, (Plate 11). Storms are the most probably agents. However, once formed they appear to be permanent features.

c) Angled Runnels and Bars:

Angled runnels and bars form on the upper intertidal flats of the offshore bank and coastal terrace at a variable angle to the coast. They are clearly seen at Dagallah mouth (Map Ref: 1/4/H) (Plate 2), west of Dagallah mouth, (Plate 3), Quala (Plate 4, Map Ref: 1/4/H), east of Ras al Aish, (Plate 1, Map Ref: 2/4/H), and in front of Marawah (Plate 5, Map Ref: 2/5/E). They are between 12 to 20 feet across and 6 to 12 inches high, (approximately the same dimensions as the other bars of runnels and bars). Their wave length is variable. In cross-section their frontal edges are gently curved and they have steep shoreward faces. In plan, the frontal edge of any one of these is usually an undulating line, whereas the back is a series of

Plate 4

Quala bay (1/4/H) showing:

(i) Coastal terrace edge.

(ii) Axial channel and delta to the east

(iii) Angled bars and algal flat.

Scale approx. 1:30,000

PLATE 4


N
COASTAL TERRACE
DELTA
AXIAL CHANNEL
ANGLED BARS
ALGAL FLAT

interlocking crescents. Any one bar is broadest shoreward at its base and it tapers seaward. Its seaward tip is hooked back towards the shore. The surfaces of these bars are loose and fresh. This, coupled with the fact that their morphology and position was almost unchanged between 1958/1963 (cf. R.A.F. and Huntings photographs) suggests that although they do not move they are continually re-worked. These angled runnels and bars are not unlike the features described by King (1959) off the Lancashire coast and by Davies (1962) at Gibralter Point. In both cases they were inferred to have been formed by the swash of waves. The Khor al Bazam bars differ from these because along the Khor al Bazam the gradient of the intertidal flats on which they form is low (1:5,000); the tidal range is small (some 4 feet); and sometimes the bars lie normal to the shore.

King (1959) suggested such bars form on the incoming tide almost perpendicular to the waves that produce them. The orientation of the bars along the Khor al Bazam is consistent with this suggestion. They are formed by small waves that cross wide stretches of shallow intertidal flat without breaking, and are also unrefracted by the edges of the coastal terrace or barrier. The angles of the bars suggest the waves do not necessarily come from the dominant wind direction, but are generated by occasional winds from the direction of greatest local fetch. Ebb currents running out between the bars can modify the angle which bars make with the shore. This is to be seen in the lagoons of Dagallah (Southern part of

Sheet 1), near Jabal Mirfa (Sheet 3), Khusaifa and in front of Marawah (Sheet 2).

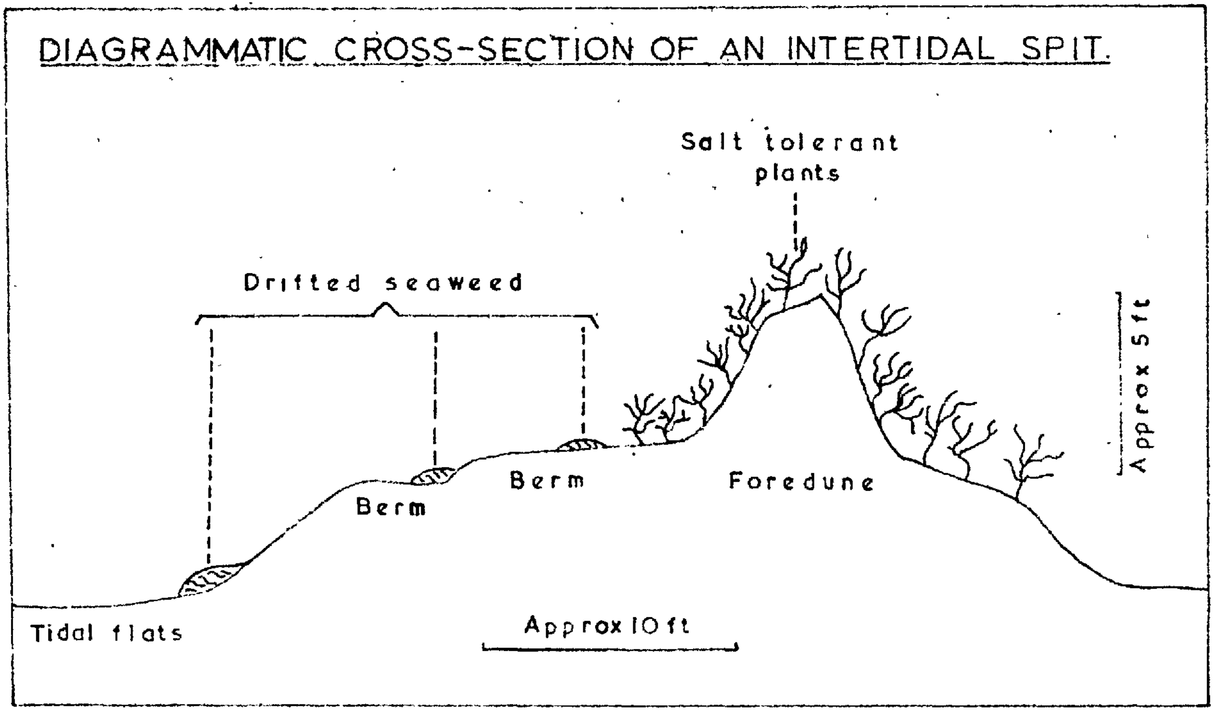
These bars are called angled runnels and bars to distinguish them from runnels and bars: the latter lie parallel to the coast and have frequent cross-cutting ebb channels. The surfaces of the angled bars are often reworked and burrowed by the crab Scopimera sp.

(iii) Intertidal Spits and Beaches

Evans (1942) defined a spit as a ridge or embankment of sediment attached to the land at one end and terminating in open water at the other. In this thesis the definition is extended to include ridges of sediment attached to shoal areas. This section deals with intertidal spits and a later section deals with submarine spits.

Intertidal spits are one of the most common beach features in the west Khor al Bazam. They exhibit a major trend from west to east and are undoubtedly formed by long-shore drift induced by the dominant northwest wind. They delineate the upper limit of the intertidal flats. The seaward side of the spit has a beach face slope that varies around 1 in 6, and is in abrupt contrast to the slope of the adjacent intertidal flat to the seaward which is normally approximately 1:500, (Figure 8). The bottom of the slope (i.e. toe of beach) is normally marked by a line of drifted seaweed. Above the beach face there is at least one berm which is backed by a line of hummocky dunes. The inner edges of the berm and the hummocky dunes are fixed by salt-tolerant shrubs like Arthrocnemum glaucum. The

Figure 8


DIAGRAMMATIC CROSS-SECTION OF AN INTERTIDAL SPIT.
Salt tolerant plants
Drifted seaweed
Berm
Berm
Foredune
Approx 5 ft
Tidal flats
Approx 10 ft

landward facing slope of the spit is convex and curves down to the approximate level of the old intertidal flat upon which it rests. These spits continue to increase in width seawards, unless another spit develops in front of them.

Spits are generated on lines of drifted seaweed that accumulate on the tidal flat. Two stages of development can be seen. The first stage is shown at the western mouth of Dagallah lagoon (plate 2). Here a barrier beach is nucleated on a seaweed line to form a lunate or cusped ridge of sand. In the second stage, which is developed north of Marawah (Plate 5, Map Ref: 2/5/E) accretion has tied a ridge of sand to the land as a spit. The initiation of new spits probably occurs at times of heavy storms (Evans et al, 1964). The whole coastline of the west Khor al Bazam is lined with compound forms of spits which are now stranded inland by coastal accretion, (Plates 1 and 28) like those of the Louisiana chenier plains (Byrnie, Le Roy & Riley, 1959 and Gould & McFarlan, 1959), or of the Niger delta (Allen, 1965). Each spit within the compound features is nearly always hooked, occasionally to such an extent that a looped bar is produced, (Plate 5), (Evans, 1942). Other spits drape headlands to form winged headlands (Thornbury, 1954). Examples of this latter feature occur at Ras al Aish (Map Ref: 2/2/H), Marawah (Map Ref: 2/4/H) and west of Mirfa (Map Ref: 3/3/I).

C) Major Geomorphological Features Produced by Currents

(i) Channels

Tidal channels are common on the offshore banks of the

Plate 5

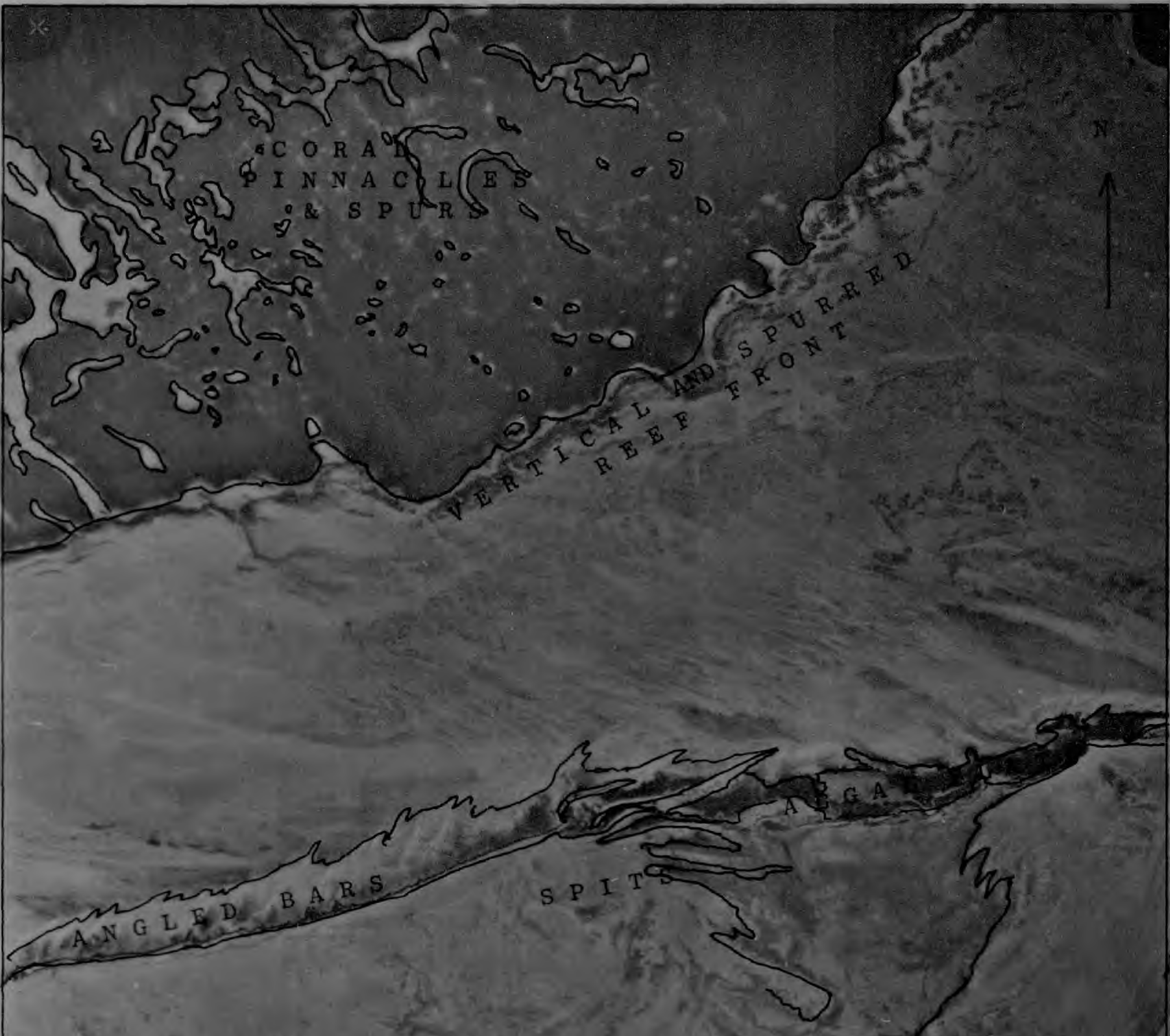
Northeast Marawah (3/1/E) showing:

(i) Coral pinnacles and spurs to the seawards

(ii) Vertical and spurred coral reef front

(iii) Series of angled bars, spits and algal flats.

PLATE 5


CORAL PINNACLES & SPURS
VERTICAL AND SPURRED REEF FRONT
N
ANGLED BARS
SPITS
ALGA

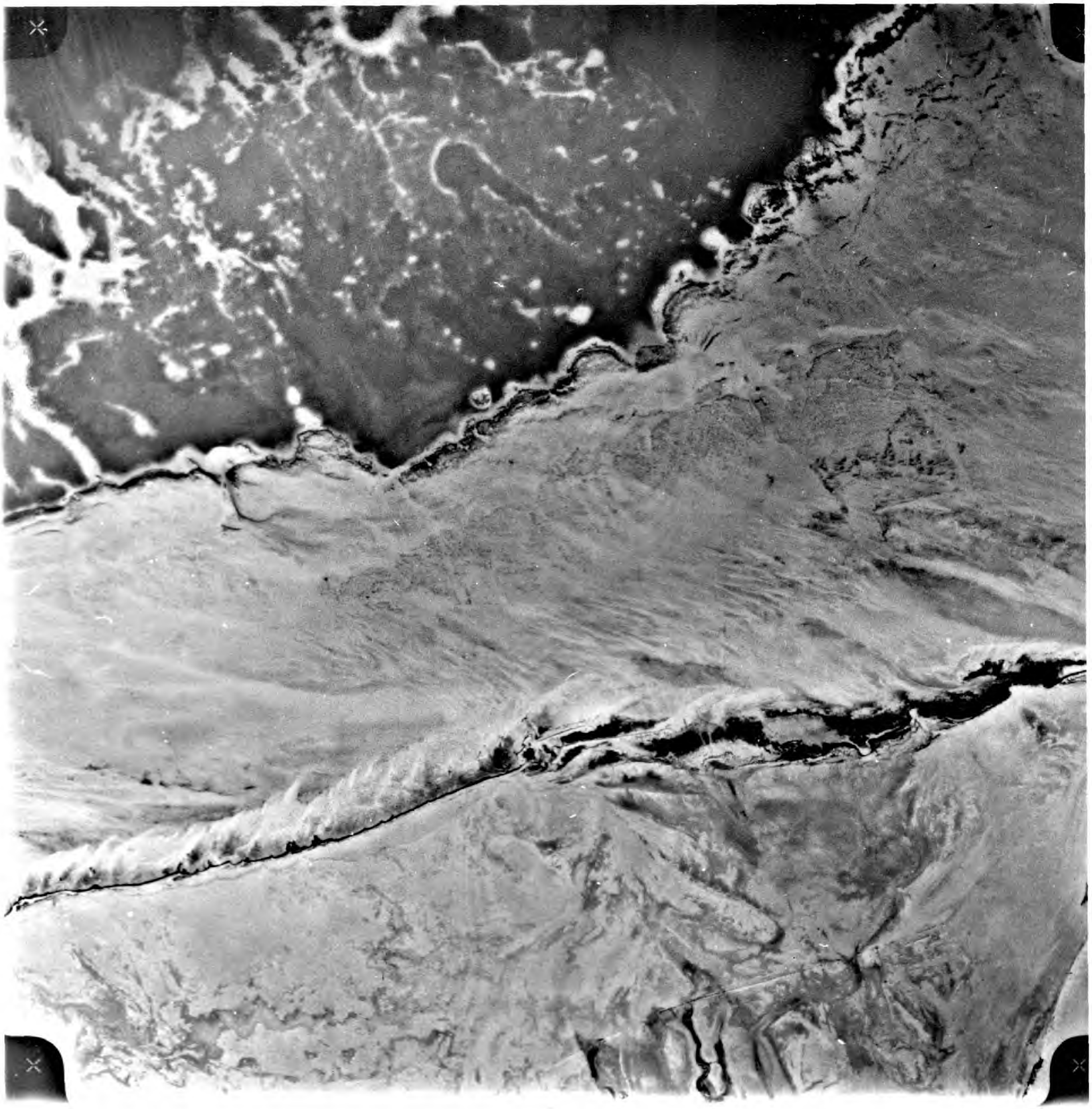


Plate 28

Southeast of Quala bay (1/5/H) showing:

(i) Two islands formed from spits and cusped barrier beaches.

(ii) Algal creek.

(iii) Coastal sabkha composed in part of spits and beach lines.

(iv) Tertiary hills to the southwest.

Scale approx. 1:30,000

PLATE 28


ISLAND
ALGAL FLAT
ISLAND
SPIT
ALGAL FLAT
SPITS
TERTIARY
HILLS
N

Shelha al Bazam and on the banks surrounding the Dagallah lagoons. To discover the direction of flow of predominant currents along the channels the criteria suggested by Van Veen (1953) and Price (1963) were used. These include: (i) The bifurcated end of a straight channel is presumed to be directed towards its lower reaches. (ii) Dendritic patterns in intertidal areas represent drainage. (iii) Spits are thought to be aligned down the major current direction. (iv) Linguoid ripples are convex downstream, as are the deltas. On the maps the principal channels are shown in dark blue. There are two sets of tidal channels which are particularly noticeable on the Shelha al Bazam; one is a set of probable flood tide channels southwest of Hail and the other is a set of flood and ebb channels east of Janana. Both sets have deltas on their southern ends. The Hail group have their deltas markedly displaced westwards by the westward flowing flood tide of the major channel. The Janana set are also displaced westwards, but here the effect is not so strong. In the Janana group, the flow direction of the ebb in the eastern channels is the same as the flood. But the direction in the western ones is the reverse. The evidence for this is the occurrence of linguoid megaripples at their northern ends and the orientation of sand tails behind coral pinnacles on the bank. Many of the channels near Janana exhibit the sand ribbons or rhomboid sand-streaks discussed in the next sections (Plate 6). Also of interest on the bank to the west of Hail (Plate 7) are two multiple deltas which have been formed at the mouths of a

Plate 6

Coral reef flat northwest of Salaha (3/5/F) showing:

(i) Coral spurs and pinnacles to seawards

(ii) Terraced coral fronts.

(iii) Coral spurs and grooves on reef flat.

(iv) Hollows

(v) Linguoid megaripples to west

(vi) Series of old coral fronts exposed on reef flat and in channels to south.

(vii) Rhomboid megaripples to southwest.

(viii) Sand ribbons to northwest of Salaha.

Scale approx. 1:30,000

PLATE 6


N
CORAL SPURS & PINNACLES
TERRACED CORAL FRONT
HOLLOW
LINGUOID MEGARIPPLES
CORAL SPURS & GROOVES
OLD CORAL FRONTS
HOLLOWS
RHOMBOID MEGARIPPLES
SAND RIBBONS
OLD REEF FRONTS
SALAHA

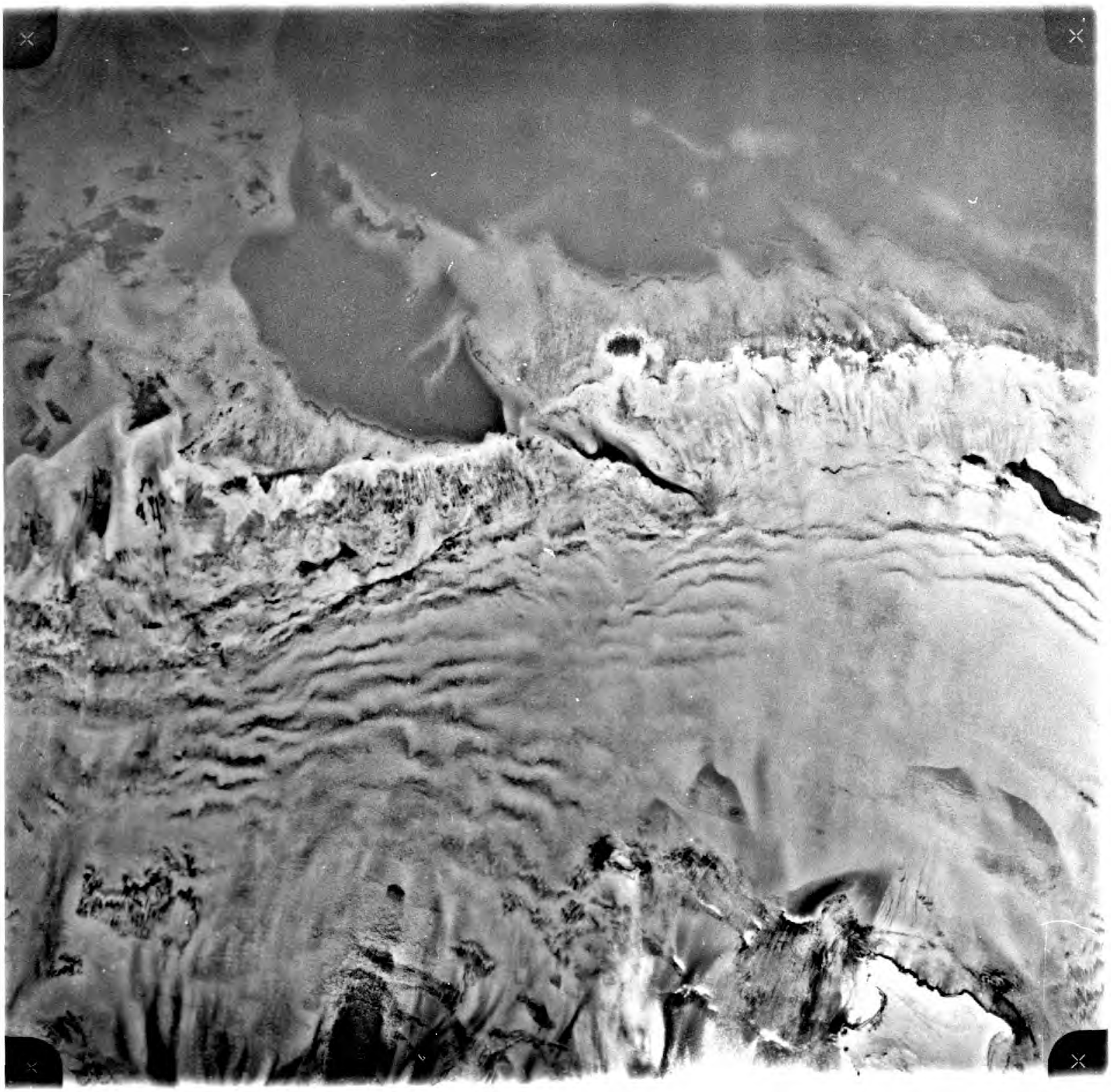


Plate 7

The bank around the island of Hail (3/2/C) showing:

(i) Series of coral fronts and hollows along the northern edge of the bank.

(ii) Multiple deltas and a channel with levees to centre of the bank.

(iii) Flood channels with deltas to southwest of the bank.

(iv) A major channel complex to south with spits trending towards west.

Scale approx 1:90,000

PLATE 7


HAIL
CORAL FRONT SAND HOLLOWS
MULTIPLE DELTAS
MULTIPLE DELTAS
MAJOR CHANNEL COMPLEX

series of short shallow channels along which tidal movement is from east to west. The fronts of the deltas are deflected by waves from the dominant wind direction. Maxwell et al (1964) suggested that such deltas are produced by currents and waves working in opposition.

D) Minor Geomorphological Features Formed by Currents

(i) Submarine Spits

Submarine spits occur both attached to land as defined by Evans (1942), and attached to shoal areas as defined earlier in this thesis. Most of the submarine spits of the west Khor al Bazam area are formed by tidal currents, though wave action probably plays some part in modifying their form. The small scale photograph (Plate 7) of the Hail bank shows two such spits which form levees bounding a flood channel. Similarly, numerous underwater spits occur in the major channel south of this bank. They are formed by the flood tide. However in the mouth of West Dagallah lagoon, spits are produced by both ebb and flood tides. (Map Ref: 1/1/H, Plate 2). Another good example of this type of spit occurs at (1/3/H), just south of Dagallah.

(ii) Megaripples

In the west Khor al Bazam the following varieties of megaripples are found. (Terminology of Van Straaten, 1953):

a. Transverse
b. Diagonal
c. Longitudinal

a. Transverse Megaripples:

Transverse megaripples form at right angles to the dominant current. Their commonest occurrence in the west Khor al Bazam is on the weed-covered platforms of the coastal terrace. (Plate 1). They also occur just northeast of Fiya, north of Bazam al Garbi, the north of Marawah, and in the lagoons southwest of Dagallah. On the weed-covered platform, the height of the ripples is between 1 to 2 feet and their width is between 100 to 600 feet. They are all aligned northwest to southeast, and in plan their northeast faces are gently scolloped whilst their southwest faces are far more irregular. Lines of weed often grow between the crests.

The constant alignment of these structures, their fresh surfaces and their completely unaltered appearance between 1958 and 1963 (cf. R.A.F. and Huntings photographs) suggest that they were produced and maintained by some unvarying agent. Since their angle is perpendicular to the direction of movement of the flood, and so obviously unrelated to the orientatio of the adjacent wave-formed features, it is tentatively assumed that they may be formed by tidal currents (probably flood). The alternative is that they formed as the result of an onshore storm. These structures are very similar to the barchan like 'underwater dunes' observed by Newell and Rigby (1957, p.51) in the Bahamas.

b. Diagonal Megaripples:

There are two kinds of diagonal megaripples:

I) Linguoid megaripples

II) Rhomboid megaripples

I) In the west Khor al Bazam as in the Bahamas (Evans, G., personal communication) the linguoid megaripple is a common feature of shallow tidal channels. Examples can be seen at map reference 3/2/E, 3/3/E and 3/4/F. The small scale photograph Plate 8, of the bank east of Janana shows them on the northern edge of the bank, as also does the large scale photograph (Plate 6). Van Straaten (1953) suggested that such ripples form in the same way as transverse megaripples, but in shallower water.

II) Rhomboid megaripples or sand streaks are usually found in shoal areas crossed by sheets of fast moving tidal water. The wide stretches of shoal water found in the Khor al Bazam are ideal for their formation. Good examples can be seen on the banks to the east of Janana, to the northeast of Marawah (3/2/D, Plate 10), and southwest of Fiya (2/2/E). The lower edge of the small scale photograph of the area north of Salaha, (Plate 6) shows several of these rhomboid ripple marks and associated weed patches. Bar sand to weed is approximately 50/50. In deeper water the ripples pass into sand ribbons (as defined by Stride, 1963) which develop in conjunction with parallel lines of weed of approximately the same width as the sand. This can be seen in the southernmost channels of the Janana-Salaha bank (Plate 6). The rhomboid pattern seen in all these areas may have been formed in one of two ways. Either, by the accretion of rhomb-shaped tongues of sand on the edges of weed patches, or, by the erosion of romb-shaped

Plate 8

Janana-Salaha (3/3/5) bank showing:

(i) Major channel complex to north

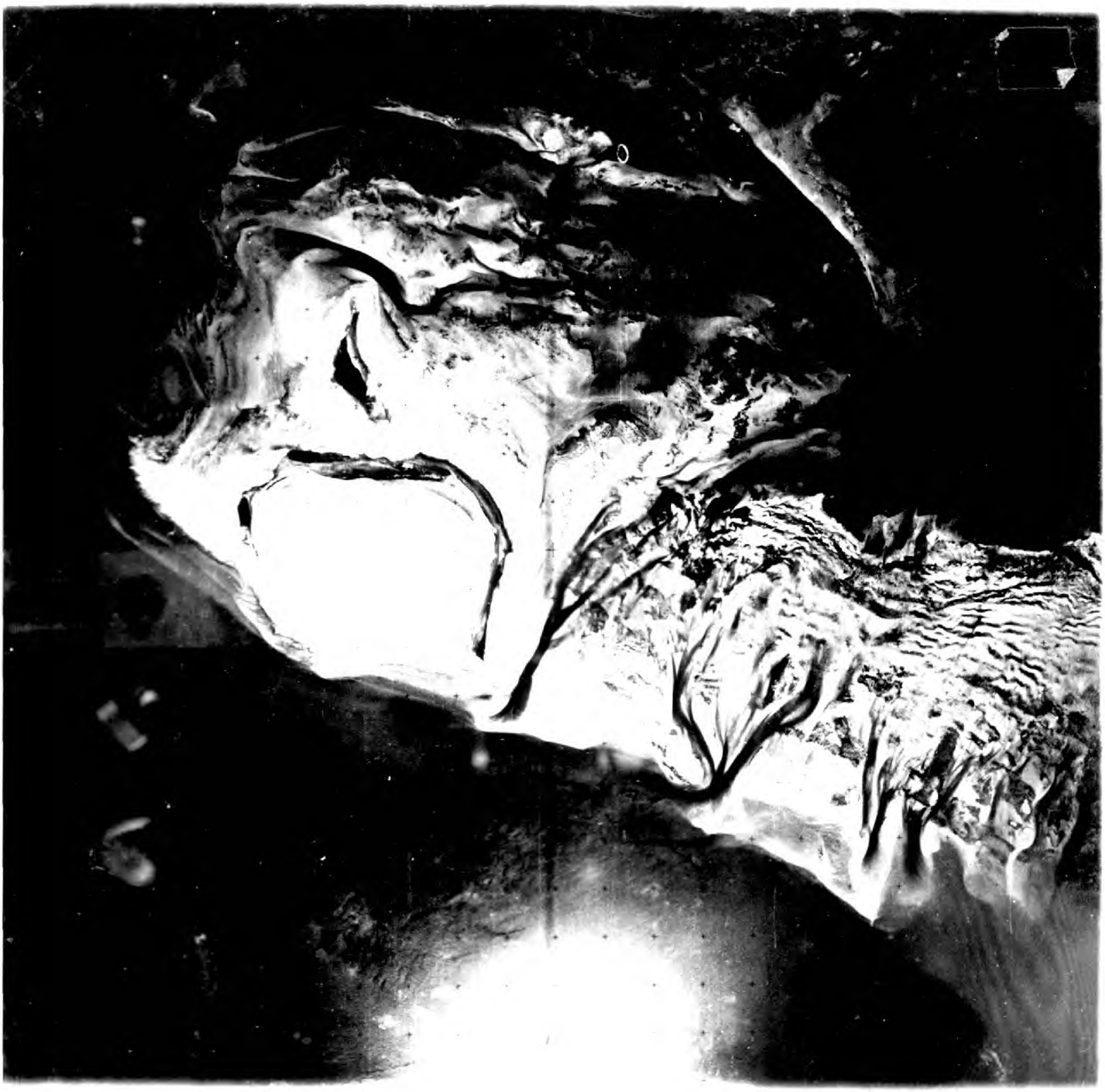
(ii) Coral/coralline algae reef complex to north and deltaic complex to south

(iii) Janana rimmed on its northern shore by algal flat.

Scale approx. 1:90,000

PLATE 8


MAJOR CHANNEL COMPLEX
Algal flat
JANANA ISLE
REEF COMPLEX
DELTA COMPLEX
N



scours on the edge of the weed patches into the sand below. The relief of the features was not determined, but P. Roy (personal communication) has seen similar features on the Norfolk coast. These are only 2 to 3 inches in height and have the same areal extent as those of the Khor al Bazam. Such patterns of ripples can be anything from a few square yards to a square mile in extent. There is a certain amount of ambiguity in interpreting the direction of the currents which form these features. To the northwest of Salaha (Plate 6), the linguoid megaripple marks and the sand tails behind small coral pinnacles, suggest a northward current. The weed patches associated with the rhomboid ripples have serrated edges pointing into the current. This convention cannot be applied to the weed and sand patches in the southern part of Plate 6, to suggest that they formed by a southward flowing current, because they may be erosional rather than accretionary features. The uncertainty of any such convention can be seen at Khusaifa, where the serrated edges of the boundary of the Khusaifa algal flat are clearly erosional scours (Plate 1) and point down current. However, just north of this edge, there are rhomboid sand streaks and weed patches similar to those near Janana. If these are accretionary then they indicate a current direction the reverse of that flowing off the Khusaifa algal flat. Whatever the origins of the rhomboid megaripples, they are fairly permanent features altering little between 1958 and 1963 (see R.A.F. and Huntings photographs) and theyobviously exist under a variety of current and wave conditions.

(iii) Ebb Gullies or Creeks

Ebb gullies or creeks occur extensively on algal flats and in mangrove areas. They are also found just east of Janana (Map Ref: 3/3/G) and north of the barrier beach of Dagallah (Plate 9). They are formed by ebb tide erosion. This sort of feature is common in tidal flats and marshes all over the world. Van Straaten (1954) described the morphology and genesis of creeks in the Wadden Sea. Evans (1965) has discussed similar features from the tidal flats of the Wash.

5. MAJOR GEOMORPHOLOGICAL FEATURES PRODUCED THROUGH BIOLOGICAL AGENCIES

A) Coral Reefs

Coral reefs flourish in tropical marine waters shallower than 60 feet, where winter temperatures do not often fall below 16°C and summer temperatures do not rise above 40°C, Kinsman (1964 'b'). Coral grows profusely along the northern edge of the offshore bank, and is also found growing on the top of the bank, but not in such profusion. Along the seaward edge of the coastal terrace there are corals but they do not flourish. It is possible that here the salinities are at the limit of tolerance for corals (Kinsman (1964 'b'). No extensive collection was made of the coral but Acropora sp. and Porites sp. and several species of brain coral were recognised in the field to be the main reef builders in conjunction with calcareous algae. Kinsman (1964 'b') found the same corals abundant in the Abu Dhabi reefs. Most of the coral examined in the Khor al Bazam

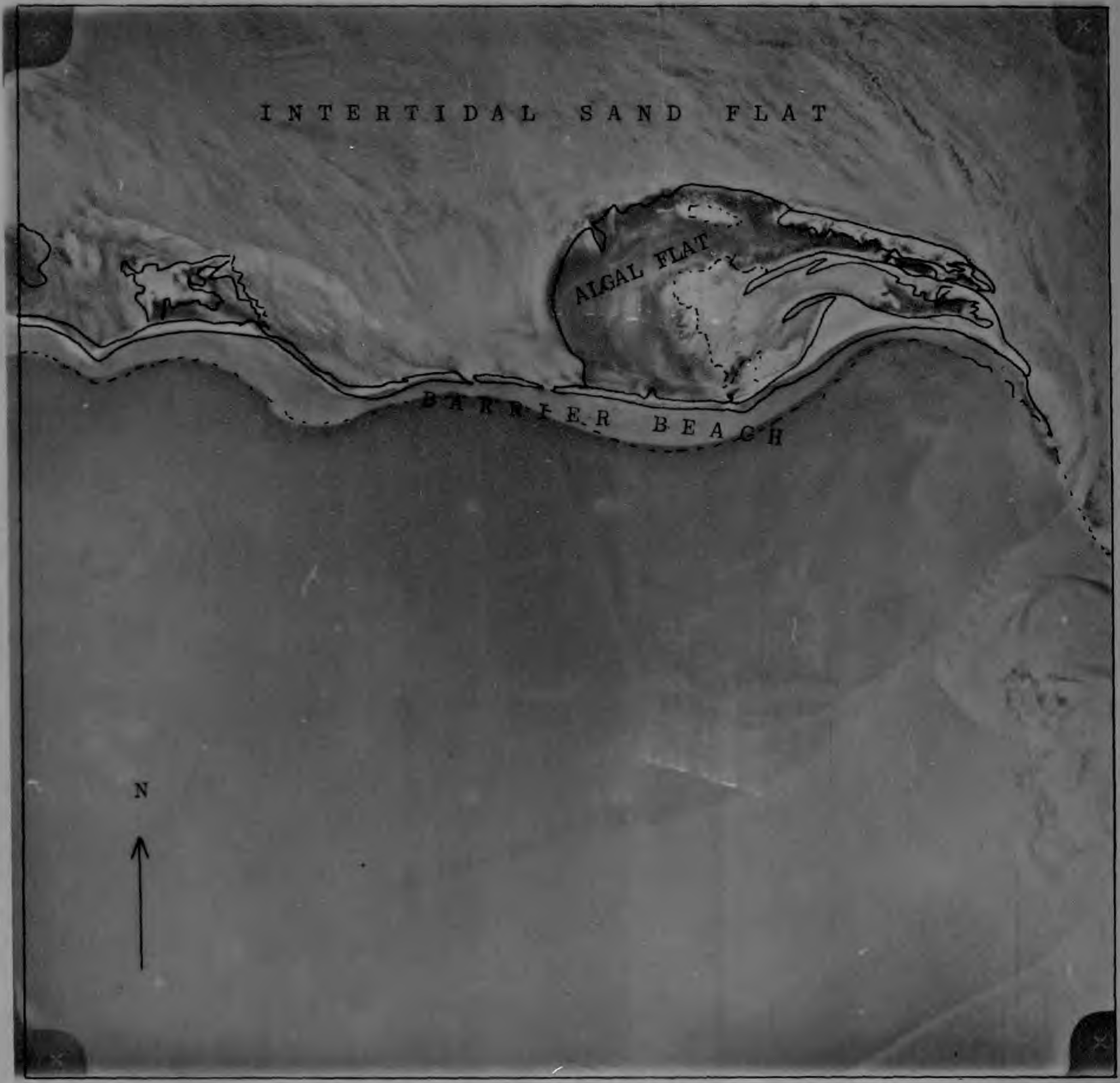
Plate 9

The north side of the Dagallah (1/2/5) lagoon showing:

(i) An intertidal sand flat passing southwards into a barrier beach and a complex of algal flat and spit accumulation.

Scale approx. 1:30,000

PLATE 9



was being colonised and bored by other organisms. Newell *et al* (1957 p.48) noted this to be occurring in the Bahamas. Geomorphological features shown by the coral reef in the Khor al Bazam can be classified in the following way:-

(i) Coral Reef Front
(ii) Reef Flat

(i) Coral Reef Front:

Coral fronts exist along most of the northern edge of the offshore bank (the Shelha al Bazam), and along the edge of the coastal terrace, northwest of Mirfa, off Khusaifa and Ras al Aish. The front may take several forms:-

a: Vertical Front
b: Spurred Front
c: Pinnacled Front
d: Hollows
e: Terraced Front

a: Vertical Front

The commonest is the vertical front which consists of a vertical wall of corals and calcareous algae. It is found round the northeast edge and the northern tip of the Hail bank (Plate 7) and in front of the coastal terrace of the mainland off the south Khor al Bazam. This type of front is probably initiated on break point bars which parallel pre-existing coral banks. These bars have some permanence since aerial photographs show little alteration between 1958 and 1964 (RAF and Huntings). The sand of the break point bars is in constant movement and so, it might be argued, could not form the substrate for coral growth. However, Cloud (1952) stated that "specially adapted types of coral (such as species of Porites, Acropora and Pocillopora among living and Pleistocene genera) may grow on bits of shell or pumice pebbles on silty or even muddy bottoms and from these spread out to build the firm base from which a reef may be erected." In the Khor al Bazam Acropora has been found growing on shells on banks of moving sand. Thus the colonisation of the break point bars is by no means improbable.

b & c: Spurred and Pinnacled Fronts

Shinn (1963) reviewed the development of spurs and grooves, and from evidence collected on the Florida reef tract, suggested that spurs are growth features which are periodically trimmed back by severe storms. The storms remove the detritus from the grooves between the spurs and thus prevent them from becoming infilled. The direction of growth of the spurs is seawards, because only those coral heads which point directly into the heavy seas are not destroyed. These spurs and grooves line the reef front and are normally 10 to 12 feet high. The spurs are as much as 50 feet wide, and the grooves are approximately 15 feet wide. Newell, Rigby, Whiteman & Bradlay (1951) discussed similar features in the Bahamas and Cloud (1959) studied them in Saipan. In the Khor al Bazam it is possible to recognise three forms of spurs and grooves which are distinguished by their sizes and positions on the reef.

Associated with the spurred fronts are coral pinnacles. Shepard (1948) discussed these features in the atoll lagoons of the Pacific. They are narrow columns of coral colonies that rise abruptly from the sea floor. In the Khor al Bazam region they range in height from a few feet to twenty feet, with diameters varying from three feet to a quarter of a mile.

I) Spurs and Grooves Seawards of the Reef Front:

Seaward of the reef front spurs can be as much as one mile long, a quarter of a mile wide and between 15 to 30 feet high. The grooves may be half a mile wide.

II) Spurs and Grooves on the Reef Front:

Spurs on the reef front are between 10 and 15 feet high and sometimes over 50 feet wide. They can be between a quarter and a half of a mile long. The grooves are between 10 and 20 feet wide. Together they resemble the spurs and grooves of Florida and Saipan.

III) Spurs and Grooves on the Reef Flat Behind the Reef Front:

On the reef flat behind the reef front spurs can be as much as a half of a mile long, 2 to 6 feet wide, and 2 to 4 feet high. The grooves are some 6 to 20 feet wide.

Each of these varieties will now be described in detail:-

I) Spurs and Grooves Seawards of the Reef Front:

The most striking example of spurs and grooves seawards of the reef front occurs just north of Marawah (Map Ref: 2/5/D, Plate 5). Less spectacular examples are present in front of the Janana-Salaha Shelf and to the northeast and northwest of Bazam al Garbi. These spurs and the long axes of most of the pinnacles are aligned along the dominant wind direction suggesting a relationship between the two. This association can be explained by examining the area just north of Salaha (Map Ref: 3/5/F, Plate 6) and the interpretive diagram (Figure 6). These suggest that once pinnacles begin to grow on the sea floor they act as sediment traps. As they grow, material broken from them or stirred up on the sea floor round them by wave action, collects in their lee. Whilst the pinnacles expand radially to form microatolls as defined by Krempf (1927), their sediment tails become fixed by coral and calcareous algae. These tails gradually extend towards the reef front till they join it to form a spur. Shinn (1963 p.301) suggested that an orientated colony protected in the lee of another colony is able to grow seawards and connect; this increases the linearity of the growth centres. Once initiated the spurs grow slowly seawards in the manner suggested by Shinn (1963), the grooves between the spurs being maintained by wave and tidal scour. As Skipwith (personal communication) points out, these spurs could not develop on the reef front where there are strong cross currents.

II) Spurs and Grooves on the Reef Front:

It is suggested that spurs and grooves on the reef front were initiated as patch reefs. These then developed tails that became fixed in the same way as the larger spurs already described. Any gaps between adjacent patch reefs were kept clear by heavy storms (Shinn, 1963). These gaps are maintained as the spurs grow forwards. The best example of these features can be seen northeast of Marawah, (Plate 10).

III) Spurs and Grooves on the Reef Flat Behind the Reef Front:

To the northeast of Marawah (Plate 10) and northwest of Salaha (Plate 6) there occur lines of coral. Like pinnacles and patch reefs, individual coral colonies act as sediment traps behind which tails of sediment develop and are fixed by coral growth. Once the coral line is initiated it grows shorewards and because of its configuration maintains itself. Similar linear patterns were observed in the back reefs of Kharg Island (Kaulback, Kendall and Skipwith, 1962). Cloud (1959) suggested that similar features in the back reef lagoon of Saipan are produced by movement of sediment trains which etch deeply into the floor of the lagoon and reef.

A fourth type of grooving which was observed in Saipan and on the Alacran reef (Kornicker and Boyd, 1962) was not seen in the Khor al Bazam region. This type consists of potholes within the grooves.

d: Hollows:

Reef fronts which are initiated offshore often enclose areas of deeper water containing coral spurs and pinnacles (Figure 6). On the bank southeast of Hail these hollows can be up to 3 miles long and 1 mile wide, (Map Ref: 3/3/C, Plate 7). They are up to 30 feet deep and are slowly filled by reef debris, broken off by storm and biotic activity, and by other material derived from the bank including mud and silt sized carbonate. Before the hollow is completely filled the reef front may have advanced seawards by several miles. The hollows are clearly not erosional, but are residual hollows

Plate 10

The coral reef northeast of Marawah (3/2/C) showing:

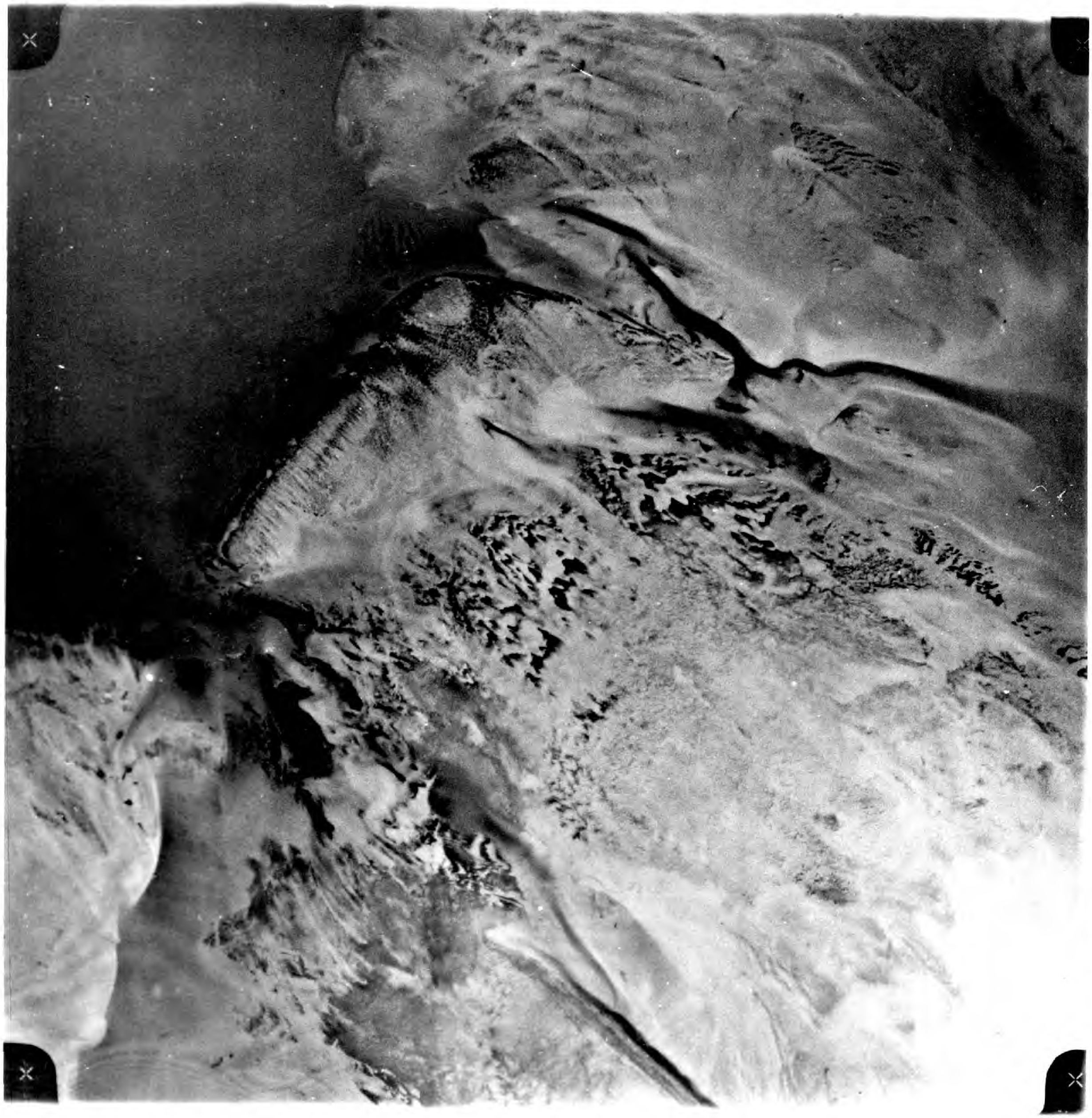
(i) Reef front marked by spurs and grooves

(ii) Reef flat marked by spurs and grooves

(iii) Rhomboid megaripples

Scale approx 1:30,000

PLATE IO



left behind as the reef advanced around them. Examples can be seen clearly on the north Janana-Salaha Bank, (Plate 6) and are marked on the map as deeper water on the Janana-Salaha Bank and southeast of Hail. Cloud (1959) discussed similar hollows in the Saipan reef but suggested an erosional origin for them. The hollows are not comparable to the 'blue holes' of the Bahamas, (Newell & Rigby, 1957) which are believed to be sink holes.

e: Terraced Fronts:

Terraced fronts consisting of two or more levels of coral growth occur along the southeastern edge of the Hail bank and in front of the Janana-Salaha Bank. Plate 6 shows an example of a double terrace with thick coral growth on the fronts of eac These terraces are believed to be of similar origin and to have nucleated on offshore bars. The reason they exhibit a difference in level is that the coral on them began growth at different times. Eventually they will have the same depth because their upward growth will be limited by the lowest tidal level. Coral which forms the lower level terraces are the spurs and pinnacles seawards and probably began growth at the same time because these features have the same depth. Shinn (1963) recognised similar terraces in the Florida reef tract and suggested the similar upward growth of coral limited by the lowest tidal level. However these terraces in Florida and the Bahamas (Newell *et al* 1957) are believed to record erosion at different Pleistocene sea levels.

(ii) Reef Flat

Reef flats consist of bands of old reef front which parallel the present advancing edge of the bank and which are separated from each other by infilled hollows (Plate 6 & 8). These linear features are zones of coral and seaweed growth. The infilled hollows are marked by areas of rippled sand with very occasional solitary corals. The flat is just awash at low tide as in the Florida back reef (Ginsburg, 1956).

Evidence from aerial photographs suggests that most of the Shelha al Bazam is underlain by a succession of parallel coral fronts, while the narrow inner edge of the bank is a system of coalescing deltas. The clearest proof of coral accretion occurs on the Janana-Salaha Bank where the successive coral fronts and hollows are exposed by tidal scouring action. South of this area a narrow belt of deltaic sediment can be seen. The Plates 6 and 8 are large and small scale photographs of the Janana-Salaha Bank, and they show all these features. The reef lines trend from east to west, and on the north of the bank unfilled hollows are exposed. In the south, scour channels cross the old reef fronts and filled hollows. The thickness of the fronts is unknown: they may be a thin veneer over Tertiary and Quaternary rocks. All the evidence clearly shows that the Shelha al Bazam fits Darwin's (1889) definition of a barrier reef.

The coastal terrace of the southern side of the Khor al Bazam is partially rimmed by poorly-developed coral fronts. It is possible that these once extended along the whole length of the coastal terrace, and that old coral reefs underlie much of this terrace. Coral growth was no doubt inhibited as the Shelha al Bazam has become a more and more effective barrier. It would appear that salinity and temperature have become too high and turbulence too low in the now confined lagoon for the development of a flourishing reef and, as these conditions become more extreme, so the corals die off. The terrace is thus a dying fringing reef. Kinsman (1964 'b') demonstrated this effect in the Halat al Bahrani inlet.

B) Seaweed-covered Areas

The seaweeds growing in the west Khor al Bazam include:-

(i) Bladder wrack
(ii) Green Filamentous Algae
(iii) Small Broadleaved Seaweeds
(iv) Halodule (Diplathora) uninervis

These weeds grow singly or in patches, the latter occurring through the west Khor al Bazam. The exact distribution of the different types of weed cannot be determined from aerial photographs and this discussion is largely based on field observations. Areas of seaweed growth may be considered geomorphological features, because they profoundly modify wave and current movement, and act as sediment traps (Ginsburg and Lowenstam, 1958).

(i) Bladder-wrack Areas

The Bladder-wrack weed (brown algae) commonly grows in large patches along the edge of the coastal terrace, on the

Khor al Bazam floor (unmarked on the maps since much of this lies below 10 feet and so is not revealed by aerial photography) and in patches on the Shelha al Bazam. In the shallow-water regions where direct field observations could be made it was seen that the bladder-wrack tended to grow on rock. This could be rock terrace, fragments of colonial coral or individual small boulders. Sugden (1963 'b' p.363) remarked on the presence of layers of aragonite encrusting the stems of bladder wrack off Qatar. He suggested that rich benthonic floras promote aragonite precipitation as a result of photosynthesis. This process would account for not only the veneer of aragonite but also the cemented sediment around the bases of the weeds. However it is improbable that the rock platform beyond these cemented bases was formed by the same process but instead it represents beach rock developed at lower sea levels.

Though obviously a hindrance to sediment movements, these weeds do not prevent the formation of transverse megaripples which are so common along the edge of the coastal terrace. (Plate 1). They also grow on the terrace in conjunction with the "unhealthy-looking" corals of the terrace edge.

On the Shelha al Bazam, the bladder-wrack grows with coral on rock platforms as it does on the coastal terrace. This is particularly marked on the reef northwest of Bazam al Garbi and on the old reef lines north of Salaha, (Plate 6). The same weed grows in parallel lines alongside sand ribbons in channels (Plate 6).

The bladder-wrack may break free from the sea floor, and great 'Sargussum'-like rafts of seawood float on the Khor al Bazam. This accumulates on beaches and is incorporated in the sediment as they accrete seawards.

(ii) Areas of Green Filamentous Algae

Green filamentous algae are not as wide-spread as bladder-wrack. They grow on intertidal areas which consist of rock and are free of violent wave action most of the time. They occur in shoals between the bladder-wrack weed and are protected from waves by the shallowness of the water. Places in which they are found include parts of the southern edge of the Shelha al Bazam. On the coastal terrace several areas of growth occur: the tidal flats just north of the Dagallah beach barrier, the bank north of Quala and Thimairyan, and the bank between Abu Shiyarar and Ras al Aish.

(iii) Small Broad-Leaved Seaweeds

The distribution of the small broad-leaved seaweeds is not marked on the geomorphological map. It extends along the floors and sides of deeper channels, and along the lee slopes of the Shelha al Bazam and the Dagallah offshore bank. The areas in which this weed grows are either too deep or too sheltered to be affected by violent wave movements. Thus the weed binds the sediment together to drape the banks and form~~s~~ centres about which mounds of mud accumulate. These mounds are aligned along major current directions and are probably very similar to the mud mounds described by Ginsburg (1956) in the Florida embayment, where they are fixed by

Halodule sp. and *Thallasia* sp. (p. 2400).

(iv) *Halodule (Diplathera) uninervis*

Halodule (*Diplathera*) *uninervis* grows over much of the floor of the west Khor al Bazam. It extends up onto the off-shore bank and the coastal terrace, and also grows in the broad leaved weed and 'bladder-wrack' areas. Like the Thallasia of Florida Bay, it grows essentially in what is a 'back reef' area (Ginsburg, 1956, p. 2400). Undoubtedly this weed acts as a sediment trap. Its grass-like colonies are centres of much animal life, with the subsequent accumulations of untransported death assemblages. Murray (in press) agrees with this observation in the case of foraminiferal assemblages.

C) Mangrove Areas

Mangroves occur in sheltered intertidal waters of tropical seas, as, for instance, on the Florida Coast (Davis, 1943), the Guiana Coast, (Vann, 1959), the West African Coast, (Guilcher, 1959, Allen, 1965) and the North Coast of Australia (Valentin, 1959). On the Trucial Coast only the black mangrove, *Avicennia marina*, has been found. This grows in the inter-tidal zone so that its roots and lower trunk are normally covered at high tide. It occurs in the Khor al Bazam, as in the Bahamas (Black, 1933, Newell *et al*, 1951, Illing, 1954, Map p. 14) in areas protected from heavy wave action. These areas include the sheltered southern and eastern shores of the islands of Bazam al Garbi, Fiya and Marawah.

The black mangrove, as Davis (1943) described it, produces many erect roots, known as pneumatophores, that stick

Plate 11

The coastal terrace northeast of Mirfa (3/4/I) showing:

(i) Series of runnels and bars with few cross-cutting channels. The bars are fixed by weed.

(ii) Narrow coastal dune strip.

Scale approx. 1:30,000

PLATE II

up through the mud and water and look like asparagus tips. In the Khor al Bazam, these roots are surrounded by aragonitic mud which probably accumulated here because the environment is so protected that mud transported from other regions can settle out. Newell et al (1951) also noted this in the Bahamas. It is probable that some of the aragonite is precipitated here as the result of evaporation of these very shallow waters. These aragonitic muds are characteristically burrowed and reworked by crabs (Plate 12).

The mangrove areas in the Khor al Bazam take two forms. They either occur as narrow strips parallel to the shore at the very top of the intertidal flats, or line the edges of creeks draining algal flats.

Mangrove strips occur parallel to the northeastern shores of Bazam al Garbi (2/1/E) the southern shore of Fiya (2/3/E) the northwest tip of Marawah (behind the headland) (2/4/E), the southwestern and eastern coasts of Marawah (3/1/E). The mangroves in these areas may grow as much as 15 feet high but are seldom found to this height since local Bedu cut them down as green feed for their livestock (Figure 9).

Small intertidal channels, or creeks, lined by mangroves occur on the east coasts of Bazam al Garbi and Fiya, and also around part of the southern shores of Marawah. The algal creek area of central Marawah typifies this type of mangrove growth (Plate 13, Figure 9). As on the Niger River delta (Allen, 1965), the larger mangroves grow at the edges of the channels and diminish in height and distribution inland. The mangrove

Plate 12

Crab burrow in aragonite mud.

Plate 13

Mangrove creek, algal flats and dunes. Foreground shows a mound covered by salt tolerant plants. Note the beach rock crust that surrounds it.

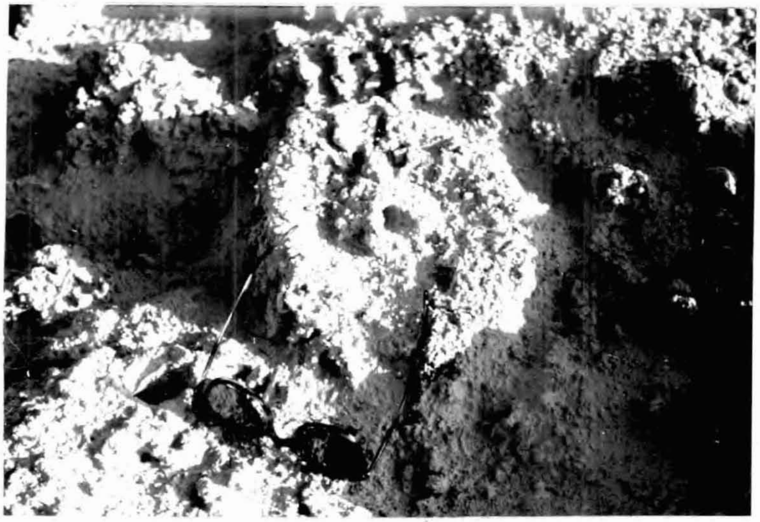
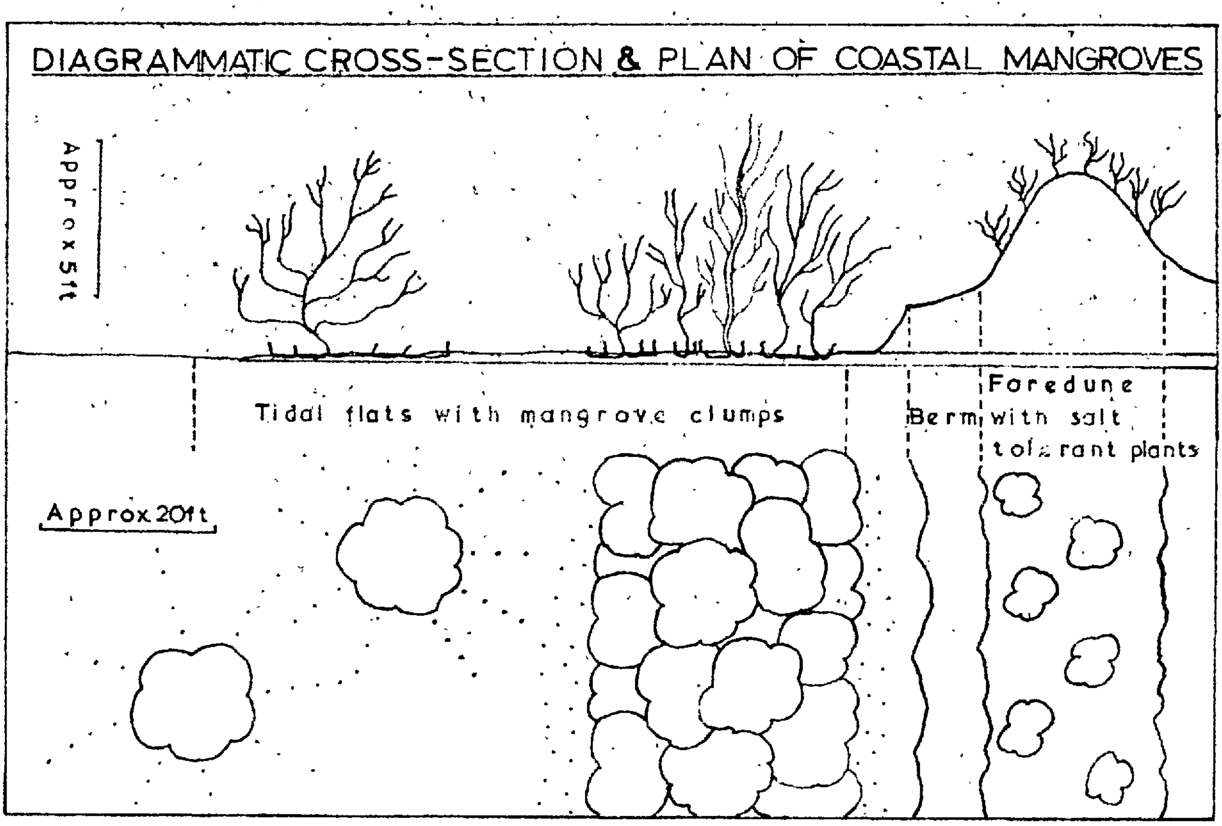
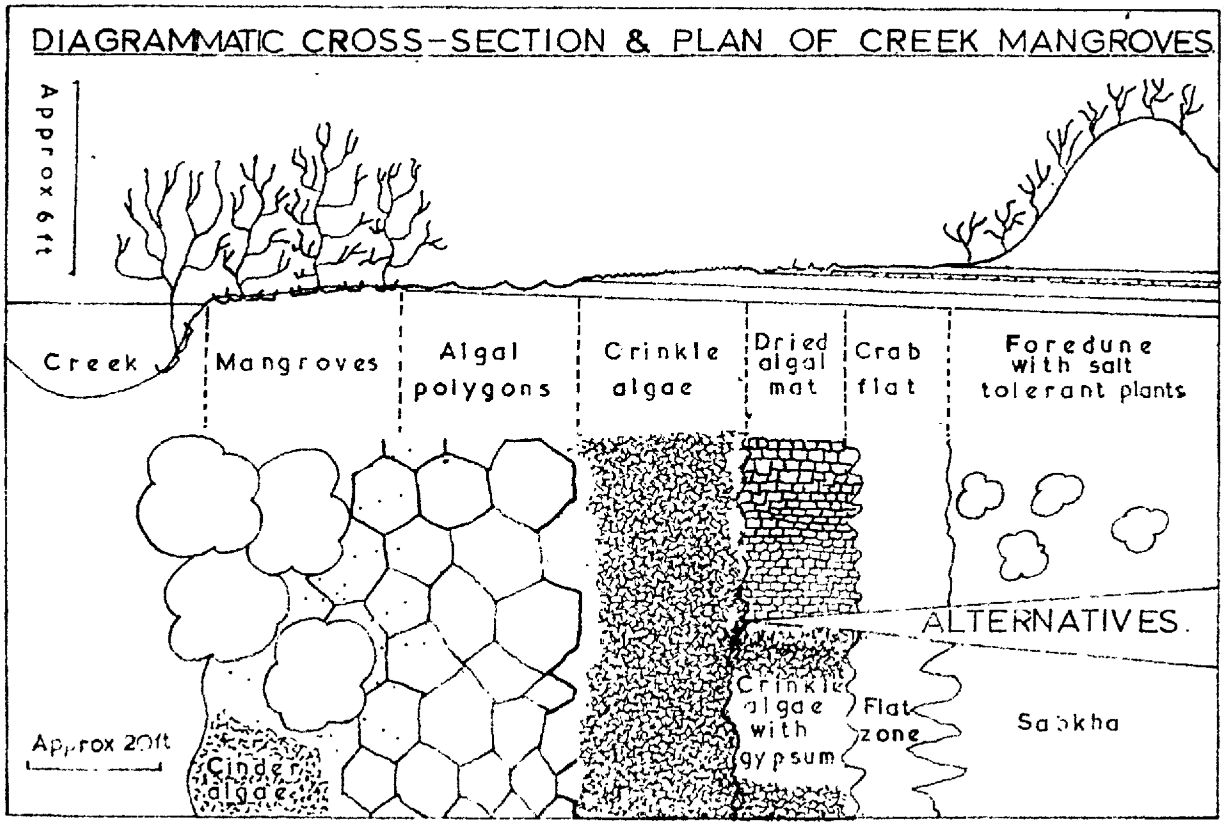


Figure 9



DIAGRAMMATIC CROSS-SECTION & PLAN OF COASTAL MANGROVES



DIAGRAMMATIC CROSS-SECTION & PLAN OF CREEK MANGROVES area passes laterally into a blue-green algal flat, which on the creek banks looks like an irregular layer of crushed cinders. This is often cemented to form a beach rock. Shinn, Ginsburg and Lloyd (1965) illustrate a similar rock in the Bahamas. Inland, however, the mangroves pass into an algal mat marked by a superficial polygonal pattern. This area is backed by dunes (sometimes of gypsum) covered by halophytes like *Arthrocnemum glaucum*. As with the mangroves described by Vaughan (1909) from South Florida, those in the Khor al Bazam play an important geological role in binding the sediment together. Muds bound by the mangrove roots are often found preserved beneath the accretional sabkha plains of the Abu Dhabi area (Butler 1965).

D) *Algal Flats*

Laminated algal mats which resemble stromatolites of ancient limestones, grow in the intertidal areas in many parts of the world today. They occur in the Bahamas (Black, 1933), the west Mexican Coast (Phleger *et al*, 1962), the Great Salt Lake Utah (Carrozzi, 1962), Australian Salt Lakes (Clarke *et al*, 1946), and along Australia's west coast at Shark Bay (Logan, 1961). They were described from the Persian Gulf by Kinsman (1964c).

Recent marine algal mats may form in shallow protected water (Ginsburg, 1955) in the intertidal or supralittoral zones where the sea covers them at some time during the year (Logan 1961). These algal mats are all characterised by the presence of films or layers of blue-green algae which bind and trap sand, silt, and clay size sediment to produce a laminated structure (Logan, Rezak & Ginsburg, 1964). This material is washed onto the mats so that the laminae reflect in part the predominant sediment adjacent to the flats. However, since the algae are growing in such a protected zone the sediment collecting here is usually much finer grained. Logan _et al_ (1964), state "a diversity of form is produced by the interaction of the algae film, detrital sediment, and physical environment factors". They suggest that the organic film, active in the formation of most ancient algal stromatolites has probably been a complex of filamentous and unicellular green (_Chlorophyta_) and blue-green (_Cyanophyta_) algae. These are certainly active in formation of the Khor al Bazam mats. Here and on the rest of the Abu Dhabi coastline these algae withstand enormous temperature ranges from 12°C (winter 1964) to above 50°C (spring 1964). They also tolerate salinities of over 180 to 196 parts per thousand in algal pools (Kinsman, 1964c). Shearman (personal communication) suggests these algae are able to withstand these vigorous conditions since they are protected by the mucilagenous jackets which they secrete.

Logan, Rezak and Ginsburg (1964) classified algal flats on the basis of their geometric form and its relation to sites of growth relative to sea-level environments. The geometric units of hemispheroids and spheroids are used. Three major classes are established as follows:

1. Laterally-linked hemispheroids (LLH); subdivided

into close-linked hemispheroids less than a diameter apart (LLH-O) and spaced hemispheroids (LLH-S).

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

Though other factors affect the shapes produced, these classes in the Khor al Bazam are generally related, not so much to progressively higher energy environments as suggested by Logan et al (1964) but to frequency and length of time the water covers the algae. The laterally linked hemispheroids (LLH) are least often covered by water and what few stacked hemispheroids (SH) exist are more often exposed to water cover: the spheroids (SS) are the only features related to hydrodynamic activity requiring agitated water below the low water mark. However the classification itself is useful because of its simplicity but does not have universal application. It does not describe all the structures found in the Khor al Bazam algal flat and where it does further subdivisions have to be made based on other features of surface morphology.

In the west Khor al Bazam, algal flats occur on sheltered areas such as those behind islands, sand bodies, and wide shallows over which no large wave can cross. The algal mats may cover wide areas. The largest is at Khusaifa where a flat occurs which is 5 miles long parallel to the coast and in places is over 1 mile across. Alternatively extremely small flats are found which cover only few square yards, as for instance those on the beach between Mirfa and Khusaifa. The variety and form of the different growth features produced is related to the size of the algal flat. The Khusaifa flat for instance has many features whereas the local small flats have very few.

(i) The Khusaifa Algal Flats

The algal flats of Khusaifa can be divided into four zones (Figure 10):

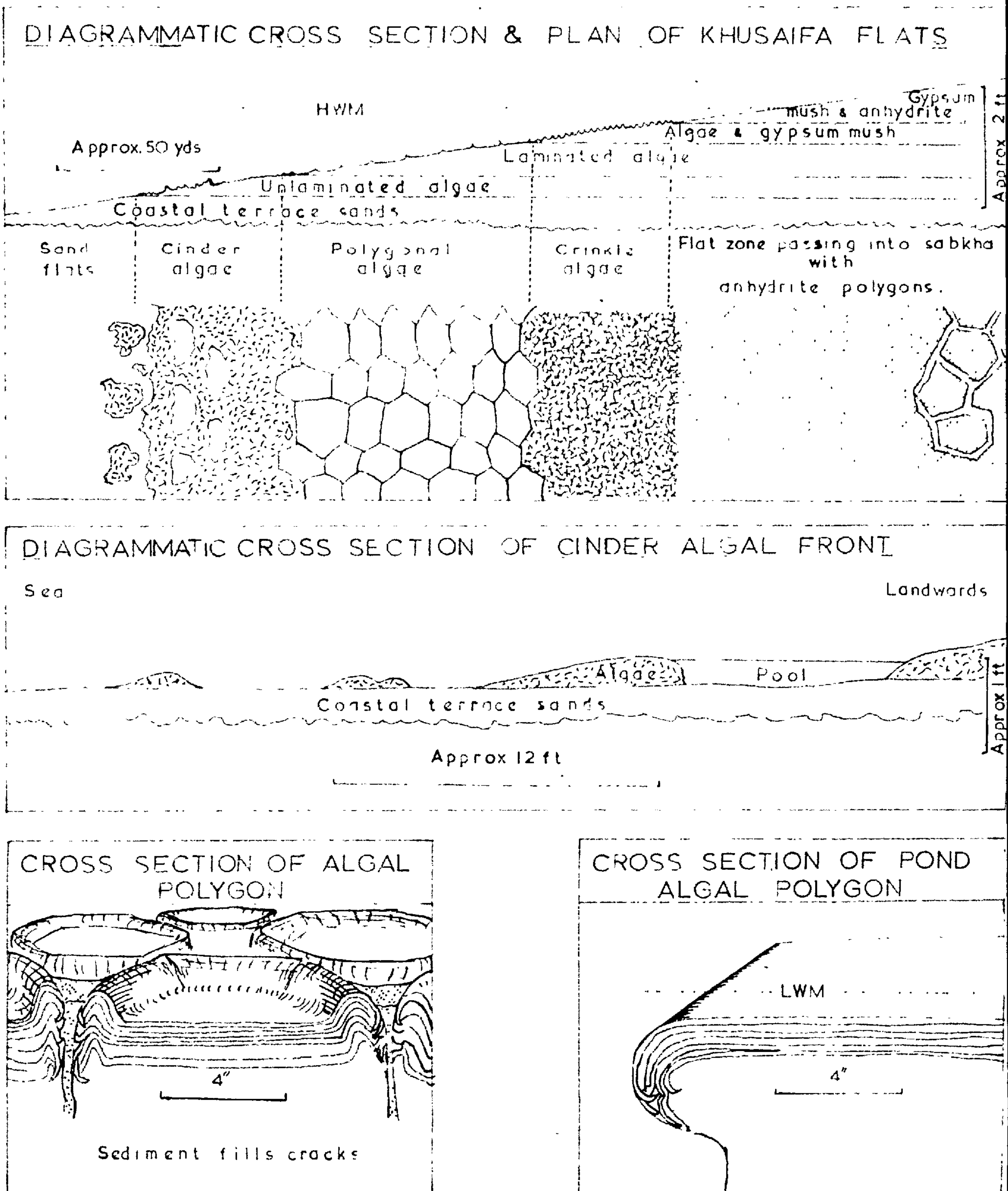
(a) Cinder algal zone
(b) Polygonal algal zone
(c) Crinkle algal zone
(d) Flat zone.

The whole flat is bounded to seaward by intertidal sand flats and landwards by sabkha. The intertidal sand flats are crossed by wide shallow creeks with small deltas at their seaward end. The sand flats may be gently rippled and sometimes scoured (Plate 14). The sands interfinger landwards with the seaward edge of the algal flats.

a.) Cinder Algal Zone

On the sand flats seaward of the algal flat small raised features from a few mm. to several metres diameter occur draped by colonies of filamentous algae. From a distance, the surface of these colonies looks very like a layer of

Figure 10



DIAGRAMMATIC CROSS SECTION & PLAN OF KHUSAIFA FLATS

DIAGRAMMATIC CROSS SECTION OF CINDER ALGAL FRONT

CROSS SECTION OF ALGAL POLYGON

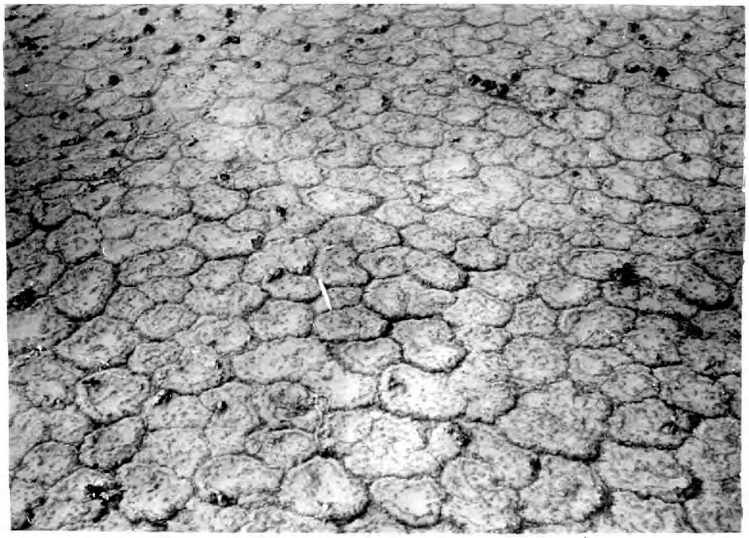
CROSS SECTION OF POND ALGAL POLYGON

Plate 14

Intertidal sand flats seawards of the Khusaifa algal mats showing well rippled scours.

Plate 15

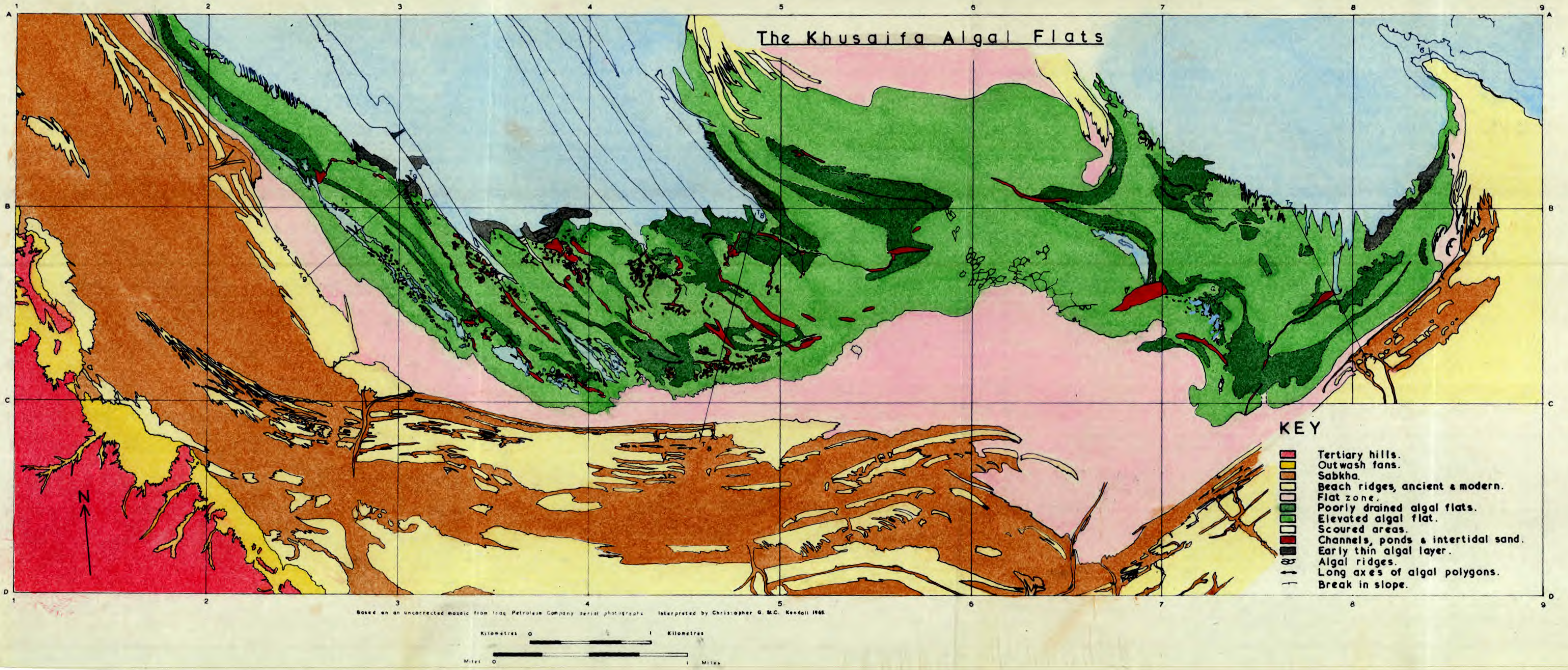
Polygons of cinder type algae from front of Khusaifa algal mats.



crushed coal cinders. These features, though they are poorly formed, superficially resemble Logan's stacked hemispheroids (SH) and the Cryptozoons of the ancient rocks. When examined closely the surface is found to be formed into small (1 to 10 mm.) tight crenulations and blebs, which may be classified as laterally-linked hemispheroids type C (LLH-C) This cindery crenulated texture is confined to the outer algal zone and is a valuable criterion of zonation. Towards the algal flat proper, these raised algal colonies (6 inches to 1 foot high) coalesce and form features which are resistant to wave erosion, whereas the sand around them is uncemented and may be eroded. This is particularly noticeable shorewards, where small depressions are produced which retain water to form pools at low tide (Figure 10). The map (Figure 11) shows some of the largest of these depressions (coloured grey: Map Ref: 3/C). Though not shown on the map, pools of 6 to 10 feet diameter occur along the whole of the algal front with their long axes parallel to the front.

The floors of the pools are covered by blebs of algae (1 to 10 mm. diameter) broken off from the larger colonies. No sample was collected but the blebs superficially resembled the discrete spheroids (SS) of Logan's classification. As the algal flat accretes seawards, pools become overgrown by algae.

In the northwest of the main flat (Figure 11 and Plate 1 Map Ref: 2/B) and the northeast of the main flat (Figure 11, Map Ref: 7/B) are areas of frontal algal flat which are



Based on an uncorrected mozaic from Iraq Petroleum Company aerial photographs. Interpreted by Christopher G. St.C. Kendall 1965.

Plate 16

Khusaifa algal flats showing algal polygons with raised edges

heavily scoured. Although not visited in the field the ridges between the scours may be the place to look for the Shark Bay hemispheroids. In cross-section the cinder algal sediments can be seen to contain large quantities of aragonite mud. They show little lamination (Plate 17 BC 4 & 5) and are often full of anastomosing tubelike holes. This spongey texture is believed to be formed when the rising tide forces trapped air through the algal mats. A similar texture was observed in soft sand by Hoyt and ~~Henry~~ Vernon (1963) and in laminated fine sand overlain by laminated algal mats in S. Texas.by P. Andrews (personal communication 1966).

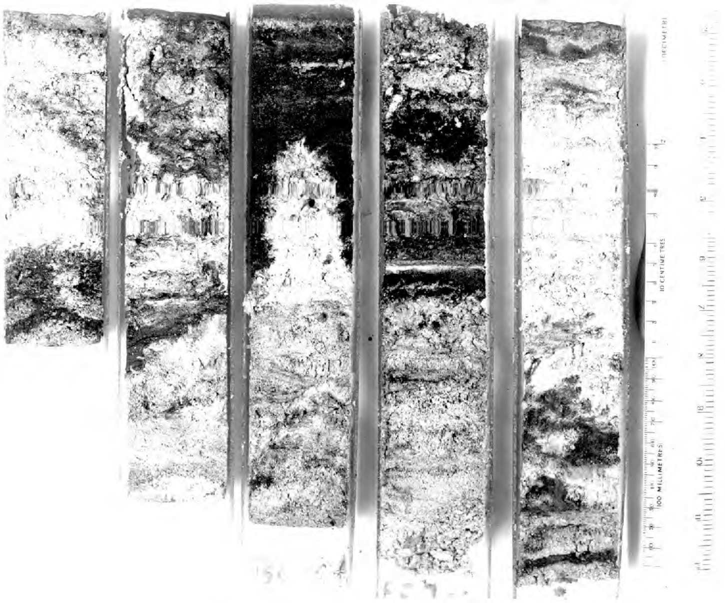
(b) Polygonal Algal Zone

Inland from the edge of the cinder algal zone, the cinder-like colonies form flat surfaces, which are marked by desiccation polygons, that are normally hexagonal in plan. The surfaces of the polygons are flat and the edges are not raised, (Plate 15). The cracks at the edges of the polygons can be as much as 6 inches deep. In cross-section, the structure is poorly laminated, (intermediate to Plate 17 BC5 and Plate 18 BC6). These polygons cannot be classified after Logan (1964). Polygonal shapes cover about $\frac{2}{3}$ of the total area of the algal flat. Landwards, the cinder-like surface of the algae changes to a leathery slimy one that is also cracked into polygons. The edges of these polygons curl up but as the algae continue to grow,

Plates 17, 18 and 19

A series of cores from traverse 9 of the Khusaifa algal flat.

Plate	Cores	
17	BC 4 & 5	Algal flat front. Poorly laminated algae intermixed with high percentage of aragonite mud. Base of cores are of sand flat sediment.
17	BC 6,7 & 8	Front of polygonal algal zone. Disturbed but laminated algae. Base of cores are of sand flat sediment.
18.	BC 9, 10 and 11	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.
18 & 19	BC 12 & 13	Crinkle algal zone. Top of cores have a mixture of algae and gypsum crystals. Layers below represent earlier stages of algal flat.
19	BC 14, 15 16 & 17	Flat algal zone. Tops of cores are very rich in gypsum. Periods of algal growth represented by dark crenulated line.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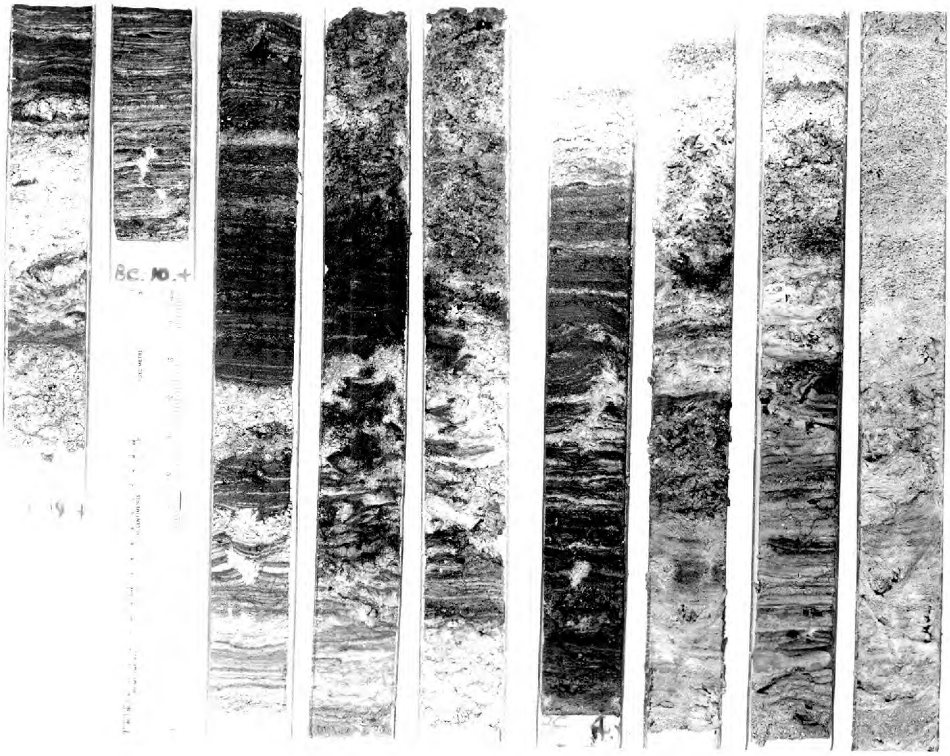
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the edges become rounded and act as lips round the polygons. These trap water when the tide goes out (Plate 16 and Figure 10 and Plate 19). The shape and size of any polygon and the morphology of its raised lip may be determined by the following factors:

i. The moisture-retention properties of the algae
ii. The intensity of the desiccation
iii. The duration of desiccation.

The effects of the first factor are not obvious in the field but the result of the last two factors is that mats on higher better-drained ground form small polygonal saucers ranging from 1 inch to more than 1 foot across. These saucers have prominant raised lips. Mats on the lower poorly-drained ground are formed into large polygons which tend to have no lips (Plate 22). These polygons can be as much as 12 feet across where they form in the ponded ebb creeks that meander across the algal flats, (Figure 11). The colour of the map on the better-drained areas is a dark brown, whereas on the poorly-drained areas it is usually a vivid crimson. The centres of some of the small polygons can also be of this crimson colour, whilst the raised lips are dark green.

In cross-section, these polygonal saucers exhibit well marked horizontal laminae. This structure of stacked polygonal saucers cannot be classified after Logan <u>et al</u> because the polygons are concave upwards and not downwards as shown in the examples of stacked hemispheroids described by Logan.

Plate 20

Khusaifa algal flat. Algal polygons on which colonies of calcareous algae and drifted seaweed have accumulated. The algal mat has grown over this debris.

Plate 21

Gas dome on algal flat

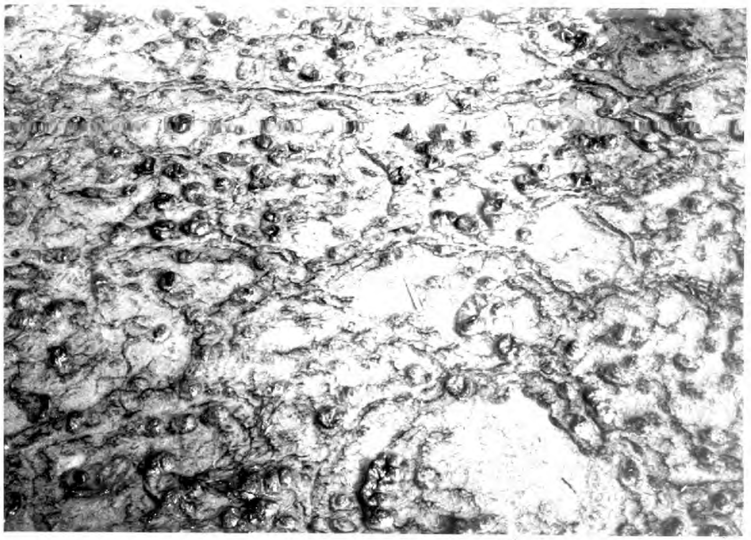


Plate 22

Khusaifa algal flat. Poorly drained algal flat with large polygons. Adjacent better drained areas have smaller polygons.

Plate 23

Khusaifa algal flat. Raised edges of algal polygons. Note sediment infill of boundary crack.

There are often other morphological features superimposed on the surfaces of these polygons and these usually take the form of Logan's laterally-linked hemispheroids, (LLH-S). They are formed by the algal surface growing over pieces of flotsam washed onto the flat. This flotsam may consist of calcareous algal colonies, seaweed or pieces of driftwood, each of which produces different kinds of doming. Plate 20 shows a colony of *Jania* and some seaweed, covered by the blue-green algal mat. Seaweed which has drifted onto the flat, in long streaks parallel to the shore, may become fixed by algae to form the low parallel ridges and shallow basins common to some parts of the flat. These are similar to those formed in the cinder algal zone. Another factor producing doming is gas. This forms the most perfect of the hemispheroid shapes found in the Khusaifa flats (Plate 21). Logan believes the same agencies are responsible for dome formation.

The polygons themselves are superimposed on larger features. This is particularly noticeable in the west Khusaifa flat. Here the front of the algal flat projects seawards in a series of lobes. 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 the ebb channels. The lobes are thus the frontal expressions of lines of high relief which extend across the algal flat, and the embayments the expressions of lines of low relief. Kinsman (1964) noted this same development west of Abu Dhabi, as did Evans (1965, p.219) in the marshes of the Wash. The areas of higher relief are well drained whereas those of low relief are poorly drained, and are easily recognisable from the small meandering ebb creeks that dissect them. These creeks, which have levee-like banks, terminate in pools very similar in shape to the salt pans of temperate salt marshes (Davies, 1962, Evans 1965). Many of these pools lie well back in the algal flat and it is obvious that something is preventing the algae from growing across them and infilling them. Logan _et al_ (1964) proposed that prolonged wetting in low areas inhibits algal mat growth. In this thesis the idea is taken further and it is suggested that the algae are in fact inhibited in their growth not only by the water ponded ~~in these ponded~~ in these pools, but also by its high salinities.

Apart from the terminal pools, other ponds develop. These are produced when the meandering creeks are dammed by vigorous algal growth (Figure 11, Map Ref: 3/C and 4/C). Similar long ponds are also seen in temperate salt marshes. It is in these that the largest of all the polygons form, their edges often being eroded by ebb movements. This edge closely resembles half of one of Logan's vertically stacked hemispheroids type C (SH-C) (cf. Plate 22, Figure 10).

The crimson colour of the pool floor is the same as that assumed by the algal surface beneath the halite crust of the highest zone of the algal flat: the flat zone. Also it is interesting to note that in the winter months, the crimson colour of the mats in the pools is overgrown by a thin green surface layer. Thus the possibility arises that the laminae are produced during periods of seasonal growth. Monty (1965) studying Recent algal stromatolites in the Bahamas found that lamination could be produced diurnally but in this particular case growth only took place at the height of summer.

(c) Crinkle Zone

About $\frac{3}{4}$ mile across the algal flat just below the mean high water mark, the polygonal mat interfingers with a crinkled surface without polygons. This type of crinkle is analagous to Logan's (1964) laterally-linked hemispheroids (LLH) of both type C and type S; the spaced laterally-linked hemispheroids, type S, occurring at both the seaward and landward boundaries of the Crinkle zone, (Plate 24). They do not tie up with the genetic implications of Logan et al's classification. Landwards, the crinkles become gypsum-filled and in cross section show very little ordered structure, (Plate 25). The non-gypsiferous areas are filled by anastomosing air holes. The crinkled surface is probably produced by rapid drying in summer at low tides, with the creation of very small (2 to 3 inch diameter) curled-up mud cracks. These are covered so quickly by further growth of algae that a crenulated surface results. Both Black (1933) and Fisk (1959) described similar effects in the Bahamas and the Laguna Madre, respectively.

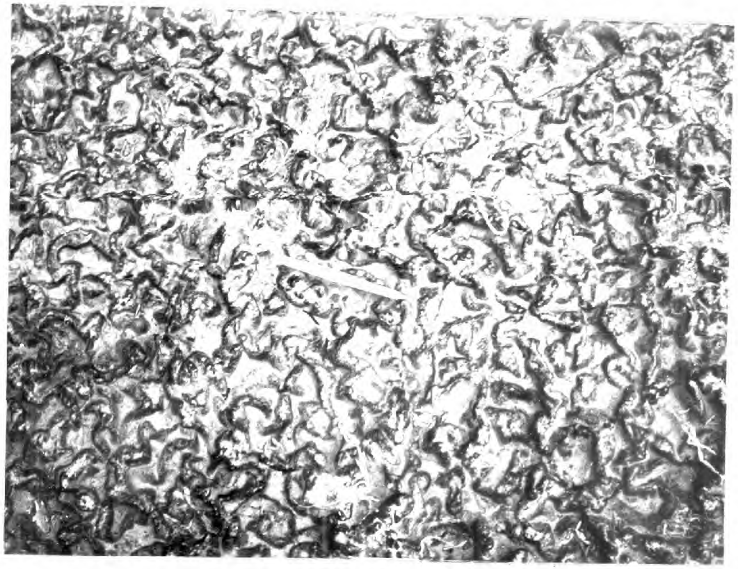
The gypsum crystals associated with the crinkles are produced by the evaporation of capillary water beneath the algal flat at low tide. The algal mat probably acts as a membrane which prevents tidal water flushing the groundwater. The

Plate 24

Khusaifa algal flat. Surface of crinkle zone.

Plate 25

Khusaifa algal flat. Sharp boundary between laminated algae of polygonal zone and disorganised material of crinkle zone.



gypsum does not produce the crinkles since these may form with no gypsum present, and gypsum may be overlain by horizontal layers of algae in the higher flats with no apparent effect. The surface of the crinkled zone forms a continuous layer which is not fastened firmly to the substrate. Thus if on a high tide, heavy waves reach the crinkled zone, it is often stripped off. (Plates 26 and 27). These are the scoured areas shown on the map.

Near the middle of the Khusaifa algal flat, (Figure 11, Map Ref: 7/C northern section of square), large parts of the crinkle zone form a beach rock covered by a thin layer of growing algae. This surface layer is often cemented and thus becomes incorporated into the cemented sediment. The cementation is probably induced by better drainage of the tidal wave table at this point, so that the capillary water has time to evaporate and precipitate aragonite.

(d) Flat Zone

Landwards of the crinkle zone, the surface of the mat becomes virtually featureless. This flat zone can be easily differentiated on aerial photographs and is from 100 to 500 yards in width. It is crimson in colour and is invariably covered by a thin salt crust of one to two millimetres which thickens to one to two centimetres, and crumples towards its landward edge. In cross-section the mat can be seen to consist of a thin, $\frac{1}{8}$ inch algal layer beneath which is a mush of gypsum crystals which may be as much as 6 inches thick. At the inner edge of the flat zone, anhydrite is forming as dis-

Plate 26

Khusaifa algal flat. Surface of crinkle zone stripped back after heavy seas.

Plate 27

West of Ras al Aish. Roll of algae from crinkle zone washed to H.W.M.

Plate 29

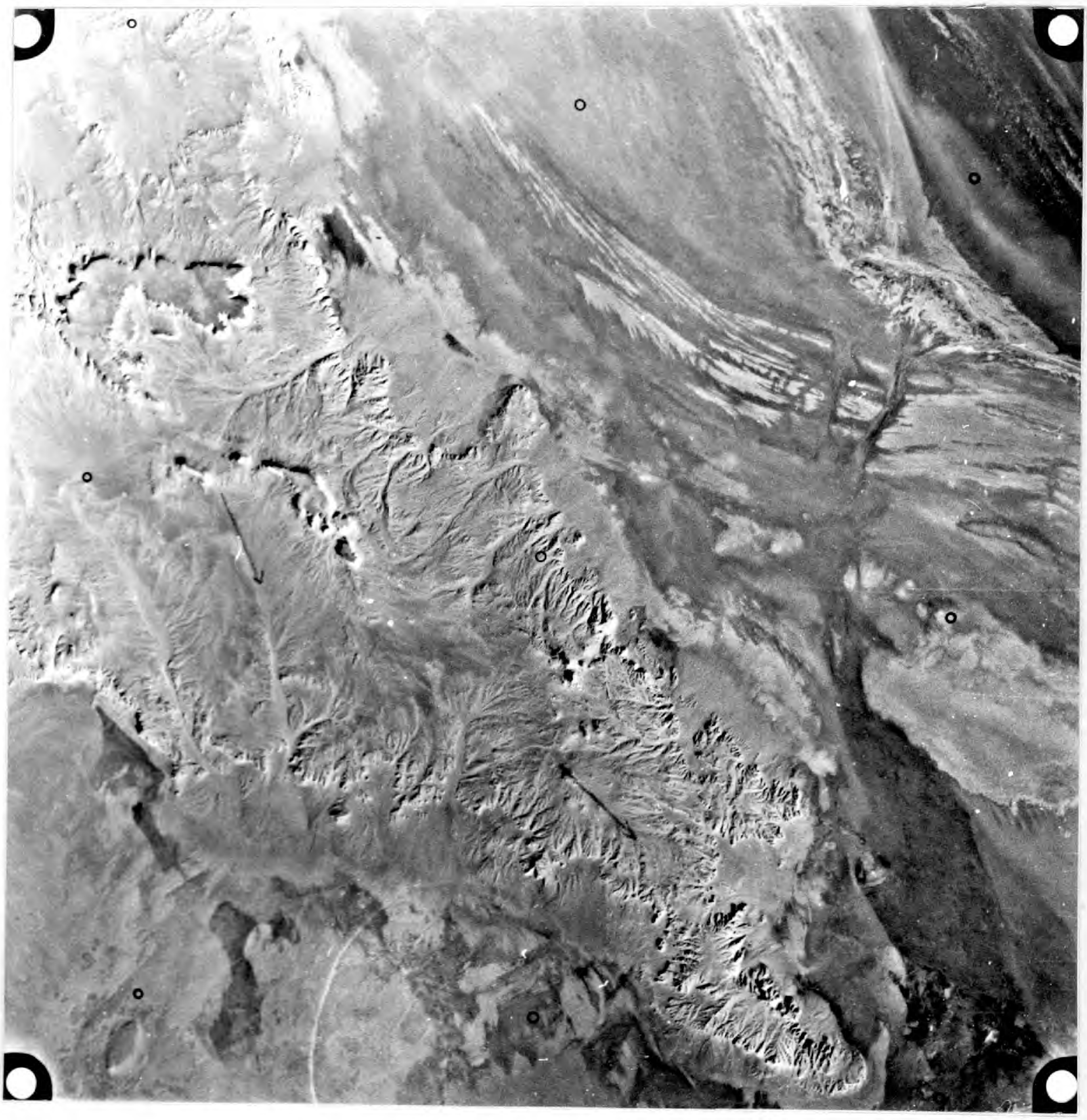
Southwest of Khusaifa algal flat (2/4/I) showing:

(i) A flood outwash fan on the edge of the algal flat to the northeast.

(ii) A series of stranded spits in the accreting sabkha plain.

(iii) A series of Tertiary hills rimmed by outwash fans.

Scale 1:30,000



continuous blebs and layers above the gypsum (Plate 30). Landwards, the algae die out and the sabkha plain starts. (Figure 11 shows the areal distribution of the Flat zone).

The history of the Khusaifa algal flat can be interpreted from aerial photographs and from the study of cores which provide vertical cross sections. Information from the aerial photographs has been superimposed on the map and from this it can be seen that Khusaifa Bay was formerly a high energy environment. This is shown by the line of old beaches and spits now stranded and partially buried in the sabkha plain. The bay has since silted up to such an extent that the environment has become quiet enough for algal development.

Cores (Plates 17, 18 and 19) reveal a series of horizons that represent diachronous layers of algae and sediment that have been accreting seawards. For instance, cores in the Flat zone reveal lagoon sediments at the bottom with cinder algae above, followed by laminated algal mats, culminating in the final gypsiferous layer.

(ii) Algal Flats Occurring Elsewhere in the West Khor al Bazam

None of the other algal flats in the west Khor al Bazam are as extensively developed as they are at Khusaifa. Where they do occur, however, they can be grouped as follows:

(a) Flats of intermediate size, over ½ square mile in area.

(b) Small flats under ½ square mile in area.

(a) The flats of intermediate size occur in two forms, those open to the sea, and those enclosed by barrier beaches. The

Plate 30

Sabkha behind Khusaifa. Early development of anhydrite at the back of the algal 'Flat' zone.

Plate 31

Sabkha west of Ras al Aish. Nodule of anhydrite from sabkha sediment.

flats open to the sea occur south of the island of Thimairiyan (Map Ref: 1/5/H, Plate 28), on the west flank of Ras al Aish (Map Ref: 2/2/H), seawards of the Dagallah lagoon beach barrier (Map Ref: 1/1/G and 1/2/G, Plate 9), in the lee of Mahmeen (Map Ref: 3/2/F), and to the north of Janana (Map Ref: 3/2/G, Plate 8). These flats have no well-developed polygonal algae areas and a very poor cinder algae zone. This may be because they are not wide. The dominant growth form is the crinkle and landwards these crinkles are filled by gypsum as at Khusaifa. Behind the crinkle zone a Flat zone occurs. This is particularly well developed on the flat just west of Ras al Aish, but is almost non-existant behind Mahmeem and Thimairiyan.

The enclosed algal flats are found all round the island of Marawah and on the island of Hail. They are particularly well protected by beaches and are closely associated with mangroves which line the meandering channels that drain them. Landwards of the channels, algal flats are found which can be divided into the following zones:-

I. Cinder algal zone;
II. Polygonal algal zone;
III. Crinkle algal zone;
IV. Flat algal zone.

Inland of the flat algal zone there is a crab flat which passes back into a zone of dunes with halophytes (Figure 9).

I. Cinder Algal Zone

As with the cinder algal zone of the Khusaifa flat, the algal mats of this zone take the form of Logan's stacked hemispheroids (SH-V); the surface being formed into small crenulations a few millimetres across which resemble Logan's laterally linked hemispheroids (LLH-C). Here the cinder zone is only sparsely developed and is often cemented into a beach rock. This beach rock and the beach rock which may form in the higher algal zones in cross-section do not show the fine laminae of the uncemented algae but form into thicker layers of cream coloured limestone similar to that described by Newell *et al* (1957, p.50) in the Bahamas behind Andros Island, and the Recent supratidal dolomite from nearby described by Shinn, Ginsburg and Lloyd (1965).

II. Polygonal Algal Zone

Landwards of the cinder algal zone - or if this does not occur, directly behind the mangroves - there may be a wide expanse of leathery mat shaped into polygons. The surfaces of these mats are elephant-grey in colour, as distinct from the reds and browns of the Khusaifa flat. However, they have similarly raised lips. The seaward edge of the polygonal zone, and parts of the cinder zone, are usually highly burrowed by crabs.

III. Crinkle Algal Zone

A crinkled algal surface interfingers with the polygonal zone on its landward edge. This is often desiccated so that the crinkles have shrunk and have peeled off. The resulting surface looks as if it were covered by rotting leaves, (Plate 13). Fisk (1959) and Logan (1964) also noted this texture, as indeed have many other workers. The zone may be gypsiferous, but gypsum does not necessarily develop and the flat then passes directly into a crab flat.

IV. Flat Algal Zone, Crab Flat, and Halophyte and Dune Zones

The Flat zone is similar to that described from Khusaifa. The alternative to this zone is a crab flat. This is a sand surface which contains little or no gypsum and which is extensively burrowed by the small sand crabs, e.g. *Scopimera*. The crab flat is backed by salt-resistant plants, including *Arthrocnemum glaucum*, which grow on small low dunes of up to 6 feet high. Quite often *Arthrocnemum glaucum* occurs in the middle of the crinkle zone on small hummocks. Kinsman (1964 c) noted similar occurrences on the algal flats west of Abu Dhabi. He also observed that mangroves may sometimes grow in a higher zone than the Arthrocnemum hummocks. An arthrocnemum hummock occurring in the crinkle zone is illustrated in Plate 13. The beach rock crust that surrounds it is similar in appearance to the dolomite crust described by Shinn *et al* (1965) but contains no dolomite.

Phleger *et al* (1962) found a similar association of salicornia and algal mats in the lagoons of Baja, California. Like Fisk (1959), and other authors, Phleger also found gypsum in places under the algal mat.

Small flats occur extensively along the front of Marawah, along the beach between Mirfa and Khusaifa, and along the shores of the Dagellah lagoons. They have no polygonal or cinder zones at their frontal edges, but pass directly from sand flats into crinkled algal mat, usually backed by a poorly developed Flat zone with an underlying gypsum mush.

6. MARINE AND SUBAERIALLY FORMED GEOMORPHOLOGICAL FEATURES.

A. The Sabkha:

The coastal plains and many of the islands of the Trucial Coast are forming through the agency of subaerial processes and are called sabkhas. Evans, Kendall and Skipwith (1964) distinguished sabkhas from other coastal plains and islands, forming elsewhere in the world, by showing that they are composed largely of unconsolidated carbonate sediment and are the site of deposition of various evaporitic minerals. Illing et al (1965) call them 'sebkhas!

In the west Khor al Bazam two forms of sabkha are recognised: that which forms islands and that which comprises the coastal plain.

(i) Sabkhas that Form Offshore

Sabkhas that develop from offshore beaches to form islands are common. The beaches and islands are termed 'barrier' beaches and 'barrier' islands. Price (1951) first proposed the use of the term 'barrier' to describe subaerial offshore sand masses which can extend parallel to the coast. Shepard (1952) incorporated the term in his 'Revised Nomenclature for Depositional Coastal Features' and King (1959) uses the term rather more loosely. Shepard's classification is used. The term sand cay (Fairbridge 1950, Stoddart 1962) is not used here since though it refers to subaerial offshore sand masses it has more general connotation.

a) <u>Barrier Beaches</u>

Barrier beaches are commonly cusped and lie on the landward side of the offshore bank bordering the Khor al Bazam (Map Ref: 3/3/G) and on the landward side of the bank bordering the lagoon of Dagallah (Map Ref: 1/1/G). Both the maps and Plate 9 show that although the sand that makes up the beach barrier is derived from the bank it borders, the origin of the beach is related to the inner edge of the banks. The steep slope of the beach faces the inshore lagoon and the slope of the beach continues without a break into the deeper water as a smooth curve. These beaches probably are produced by waves formed by offshore winds. (Sheets 1, 2 and 3). Waves breaking on the banks from the lagoon side would meet a tidal flow across the bank from the open sea and so produce a beach. Maxwell <u>et al</u> (1964) cite the same mechanism to explain intertidal gravel bodies on the Heron Island Reef. The meeting of these two transporting agents would lead to the development of a 'dead' area and any load which they were carrying would be dumped. Eventually the accumulation of this load would be heaped up into a beach by the swash of the lagoon waves. Steers (1929) and Stoddart (1962) relate these accumulations of sand ~~towards~~ to wave refraction around the platform to meet at the back. The early phase, before the development of the beach, is seen to the east of the algal barrier island in Plate 9 (Map Ref: 1/1/G) and east of Janana (Map Ref: 3/3/9). These beaches do not form at the seaward edge of the banks since the onshore waves are larger and more destructive than the smaller offshore ones. They transport any load carried by an offshore tidal currentback onto the banks to add to pre-existing beaches and islands. The barrier beaches are often cemented to form beach rock and also act as a base upon which the barrier island develop. They must thus be permanent features. In early stages of beach accumulation they are often breached by ebb tides and probably by flood tides coming across the bank when these are backed by strong onshore winds.

b) Sabkha Barrier Islands

Sabkha barrier islands are common to the Shelha al Bazam and to the bank offshore from the Dagallah lagoons. Their development from barrier beaches can be traced in the Khor al Bazam. The earliest stages are found near Dagallah where there is a complex of lunate beaches, spits and algal flats. Janana, the next stage, is an island of accreting algal flat and chenier-like beach ridges. These beach ridges began as beach barrier which enclosed successive growths of algal flat. Marawah, in contrast, is a complex of several stages of accretion and erosion. The islands of Fiya, Bazam al Garbi and Salaha are all smaller versions of this complex type of barrier island. Thus the outward growth of these islands is the result of the extensive and prolonged intertidal flat sedimentation. Occasionally the islands incorporate outcrops of Quaternary age and some of the smaller islands may be entirely of this rock.

In Allen's (1965) paper on the Niger delta, barrier islands in a wet tropical climate was discussed. It is very similar to the role which they play in the Khor al Bazam, the Wadden Sea, and the Louisiana and Texas Coasts, (Byrnie~~,~~ et al 1959, and Gould et al, 1959). However, the feature which distinguishes the islands and recently accreted coastal sediments of Abu Dhabi from similar barriers occurring elsewhere in the world, is that the former are composed dominantly of calcareous sediment and also provide an environment in which suites of evaporitic minerals form.

(ii) Mainland Sabkha Plain

The 'sabkha' barrier islands like the mainland 'sabkha' plain of the coastal strip represent the recent accretion of intertidal and lagoonal sediments. Kinsman (personal communication) has shown from radiocarbon dating that the inner parts of the sabkha are no more than 3,000 years old. Evans, Kendall & Skipwith (1964) described how the mainland sabkha stretches "from Ras Ghanada to almost the Qatar peninsula in the west, a total distance of almost 200 miles". The width of the sabkha in the west Khor al Bazam varies and can be anything up to ten miles. It backs the intertidal flats of the coastal terrace except where hills of Tertiary and Quaternary rocks jut out as peninsulas (Ras al Aish, Map Ref: 2/2/4, Quala, Map Ref: 1/4/H, and Mirfa, Map Ref: 3/4/I). In places its surface lies flush with eroded Quaternary rocks and from a distance it is hard to distinguish the two. This eroded surface may be a marine platform or the result of wind abrasion. The latter could easily be the case since the Quaternary rocks are poorly cemented and in consequence easily eroded by the wind.

The surface of these flats can take several forms and can represent the last deposited intertidal sediments. These may be the sediments of old algal flats, beach ridges or the sandy zone which forms between the behind beach ridges. However, these features are often eroded or obscured by aeolian sediment.

The most conspicuous features of the sabkha are the old beach ridges and these can be identified by their distinctive appearance in the field or directly from aerial photographs. Like 'cheniers', they have linear shapes with a smooth seaward margin, an irregular landward outline and are biconvex in cross-section, (Byrnie et al 1959). They normally consist of well sorted coarse skeletal sands. These beach ridges mark various stages of the outward growth of the sabkha, and usually represent the intertidal spits of earlier marine phases, (Plates 2 and 29). They drape headlands, (e.g. Ras al Aish, Map Ref: 2/2/H), and cross embayments (e.g. Mirfa and Khusaifa). However, it is not unlikely that some of the beach ridges of sabkha embayments represent barrier beaches that formed seawards of now infilled lagoons on the lee of their offshore banks. The sediments south of such ridges are very sandy, and probably represent the final infill of these lagoons. Certainly it is only north of these ridges, in the west Khor al Bazam, that algal flats have been identified incorporated in the sabkha. Cross-sections cut in the sandy sediment revealed cross bedding very similar to that shown by much of the Quaternary rock. This raises the possibility that these sediments, though uncemented, are of Quaternary age and are equivalent to the poorly cemented patches of rock that lie flush with them. These cross bedded sands are not confined to this area but are common to and underlie much of the sabkha adjacent to Abu Dhabi (Socony Mobil/Imperial College expedition, 1965).

Just to the west of Ras al Aish is one of the best developed algal flat sabkhas identified in the west Khor al Bazam (Map Ref: 2/2/I). Here cross-sections reveal that the algal laminae are still preserved at least 1½ miles inland from the present high water mark. Lagoonal sediments and the beach rock platform of the coastal terrace occur beneath the algal layers. Gypsum and anhydrite first appear at the landward edge of the algal flat, and are found in the aeolian sediments above the mats. These evaporite minerals form many interesting structures. Their occurrence is not confined to the algal flat sabkha though they are probably best developed here. They form from marine derived ground waters which are concentrated by continual evaporation. These have been described in detail by Kinsman (1964 c) and Butler (1965).

Plate 32

Abu Dhabi sabkha. Edge of anhydrite polygons exposed by erosion.

Plate 33

Contorted anhydrite passing laterally into gypsum after anhydrite.

All the structures described are sometimes destroyed by aeolian and marine erosion. The process of aeolian erosion and its results have been described. Marine erosion when it takes place is more effective. The most obvious features that are eroded in this way are beach ridges. Wind only carries away the finer grades of sand leaving a lag deposit of gastropod shells. However, extreme high tides backed by strong onshore winds sweep water across the old beach lines, breaching them, and transporting their sediment onto the sabkha behind, e.g. Traverse 3 just west of Mirfa (Map Ref: 3/3/I). The outgoing tide from such a flood breaches the beach ridges again to produce small deltas seawards of the ridges, e.g. west of Khusaifa (Map Ref: 2/4/I), and west of Quala (Map Ref: 1/3/H). Sometimes sheets of flood water can remain in the depressed areas of the sabkha and will move about them when driven by strong winds. While aeolian erosion stops short when it reaches sands dampened by capillary water from the water table below, marine erosion can extend deeper and in parts of the sabkha when it has been particularly effective, the water table comes to the surface. Such areas can prove treacherous when driving a vehicle across them, because they are usually disguised by a thin dry salt crust. (Plates 34, 35, 36 and 37). In areas where erosion has taken place evaporite minerals are often exposed. For example, gypsum is common on the sabkha surface, protruding as vertical sand crystals, and anhydrite occurs in the form of polygons. Plates 33 and 32 show a contorted band of anhydrite at depth and the effect of erosion of this at the surface.

Plate 34

Khusaifa sabkha. Halite in the form of Hopper crystals at surface.

Plate 35

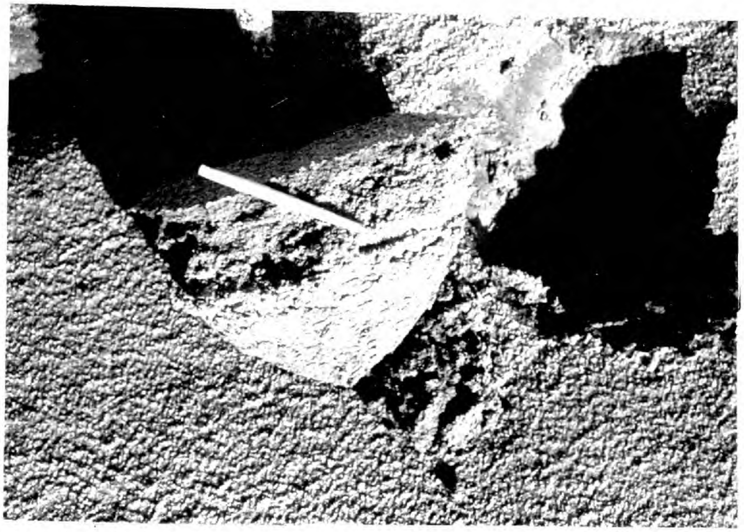
Khusaifa sabkha. Mud cracking of surface.

Plate 36

Sabkha west of Ras al Aish. Development of halite crystals both above and below surface of sabkha (see tip of pen).

Plate 37

Khusaifa sabkha. Contorted surface where gypsum has formed after anhydrite.



7. MINOR SUBAERIAL GEOMORPHOLOGICAL FEATURES

A. Aeolian Features: Coastal Dunes

King (1959) classified coastal dunes and explained how they form from sand blown off the beach at low tide, which is then trapped by vegetation lining the shore. In the west Khor al Bazam, Halophytes like Arthroconeum glaucum line the shore in areas above the high water mark, where intertidal spits develop. Despite the almost complete lack of rainfall, the plants appear to survive on the heavy nightly dews, and on the moisture retained by the large quantities of seaweed humus in the beach sediments. These plants nucleate lines of foredunes which fit King's definition, since they are mounds of up to 10 feet high, adjacent and parallel to, the beach. The older dunes behind lose their plant cover and are blown away. The plants which line the dunes die when more than 100 yards from the shore, and it appears that the amount of dew decreases rapidly with increasing distance from the sea. Folk (in press) also notes the destruction of dunes inshore on some of the islands of Alacran reef. However these are destroyed by nesting birds and crabs.

8. MAJOR GEOMORPHOLOGICAL FEATURES OF MARINE & SUBAERIAL ORIGIN

A. Hills and Alluvial Fans

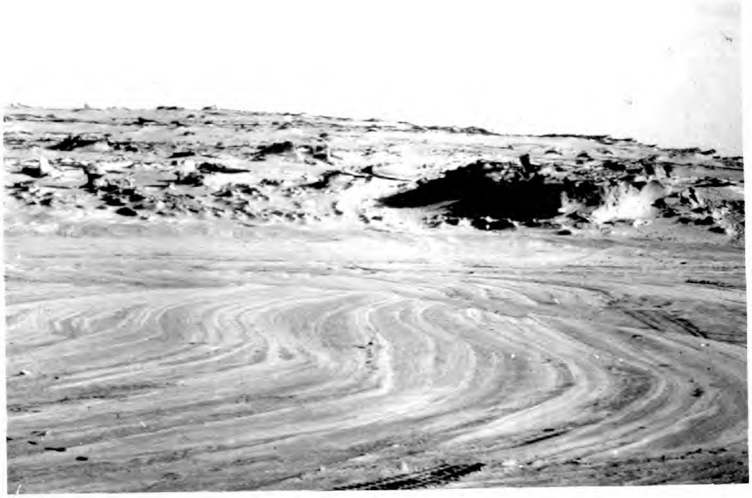
Cropping out along the west Khor al Bazam coastline are rocks of Quaternary and Tertiary age. The Tertiary rocks form lines of low hills (seldom above 50 feet) which are almost perpendicular to the shore and are parallel to the dominant wind direction. These hills are remnants of a once much more continuous cover of almost horizontal rock eroded by the combined action of flash floods and wind. Their alignment with the dominant wind direction may be significant. Their form is typical of hills in arid regions elsewhere and they are surrounded by alluvial fans deposited by occasional flash floods, (Plate 29).

The Quaternary beds, like the Recent sediments, are banked against the Tertiary rocks on higher ground and overlie them in low lying areas. The Quaternary rocks (known locally as Miliolite from their abundant content of Miliolids), are described in detail by Kinsman (1964 c). They form two distinctive limestone beds. The lower one is over 20 feet of fine grained carbonate with little or no coarse grained skeletal material. It exhibits large scale festoon or trough bedding which is directed onshore and is probably of aeolian origin. The upper one is a coarse shelly limestone with localized in situ coral development. It is of variable thickness and lies unconformably on the lower one. These limestones resemble the cay rock of the Bahamas, (Illing, 1954) and probably formed during the fluctuating sea level of Pleistocene times.

The top of the Miliolite is often truncated and this surface underlies quite wide areas of sabkha and parts of the coastal terrace. It is hard to tell whether its eroded surface was caused by aeolian or marine erosion (Plate 38). Where it is adjacent to the coast, often projecting as peninsulas into the sea, its surface is etched by sea water, algal

Plate 38

Erosion surface of festoon or 'trough' bedded 'Miliolite' at back of sabkha. This same rock forms low hills in background.



boring, and animal activity as is the cay rock in the Bahamas, (Newell *et al*, 1957, p.63).

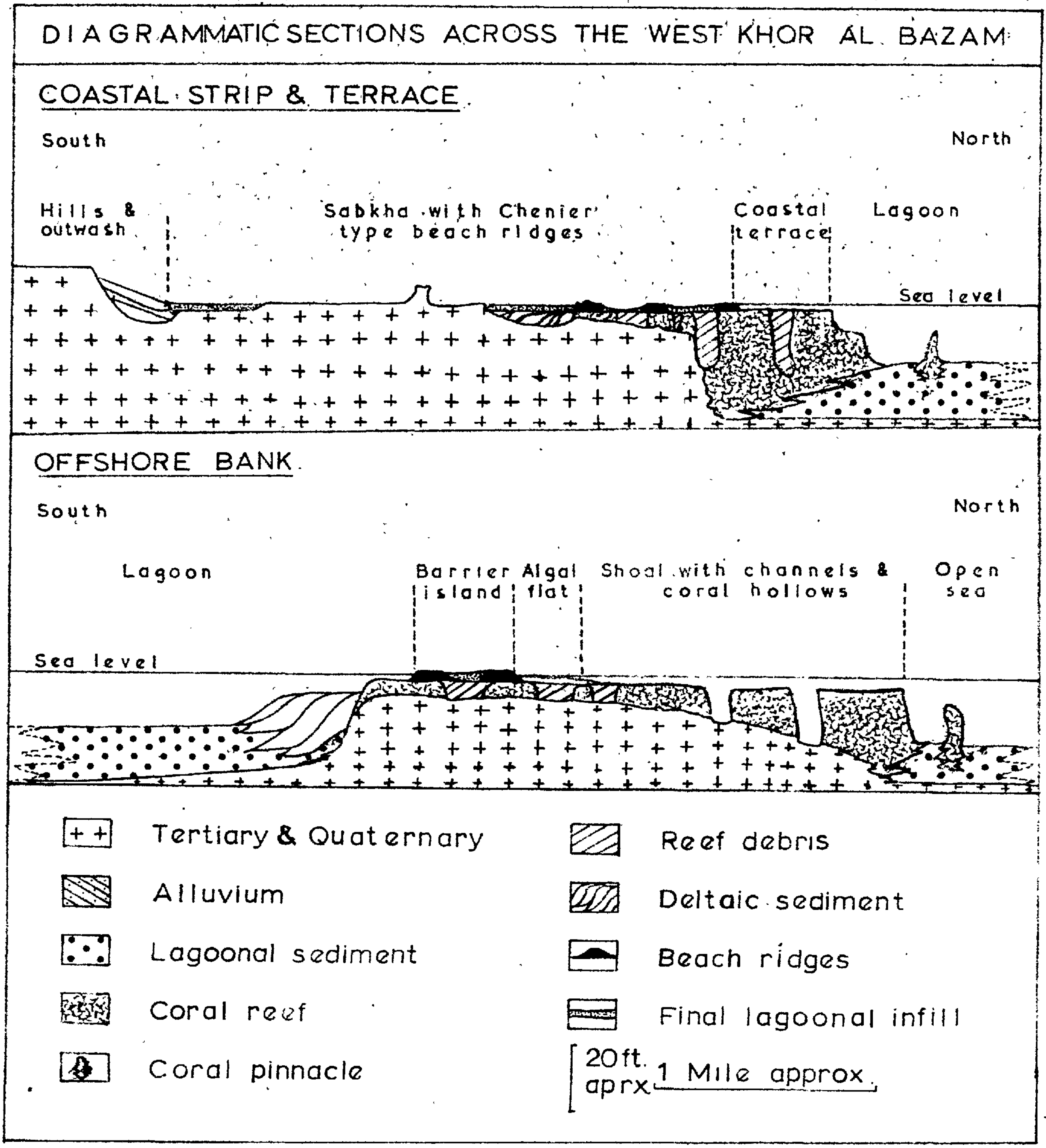
9. GEOMORPHOLOGICAL HISTORY

The elucidation of geomorphological history of the area is based on aerial photographs and field observation. It is described from north to south.

In the north the offshore bank probably originated as a coral shoal nucleated on a high of Tertiary and Quaternary rock, and progressively accreted northwards leaving behind coral hollows and lines of old fronts. Tidal currents and waves carried coral debris, and sediment from other sources, across the bank. Thus, the top slowly silted up so that tidal movement was channeled along specific lines to form inlets. The mouths of these inlets became marked by deltas that coalesced and advanced shorewards into the lagoon. As sediments on the bank accreted, barrier beaches formed,and became the nucleus of islands. (Figure 12). These may in some cases be comparatively recent, and it is probable that several generations of islands have been accreted and eroded. Where total erosion has taken place areas of cemented cross-bedded rock platforms below H.W.M. may show the site of these earlier islands. Alternatively some of these cross-bedded rocks may be Miliolite.

The large channel between the Janana-Salaha bank and the Marawah-Hail bank is probably not of erosional origin but is due solely to a lack of sedimentation. Whatever its origin,

Figure 12


DIAGRAMMATIC SECTIONS ACROSS THE WEST KHOR AL BAZAM
COASTAL STRIP & TERRACE
South
North
Hills & outwash
Sabkha with Chenier type beach ridges
Coastal terrace
Lagoon
Sea level
OFFSHORE BANK
South
North
Lagoon
Barrier island
Algal flat
Shoal with channels & coral hollows
Open sea
Sea level
Tertiary & Quaternary
Alluvium
Lagoonal sediment
Coral reef
Coral pinnacle
Reef debris
Deltaic sediment
Beach ridges
Final lagoonal infill
20ft. aprx
1 Mile approx

it developed into a complex of smaller channels, banded by sandspits, levees and shoals. At either end of the major channels are deltas. To the south of the offshore bank the Khor al Bazam forms a lagoon. Both the dissected areas to the west and the undissected areas to the east are centres of sedimentation. The weed on the bottom acts as a baffle in which sediment is trapped. Probably this lagoon was once more open to the sea, and was an area in which vigorous coral growth was able to take place. Its dissected floor was possibly formed during a low sea level in the Pleistocene due to fluvial action. During the present cycle the lagoon floor has always been a site of sediment accretion.

The west Khor al Bazam is banded to the south by the coastal terrace and strip. These features probably once resembled the lagoonal complex west of Ras al Aish but have since been infilled. Thus the terrace represents the front of an offshore coral bank which has since been joined to the mainland. (Figure 12). In part, however, this terrace is erosional, having been cut into headlands of Tertiary and Quaternary rocks. Old beach lines across embayments may represent barrier beaches that formed on the lee sides of the coral banks, the sabkha south of these being infilled lagoons.

10. CONCLUSIONS

The west Khor al Bazam is a Recent example of a nearshore carbonate and evaporite complex developing in an arid climate. Its geomorphological features are common to many parts of the world. This suggests that in shallow water carbonate environments and indeed many other shallow water environments of the past similar features should be recognisable. In well exposed rocks a straightforward field analysis would immediately reveal any comparable features, but in poorly exposed rocks and well chippings, other criteria are required. Here the identification of sediment types is important and should be coupled with some form of granulometric analysis. This is expanded in the next chapter.

CHAPTER III

THE SEDIMENTS

1. INTRODUCTION

The purpose of this study of the sediments in the west Khor al Bazam was twofold. Firstly, to establish criteria of environment which could be used to reconstruct the pattern of sedimentation in ancient carbonate provinces; and secondly, to establish the origin of specific components of the sediments common to both ancient and modern limestones. For this a system of classification was necessary. The most useful classifications for this purpose are those which are purely descriptive, since they are independent of hypotheses concerning genesis. However, valuable information for the classification can be collected by studying the genesis actually taking place. Even so the classification, though consistent with any such hypotheses, should not be used as the criterion of the validity of the latter.

Study of genetic environment is one of the major objectives in investigations carried out on modern sediments. It may be achieved in a variety of ways, each emphasising some particular aspect of environment. These differences in approach can be seen in the trend of work on modern carbonates over the last decade. For example, in his classical study of the Bahaman calcareous sands, Illing (1954) described the component carbonate particles. These were mainly non-skeletal in origin and included ooids, pellets and other accretionary grains, all of which he established to be forming in the area. He discussed the mineralogy of these grains, their shape, size and internal structure, together with their general distribution, and geomorphological setting. He inferred their genetic background from these observations. The importance of the work was the completeness of the description of the grains, though the relationship of these grains to one another was not discussed in great detail. Thus only general environmental predictions can be made for similar grains in ancient environments (Beales 1958).

Ginsburg (1956) studied the environmental relationships of grain size and constituent particles in some carbonate sediments of South Florida. He was particularly concerned with finding parameters of the sediments which could be used for comparison with similar ancient limestones. He noticed that the very different characteristics of some of the sediments could be correlated with local changes in environments, coarse skeletal debris accumulating in reef areas and fine muds in sheltered lagoons. He emphasised the use of parameters that persist laterally and are least affected by these local changes. He traced the history of the use of grain size distribution and the identification of constituent particles and fabrics. Like Illing (1954) he described the grains and their geomorphological background. He found the grains to be largely skeletal, so that their genesis was easily recognised. Also like Illing (1954) he only discussed the general relationships of the grains. However, this was justified by his observation that "no distinct sub-environment could be recognised from the gross-grain size and constituent particle composition". He recognised the importance of organisms whose activities leave their imprint, not only on the constituent grains, but also on the structure of the final sediments. He expanded his study of these early diagenetic effects in 1957 and with Lowenstam (1958) showed how early diagenesis can be a sensitive indicator of sub-environment. Swinchatt (1965) reviews this problem.

Other papers like those by Newell & Rigby (1957) on geological studies on the Great Bahama Banks, by Newell, Purdy & Imbrie (1960) on Bahaman oolitic sand, and, that by Kornicker and Boyd (1962) on the shallow-water geology and environments of the Allacran reef complex of the Yucatan peninsula, all followed similar plans. Some emphasised one or other component and some, the finer detail of the geomorphology.

Cloud and his co-authors (1962) described the calcium carbonate deposition west of Andros Island. They followed the same approach as previous workers by discussing the sediments in relation to their geomorphological background. However, they also discussed the genesis of the sediments from a chemical point of view. This provided the genetic background to the understanding of the chemistry of the sediments described by Illing (1954) and other similar sediments from ancient environments. Such information can be used to interpret palaeoclimate and palaeogeomorphology. Kinsman (1964c) working on the Trucial Coast followed a similar approach to that of Cloud, but emphasised different aspects of the chemistry, particularly of the trace element strontium, as an indicator of environment.

Yet another approach to the study of the carbonate environment which involves the detailed relationship of the different component grains was begun by Imbrie and Purdy (1962) for the Bahamas and was continued by Purdy (1963). Here, backed by complete description of the components, their various attributes were analysed by computer. Thus the different environments could be established by total observed characteristics. This approach has been expanded by Folk and Robles (1964) to establish the genetic relationship of these grains. This was done with detailed grain size and component analysis for the carbonate sands of Isla Perez. Maxwell, Jell and McKellar (1964) did the same for the carbonate sands in the Heron Island Reef, Australia. From these works it can be seen that each component tends to have a modal size which is based on the morphology of the grain and its history. For example Sorby (1879 p.69) noted that the size of the fragments from a shell were controlled by the mineralogy of the shell. Thus the movement of these components will obviously affect the size characteristics of the sediment at any one point. It should be possible to relate this characteristic to the agencies acting in the environment. Both Folk and Robles (1964) and Maxwell et al (1964) were able to show the overall movement of the components and establish their genetic history. This method can only be of use where close sample control exists. Where this does occur the detailed pattern of sediment movement can be inferred.

Irrespective of the specific topics of these studies, all of them follow descriptive classifications. The chemical and/or mineralogical data of the classifications are integrated with theories of genesis and/or sediment movement.

It is sometimes difficult to compare the results of studies of modern carbonates with ancient limestones, because of the problem of classification. This diversity of classifications can be seen in the reviews published by the American Association of Petroleum Geologists (1962). These attempted to clarify just what classifications should achieve. Ham and Pray (p. 2-20) emphasise the blend of descriptive and genetic parameters. Other authors like Plumley, Risley, Graves and Kaley (p. 85-198) dealt with the role of genetic environment. Feray, Heuer and Hewatt (p. 20-33) accepted the importance of all these but stressed the utilitarian aspects. Leighton and Pendexter (p. 33-62), Folk (p. 62-85) and Dunham (p. 108-122) concentrated on the description of the components and their textures. From the latter classifications genetic and utilitarian inferences surely can be drawn.

In this section of the thesis the approach is similar to that of Illing (1954) and Ginsburg (1956) in that it classifies the components descriptively and discusses their distribution. Two investigations were carried out. A general one of the whole of the west Khor al Bazam, and a specific one of the Quala embayment. The general study included the analyses of the percentage composition of the sediments in the seven Wentworth (1922) size grades (Table 4). This data is presented as cross-sectional variation diagrams, which show changes in magnitude of the percentage composition in the sieve grades across the lagoon. These diagrams are similar to those used by Shepard (1956) and Houbolt (1957), but are more detailed.

TABLE 4 Westworth Grade Scale

Granules	4 - 2 mm.
Very coarse sand	2 - 1 mm
Coarse sand	1 - ½ mm
Medium sand	½ - ¼ mm
Fine sand	¼ - ⅛ mm
Very fine sand	⅛ - 1/16 mm
Silt and clay	1/16 mm

In the examination of the sediments of Quala Bay, detailed grain size analyses were carried out, the samples being sieved into ¼ ø intervals. A study was made of the frequency of the distributions of the components in the various size grades. Each component was found distributed differently and the differences were used to indicate the position of the component and its hydrodynamic behaviour.

2. LABORATORY TECHNIQUES

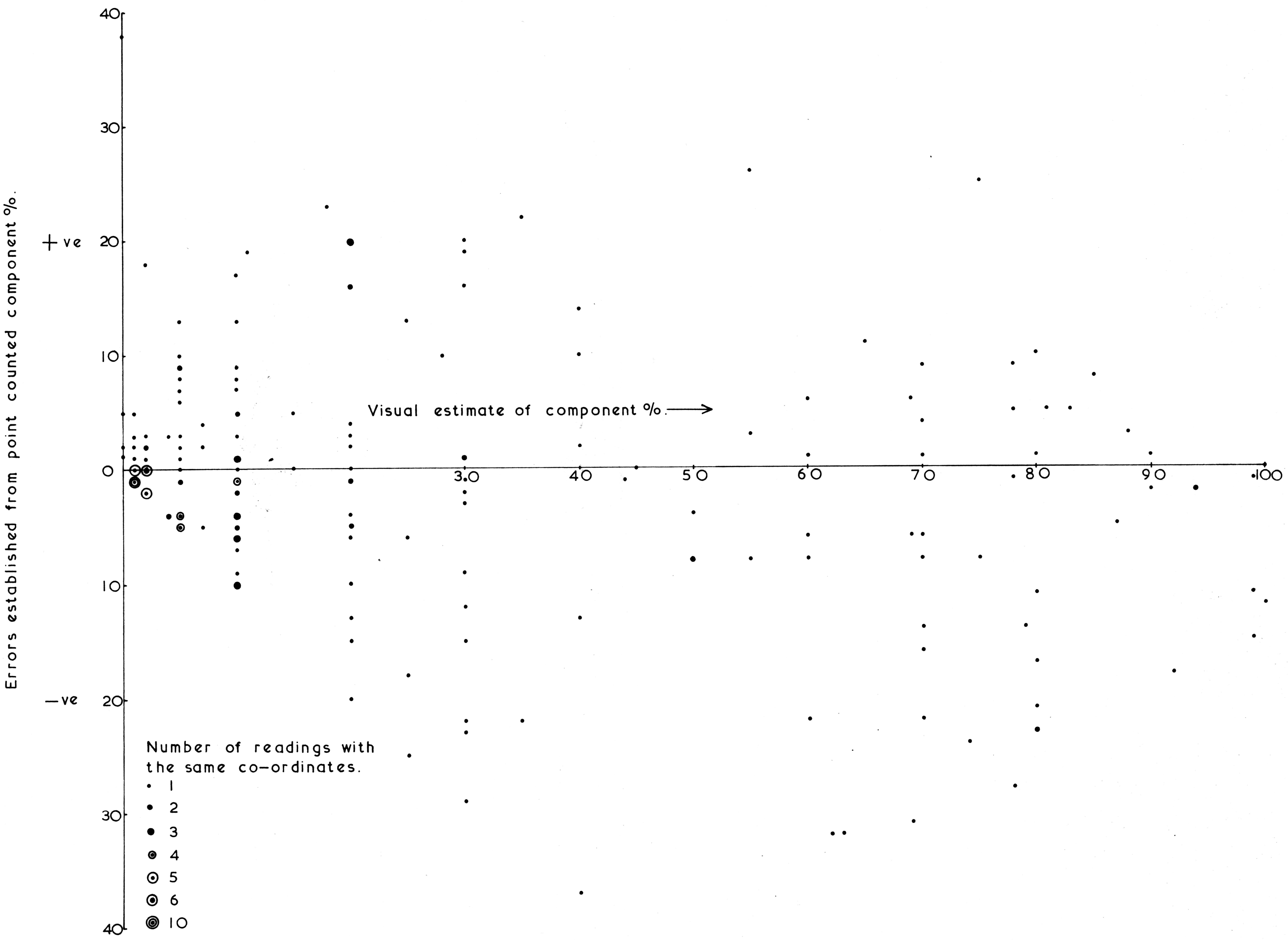
In the first instance, samples were sieved to facilitate identification of the component grains, because it was found the coarser grades obscured the finer ones. Splits were made of the samples by "coning and quartering" (Krumbein & Pettijohn, 1938). A split sample of approximately 30 grams was placed in a beaker of tap water and stirred for some 30 seconds. The sample was then washed with tap water over a 240 mesh B.S. sieve to remove the silt and clay grades. The latter were collected and the water removed by filtering. They were then dried in an oven and weighed. The sand grades of the sample were dried at room temperature, so as not to disrupt any delicate grains and change their appearance. These were then sieved and each sieve grade weighed.

Hydrogen Peroxide was not used to remove the organic matter, because this tended to disrupt cryptocrystalline grains and did not have much effect on the organic matter except to bleach it. Ginsburg (1956) also found a disruptive effect with hydrogen peroxide, as did Cloud (1962), in particular reference to soft faecal pellets. The effect of the organic matter was negligible and did not disguise the overall shape of distribution curves and diagrams.

The various size grades of the samples were examined with a stereoscopic microscope, and the percentages of the component grains estimated. Initially the component grains were point counted. However, this took considerable time, but enabled the development of accuracy in visual estimation. This visual method was used for most of the samples of the west Khor al Bazam, but the point counting method was used for the Quala embayment. It was believed that by the visual method differences in composition between adjacent samples were greater than the experimental errors. It is, after all, the order of magnitude of the components present, rather than some very precise figure, that establishes the overall character of the sediment. As Emrich and Wobber (1963) found, the errors involved in estimating by eye are low. Similarly, the reliability of the method was confirmed by Folk and Robles (1964) using visual estimation on the sediments of the Isla Perez. The approach used on the samples from west Khor al Bazam was, first to identify the components present in the sieve grades, and then to estimate the percentage of each grain type. This was carried out by mentally splitting the grains in the field of view into equal groups. These could be of ten grains, twenty grains, thirty grains, or more, each. Then an estimate was made of the frequency of any one grain in these groups. Thus a grain type occurring once in every ten grains forms ten per cent of the components, whilst a grain type occurring once in every fifty grains forms two per cent, etc. To keep a check on the accuracy of the visual method, randomly picked sieve grades from every other sample across the west Khor al Bazam were point counted (100 to 300 grains). Figure 13 shows the distribution of errors resulting from visual estimation of composition of these checked samples. It conforms approximately with the findings of Emrich _et al_ (1963) and the errors, like theirs, are greatest in the 50% range.

Variation diagrams were produced for the samples collected on traverses across the west Khor al Bazam, (Sheets 4 - 19). These were based on the variations in weight

Figure 13. Errors in visual estimatation of component %.



percentage of the different size grades and the changes in composition within those grades as estimated visually. The diagrams show clearly differences in size and compositional trends across the lagoon. These differences can be seen to coincide with changes in bathymetry and hydrodynamic activity. Minor changes induced by local conditions, or by the technique of measurement, can be seen to be unimportant. Ginsburg (1956, p. 2419 - 2423) discussed this same problem of generalization of environmental properties.

Thin sections were made of a few selected samples to establish the internal texture of the component grains. A variety of cements was tried, one of the most suitable proved to be plaster of Paris. (Tipper 1914).

Plaster of Paris was used because when some conventional resins and plastics set, they contract and so crack the softer carbonate particles. Further, these resins take a long time to set, they are not easy to grind down and tend to buckle when heated for mounting. However, plaster of Paris not only leaves the grains uncrushed, but is easy to mix, sets quickly and is soft to cut and grind. It is also easily differentiated from the sand grains. It is transparent and colourless in polarised light and shows up as a felt of small crystals under crossed nicols. The only disadvantage of the plaster is that its adhesive strength is low, but this can be improved by impregnating with Gum Dammar.

Staining techniques were used on thin sections and individual grains to distinguish calcite from aragonite. Both

Feigl's solution and cobalt nitrate were used but they proved unsatisfactory because of the presence of organic mucilage which interfered with these stains, preventing their action.

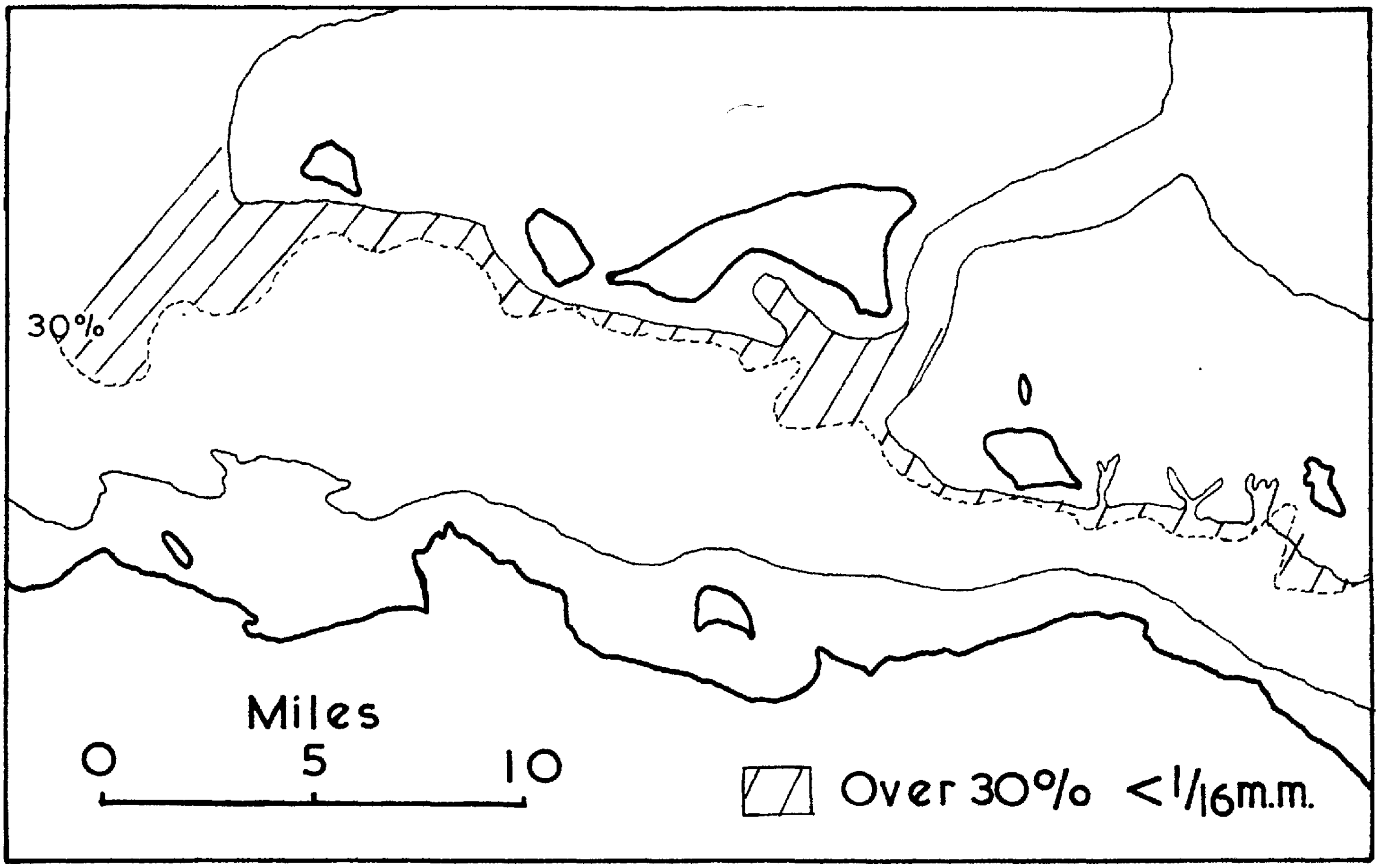
3. GRAIN SIZE DISTRIBUTION OF THE SEDIMENTS OF THE WEST KHOR AL BAZAM.

The variation diagrams (Sheets 4 - 19) show the changes in weight percentage exhibited by samples on the traverses across the west Khor al Bazam. These show that there is a consistent pattern of grain size distribution, maximum changes in this pattern being induced mainly by changes in relief of the sea floor. The sediments of the lagoon are poorly sorted, and away from the influence of the offshore bank and coastal terrace, most of the sediment is in the coarse to fine sand grades (Sheet 4). The sediments tend to be positively skewed and centred round a mode in the medium sand grade.

In the lee of the offshore bank and at the western end of the Khor al Bazam opposite Bazam al Garbi, the silt and clay content of the sediments often rises above 30% (Sheet 4 and Figure 14). This material is probably a product both of transport and deposition of the 'fines' from the offshore bank, and also direct precipitation.

Ginsburg (1956) set the precentage of material of < $\frac{1}{8}$ mm as the most critical environmental indicator in Florida Bay and the adjacent reef tract. These size grades are also sensitive indicators of environment in the west Khor al Bazam, but as the variation diagrams show the percentage < 1/16 mm is

Figure 14



Distribution of sediment with over 30% in silt and clay grades.

even more sensitive. Figure 14 shows sediments with over 30% of the sediment under 1/16 mm. diameter. This distribution coincides with an area of mud mounds fixed by Halodule and Thallasia, much like the mounds described in Florida Bay by Ginsburg (1956).

It is at the edge of the coastal terrace that the $\frac{1}{8}$ - 1/16 mm. sieve size is important. Here it can be seen that 'fines' transported from the terrace collect in the lagoon. However, the percentage of $\frac{1}{8}$ - 1/16 mm. sand falls rapidly across the lagoon away from the shelf. Apart from the variations in the $\frac{1}{8}$ mm. grade and below there appear to be no other patterns of grain size that are immediately significant. The reason for this may be that the Khor al Bazam samples were so widely spaced. The components prove better indicators of environment.

4. COMPONENT DISTRIBUTION IN THE WEST KHOR AL BAZAM

The following major components were identified in the sediments from the area of study. They all constitute more than 1% of the sieve grades. Calcium carbonate grains:

(i) Mollusc shells and fragments
(ii) Ostracod valves
(iii) Foraminifera tests
(iv) Calcareous algae
(v) Coral fragments
(vi) Bryozoan skeletal structures
(vii)) Aggregates

(viii) Faecal pellets

(ix) Unidentifiable particles

Non-Carbonate grains:

(x) Quartz

(xi) Heavy mineral grains

(xii) Unidentified grains which are characteristically sugary brown

(xii) Gypsum

The following minor components were identified. They all form less than 1% of sieve fractions.

(i) Oolites

(ii) Serpulid tubes

(iii) Sponge spicules

(iv) Echinoid fragments

(v) Fish bones

(vi) Crustacean fragments

These lists are similar to those of the components of the sediments of the Bahamas (Illing, 1954, p.17 and p.22), and with those of the sediments of Florida Bay (Ginsburg, 1956, p.2421). There are exceptions however. Firstly, bryozoan skeletal structures occur in greater amounts than in Florida and the Bahamas; secondly, detrital grains of quartz, and other non-carbonates do not occur in Florida or the Bahamas, nor do gypsum crystals.

A. MAJOR COMPONENTS

The distribution of the major components across the west Khor al Bazam is shown on the variation diagrams (sheets 4-19).

To interpret this distribution it is necessary to know whether the components formed in situ, or were transported, or are a result of the mixture of the two. The problem can be generally resolved if the distribution of the grains is compared with the distribution of others which are known to have undergone transport to, or formed in the sample localities. Though not of universal distribution, quartz grains and carbonate pellets partially fulfil this role as markers, and the percentages of other components can be compared with them. The maximum occurrence of these marker grains is restricted to the coastal terrace and the offshore bank. The quartz grains were derived from headlands of Tertiary and Quaternary rocks, while the carbonate pellets were generated in the shoal areas. The size of the marker grains tends to lie between ½ to 1/16 mm., the coarser grains showing the most variable spatial distribution. Their percentages in the sieve fractions often fall rapidly a short distance from shoal areas (Sheet 6). It is possible that the percentage of grains larger than the pellets and the quartz may fall more gently. If this occurs, it can be assumed that although some of the grains were transported others definitely formed in situ. If the gradient of the larger grains is horizontal or rises, these grains formed mainly in situ. If the curve falls more steeply than that of the marker grains, then the larger material was transported, but over a shorter distance.

(i) Mollusc Shells and Fragments

The following molluscs were collected in the Khor al Bazam, and were identified by the Reverend H.E. Biggs, of the British Museum. He is shortly to publish papers on their distribution, ecology and taxonomy.

BIVALVIA

Angulus (Fabulina) rhomboides Quoy and Gaimard
Angulus (Fabulina) immaculata Philippi
Arca plicata (Chemn) Dillwyn
Arca lacerata Linné
Arca tortuosa Linné
Arcopagia robusta Hanley
Brachidontes variabilis Krauss
Cardium sueziensis Issel
Chlamys ruschenbergeri Tryon
Circe corrugata (Dillwyn)
Circe scripta (Linne)
Codakia fischeriana Issel
Corbula acutangula Issel
Corbula subquadrata Melvill
Crenella adamisiana Melvill and Standen
Diplodonta ravayensis Sturany
Diplodonta sp.
Dosinia histrio Gmelin
Dosinia sp.
Grastrochaena cuneiformis Spengler
Glycymeris hoylei Melvill
Glycymeris pectunculus (Linné)
Glycymeris spurcus Reeve

Lima tenuis A. Adams

Lime (Limatula) leptocarya Melvill

Lioconcha picta Lamarck

Laevicardium papyraceum (Bruguière)

Lucina edentula (Linné)

Mactra cf. olorina Phillippi

Macoma jeanae Dance & Eames

Malleus regula Førskål

Meretrix sp.

Motirus irus (Linné)

Nuculana confusa (Hinds)

Phacoides semperianus (Issel)

Pinna sp.

Pinctada radiata (Leach)

Pitaria spp. (incl. *hagenhowi* Dunker)

Quadrans pristis (Lamarck)

Solenocurtus strigullatus (Linné)

Spondylus exilis Sowerby

Sunetta effosa Hanley

Tapes Undulata Born

Tellina pygmaea Leven

Tellydora pellyana A. Adams

Timoclea sp.

Trachycardium lacunosum Reeve

Trachycardium maculosum (Wood)

Venus (Callanaitis) calophylla Hanley

GASTROPODA

Atys cylindrica Jan

Ancilla cinamonea (Sowerby)

Ancilla eburnea Deshayes

Calyptraea pellucida Reeve

Bullaria ampulla (Linné)

Cerithidea cingilatus Gmelin

Cerithium morus Lamarck

Cerithium scabridum Philippi

Cerithium petrosum Wood

Clava (Clava) fasciata (Bruguière)

Columbella sp.

Cypraea caurica Linné

Cytherea sp.

Diodora funiculata (Reeve)

Drupa margariticula (Broderip)

Euchelus bicinctus Philippi

Finella pupoides A. Adams

Finella scabra A. Adams

Laemodonta (Laemodonta) bicolor (Pfr.)

Minolia gradata Sowerby

Minolia holdsworthiana (Nevill)

Monilea obscura (Wood)

Murex (Chicoreus) anguliferus Lamarck

Mitrella (Mitrella) blanda(Sowerby)

Perrinia stellata (A. Adams)

Phasianella nivosa Reeve

Phasianella sp.

Persicula sp.

Pterigia sp.

Pyrene (Seminella) phaula (Melvill)

Retusa omanensis Melvill

Rissoina sismondiana Issel

Rissoina distans (Anton)

Rissoina savignyi Jousseaume

Scaliola arenosa A. Adams

Scaliola elata Semper

Ringicula propinquans Hinds

Strombus sp.

Tricolia foridana Pilsby

Trochus (Infundibulops) erythraeus Brocchi

Turbo radiatus Gmelin

Turbo coronatus Gmelin

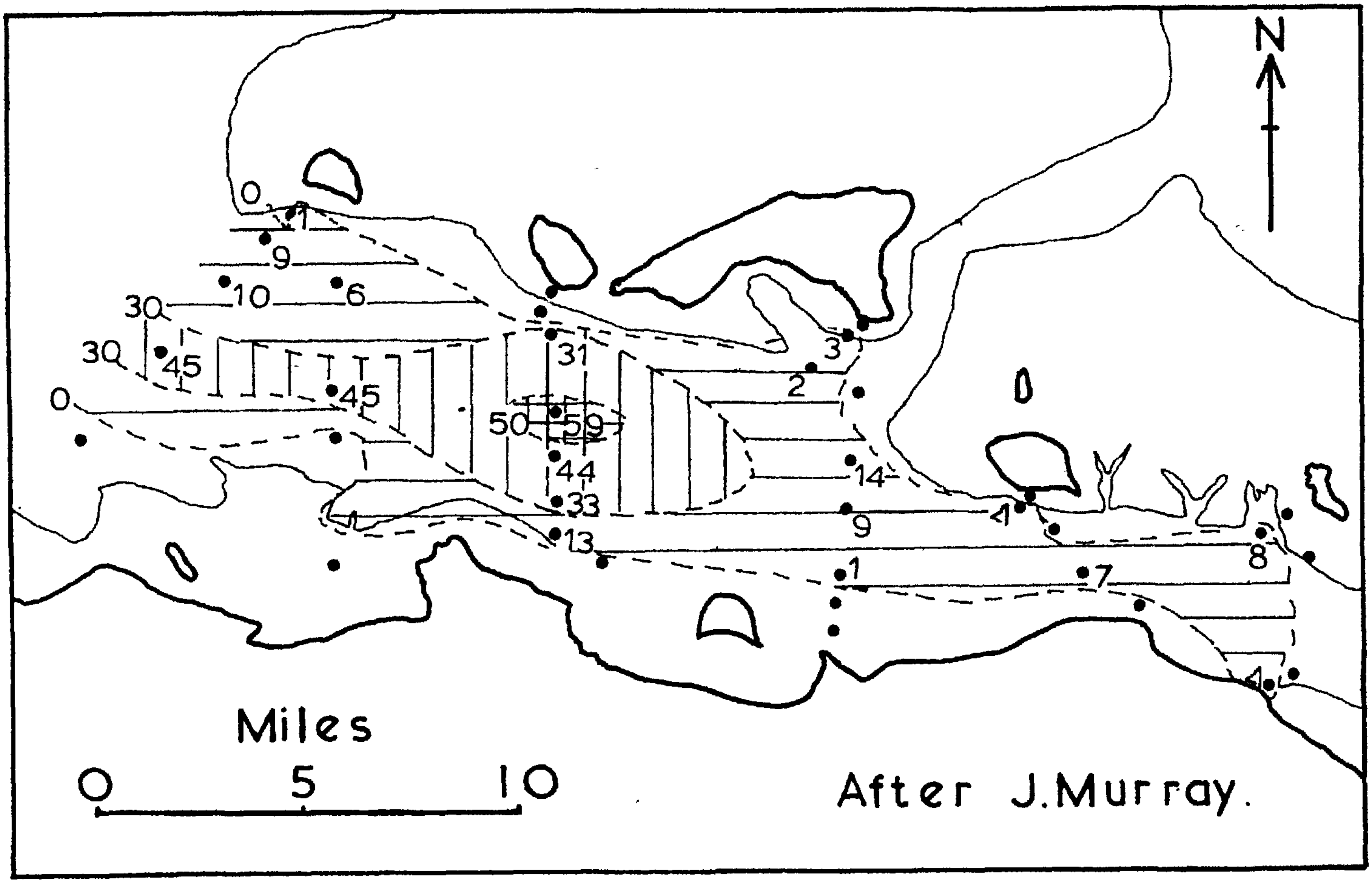
Turitella aurocincta v. Martens

Umbonium vestiarium Linné

Xenophora caperata Philippi

The molluscs are distributed so that the heavy robust forms, mainly gastropods, occur on the coastal terrace and bank, whilst thin shelled lamellibranchs, often still articulated, dominate the lagoon sediments. As Illing (1954, p,18) found, on the interior of the Bahama Bank, these shells were commonly uncoloured or poorly so. It was found that many of the shells were being affected by destructive agents. These included boring and crushing organisms, and the

Figure 15



Distribution of blackened foraminifera expressed as a ratio of black to black plus white.

destructive force of waves. Though boring may be produced by small molluscs, worms and sponges, the most distinctive is that caused by blue-green algae. As Ginsburg (1956) found in Florida Bay, the shells affected by blue-green algae eventually become unidentifiable. This role of the blue-green algae is discussed in more detail in a later section of this thesis. The results of wave action are largely confined to the edges of the offshore bank and the coastal terrace. The crustacea, though varying in species, roam the whole of the Khor al Bazam and offshore bank. Many of them crush and eat molluscs. On the rock platforms, which are covered by filamentous green algae, crabs are particularly active and at low tide the sound of shells being crunched can be heard in every direction.

In the central parts of the west Khor al Bazam, particularly to the west, shells and other carbonate particles may be blackened. Houbolt (1957) noted this blackening in sediments off the Qatar peninsula. Study of the blackening in the west Khor al Bazam suggests that it is a discolouration of the organic matter which is the result of chemical reactions in the reducing zone, a few inches below the sediment surface. All stages of the blackening can be traced from organic matter containing living blue-green algal cells. The blackest grains tend to occur in the centre of the lagoon to the west. Murray (in the press) showed that the ratio of the components of the blackened sand to the components of the unblackened sand is the same. This suggests contemporaneous origin (Figure 15). It has been found that benzene bleaches the black grains. At a few sample localities, particularly on rises on the lagoon floor, instead of being blackened the grains are brown. At present there is no explanation for this.

Using the system outlined earlier, it is possible to interpret the distribution of the mollusc shells. The distribution in the undissected lagoonal area of the east part of the west Khor al Bazam is easy to interpret, but that in the dissected area is a little more complicated. In the coarser fraction of both areas the shells normally occur in abundance over the offshore bank and directly in the lee of it, but fall rapidly beyond. Further away from the bank the shell percentage rises again. This falls to the coastal terrace where it increases yet again. On the bank and terrace the coarse shells and fragments are probably formed in situ and are not being carried into the lagoon. However, the "fines" are removed, and just lagoonwards of the shoals these constitute a high percentage (Sheet 4 and 8). The fact that the quartz falls off rapidly away from the shoals while the shell percentage maintains itself or rises suggests that the molluscs live and die in situ on the lagoon floor. The articulated shells and the lack of abrasion support this theory. The most clearly defined of these environments is the one to the lee of the offshore bank, where molluscan development coincides with the higher percentages of carbonate mud (Sheet 4).

From Khusaifa and Ras al Sehama westwards the pattern described continues in a general way. It is, however, affected by changes in relief of the lagoon floor. Further, the effects of blue-green algae on the sediments of the bank and coastal terrace cause them to recrystallise and to become ultimately unidentifiable. This process of recrystallization is at work on areas of high relief in the mid lagoon, with the result that the apparent molluscan composition falls over these areas.

The highest concentration of shells are found in some beaches where they form nearly 100% of the components in the coarser grades. (Sheet 14 Sample 1). Common to most beaches are the skeletons of cuttlefish.

(ii) Ostracods

A collection of ostracods was made, but these have not yet been identified. In the lagoon samples they tend to be articulated, but in shelf samples they are disarticulated and bored. Their distribution can be clearly seen on the variation diagrams of the west Khor al Bazam traverses. (Sheets 4, 5 and 11). It can be seen that the ostracods are growing in the central lagoon. This tendency is particularly marked in the coarser grades. However, in areas with a high mud content, the finer sized ostracods are evenly spread. (Sheet 13). The high percentage in the muddy areas suggests the "fines" have been derived from the adjacent bank. When this high percentage is compared to the quartz values the interpretation suggests the ostracods are <u>in situ</u>, (Sheet 5). The hydrodynamic difference between the quartz and the ostracods may account for this.

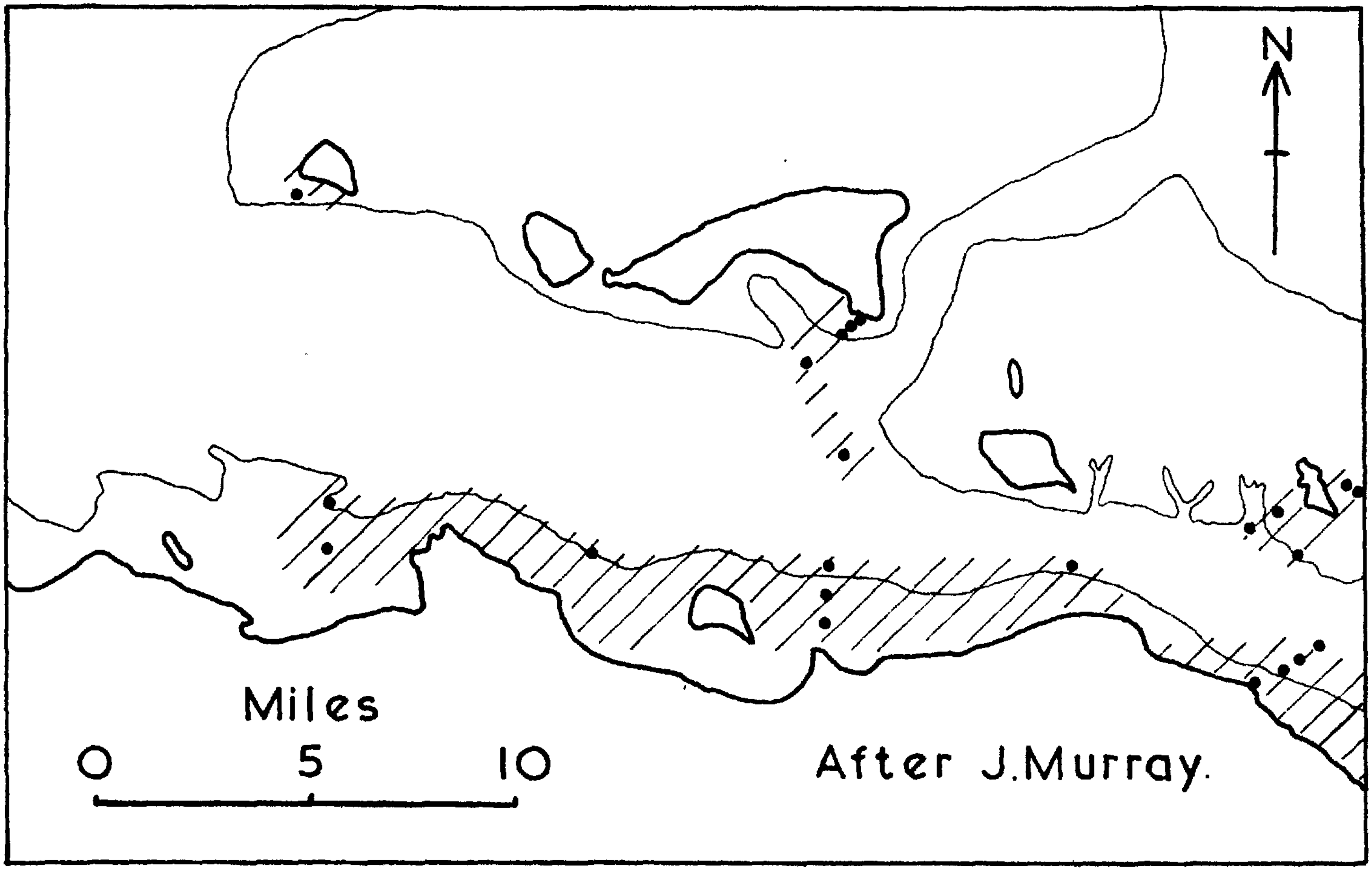
(iii) Foraminifera

J. Murray (Department of Geology, Bristol), identified the foraminifera collected in the Khor al Bazam. His findings are to be published shortly in a paper on 'Foraminifera of the Persian Gulf. Pt. 4. Khor al Bazam'. He found very few living individuals in the samples but variable percentages of the tests of dead individuals. Representatives of the supra-family Miliolidacea make up the major part of the populations, the dominant forms being species of Quinqueloculina, Triloculina and Peneroplids. He showed their areal distribution and suggested that largely they represent untransported death assemblages. He concluded that the foraminifera must be living on the seaweed which had not been sampled.

In the shoal areas around the margins of the Khor al Bazam, the foraminifera tests may be partially or wholly altered by the activities of blue-green algae (Figure 16). Murray found that pitting of the surfaces of the test by algal "attack appeared to be restricted to members of the supra-family Miliolidacea and is particularly common in the peneroplids. It is dominantly found in the larger specimens but is rarely seen in small forms." The process of algal recrystallization, in particular reference to foraminifera, is discussed in a later section of this thesis.

Murray also discussed the blackening of foraminifera. His map of the distribution of this phenomena is shown in

Figure 16



Distribution of foraminifera tests affected by blue-green algae.

Figure 15.

The variation diagrams presented in this thesis support Murray's ideas of growth, death and accretion in situ. The percentage distributions of the various foraminifera are evenly spread over the lagoon, with the 'highs' coinciding with high percentages of mud. (Sheet 4). Comparison of the distributions of other components with those of the foraminifera suggest growth in the lagoon with limited contribution from the banks. In the lee of the banks, however, there is a small proportion of foraminifera arriving from the bank. (Sheet 4).

In the intertidal areas of the coastal terrace, the foraminifera percentages can be quite high but decrease landwards over algal flats. (Sheet 18). Some beaches have high percentages. (Sheet 17).

(iv) Calcareous algae

Large robust red calcareous algae like Lithothamnium sp. and Archaeolithothamnium sp. are living along the reef front of the offshore bank and parts of the edge of the coastal terrace. These undergo rapid recrystallization, and a short distance from their source areas become indistinguishable from other cryptocrystalline grains. Illing (personal communicatio 1966) points out that the calcareous algae Goniolithon is common in the reefs off Qatar. It is probable that this algae occurs widely in the reefs of the west Khor al Bazam.

The smaller green calcareous algae, dominantly Jania, form a more important component. It is these small algae which are the components shown in the variation diagrams in the finer grades of sand. Jania grows in small colonies over much of the coastal terrace, and these are broken up to form rod-like grains. The variation diagrams of this algal detritus shows that its influence begins at the headland west of Mirfa (Map Ref: 3/3/1) and continues to the terrace just north of Bu Shiyarar, a distance of 25 miles. The percentage of the algal fragments falls rapidly lagoonwards and rises shorewards. (Sheet 10).

Like other components, the rods of Jania are subjected to blue-green algal recrystallization but despite this they remain recognisable because of their distinctive shape.

(v) Coral Fragments

It was found very difficult to identify coral fragments with the stereoscopic microscope. In part this was because the grains appear to recrystallize very quickly. Further even where recrystallization has not occurred, the grains abrade readily and thus their characteristic surface texture is destroyed. Both Illing (1954) and Ginsburg (1956 p.2424) used thin sections to identify reef-tract sediments. This was not done in the case of the west Khor al Bazam samples because of the time involved in making a thin section of each sieve grade of every sample. This is the next/logical step to be carried out and it is hoped to achieve this in further investigations of the samples.

Because of this difficulty, many of the components which were classed as unidentifiable on the offshore bank and coastal terrace may in fact be of coralline origin. Offshore bank samples, (these are not shown on the variation diagrams), have high percentages of coral when traced across the bank from the reefs. It is interesting to note that Folk and Robles (1964) working round Isla Perez, were able to identify coral fragments with the stereoscopic microscope. This suggests that in some cases the process of intense recrystallization may be strictly localized.

(vi) Bryozoa Skeletal Structures

Mrs. Patricia Cook of the British Museum identified the specimens of bryozoa. These were:-

Cheilostomata, Anasea *Thalamoporella gothica* var *indica* Hincks., and
Ctenostomata, Carnosa. *Sundanella sibogae*. Harmer

Thalamoporella gothica is very common, and grows as encrustations on the stems of the 'bladder wrack'. It forms a very light cellular structure which accumulates as detritus in the areas of the maximum development of 'bladder wrack'. This is particularly so on the terrace and southern part of the west Khor al Bazam between Mirfa and Khusaifa (Sheets 4, 5 and 6). When the 'bladder wrack' breaks free from the sea floor, it drifts about as 'Sargassum-like' rafts which eventually are washed up on the sea shore. The strandline of all the beaches is lined by the accumulation of this weed which becomes incorporated in the beach ridges as they build seawards. The weed rots in the beach ridges and leaves the

Thalamoporella gothica which in places now forms lenses of 6 inches or more in thickness.

Illing (1954, p.23) also reported the occurrence of this species in the Bahamas, ~~and~~ where it accumulates on spits and beaches.

(vii) Aggregates

In the Bahamas Illing (1954) recognised the following sand sized accretionary grains, all of which occur in the west Khor al Bazam.

6

GRAIN TYPE	COMPOSITION	LOCALITY
a: Friable aggregates	Discrete silt sized particles bound by organic fibres	Grass areas of the lagoon
b: Lumps		
i: Grapestones	Discrete sand sized particles bound by and protruding from an aragonite cement	Lagoon floor coastal terrace and the off-shore bank
ii Botryoidal lumps	As for grapestones, but with polished aragonite envelope which disguises components	Coastal terrace
iii Encrusted lumps	As grapestones, but with surface so bored by blue-green algae and recrystallized as to be unidentifiable except in thin section	Lagoon floor, coastal terrace and offshore bank.

Also recognised in the west Khor al Bazam but not listed by Illing for the Bahamas are:-

c: Worm tubes	Discrete sand sized particles bound by aragonite cement to form tubes.	Coastal terrace and offshore bank.
d: Shell infillings	Discrete sand sized particles bound by aragonite cement and enclosed or partially enclosed by mollusc shells.	Lagoon, coastal terrace and offshore bank.

A detailed description of these components follows.

a) Friable Aggregates:

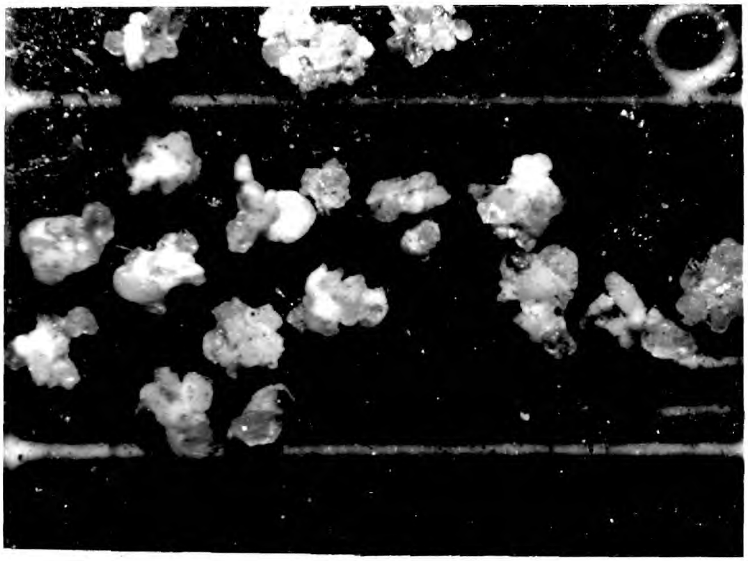
Friable aggregates are composed of discrete silt sized particles. The aggregates are generally lightly bound together by threads of seaweed, algae, or some other organic tissues, (Illing, 1954). The component particles of the aggregates in the west Khor al Bazam are of nearly equal proportions of quartz and carbonate. These contrast with those described by Illing, which are exclusively carbonate. The complete sequence illustrated by Illing of the progressive cementation of these grains to form ovoid grains was not found. However, the two end members were. The uncemented friable aggregates being found mainly in sea grass areas of the lagoon floor and the ovoid grains both there and on the coastal terrace. Friable aggregates can be distinguished from the other aggregates by the size of their components.

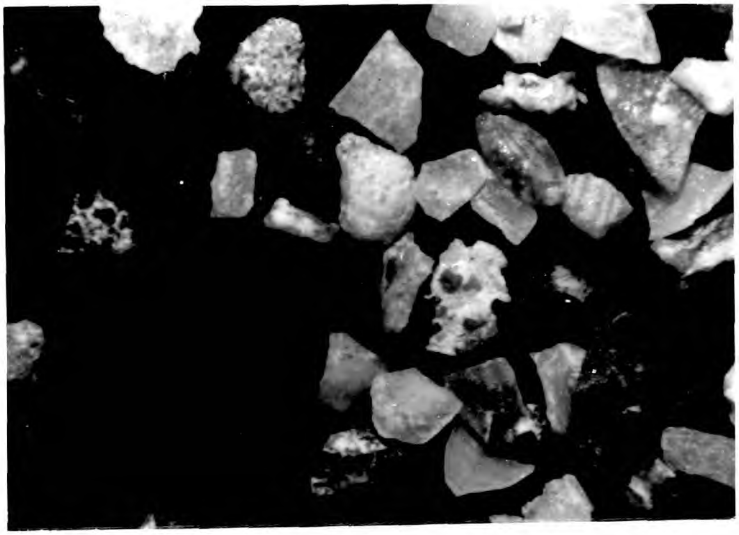
Plate 39

Grapestones (x 15)

Plate 40

Skeletal material and aggregates showing blackening.
(x 15)





(b) Grapestones:

Grapestones are aggregates composed of sand sized particles bound together by an aragonite cement. The component grains protrude simulating a bunch of grapes. The components are mainly of aragonite with up to 20% quartz. (Plate 39). Illing's (1954 p.30) description of the Bahamian examples fits the west Khor al Bazam grapestone. "The cement that joins the grains is finely divided aragonite of varying texture. It forms first around the points of contact, and is friable and chalky white, in contrast to the greasy or matt textured grains. It can be easily scraped off with a pin point, and is composed of aggregated particles of mud dimensions. From its occurrence, it is clear that it is being precipitated from sea-water, yet the particles show no recognizable crystalline shape, and are similar to the material that forms the matrix of the grains themselves. Externally, the chalky white cement is restricted to the crevices between the protruding grains. As cementation proceeds, the cement beneath this surface layer becomes firmer and matt textured. Further grains or small lumps may be joined on by the same sequence of stages. However, the forces of mechanical disintegration prevent unlimited growth and finally all traces of chalky white texture are lost."

In the Khor al Bazam grapestones form both on the grassy lagoon floor, and the shoal areas. In these areas during periods of minimum wave activity the surface is initially bound by an organic slime. The longer the surface is undisturbed by wave action, the better developed the binding. These lightly bound grains then become cemented by aragonite, which appears to be precipitated as a result of the photosynthetic activity of blue-green algae. On the shoal areas in intertidal waters this cementation is added to by aragonite precipitated by evaporation. In a sense this later is analogous to beach rock cement described in Florida by Ginsburg (1953). This partially cemented surface layer is easily broken into small lumps, their sizes being related to the intensity of the waves. Thus in grass areas of the lagoons, the aggregates tend to be on the average larger and more irregular than those of the shoal regions.

In thin section, it was found that the initial cement binding the grapestones is of darker colour, and is apparently coarser grained than the final cement. As the process proceeds the textures of the cement and the component grains become indistinguishable in texture. Purdy (1963) remarks on a similar sequence in the Bahamas. Very few of the grapestones were found bound by foraminifera as described by Baars (1963).

In the west Khor al Bazam the occurrence of acicular aragonite crystals as a cement in the voids of grapestones is rare, but it does occur. A similar development of crystals sometimes occurs below the intertidal level, and Kinsman (personal communication) found it in the base of corals from the Abu Dhabi area.

Often some of the component carbonate particles are blackened but are bound by white aragonite cement, (Plate 40). Occasionally the cement itself is blackened. As with the molluscan shells previously described, this blackening is largely confined to the lagoon samples, and follows the pattern shown in Murray's (in the press) Figure 16.

(c) Botryoidal Lumps:

Botryoidal lumps are like the grapestones in that they are composed of discrete sand-sized particles. However, they differ in that they are covered by a sheath of polished aragonite. As with grapestones, the mamillated surface of these grains is grapelike, hence Illing's term botryoidal, (resembling a bunch of grapes). In the west Khor al Bazam they do not grow larger than about .599 mm. in diameter. The smaller the grain, the more complete the cover and the better the polish. Botryoidal lumps represent grapestones that, by a process similar to oolite formation, acquire successive coatings of aragonite, which eventually disguise the component grains and infill the cracks between them (Plate 41). These lumps form in the shallow and intertidal waters, which are the highest energy environments of the west Khor al Bazam.

(d) Encrusted Lumps:

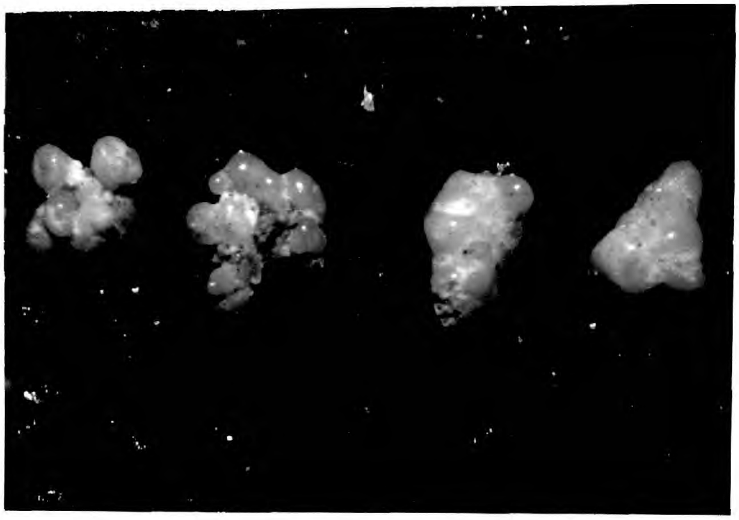
Encrusted lumps are grapestones with surfaces that have been modified by intense algal activity. The process of recrystallization so alters the surface that it ultimately becomes impossible to distinguish it from other amorphous grains. (Illing 1954). They are most abundant in the areas

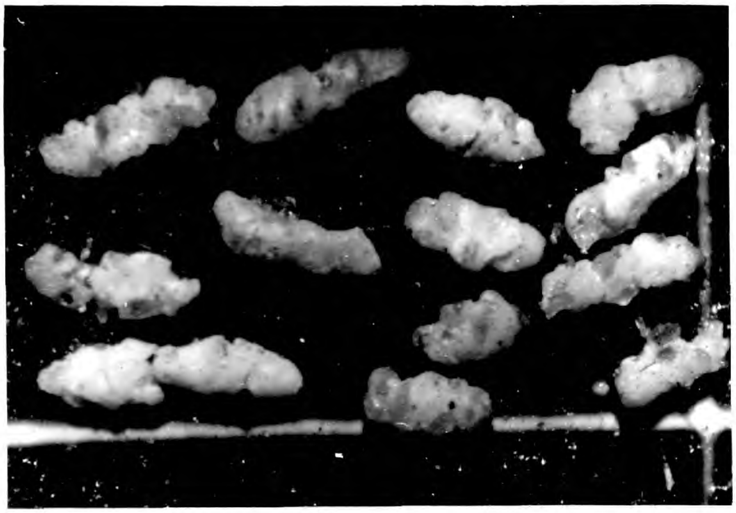
Plate 41

Sequence of gratestone to botryoidal grains. (x 20)

Plate 42

Partially abraded ellipsoidal pellets. (x 20).





of greatest development of 'bladder wrack'.

(e) Worm Tubes:

Worm tubes are the cemented walls of worm burrows. When fresh they are easily distinguished by their shape, but if they are broken and abraded, it becomes increasingly difficult to separate them from grapestones, into which they ultimately merge.

Normally the thickness of the wall of the worm tube is formed of no more than three layers of sand grains. Other tubes do occur that can have walls over two centimetres thick. These probably are the work of lamellibranchs or arthropods. The tubes, when broken free from reworked intertidal sand, often litter the beach.

(f) Shell Infillings:

Shell infillings are the cemented aggregates that accumulate in the protection of shells. These, like the worm tubes, can be an important source of grapestones. When freshly formed they are easy to identify but if broken, abraded or recrystallized, it is hard to establish their origin.

The friable aggregates, grapestones, botryoidal grains, encrusted lumps, and shell infillings are all represented as aggregates on the variation diagrams. If these are studied, using quartz and pellets as marker components, it can be seen that the aggregates formed on the lagoon floor and on some of the adjacent shoal areas, (Sheets 4, 5 and 6).

Material from the shoal areas is not transported far into the lagoon.

Samples across the algal mats show that, although aggregates are forming in front of them, they are not transported across them, (Sheets 16 and 18). The percentage of aggregates decreases sharply landwards, but the old frontal algal mats, now buried, show a higher proportion. The distribution of aggregates can be seen to be variable in all the beaches between Khusaifa and Mirfa. A more exact discussion on these aggregates of the intertidal zone is given in a later section. This results from the detailed study of the area east of Quala.

(viii) Pellets

There are three types of pellet forming in the west Khor al Bazam. They range in size from 1 mm. to 1/16 mm. and may be divided into:-

(a) Cylindrical and ellipsoidal (Plate 42)
(b) Spherical (Plate 43)
(c) Irregular (Plate 44)

(a) Cylindrical and Ellipsoidal Pellets

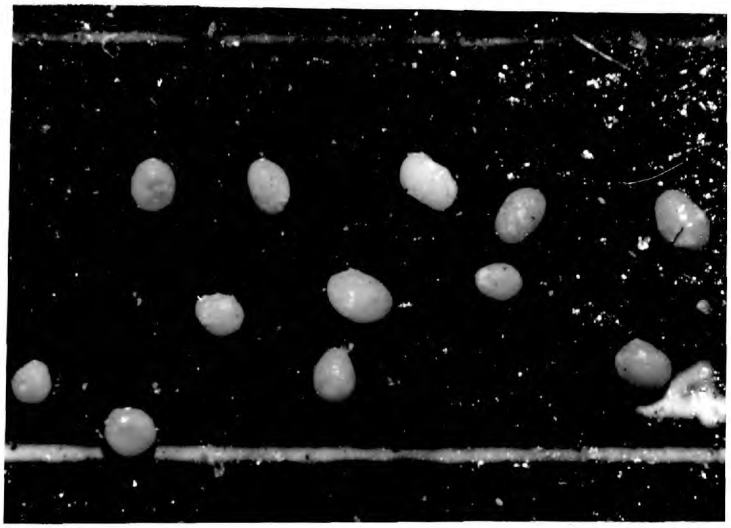
Cemented ellipsoidal, and cylindrical pellets of aragonite mud are rare in the west Khor al Bazam samples. They appear to be faecal in origin and may be produced by the myriads of burrowing worms in the sediment. Certainly pellets have been found in the guts of some worms. Alternatively, some may be excreted by molluscs. Both

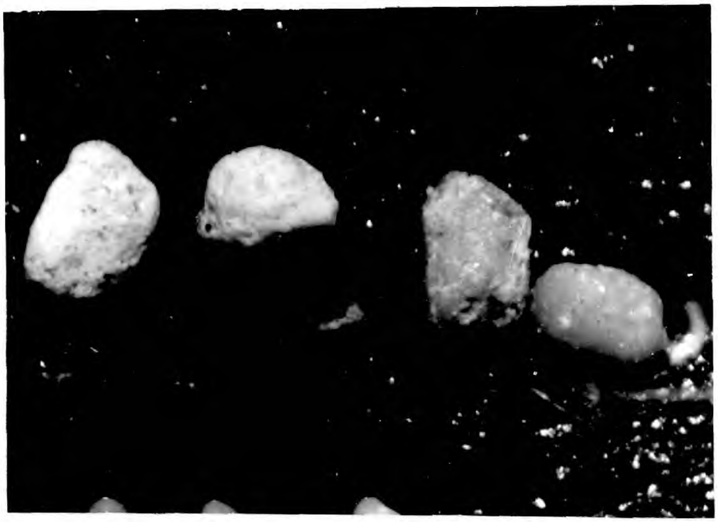
Plate 43

Spherical pellets (x 20)

Plate 44

Irregular pellets. (x 20)





Kornicker and Purdy (1957) and Folk (1964) found that the gastropod, *Battilaria minima*, a species of cerithium produces pellets similar to the ones observed in the Khor al Bazam. Whatever their origin, these pellets are initially very soft, like those described by Illing (1954, p.24). It is reasonable to suppose if they are subjected to any violent wave or current movement, they are easily disrupted. If conditions are quiet, the pellets cement up and harden. In the Bahamas Illing showed this hardening to be very rapid. The fact that few pellets occur in the Khor al Bazam and those which do are so soft, suggests that in this region the hydrodynamic environment is too violent to allow many to be preserved. The surface of some of the grains suggests that during cementation they were abraded. (Plate 42).

(b) Spherical Pellets

Spherical pellets are distinguished from the faecal pellets by their high sphericity. This type of pellet is more common than the faecal pellets in the west Khor al Bazam. They are normally confined to shoal areas or close to them, as the Quala embayment. They may have three possible origins. They may represent material recrystallized by blue-green algae; be derived from broken faecal pellet fragments; or be comparable to Illing's (1954) friable aggregates.

(c) Irregular Pellets

More irregular and consequently less readily identified pellets also occur in the lagoon. They are normally classified as unidentifiable grains except where formed into near perfect ellipsoids or ovoids.

Since as already mentioned the spherical and faecal pellets are not transported far into the lagoon, they form valuable marker components. The relative rareness of pellets in the lagoon may be because they have been destroyed. Some, however, may have been incorporated in aggregates. Those that remain as discrete grains are restricted to the offshore bank and terrace edges. They usually have an unpolished surface and may often be discoloured.

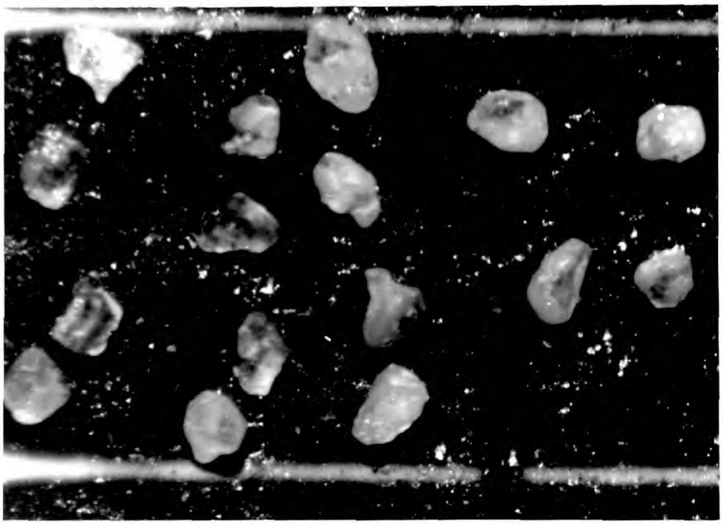
Solution of all the pellets with hydrochloric acid leaves a mucilagenous sludge which often contains cells of blue-green algae. The process by which the pellets are hardened may be related to the organic matter they contain, particularl if it includes blue-green algae (see later section).

(ix) Unidentifiable Grains

There are a number of unidentifiable grains of extremely variable appearance and probably diverse origins. It seems that the highest percentage of these grains are products of the recrystallization of other carbonate grains. The exception to this are the materials occurring in the finer grades. These may represent disaggregated or poorly formed pellets. The unidentifiable material is often blackened. This is particularly marked in the western part of the west Khor al Bazam, where the blackening appears to be

Plate 45

Quartz with carbonate jackets. (x20)



the result of a discolouration of organic mucilage.

The distribution pattern of the variation diagrams shows that in the finer grades of sand the unidentifiable material has an evenly spread high percentage over the lagoon but tends to fall on the coastal terrace (Sheets 4 and 6). In the case of the coarser sand, the unidentifiable material is concentrated on the edges of the shoals, (Sheet 4), and in areas of high relief in the lagoon, (Sheet 11). There are exceptions, but these may be areas where local conditions encourage recrystallization. Certainly, apart from the disaggregation of pellets in the finer grades, the distribution of this component favours the idea that recrystallization and precipitation occur over shoal areas. This is where the blue-green algae are particularly active, as is evidenced by the intense pitting of the surface of the grains.

(x) Quartz Grains

Quartz grains, though they can be of eolian origin, appear to be derived largely from outcrops of Tertiary and Quaternary rocks. Some of these rocks crop out beneath the low water mark, but, from the distribution of the grains, this appears unlikely to supply much detrital quartz. Most of the identified outcrops lie above the low water mark on the coastal strip and on the offshore bank. If it is assumed that this is the source area, then quartz grains can be used as a marker component. Thus the variation diagrams show a rapid decrease in quartz percentage away from the shoal areas, particularly in the fine to medium grades (Sheet 5). The finer grades are more evenly spread and hence may be transported more easily.

The surface of the quartz grains often have a partial carbonate coating, (Plate 45). This bears out Illing's hypothesis that once a sand grain exists in a carbonate province, then more often than not it starts accreting until an optimum size is reached. This is controlled by the hydrodynamics of the environment. The west Khor al Bazam grains tend to have thicker carbonate jackets in shoal areas and thinner ones in the lagoonal areas. The development of these jackets was studied in the Quala embayment and is discussed later. Freeman (1962) discusses similar jackets forming in the Laguna Madre, Texas.

(xi) Heavy Minerals

Heavy minerals, like the quartz and sugary brown grains, are largely derived from the Quaternary and Tertiary rocks. If a heavy mineral analysis is carried out, the distribution of these grains may prove an extra guide to sediment movements in the lagoon and on the shoals.

(xii) Unidentified Grains Which are Characteristically Brown

Sugary brown grains composed of stained quartz, calcite and felspars are widespread but not abundant. They are unimportant except that they parallel the quartz distribution and hence probably have the same origin.

(xiii) Gypsum

Unlike the previously described grains, gypsum forms in the sediments after deposition. The occurrence of gypsum has been described in some detail in the chapter on the geomorphology. Two cross-sections across algal flats are shown in the variation diagrams of Sheet 16, Traverse 3 and Sheet 18, Traverse 5. Gypsum occurs within the granular grain size. At the front of the algal mat the gypsum is most abundant in the coarser grades, and is rare in the finer grades. At the back of the mat the gypsum mush includes some of the finer grades. This may be because solutions of seawater are of high concentrations at the back of the mats, favouring the formation of larger crops of small crystals.

B Minor Components:

(i) Oolites:

Oolites were recognised in thin sections in sediments from one or two localities on the shelf. It is improbable that they formed there and it is more likely that they are derived from Quaternary outcrops. Skipwith (personal statement) found much the same distribution adjacent to Quaternary headlands of oolitic rocks in the east Khor al Bazam.

(ii) Serpulid Structures:

Serpulid structures form accretionary nodules of up to 1 foot or more in diameter on the intertidal flats and the shoals. Specimens are at the British Museum awaiting identification. These nodules are colonised by gastropods, lamellibranchs and barnacles.

(iii) Sponge Spicules:

Sponges grow in abundance in parts of the 'bladder wrack' weed-zone. Spicules released by the decay of sponges are present in the finer grades of sand and dirt.

(iv) Echinoid Fragments:

Echinoids are common. They are of the flattened sand dollar type in the lagoons, but are of the regular type in the reefs. Their fragmented skeletons are so quickly dispersed that they do not form an important constituent of the sand.

(v) Fish Bones and Teeth

A few fish bones and teeth were found in one or two samples.

(vi) Crustacea:

Though living crustacea are common, their skeletal remains are quickly fragmented and dispersed, so that they locally form a minor constituent of the sediments. Barnacles colonise the serpulid nodules but otherwise they are rare. They include Chthamulus cf. Hoelc and Banalus Amphitrite Darwin.

CHAPTER IV

DETAILED DESCRIPTION OF THE QUALA EMBAYMENT SEDIMENTS

1. INTRODUCTION

At map reference 1/4/H the headland of Quala and the island of Thimairiyan project into the Khor al Bazam enclosing a small bay. This is the Quala embayment. It is some two miles wide at its mouth and narrows in the south-east to a small creek. This connects around the south end of Thimairiyan with the coastal terrace and the lagoon south of Bu Shiyarar (1/5/H). The map (Sheet ~~X~~ 20) , was traced from an aerial photograph (Plate 4) and shows the relationships of hills of Tertiary rock, sabkha and algal flats within the embayment.

The bay forms part of the coastal terrace and its mouth is marked by a break in slope which lines the edge of the terrace. The bay is almost entirely intertidal, except in its outer part, adjacent to the terrace edge. The lagoon in front of the terrace is between 10 and 15 feet deep. At either side of the bay the headlands consist of poorly cemented Tertiary sandstone. They are some 50 feet high and dissected by radiating wadis. These headlands reach to within ½ a mile of the terrace edge and it is probable that the area directly in front of them represents a platform cut across them by marine erosion. On their landward side, evidence from aerial photographs shows that the headlands have acted as the loci for spit accretion. Both started as islands, but Quala is now joined by a sabkha to the mainland and Thimairiyan appears to be following suit.

In the eastern part of the bay there is a small creek, not more than 3 feet deep at low tide, which drains the bay and is connected with the lagoon south of Bu Shiyarar. This creek forms the axial channel of a low northeast-southwest trending delta which lies on the east side of the bay.

The inner intertidal flats are lined on their shoreward side by algal mats. The flats to the west are protected on their seaward side by angled bars. Around the perimeter of the bay at just above the high water mark are a series of narrow beaches and low vegetated dunes which extend inland for a hundred yards or so. Behind them is a wide Sabkha plain.

The bay faces the prevailing wind direction and consequently the direction of heaviest seas. Thus waves break against the headlands eroding the sandstones to add quartz grains to the local beach sands. When an onshore gale coincides with a high tide, the embayment acts as a funnel to the sea, which floods onto the Sabkha to the south. When the tide changes and the wind diminishes this water is able to escape seawards again along much the same path. Wave action coupled with longshore drift forms the angled bars.

The flood tide moves gently into the area over a wide front, being more a passive rise in sea level rather than a tidal current. However, the ebb tide current tends to be channelled and is responsible for the formation of the delta and its axial creek. All the sediments within the bay must either have formed within it or have come directly from the seaward. The peninsulas act as barriers to regional long shore drift because the onshore wind produces waves that are directed down either side of the headlands but not round them. For this reason then, the study of the sediments of the region is simplified. The sediment rests in varying thicknesses on a series of cemented layers. These have flat upper surfaces, irregular lower surfaces, and are composed of sediment similar to that of the present embayment. They are probably beach rock crusts formed at low tide in the hot summer months similar to those of Florida (Ginsburg, 1953).

Sediment samples were collected at all the localities marked on the map (Sheet 20) and were positioned by dead reckoning. The collection took place over a period of 4 days, a short time after a violent onshore gale. The specimens were initially examined in the field with a stereoscopic microscope and the major components, as listed in the earlier sections, identified.

The samples were prepared in the same way as the main lagoon ones, but were sieved into $\frac{1}{4}$ ϕ intervals. All the sieved samples were examined, and selected ones giving a good spread over the embayment were point counted to establish their composition.

The sediment of the bay was found to be largely of carbonate sand but increasingly high percentages of quartz occur nearer and adjacent to the headlands of Tertiary sandstone. Caught up with the sediment are quantities of sand size blebs of organic matter which appear to be mainly cells of blue-green algae invested in mucilage.

One of the commonest components is aggregates which in thin section can be seen to be composed of some 60% carbonate pellets, 20% quartz grains and 20% carbonate cement. It was in an attempt to discover the origin of these grains that the sampling programme was extended so that a wide range of specimens could be taken back to the laboratory and examined in detail.

It is apparent that although the aggregates are composed of a ratio of 3:1 of carbonate pellets to quartz grains, the ratio of discrete unattached carbonate pellets to discrete unattached quartz grains, in the sediments is the reverse and is 1:3. (Figure 17) Thus, if the aggregates form in the embayment then the process by which they form is selective and is more likely to cement aragonite pellets together than quartz grains. This is in spite of a preponderance of quartz grains in the sediment.

To discover the relationship of the aggregates to the quartz grains and the aragonite pellets, a series of maps and diagrams were drawn up on the basis of the sieve analysis and point counting. The maps, (Figures 18, 19, 20 and 21), show the number percentage of the aggregates, quartz and pellets in the different size grades of the sediment. The

Figure 17

Ratio of aggregate to quartz to pellet at Quala.

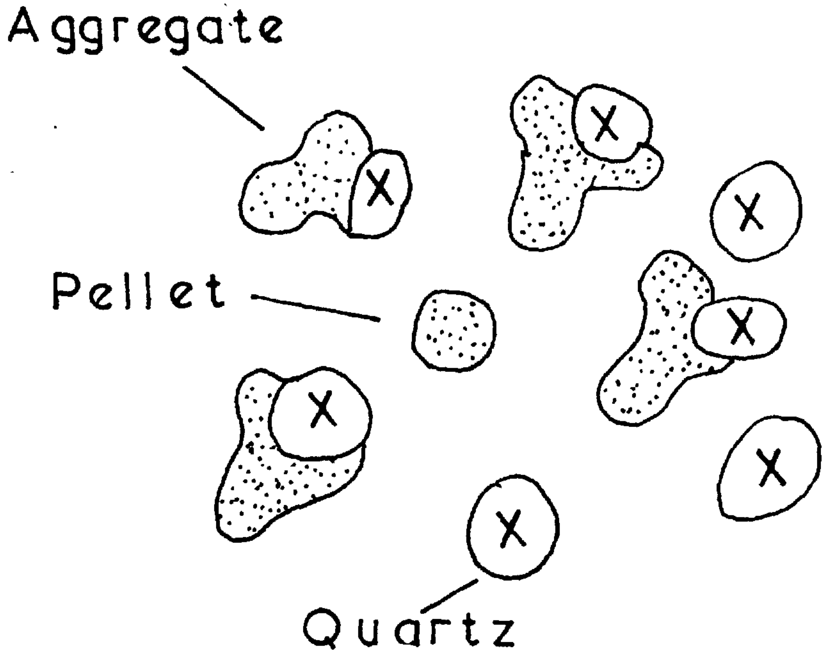


Figure 18

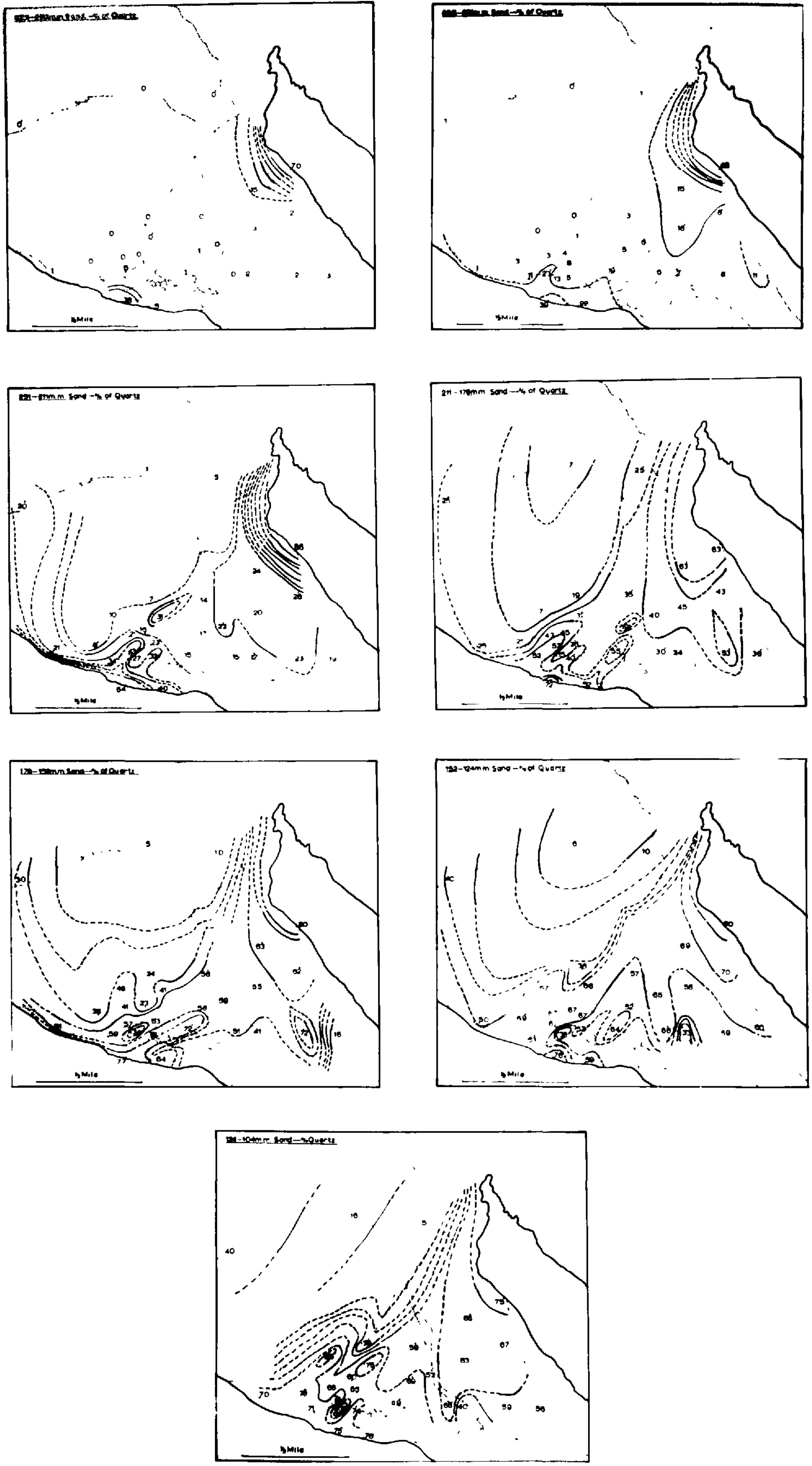

[illegible] Sand — % of Quartz
[illegible] Sand — % of Quartz
251—211m.m. Sand — % of Quartz
211 - 178mm Sand — % of Quartz
178—150mm Sand — % of Quartz
152—124mm Sand — % of Quartz
124 - 104mm Sand — % Quartz
½ Mile

Figure 19

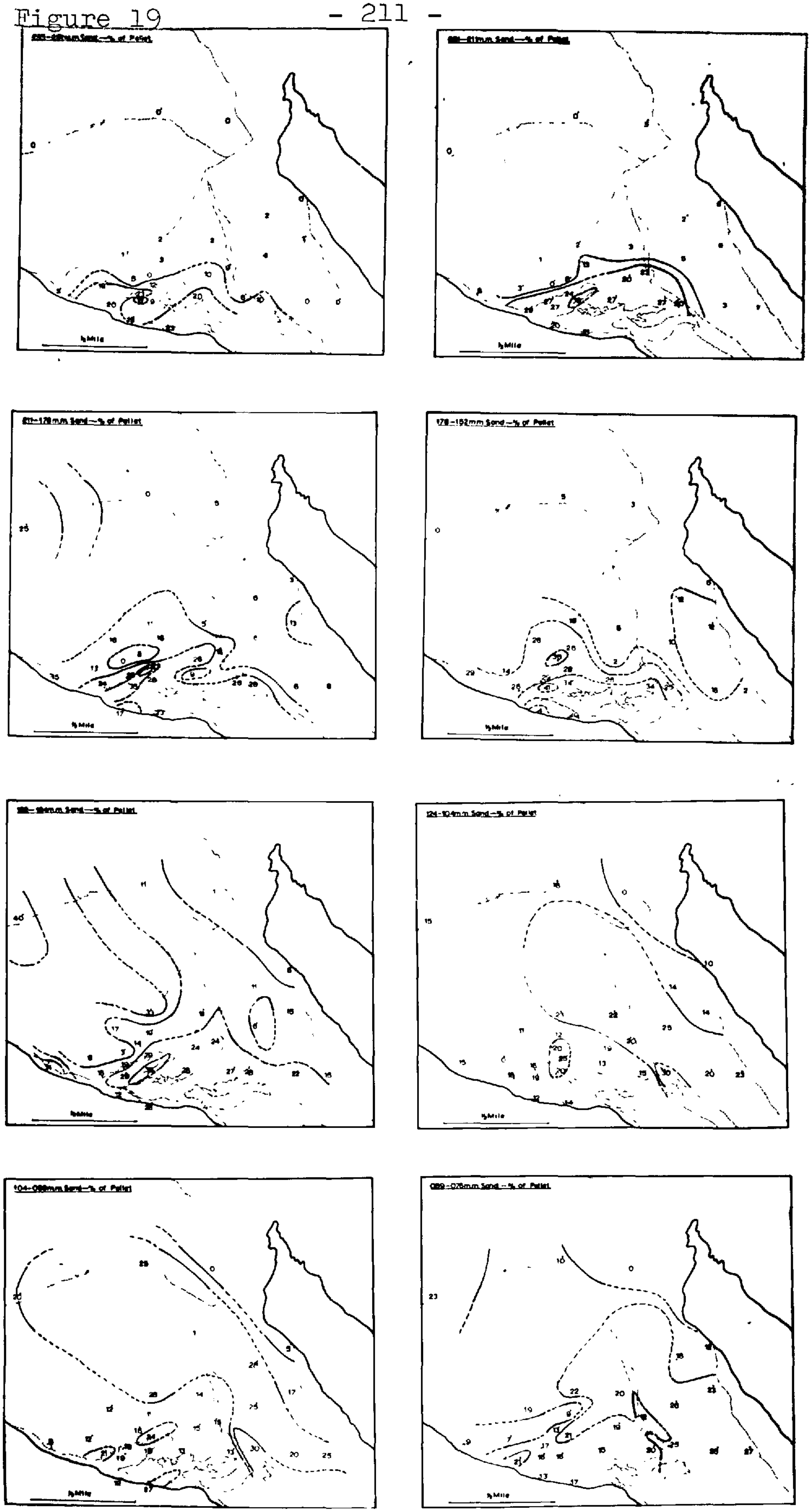
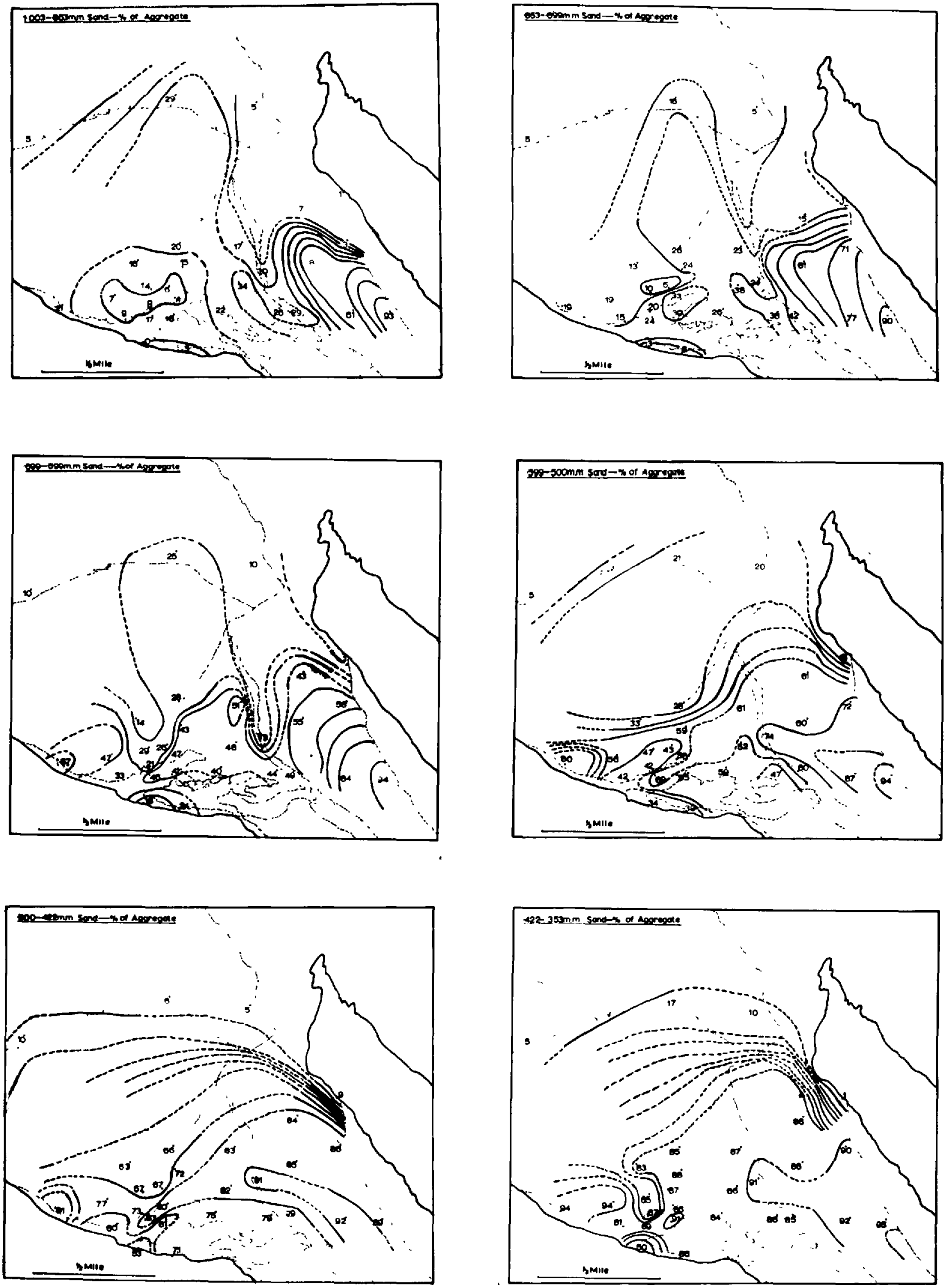

295-250mm Sand—% of Pellet
250-211mm Sand—% of Pellet
211-178mm Sand—% of Pellet
178-152mm Sand—% of Pellet
152-124mm Sand—% of Pellet
124-104mm Sand—% of Pellet
104-089mm Sand—% of Pellet
089-076mm Sand—% of Pellet
½ Mile

Figure 20



1.003–.853mm Sand—% of Aggregate

.853–.699mm Sand—% of Aggregate

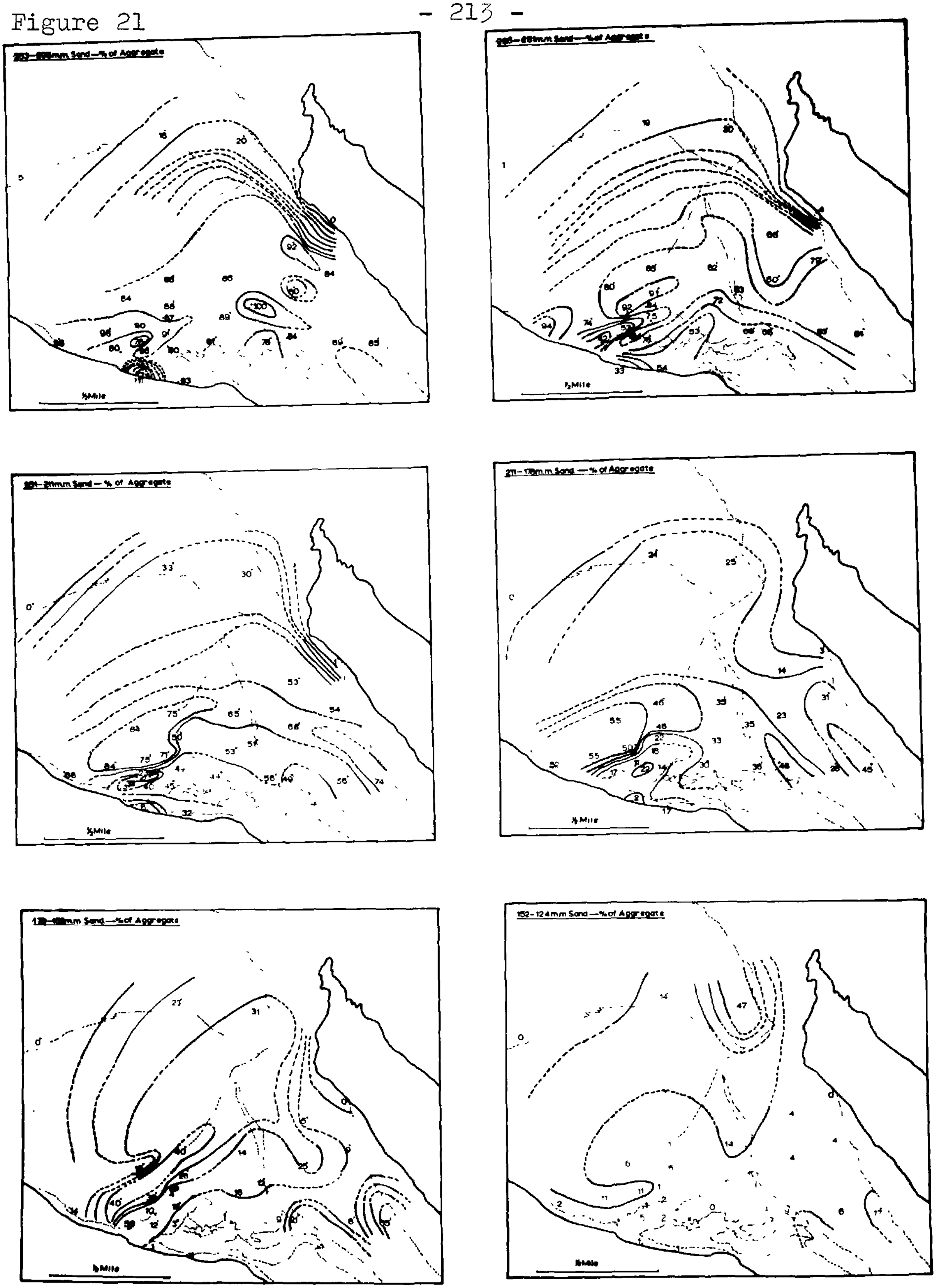
.699—.599mm Sand—% of Aggregate

.599–.500mm Sand—% of Aggregate

.500—.422mm Sand—% of Aggregate

.422–.353mm Sand—% of Aggregate

Figure 21



353–295mm Sand—% of Aggregate

295–251mm Sand—% of Aggregate

251–211mm Sand — % of Aggregate

211–178mm Sand — % of Aggregate

178–152mm Sand —% of Aggregate

152–124mm Sand —% of Aggregate

dots and numerals on the maps denote sample stations and the percentages of the particular grain type in question. The isopleth lines are interpolated and have been drawn at 10% intervals. The continuous lines represent percentages deduced from both mathematical and geomorphological evidence, broken lines representing percentages deduced from geomorphological evidence and limited mathematical evidence. The percentages are those for the particular sieve grades in question, and not of the whole sample. Thus, the maps are an expression of the changes of the ratios of the different grain types in each sieve grade. This method reflects changes of population rather than grain size. If the components at each grain size had been plotted as percentages of the whole sample the patterns would only be slightly different since the grain size distribution is much the same over the whole bay.

The regional spread of a component of a given grain size is related to: (i) the availability of the component in that size at its source; (ii) its density; and (iii) its resistance to abrasion, (Rubey, 1933).

The pattern of the distribution of a component of any one grain size reflects the action of the last agent that was able to move it. For example, a heavy storm may move a sand of specific size range and re-deposit it some distance from its source. Quieter wave movement then shifts the finer grades of sand, but leaves the coarser material behind as a lag deposit. The coarse material of the lag is evidence of former storm action, and the distribution of the finer sand reflects quieter conditions. This principle is applied to the interpretation of the distribution maps, and an attempt is made to relate the pattern to the agents which acted in the environment.

2. QUARTZ DISTRIBUTION

Quartz is supplied from the Tertiary rocks of the peninsula of Quala and the headland of the island of Thimairiyan. Adjacent to the peninsulas, the beaches and intertidal flats are composed of nearly 100% quartz sand which drowns any carbonate. Traced into the bay the percentages of quartz decrease and more and more grains acquire carbonate jackets (Plate 45). Many of these jackets show one or more projecting hemispheroids of carbonate and the process by which they form appears related to that which produces the various types of aggregate discussed earlier.

Tracing the diagrams (Figure 18) from the coarser grades to the finer ones, it can be seen that initially the coarsest material (.353 - .295 mm.) hugs the coast as it moves southwards along the edge of the bay. This distribution is probably the result of wave induced longshore drift. In the grades .295 - .251 mm. the quartz grains migrate into the bay; to the west this takes place north-eastwards along the angled bars and to the east in a general southward direction across the intertidal flats. Evidence of this is shown by the tongue shaped isometric lines which correspond to the higher percentages of quartz, and which, undoubtedly, are formed by longshore drift.

For the grade .251 - .211 mm. the map shows how the quartz is evenly distributed over the eastern bay, but does not extend into the southern section, whilst to the west the angled bars are still controlling the pattern. Quartz grains of this grade are also found at the edge of the coastal terrace where they are moving east from Quala, whereas the grade .211 - .178 mm. has much the same distribution but with higher percentages. For grade .178 - .152 mm. the localised tongues of high percentage which project from the shoreline are even more marked. This suggests that long shore drift has an even spread except for the southeast corner, where percentages are low. The grade .152 - .124 mm. shows a deterioration of the tongued distributions and this suggests that the grains are now small enough for tidal currents to exert their influences, and thus disrupt the pattern of wave deposited grains. In the coarser grades however, ebb tide movements have been important, and seem to have inhibited the transport of wave carried quartz southeast into the neck of the bay. Grade .124 - .104 mm. has an even more disrupted pattern, suggesting that the ebb movement down the channel pushed back the quartz percentage isometric lines.

In summary, the evidence suggests that onshore waves and their longshore element confine the quartz to the embayment where they control its movement. Tidal movement is locally important along the creek where it inhibits the movement of quartz southwards. Where the peninsula is close to the edge of the coastal terrace, the quartz percentages rise seawards, indicating that refracted waves carry the grains eastwards over the edge of the terrace.

3. PELLET DISTRIBUTION

Pellets in the Quala embayment take two major forms: faecal pellets and ovoids of indeterminate origin. The faecal pellets are quickly cemented and apart from small percentages of fresh grains become increasingly difficult to distinguish from the other pellets. Consequently, no differentiation is made on the maps between the two forms.

Hydrodynamically, pellets and quartz of the same size have different properties. The pellets are composed of aragonite, which has a higher density than quartz, but because they have a high internal porosity, their effective density is probably lower. This difference in properties and the lower availability of the pellets induces a different pattern in the percentage distribution on the isometric maps.

On the distribution maps, (Figure 18), it can be seen that the coarser pellets (.295 - .251 mm. and .251 - .211 mm.) are confined to the southwest of the embayment, and the pattern of the higher percentages mirrors the angled bars as did the quartz. In the grade .211 - .178 mm., the high percentage tongue shaped isometric lines are no longer confined to the west, and one now makes its appearance to the east. Provided the source of the pellets was the same, this indicates that in the coarser grades the pellets were carried landwards and were not transported by ebb movement northwestwards. However, in this grade, the ebb current is strong enough for a short distance, to retransport the wave deposited pellets and to carry them seawards.

Offshore to the west, the higher percentage suggests a west to east movement of pellets in front of the peninsula. This is the result of wave induced longshore drift. Grade .178 - .152 mm. has much the same distribution as the previous grade, and is mainly the product of wave action, with limited tidal currents from south to north. The distribution of the finer grade .152 - .124 mm. appears to be far more affected by ebb current movements which carries pellets from the back of the bay seawards, north along the axial creek. This same movement may account for the high percentage offshore to the northwest. Alternatively, the sediment may come from the more open sea to the west of Quala.

On the map of the distribution of pellets of .124 - .104 mm., the ebb movement can now be inferred to carry grains out onto the area in front of the delta. Grade .104 - .089 mm. has much the same distribution as the previous one, but the edges of the tongue shaped isometric lines over the delta are pinched in as if by wave refraction to the west. The distribution of the .089 - .076 mm size suggest that the grains are so fine that the least wave movement reworks them back along the angled bars.

Thus it appears from distribution of the coarser pellets that they are affected only by wave action. However, in smaller grades, current action is able to lift and transport them. Further, since currents flow consistently for long periods, the earlier patterns (induced by wave action) are destroyed. The finest grades are susceptible to even the slightest wave activity and show a distribution similar to that of the coarser grade.

It is important to know the place of origin of the pellets. Study of the distribution of the different grades suggests that the pellets do not come round the peninsulas in any significant quantities. It is more likely that they form in the embayment. High percentages at the edge of the algal flats suggest an origin here, because if the pellets came from offshore they would be accompanied by the more easily transported disc shaped shells of the same size that dominate the area beyond the terrace edge (Sneed and Folk, 1958, and Bluck, 1965). Characteristically, shells do not form high proportions of the sediment in the embayment. The pellets are probably nearly in situ where they occur in the coarser grades. The finest grades are spread over the bay by the combined action of waves and ebb tidal movements.

4. DISTRIBUTION OF AGGREGATES

The purpose of constructing the maps was to establish the general areas in which aggregates occur within the embayment, and to find out whether these areas coincided with high percentages of pellet and low percentages of quartz. Tracing the distributions of the different size grades of aggregates, it can be seen that the highest percentages are concentrated around the landward edges of the embayment. The highest values of all are found in the southeastern neck of the embayment. Another concentration occurs approximately at the mid-point of the west coast. These concentrations are probably near the source of the aggregates which appear to form just seawards of the algal flat in the upper parts of the intertidal zone. It is unlikely that the aggregates formed offshore and then were swept inland because no appreciable quantities of shells are carried in.

Aggregates smaller than .599 mm. diameter may acquire a polished envelope of aragonite cement which infills the crevice between the component grains. This encrustation and polishing occurs most commonly in the sediments on and about the angled bars. Here it is possible to trace the progressive cemented grapestones, (Plate 41). The hollows between the individual pellets which constitute the grapestones are progressively filled with friable, 'sugary' carbonate cement, whilst the tips of the individual grains are abraded and polished. Eventually the hollows disappear and the polish extends over the whole grain. The result is to produce botryoidal grains. (Illing, 1954). On examination of the distribution maps, (Figures 20 and 21), it can be seen that in the coarser grades (1.003 - .853 mm.) the higher concentration of aggregates are confined to the east, in the inner parts of the embayment. To the centre of the bay lobe shaped isometric lines of higher percentages occur suggesting that the grains were swept here by run off from the sabkha after the storm flooding of January 1964. These lobes are lag deposits. The fact that finer grades lack these lobate shapes indicates they were reworked more easily by onshore waves. The angled bars of the west coast of the bay are reflected in the distribution pattern of the coarse grades. Thus any pattern imposed on the angled bars during the storm must have subsequently been removed.

Projecting into the embayment along the creek is a tongue showing high percentage of shells. This splits the lobe of aggregates of the west from that to the east. The tongue represents shells carried landwards by the storm and deposited in the creek. For some reason they were not removed when the flood waters ran off the sabkha.

The grades .599 - .500 mm. are concentrated in the eastern corner of the embayment but a second area of high percentages is developed to the northwest of the angled bars. In grades .500 - .295 mm., except for the highs to the west and east, the grapestones spread as a uniform band across the delta. This band may well represent the source area. In which case, the 'highs' by the angled bars to the west and in the neck of the embayment to the east, are lag deposits. The material which now forms the lag deposits were swept off the delta and the equivalent area to the west by waves. They remain in the shore areas because here tidal current movement is at a minimum.

For the grades .251 - .124 mm. the pattern of higher concentrations forms an approximately east-west ribbon. This is confined to the embayment by onshore waves and is prevented from entering far up the neck of the embayment or shorewards by ebb current movements. The grade .124 mm. is composed largely of friable aggregates and shows its maximum in the grass area off the coastal terrace to the northeast of the bay.

5. CONCLUSION

The results of this study suggest that the aggregates and the carbonate jackets of the quartz grains are forming in the embayment, between the edge of the coastal terrace and the high water mark. The aggregates are composed of: 20% quartz, 60% aragonite pellets and 20% aragonite cement. However the sediment in which they occur contains a ratio of aggregate to quartz to pellet of approximately 3:3:1. If the sediment were cemented unselectively, then the aggregates would be expected to contain more quartz than they in fact do.

This is thought to be produced in the following way:-

1. The surface sediment is lightly cemented to form a thin crust. The initial binding agent is either organic mucilage secreted by blue-green algae or incipient aragonite beach rock cement. This latter is precipitated at low tide during the hot summer months. If the cementation process goes on for long enough, photosynthesis by the blue-green algae may precipitate more aragonite. This cements and fuses the carbonate grains and is indistinguishable from

them. Recrystallization of the acicular crystals of beach rock cement occurs and the whole grain ultimately becomes homogenous.

2. Once formed, the surface crust may be broken by wave action. It is the resulting grains that make up the aggregates. Their size depends on the strength of the cement and the force of the waves. Thus with a heavy sea and the lightest of bindings, the crust may be separated into its constituent grains, but with the gentle conditions and good cementation aggregates are produced.

If this process operates it would be expected that aggregates would have a higher percentage of quartz. The low percentage of quartz in the aggregates may be explained in two ways:

1. The percentage of quartz in the sediment is not the usual one but is abnormally high because the samples were collected only a short time after a strong onshore gale. The excess quartz was carried in from the headlands.
2. When the partially cemented surface crust is broken by waves it tends to fracture along the boundaries of the quartz grains in preference to fused boundaries of carbonate grains. The quartz grains are thus freed. Quartz grains which have become separated may retain parts of the cement which locally adhere to their surfaces. This could then

account for the fact that many of the quartz grains have carbonate jackets, while some even have one or more hemispheroid aragonite shapes protruding from their surface. The latter are fused aragonite pellets, (Plate 45).

Another process of aggregation that probably takes place involves the blebs of blue-green algae and their investing mucilage. These float about free in the sediment, and act as centres of aragonite precipitation to form pellets as did Illing's (1954) friable aggregates. In their early stages these pellets have 'sticky' surfaces which adhere easily to other grains. Thus aggregates, quartz grains and pellets quickly acquire aragonite pellets. These loosely bound aggregates then become cemented by aragonite, the latter perhaps precipitated as a by-product of the photosynthetic activities of the algae. Thus pellets formed by this process are unlikely to exist free because of their adhesive qualities. This characteristic may account for the low pellet content of the sediment. Although algae and their mucilage occur on all carbonate grains, there is as yet no evidence that algae colonize non-carbonate grains. If they do not, or only do so poorly, then this ecological factor may perhaps also influence the ratio of quartz to carbonate in the final aggregate.

In conclusion, it would appear possible to interpret the pattern of sediment movement in closely sampled areas from grain size and component analyses. One application of such a study is to the ancient rocks where predictions can be made of the interrelationship of facies including trends of shorelines.

The study also shows that grain size and component analysis, when presented in the form of contoured maps, can yield information of facies relationship independent of such properties of grain size distribution curves as modes, skewness and kurtosis. Thus, although the curves of Doeglas (1946) and Tanner (1964) were plotted, they are not presented in this thesis because the complexities of mixing are easier resolved on the distribution maps.

CHAPTER V

CONTEMPORANEOUS RECRYSTALLIZATION OF RECENT CARBONATES INDUCED BY BLUE GREEN ALGAE AND ITS RECOGNITION AFTER LATER DIAGENESIS

1. INTRODUCTION

Recent shallow-water marine carbonate sediments show a distinctive type of recrystallization which affects all carbonate grains, irrespective of their origin. The textures of the grains are progressively altered to homogeneous microcrystalline fabrics of aragonite which, in the final stage, are virtually indistinguishable from one another. Thus in many instances it is only the external shape which may give an indication of the original form of the grain.

In the study of the Bahama Banks, Illing (1954) observed that these grains form "the fundamental unit in the formation of vast spreads of calcareous sands". Subsequent workers in the Bahamas have found this process at work too. The phenomenon has not been satisfactorily explained. Various theories have been proposed. For example, Illing attributed the recrystallization to bacteria or algae. Newell, Purdy and Imbrie (1960) ascribed some of the recrystallized zones in ooids to the effects of decaying colonies of boring algae. Purdy (1963) remarked on the universal recrystallization of all calcium carbonate grains in the Bahamas and concluded that the organic matter trapped within the grains may promote the process.

In the Persian Gulf off Qatar, Houbolt (1957) observed that in some of the sands the skeletal carbonate grains are rounded and their surface characters obliterated. This was not found in the skeletal sands. collected below 11 fathoms. Similar changes in the surface appearance of skeletal grains in the Bahamas accompanies recrystallization. This is attributed to boring algae and not abrasion (Vaughan, 1919, and Illing, 1954). Wolf (1965b) discusses similar micritization of Recent calcareous algae from Portuguese Timor.

The Recent sediments of the Trucial Coast contain skeletal grains with similar textures. Foraminifera and red calcareous algae seem particularly susceptible to recrystallization, whilst thick walled shells and shells with a more coarsely crystalline fabric appear to be less susceptible. Alteration in the latter case tends to be confined to the surface, but here and there lobes of fine-grained carbonate extend deep into the shell.

Recrystallization also occurs in the aggregates of very finely microcrystalline carbonate which form faecal pellets and grapestones. These aggregates are initiated as poorly bound open textured grains, but rapidly harden and cement up as they recrystallize. Oolites from the Abu Dhabi area are similarly affected.

Drusy infillings of acicular aragonite crystals form in small internal cavities of some mollusc shells, foraminifera, and grapestone lumps. These infillings also tend to deteriorate into a disorganised microcrystalline mosaic of aragonite.

The various stages in the process of recrystallization can be most usefully studied in the peneroplids, and will be discussed in detail.

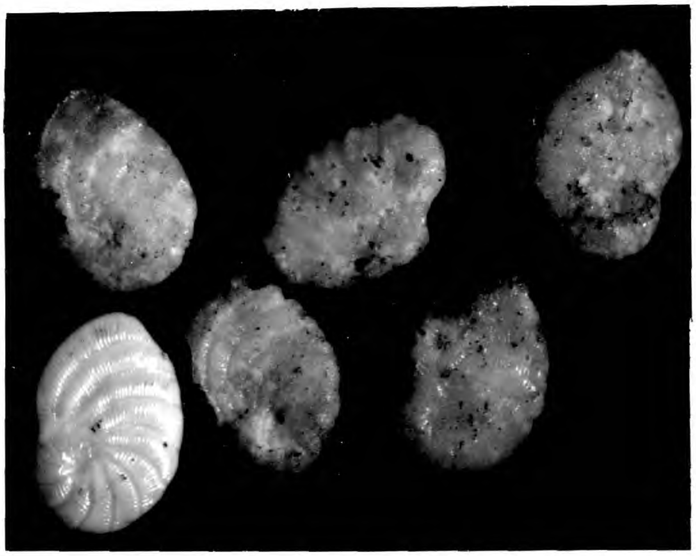
In ancient limestones many of the components exhibit a similar fabric to that found in the Recent recrystallized materials, but they differ from them in being preserved as calcite. Banner and Wood (1964) attributed this to late diagenetic grain growth; Orme and Brown (1963) and Folk (1965) apparently describing the same phenomena, postulated a late diagenetic process of 'grain diminution', confirming some of Bathurst's (1964) and Wolf's (1965a & b) findings. It will be demonstrated that these changes are not exclusively late diagenetic but are moulded on alterations of fabric initiated in the depositional environment.

2. RECRYSTALLIZATION OF MODERN PENEROPLID FORAMINIFERA

Peneroplid foraminifera are particularly liable to recrystallization. A detailed study of specimens collected from the Khor al Bazam showed them at all stages of alteration. Under the stereoscopic microscope their tests show a series of surface changes. These range from translucent and porcellanous surfaces of fresh tests to opaque and sugary ones in recrystallized specimens, (Plate 50). These changes are accompanied by rounding and pitting of the tests. Many of the pits are seen to contain blue-green algae. Recrystallization may be so pronounced that the tests become almost indistinguishable from aragonite ovoids of faecal and ac-

Plate 50

Peneroplid foraminifera being recrystallized by blue-green algae. (x 40).



cretional origin. Both Illing (1954) and Purdy (1963) noted similar changes in the foraminifera of the Bahamas. Purdy was unable to decide whether the calcite skeletal material had recrystallized to calcite or aragonite.

Thin sections of fresh peneroplid tests under plane polarized light show a brown body colour. They contain no crystal shapes apart from a faint structure parallel to the walls (Plate 46, Figure 23) and a very faint granulation under high power. With reflected light they have a milky white colour. Under crossed Nicols the tests are seen to be composed of parallel sheaths of crystals which exhibit low polarization colours and lie parallel to the curvature of the walls. These sheaths are embedded in a finely granular matrix of crystals which show pin point polarization in greys and yellows of the first order.

Thin sections of fresh tests stained with Feigl's solution suggested that they were not aragonite. X-ray analysis (by R. Curtis, Imperial College) showed the tests to be of high magnesium calcite with a small amount of aragonite. This aragonite was either part of the tests, or more probably an infilling of the chambers. If the second assumption is correct, then the result of the analysis confirms the findings of Sollas (1921) and Wood (1948).

The brown body colour and the low order polarization colours of the fresh tests are not optical properties of high magnesium calcite. Several theories have been proposed to explain these anomalies. For example, Sollas (1921) attrib-

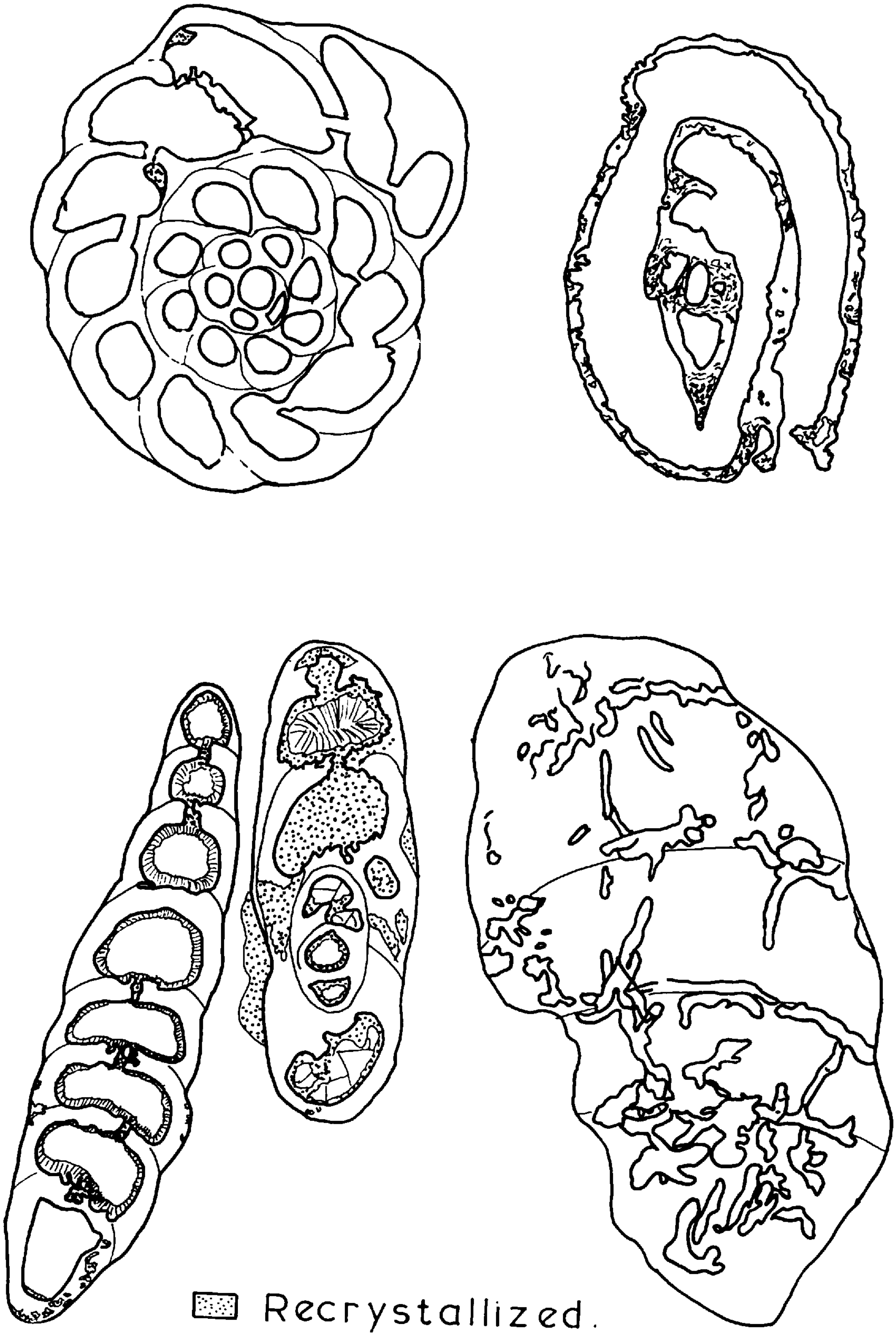
Plate 46 (see Figs. 22 & 23)*

Top left:	Modern Peneroplid in plane polarized light. Unaffected by algae. (x 70).
Top right:	Modern Quinqueloculina under plane polarized light. Partially bored by algae. (x 70).
Bottom left:	Modern Peneroplids under plane polarized light. Partially bored by algae. Acicular aragonite rims some chambers, whilst microcrystalline aragonite, of the same texture as the areas bored by algae, infills other chambers (x 70).
Bottom right:	Modern Peneroplid under plane polarized light. Bored by algae. (x 140).

* Figure 22 - Plane polarized light

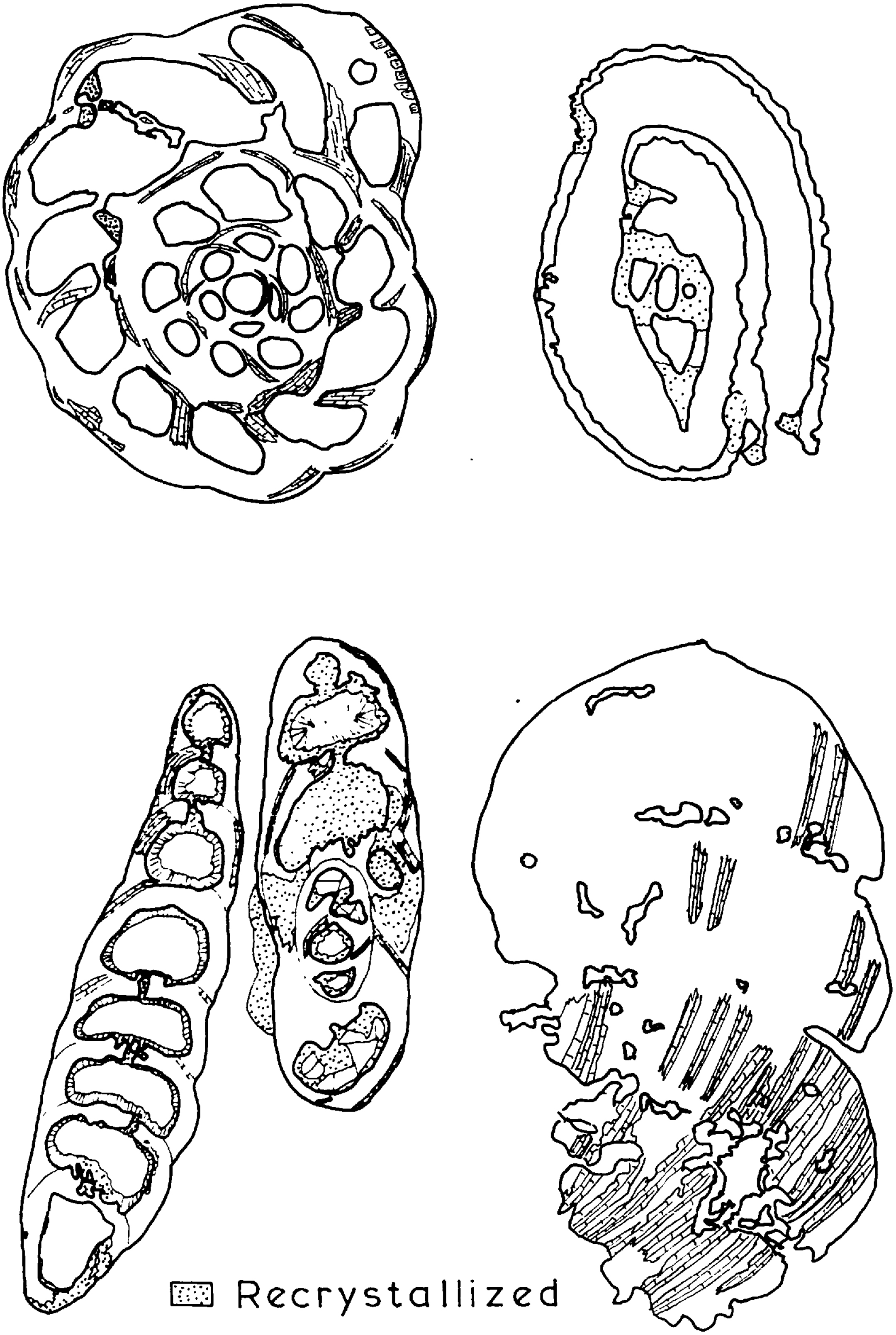
Figure 23 - Crossed nicols.

Figure 22



▨ Recrystallized.

Figure 23



utes the brown body colour in plane polarized light and the milky colour in reflected light to the reflection of light through the felted crystals of the test. He does not explain the low order polarization colours. In contrast, Wood (1948) suggests that the brown body colour may be due to small amounts of lead and iron. However Frondel, Newhouse and Jarrel (1942) were unable to trace any connection between the distribution of Fe, Cu, Mn, Al, Sr and Mg and the morphology or colour of calcite crystals. Wood (1948) also proposes that the low polarization colours are produced by small crystals optically compensating each other in the slide. The latter is unlikely because thin sections of micrite (Folk 1962) do not show low polarization colours. Another theory has been put forward by Folk (personal communication 1966). He points out that chalcedony and 'turbid' feldspars also have a brown colour in transmitted light and are milky under reflected light. These optical properties are interpreted as being caused by minute water filled vacuoles in these minerals, (Folk and Weaver, 1952, and Folk, 1955). The same properties in the peneroplids may be of the same origin. Electron micrographs of a peneroplid test from a paper by Hay, Towe and Wright (1963, Plates 5 and 6) show the test to be composed of a felt of crystals of about 0.5 microns length and 0.1 microns diameter. The disorganized way in which some of the crystals lie on each other will leave voids of at least 0.1 microns diameter. These voids are probably filled with water and, as in the chalcedony and 'turbid' feldspars, produce the brown body colour. If the voids were filled with air, then the test would be black. The presence of the water may be connected with the low refractive index of the calcite perpendicular to the C axis (1.6), the low polarization colours and the low specific gravity of 2.724 (Sollas, 1921, p.196). However this does not explain why the test exhibits low polarization colours and does not exclude the possibility that the low specific gravity may be due to the presence of organic matter (Sollas, 1921, p. 196).

In thin sections, altered tests show that recrystallization proceeds from discrete patches which become enlarged and thus gradually obliterate the original texture. This may be accompanied by the infilling of the chambers by microcrystalline aragonite, (Plate 47 Figure 26). The recrystallized areas are characteristically microgranular under plane polarized light and the brown body colour shown by fresh tests is absent. Under crossed Nicols the recrystallized areas exhibit high polarization colours, but show no extinction. The size of these crystals is of the order of 1½ microns (Plate 47 bottom left). Though Feigl's solution reacted only patchily on completely recrystallized foraminifera, X-ray analysis showed that these tests are almost entirely aragonite. The failure of Feigl's test may be due to films of organic matter over the crystals.

Hand picked peneroplids from the medium sand fraction of one of the samples were examined. These were separated

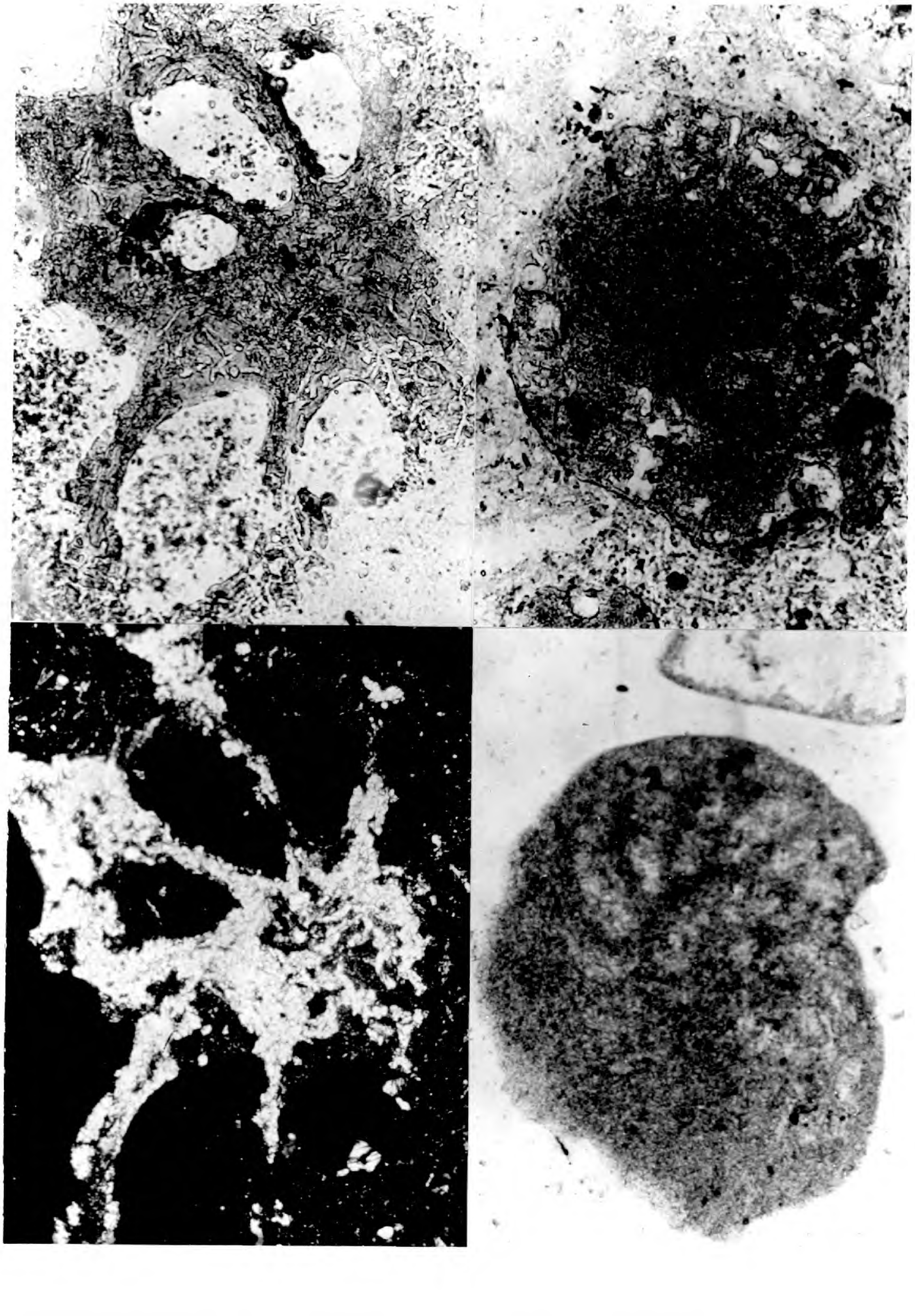
Plate 47 (See Figure 24)

Top left: Modern Peneroplid under plane polarized light. Well bored by algae. (x 174).

Bottom left: Modern Peneroplid (as above) under crossed nicols. Algal bores filled by microcrystalline aragonite. (x 174).

Top right: Modern Peneroplid under plane polarized light totally recrystallized. Chambers are filled. (m 214)

Bottom right: Modern Peneroplid under plane polarized light. Totally recrystallized. Chambers are filled by acicular aragonite which is also being recrystallized. (x 70).



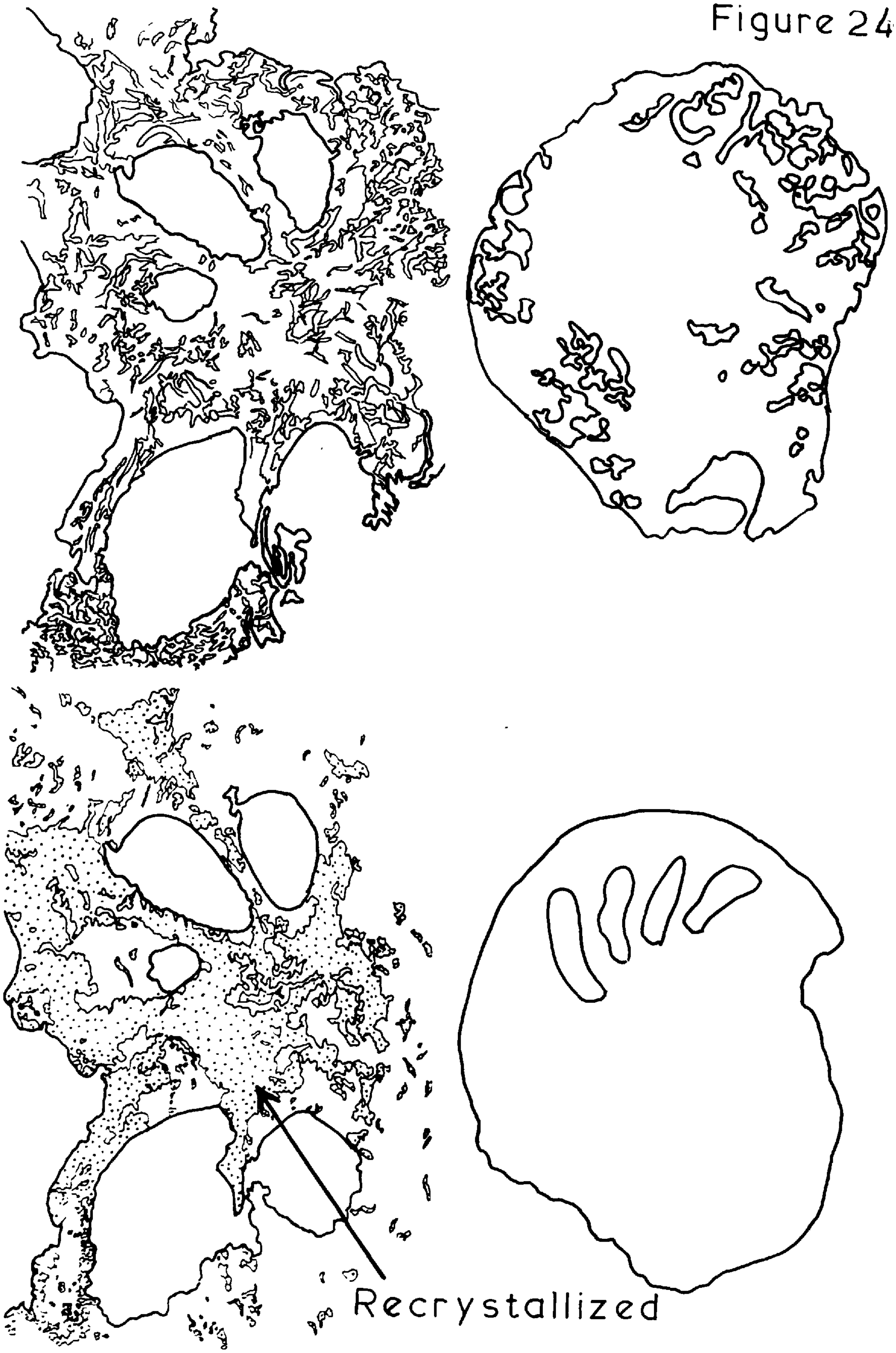


Figure 24

into five groups on the basis of the extent of external alteration. X-ray analyses showed that these five groups progressively changed from high magnesian calcite to aragonite.

Algae, similar to those which occur in the pits on the surfaces of shell fragments, were also found by Twyman (personal communication 1964) on the oolites from Abu Dhabi. These were identified by Dr. Stewart of Westfield College, London University, who found them to be Entophysalis deusta (Menegh). Drouet and Daily. Newell et al (1960) found this genus common in the Bahamas.

Algae collected in Abu Dhabi survived three years in storage jars. When they were exposed to sunlight, they started growing vigorously. The algae of several samples were separated from the associated carbonate sands by solution in weak hydrochloric acid. They consisted of several different types of globular cells and tangles of filaments in a transparent mucilagenous matrix. This matrix is believed to be mainly a secretion of algae, (Fritsch, 1952).

The algal cells and filaments were found to lie just beneath the surface of the recrystallized tests. This was shown in two ways: (i) by progressively dissolving the carbonate of the grains in 5% acetic acid or 0.2% hydrochloric acid. (ii) by rendering the surface transparent with 40% hydrofluoric acid. It was found that the algae could be made even more apparent by staining with various dyes. The most effective dye is malachite green, because this tends to stain algal cells and the mucilage with different intensities.

If the unrecrystallized tests are completely decalcified, they leave behind a thin diaphanous soft elastic membrane, which retains the original form of the foraminifera This is the 'tectin' of Hyman (1940) and is believed to be the original organic material of the test, which in life occurred in conjunction with the calcite (Sollas 1921).

Decalcified recrystallized foraminifera leave behind a much more translucent material which also moulds the test and fills its chambers, and is markedly different in appearance from the 'tectin'. In all ways it resembles the mucilage which occurs in association with the blue-green algae. It contains algal cells and also small quantities of minute mineral grains. These fragments probably adhered to the mucilage as the test rolled about on the sea floor.

If foraminifera are treated with 40% hydrofluoric acid for over ten minutes, all the calcium carbonate is replaced, molecule by molecule, by transparent calcium fluoride (Grayson, 1956). Recrystallized areas are then seen clearly because the mucilage envelope and algae resist solution (Fischer, 1897), and in consequence, stand out as translucent and green areas. Treatment with 40% hydrofluoric acid for five minutes is all that is required to clarify the surfaces of the foraminifera and reveal the network of radiating filaments and globular algae. Fresh foraminifera become completely transparent. The best optical results with the calcium fluoride specimens are obtained by viewing them under water.

If partially recrystallized foraminifera are examined in thin section, some specimens show the algal filaments penetrating both the unrecrystallized and recrystallized areas, (Plate 46, Figures 22 and 23). The filament 'bores' are usually filled with microcrystalline aragonite. This preserves the shapes of the filaments. Thus the unrecrystallized test may be penetrated by tubes of recrystallized material. The boundaries separating the unaffected high magnesian calcite areas of the test from the aragonitic recrystallized ones often resemble the boring of algal filaments Under plane polarized light parts of the test immediately adjacent to the bore shapes may show faint granulation. This is believed to be the first sign of recrystallization.

If thin sections of the recrystallized material are stained with aqueous malachite green, the effect is patchy. Deeper colours are present at the outside edges and in the chambers devoid of carbonate. When thin sections are etched with weak acid-solutions of malachite green, then the calcium carbonate is dissolved, leaving the stained insoluble algae and mucilage. Again the deeper stain is usually found at the edge of the former test and in some chambers, thus revealing algal cells and filaments both at the surface and penetrating the interior. Parts of the chambers not filled with algal cells are usually stained but less intensely, indicating that they are filled by mucilage. Solution and staining of the recrystallized walls of the foraminifera leave only a trace of mucilage which stains lightly. This may be because when the microcrystalline aragonite crystals form they displace the mucilage. The presence of this finely dispersed mucilage is confirmed by gently dissolving the whole tests. If the dissolution is too vigorous, the mucilage is ruptured and removed.

The intimate relationship of blue-green algae with recrystallization is thus established. Now it becomes necessary to explain this relationship and to demonstrate that it is the algae that cause the recrystallization. It is common knowledge that all plants photosynthesise and respire. Maslov (1961) noted the ability of blue-green algae to precipitate calcium carbonate. Park and Curl (1965) showed that in the laboratory a culture of blue-green algae in sea water produce measurable change in conductivity between day and night. From this, they inferred that in light photosynthesis transforms bicarbonate ions to carbonate, while in the dark respiration causes the opposite.

In the peneroplids of the Persian Gulf the mucilagenous envelope will tend to create a microenvironment within each test. By virtue of this restricted microenvironment, carbon dioxide given off during the respiration would promote solution of calcium carbonate. Conversely, the carbon dioxide utilized during photosynthesis would cause precipitation. Although it is high magnesium calcite which goes into solution, it is aragonite that is precipitated because this is apparently the stable form of calcium carbonate in warm marine waters, (Kinsman, 1964c). In this way, the high magnesium calcite of the foraminifera test would be progressively dissolved and replaced by aragonite on a piecemeal basis. Once all the calcite of the test has been recrystallized to aragonite, the cycle does not stop because solution of aragonite and reprecipitation continues. Once a foraminifera is recrystallized, the aragonite may be replaced many times, (Plate 47), ultimately destroying all evidence of its former origin.

This process alone could account for recrystallization. Bathurst (1964) suggested that the recrystallization is accomplished by algae boring and reboring the calcite test, which only goes into solution once it is in direct contact with the algal filaments. However, the algae are restricted to the area near the surface of the test and do not necessarily extend into all the affected parts. This distribution would tend to argue against the recrystallization being the result of boring. However, the mucilagenous envelope secreted by the algae tends to confine the carbon dioxide. This can then act at any point within the mucilagenous envelope.

Recrystallization by this process is not restricted to the foraminifera and, as was mentioned previously, affects pellets, grapestones and in all forms of bioclastic material. It also takes place in ooids.

The recrystallization of ooids is of particular interest and is therefore described in more detail.

This recrystallization is to be expected since each ooid is invested within a series of mucilagenous jackets containing algal cells (Twyman, person communication 1964). The ooids are found on exposed tidal deltas between the islands of the east coast of Abu Dhabi, These deltas are subjected to almost continuous wave and current action as indicated by the well rippled surfaces. Twyman, working on ooids from these deltas, confirmed Purdy's (1963) observations that recrystallization texture is confined to the old algal borings. Twyman also discovered that recrystallization apparently only takes place in the quieter waters of the lagoonal side of deltas, though algae are present on ooids over the wide delta. It would appear that on the fronts of the deltas agitation of the grains is so great that algal activity is inhibited and algal filaments are unable to bore into oolites. However, since the algae on the oolites of the delta front are living and mucilage invests the oolites, photosynthesis and respiration would be expected to cause recrystallization. This does not happen.

The fact that the texture of the oolites at the front of the delta is unchanged may be explained in two ways. One, that the mucilage does not hinder the free passage of carbon dioxide to and from the sea water so that the carbon dioxide balance is undisturbed. Two, that the carbon dioxide is confined within the ooid by the mucilage and although respiration causes the solution of the aragonite, it returns to its original organisation during photosynthesis.

If the earlier reasoning for the recrystallization of foraminifera is correct, it would be expected that respired carbon dioxide be confined within the mucilagenous envelope of the ooid. This possibility is enhanced by the fact that the internal surface area of the ooid is over 100 times its external area, (Twyman, personal communication 1964). If this assumption that the carbon dioxide does produce solution and reprecipitation of the aragonite is correct, then it is necessary to explain why the reprecipitated aragonite resumes its original organisation. This can be done if it is assumed that each aragonite crystal of the ooid is invested with a mucilagenous jacket. When an aragonite crystal goes into solution, the space it leaves behind acts as a mould for the reprecipitated crystal. If algal filaments actually enter the ooid layers, as they do on the back of the deltas, the mucilage within them is disrupted. Thus the aragonite now reprecipitated in the borings forms a disorganised cryptocrystalline mosaic.

The recrystallization of carbonate grains could be controlled by several factors. These include: the length and frequency of exposure of the grains to direct sunlight; the dimensions of the grains; and the size of their component crystals.

For example, if the grain is quickly buried, it may not have time to recrystallize or will only recrystallize if it has a thin delicate shell and small component crystals.

The shoal areas of the Khor al Bazam from which the recrystallized foraminifera were collected, (Sheet 20), are rippled. It may be assumed these ripples migrate slowly so that the foraminifera which are being altered will be only occasionally exposed to direct sunlight. Consequently the recrystallization process may be slow in this case.

Recrystallization is most abundant on the weed covered shoals of the coastal terrace and parts of the offshore bank. Skeletal grains from these areas have abundant algally filled pits. The prolific plant growth must upset the carbon dioxide balance of the sea water and for this reason recrystallization may be more rapid.

Wolf and Conolly (1965 p.108) point out algae are in general good shallow water indicators because photosynthesis is depth controlled. Thus recrystallization would not be expected to take place below the photic zone. This may account for the fact that off Qatar bioclastic materials are rounded and the surface characters obliterated where they occur in water less than 66' deep, but not below (Houbolt, 1957). This may corroborate evidence that recrystallization is caused by algae.

3. EVIDENCE OF RECRYSTALLIZATION BY BLUE-GREEN ALGAE PRESERVED IN ANCIENT ROCKS

The Recent foraminifera from Abu Dhabi were compared with thin sections of Tertiary foraminifera from the Middle East. These consist mostly of peneroplid tests embedded within matrices of micrite and spar. Those tests unaffected by algal borings show no body colour, the walls being composed of discrete crystals (approximately 1 micron diameter) forming a microcrystalline mosaic (Plate 49, Figure 26). The crystal boundaries are so close that the overall Becke effect makes the body appear dark grey, (Wood, 1948). The outline of the test remains sharp. This change in texture is not confined to the peneroplids, but is also seen in other foraminifera, (Plate 49, Figure 26). Wood (1948 p.236) suggests this texture is produced by the growth of the original crystals after the organic matter enmeshing them had disappeared. A similar growth would occur if water filled voids existed between the crystals. It should be noted, however, that some peneroplids like other foraminifera retain their colour from as far back as the Jurassic.

In some Pleistocene biosparites examined, the aragonite allochems have passed into solution leaving behind dirt lines or envelopes of algal mucilage which now mould the shapes of the grains they once contained (Shearman and Skipwith 1965). The exteriors of the dirt lines or envelopes and the cavities within them are rimmed with small crystals of calcite (Sorby 1879 p. 71 & Bathurst 1964). Where these grains had been recrystallized through the agency of algae, the evidence of this is preserved by the mucilagenous envelopes. After solution of the aragonite this mucilage of the envelopes remains and acts as a honeycombed framework in which the later calcite crystals grow. The size of the voids within the mucilage probably controls the ultimate size of the crystals which grow in them. Where the mucilage is not dense the crystals may burst through it and grow till they touch one another, or until the supply of calcium and carbonate ions runs out. The former effect is particularly noticeable at the edge of the envelope. (Plates 48 and 49, Figures 27 and 28).

Recrystallized ancient peneroplids are quite easily recognised when compared with unaffected ones. The texture of the affected areas is coarser grained (2-5 microns diameter) than the mosaic of the microcrystalline unaltered parts. Further, they have a fluffy 'cotton wool' like texture. The boundary of the areas of algal activity is irregular and often merges into micritic matrix (Plates 48 and 49). This is distinct from the sharp walls of the unaffected tests.

Such a mechanism would be an alternative to Banner and Wood's (1964) suggestion that the recrystallization texture (where seen in the ancient limestones) is the result of late diagenetic grain growth. It would however conform with their sequence of recrystallization (p.24) and with their statement: "it has been possible to determine that many microfossils (especially foraminifera and algae) recrystalize in a regular sequence which relates to their biological affinities but not to the sparry micritic matrix that contains them." Thus Banner and Wood's photograph of <u>Mesophyllum</u> (Plate 2B) is interpreted as exhibiting a texture initiated by algally controlled recrystallization and modified

Plate 49 & Figure 26

Top left: Tertiary Miliolid under plane polarized light, exhibiting algally produced bores. The test of the test though unaffected by algal recrystallization has lost its original body colour. (x 10).

Top right: Tertiary Miliolid under plane polarized light, exhibiting the effects of algal recrystallization. The unaffected parts of the test have lost their distinctive body colour and are finely granular (indicated by Stipple). The affected test was probably preserved in the remains of algal mucilage. This was dispersed when the aragonite went into solution during the first phases of cementation. (x 274).

Bottom left: Quaternary foraminifera under plane polarized light, exhibiting the results of algally induced recrystallization. The upper two are preserved by the algal mucilage but the lower one is only partially affected by algae and still exhibits its body colour. (x 70).

Bottom right: Tertiary Miliolid under plane polarized light rendered almost unrecognisable by algal recrystallization. The algally affected areas are now preserved by coarser calcite than the original test. This latter is darker and of finer grain. (x 180).

Figure 26

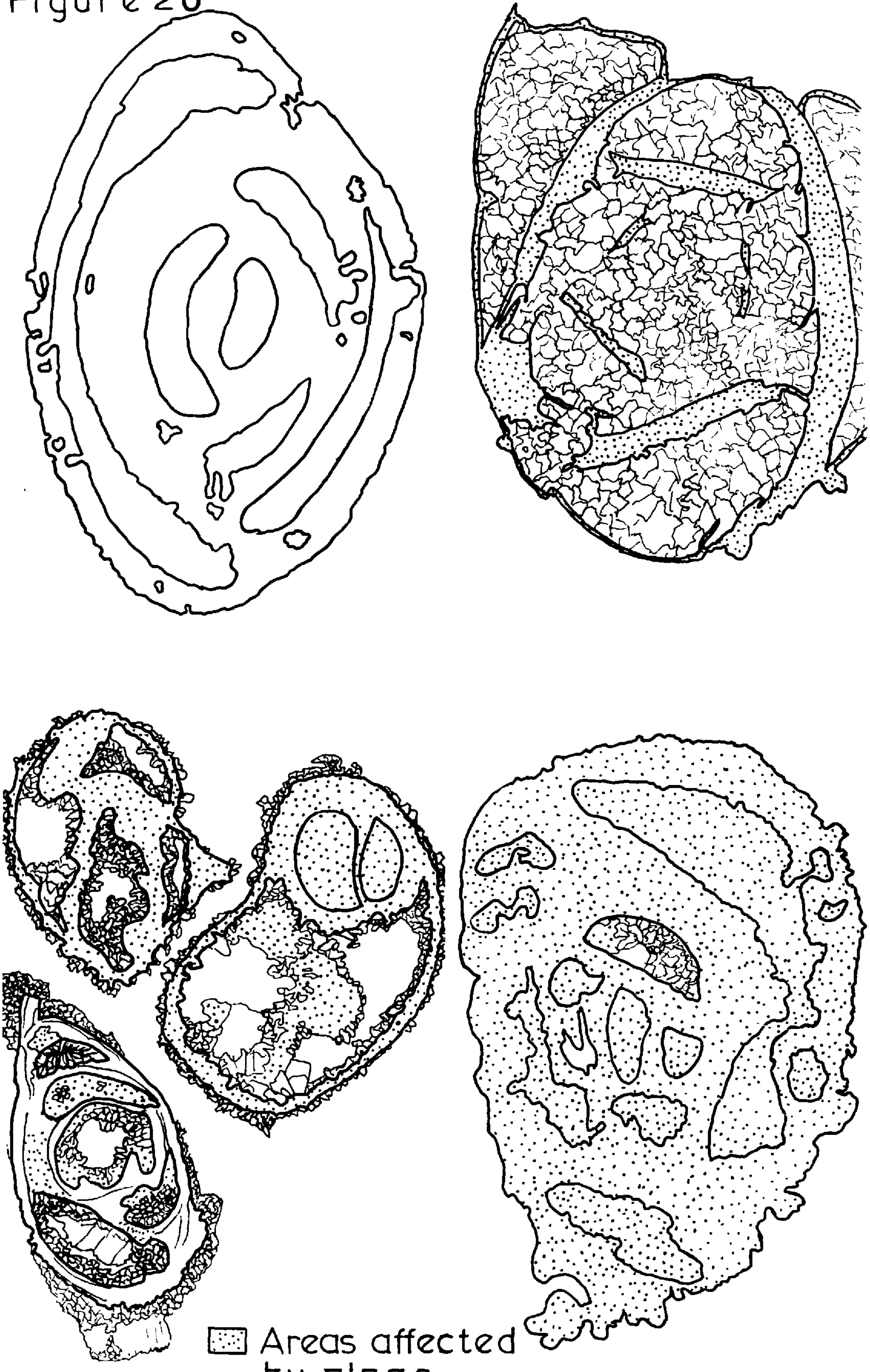
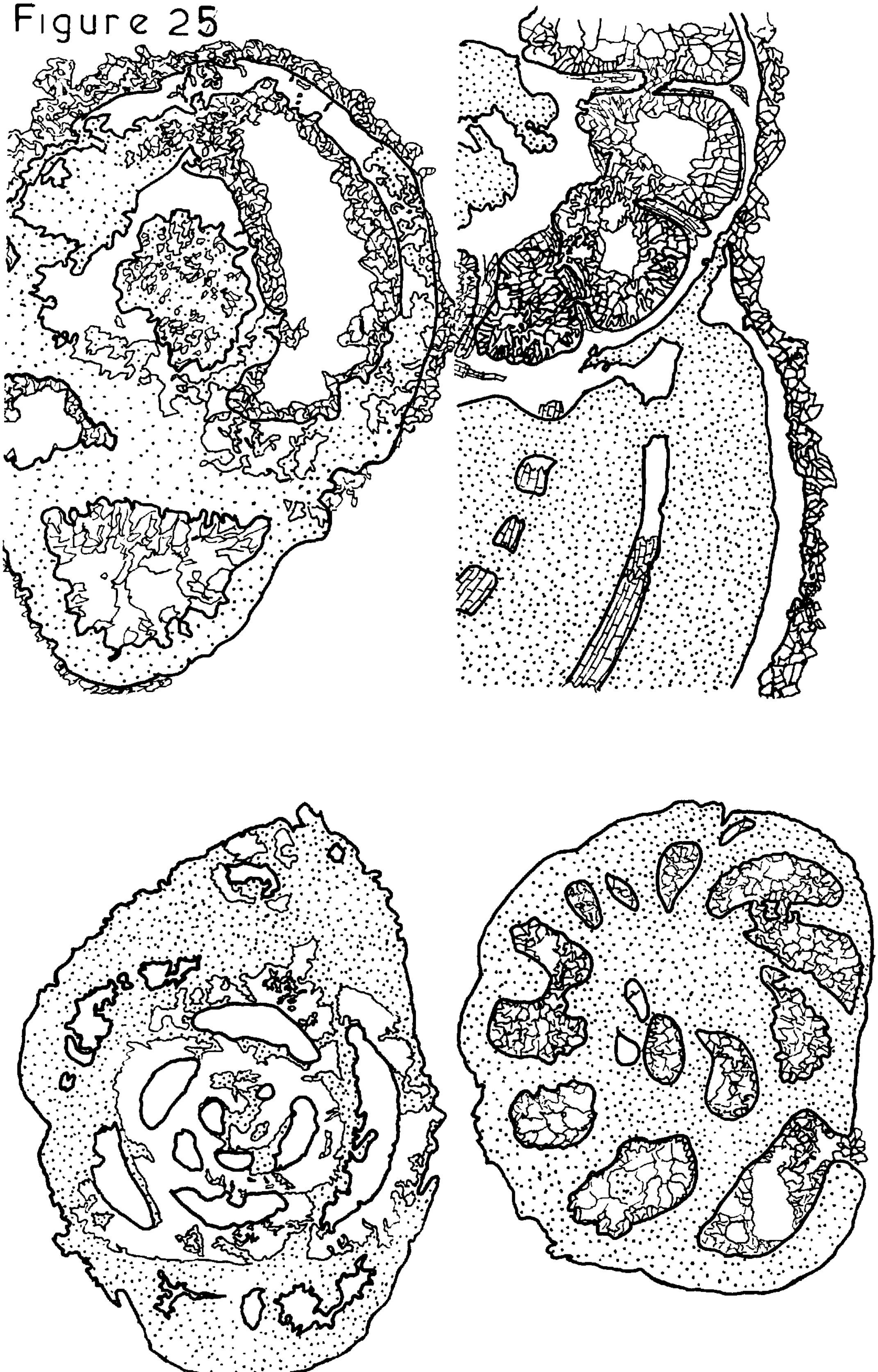


Plate 48 & Figure 25

Top left:	Quaternary *Quinqueloculina* under plane polarized light. Partially recrystallized by algae. Small calcite crystals rim test and fill mucilage. (x 280).
Top right:	Quaternary Peneroplid under plane polarized light. Partially recrystallized by algae. Small calcite crystals rim test and infill mucilage caught up in chambers. (x 270).
Bottom left:	Tertiary Miliolid under plane polarized light. The outer part of the test shows evidence of algal recrystallization which is prjcserved in calcite. The central darker area has lost its original body colour (x 70).
Bottom right:	Tertiary Miliolid under plane polarized light. Totally recrystallized by algae and now preserved in calcite (x 140).

Figure 25



░ Areas affected by algae.

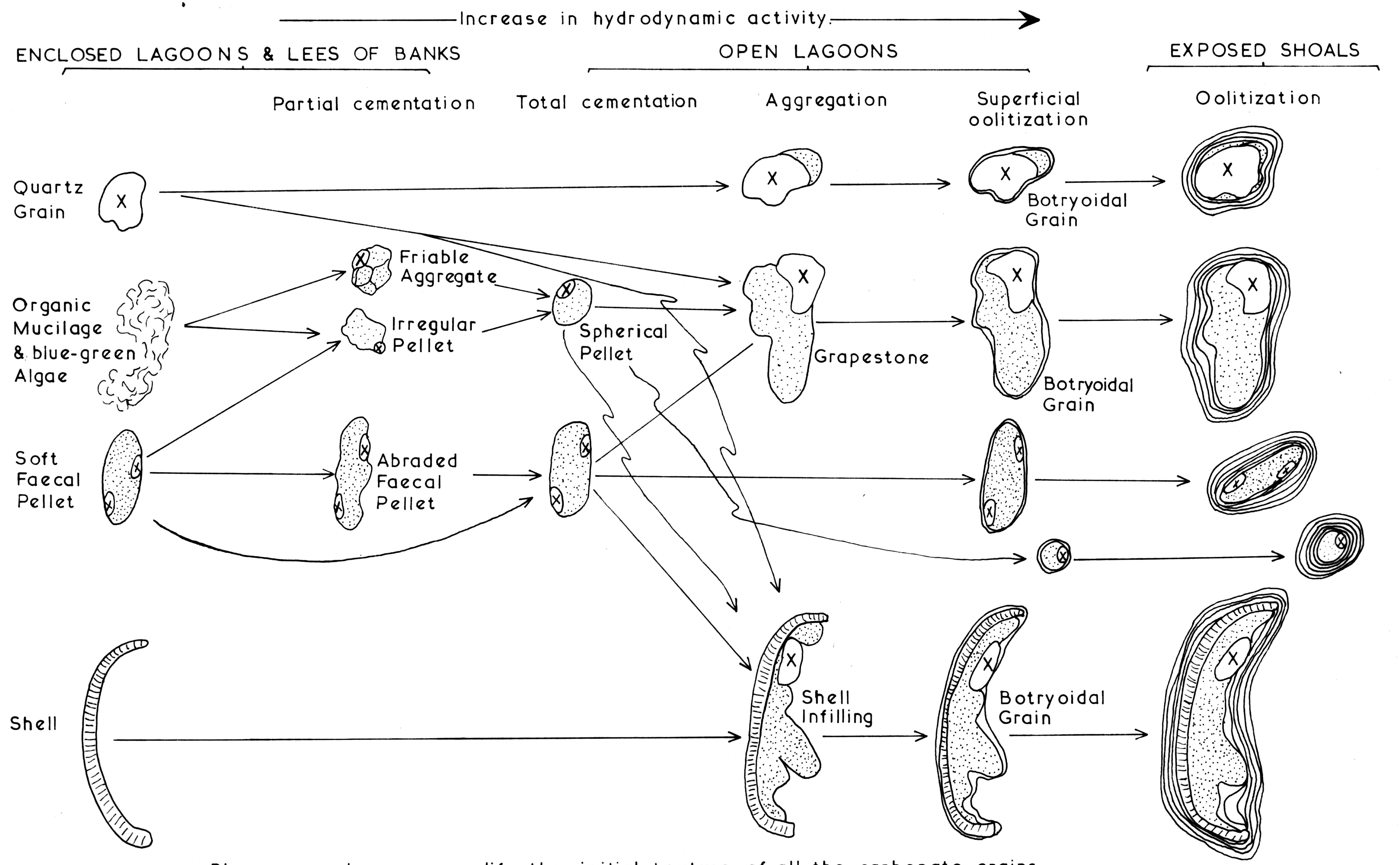
after deposition by solution and cementation. The major growth lines of the calcareous algae would have been preserved by layers of algal mucilage. The intervening cavities had little density of mucilage, and this was dispersed easily during the emplacement of the cement.

4. CONCLUSION

Peneroplid foraminifera were collected from the shallow waters of the Abu Dhabi. Their tests showed the progressive recrystallization of high magnesian calcite to aragonite. The recrystallized tests contained cells and ramifying threads of blue-green algae (myxophyceae) invested in mucilage. It appears that the algae, by the processes of respiration and photosynthesis, progressively dissolve the high magnesian calcite of the test and reprecipitate the carbonate as aragonite. This process is not confined to foraminifera tests alone, but is also found in other carbonate grains. In rocks from similar carbonate environments of the past, the cryptocrystalline aragonite of the recrystallized material is usually replaced by a mosaic of microcrystalline calcite in which algal recrystallization is still recognisable.

Figure 27

The relationship of carbonate grains to hydrodynamic environment.



Blue green algae may modify the initial texture of all the carbonate grains.

CHAPTER VI

CONCLUSIONS

A Hypothesis on the Hydrodynamic Sequence Shown in the Persian Gulf by Calcium Carbonate Particles of Physico-Chemical Origin

Calcium carbonate muds and a whole range of accretionary grains occur as components of the carbonate sediments which are forming at the present day in the shallow waters of the lagoons and shelves off the Trucial Coast (Figures 2 and 29). The distribution of the various components appears to be related to the hydrodynamic conditions prevailing in the various subenvironments. Broadly, these environments may be classed as follows: (1) Protected environments, (2) Moderately exposed environments, (3) Very exposed environments.

1. Protected Environments

These environments include enclosed lagoons and the lee areas of banks and islands. Their sediments range from aragonite muds to soft and cemented aragonite pellets. The aragonite muds are mainly confined to the sheltered lagoonal areas of Eastern Abu Dhabi, and the lee of the banks and islands of the Khor al Bazam area. The soft and cemented aragonitic pellets are found in sheltered lagoons and shallow shelves of moderate exposure to wind and waves.

In areas where aragonite mud accumulates the hydrodynamic environment is of low energy. Thus the muds are seldom disturbed. They are uncemented, probably because their pore waters do not move and so remain in equilibrium with the sediment. Associated with the muds are blebs of organic mucilage, containing blue-green algae. These blebs are common to all the environments along the coast. In this protected environment the gentlest movement of water would be expected to cause the mucilage blebs, and any recently excreted faecal pellets of low density, to saltate. The surfaces of mucilage blebs and pellets are 'sticky' and so accrete detrital aragonite. During saltation the surfaces of the accreting grains are exposed continuously to sunlight and to fresh solutions of seawater probably super-saturated with respect to calcium carbonate. Thus by the dual process of photosynthesis and respiration, aragonite is precipitated within the mucilage and the grains cement up and harden to form almost indistinguishable pellets. The longer these pellets saltate the harder they will be cemented. The balance between soft and hard pellets will be determined by the relative intensity of the turbulance of the water and the length of saltation. If one pellet adheres to another then their effective weight is of the two together and they cease to leave the sea floor. This is because water movement in pellet areas is too gentle to lift them. So long as the grains rest on the sea floor to become buried beneath other grains cementation cannot proceed. This is because the algal cells within the grains are unable to photosynthesis protected from sunlight and the sediment is in chemical equilibrium with the surrounding pore waters.

2. Moderately Exposed Environments

Moderately exposed environments are lagoon shores and offshore banks which are only partially protected from heavy seas and intense hydrodynamic activity. The sediments which form here are characterized by aggregates of cemented aragonite pellets.

Aggregates probably form when pellets are at rest long enough to adhere and form a thin crust, this adhesion being induced either through the agency of mucilage or beach rock cementation. In this environment wave action is frequent enough and intense enough to break the thin surface crust but not strong enough to split the grains into their original separate form. Aggregates develop. These are joined to further grains and acquire cement both externally and internally. When washed into the very exposed environment they develop polished oolitic coats.

3. Very Exposed Environments

The very exposed environments are those that mark the seaward edge of the complex of banks and lagoons of the Abu Dhabi coastline. Their sediments include oolites and vast spreads of coral. The oolites are rounded grains which consist of a series of spherical jackets of concentrically orientated aragonite nucleated on some small detrital grains.

In this environment of great turbulence the adhesion of one carbonate grain to another does not take place. The grains are never at rest long enough for a strong cement to develop which will not be broken by wave action. As in all previous environments the grains grow in size by the dual process of mechanical and chemical accretion. However, instead of being ellepsoid their physical environment leads to their development as spheres. Moreover, the momentum acquired by these grains leads on impact to a flattening of the elongate aragonite crystals tangentially to the surface at the point of impact (Twyman, personal statement, 1964).

The sequence from mud to oolite follows the progressive increase in the turbulence of the waters in which they form, and is similar to the succession suggested by Illing (1954) and Purdy (1963), for carbonate grains of physico-chemical origin in the Bahamas. This apparent order in the development of the carbonate grains may also be related to salinity variations. This variation probably does not change the chemical processes through which these particles acquire their aragonite, though it probably affects the speed of the processes. For instance, the water body in which the particles are being formed may be enclosed. Its size will control the concentration of salts by evaporation. Thus it may be for chemical reasons that the most easterly and smallest lagoons of Abu Dhabi have no oolites at their mouths (Evans, personal communication, 1965).

The presence of living coral, large patches of living marine weed and living coralline algae may also modify the CO_2 balance so that precipitation or crystallization of aragonite by chemical means is inhibited in these areas.

BIBLIOGRAPHY

ALLEN, J.R.L. (1965). Coastal Geomorphology of Eastern Nigeria: Beach Ridges, Barrier Islands and Vegitated Tidal Flats. Geologie Mijnb. 44, (1) 1-21.

ANDREWS, P. (1966). Personal statement.

BAARS, D.L. (1963). Petrology of carbonate rocks. Shelf carbonates of the Paradox Basin. 4th Field Conference on the 4 Corners Geological Society 101-130

BANNER, F.T. & WOOD, G.V. (1964). Recrystallization in Microfossiliferous Limestones. Geol. J., 4(1): 21-34.

BATHURST, R.G.C. (1964). The Replacement of Aragonite by Calcite in the Molluscan Shell Wall. In Approaches to Palaeoecology, 357-376. J. Wiley & Sons, New York.

BEALES, F.W. (1958). Ancient Sediments of Bahaman Type. Bull. Am. Ass. Petrol. Geol., 42, 1845-1880.

BLACK, M. (1933). Algal Sediments of Andros Island, Bahamas. Phil. Trans. R. Soc., B. 122, 165-192.

BLUCK, B.J. (1965). The Sedimentary History of some Triassic Conglomerates in the Vale of Glamorgan, South Wales. Sedimentology, 4 (3) 225-247.

BRAMKAMP, A. & POWERS, R.W. (1955). Two Persian Gulf Lagoons. J. sediment. Petrol., 25, 139-140.

BUTLER, G.P. (1965). Early diagenesis in the Recent Sediments of the Trucial Coast of the Persian Gulf. Unpublished M.Sc. Thesis, University of London.

BYRNIE, J.V., Le ROY, D.O. & RILEY, C.M. (1959). The Chenier Plain and its Stratigraphy, South Western Louisiana. Trans. Gulf Coast. Ass. Geol. Soc., 9, 237-260.

CLARKE, E. de D. & TEICHERT, C. (1946). Algal Structures in a West Australian Salt Lake. Am. J. Sci., 241, (5), 363-379.

CAROZZI, A.V. (1962). Observations on Algal Biostromes in the Great Salt Lake - Utah. J. Geol., 70, 246-252.

CLOUD, P.E. (1952). Facies Relationships of Organic Reefs. Bull. Am. Ass. Petrol. Geol., 36, 2125-2149.

CLOUD, P.E., Jnr. (1959). Geology of Saipan Mariana Islands. Part 4 - Submarine Topography, and Shoal Water Ecology. Prof. Pap. U.S. geol. Surv. 280, 361-445.

CLOUD, P.E. Jnr. (1962). Environment of $CaCO_3$ Deposition West of Andros Island, Bahamas. Prof. Pap. U.S. geol. Surv., 350, 1-138.

CURTIS, R., EVANS, G., KINSMAN, D.J.J. & SHEARMAN, D.J. (1963) Association of Dolomite and Anhydrite in the Recent Sediments of the Persian Gulf. Nature 197, (4868), 679-680.

DARWIN, C. (1889). The Structure and Distribution of Coral Reefs. (3 ed.). Smith, Elder & Co., London., 1-398.

DAVIS, J.H. Jnr. (1943). The Natural Features of Southern Florida, especially Vegitation and the Everglades. Florida geol. Surv. Bull., 25, 1-311.

DAVIES, W. (1962). Sediments of Gibraltar Point Area, Lincolnshire. Unpublished Ph.D. Thesis, University of London.

DOEGLAS, D.J. (1946). The Interpretation of the Results of Mechanical Analyses. J. sediment. Petrol. 16, 19-40.

DUNHAM, R.J. (1962). Classification of carbonate rocks according to depositional texture. In Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem. 1, 108-122.

EMERY, K.O. (1956). Sediments & Water of Persian Gulf. Bull. Am. Ass. Petrol. Geol., 40, (10), 2354-83.

EMRICH, G.H. & WOBBER, F.J. (1963). A Rapid Visual Method for Estimating Sedimentary Parameters. J. sediment. Petrol., 33, (4), 831-843.

EVANS, O.F. (1942). The Origin of Spits, Bars and Related Structures. J. Geol. 50, 846-865.

EVANS, G. (1965). Personal communication.

EVANS, G. (1965). Intertidal Flat Sediments & Their Environments of Deposition in the Wash. Quart J. geol. Soc. Lond. 121, 209-247.

EVANS, G., KENDALL, C.G.St. G. & Sir Patrick SKIPWITH (1964). Origin of the Coastal Flats, the Sabkha, of the Trucial Coast, Persian Gulf. Nature, 202, 2934, 759-761.

EVANS, G., KINSMAN, D.J.J. & SHEARMAN, D.J. (1964). A Reconnaissance Survey of the Environment of Recent Carbonate Sedimentation Along the Trucial Coast, Persian Gulf. from Developments in Sedimentology V.I. L.M.J.U. Straatan (Editor). Deltaic & Shallow Marine Deposits. Elsevier Publishing Co., Amsterdam. 129-135.

EVANS, G. & SHEARMAN, D.J. (1964). Recent Celestine from the Sediments of the Trucial Coast of the Persian Gulf. Nature, 202, 4930, 385-386.

FAIRBRIDGE R.W. (1950). Recent and Pleistocene coral reefs of Australia. J. Geol. 58. 330-401.

FERAY, D.E., HEURER, E. & Hewatt, W.G. (1962). Biological Genetic & Utilitarian Aspects of Limestone Classification. in Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem. 1, 20-33.

FISCHER, A. (1897). Untersuchungen Uber den Bau der Cyanophyceen und Bakterien Jena.

FISK, H.N. (1959). Padre Island and the Laguna Madre Flats Coastal South Texas. Proc. 2nd Coastal Geol. Conf. Baton Rouge, Louisiana, 103-153.

FOLK, R.L. & WEAVER, C.E. (1952). A Study of the Texture and Composition of Chert. Am J. Sci., 250, 498-510.

FOLK, R.L. (1955). Note on the Significance of 'Turbid' Feldspars. Am. Miner. 40, 356-357.

FOLK, R.L. & WARD, W.C. (1957). Brazos River Bar. A Study in the Significance of Grain Size Parameters. J. sediment, Petrol. 27, 3-26.

FOLK, R.L. (1962). Spectral Subdivision of Limestone Types. In Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem., 1, 62-85.

FOLK, R.L. & Robles, R. (1964). Carbonate Sands of Isla Perez, Alacran Reef Complex, Yucatan. J. Geol. 72, (3), 255-293.

FOLK, R.L. 1965. Some aspects of recrystallization in ancient limestones. Symposium of dolomitization and limestone diagenesis. Special Publ. Soc. Evon. Paleont. Miner. 13, 14-48.

FOLK, R.L. 1966. Personal communication.

FOLK, R.L. (in press). Sand cays of Alacian Reef, Mexico: Morphology.

FREEMAN, T. (1962). Quiet water oolites from Laguna Madre, Texas. J. sediment. Petrol. 32, 475-483.

FRITSCH, F.E. (1952). Structure & Reproduction of the Algae. Cambridge University Press. V. II.

FRONDEL, C., NEWHOUSE, W.H. & JARRELL, R.F. (1942). Spatial Distribution of minor elements in single crystals. Am. Miner. 27, 726-746.

GINSBURG, R.N. (1953). Beachrock in South Florida. J. sediment. Petrol. 23, (2), 85-92.

GINSBURG, R.N. (1955). Recent Stromatolitic Sediments from South Florida. (abs). J. Paleont. 29, 723.

GINSBURG, R.N. (1956). Environmental Relationships of Grain Size Constituent Particles in Some South Florida arbonate Sediments. Bull. Am. Ass. Petrol. Geol. 40, (10), 2384-2427.

GINSBURG, R.N. (1957). Early Diagenesis and Lithification of Shallow Water Carbonate Sediments in South Florida. Symposium of Regional Aspects of Carbonate deposition. Special Publ. Soc. Econ. Paleont. Miner. 5, 80-100.

GINSBURG, R.N. & LOWENSTAM, H.A. (1958). The Influence of Marine Bottom Communities on the Depositional Environment of Sediments. J. Geol. 66, 310-318.

GOULD, H.R. & McFARLAN, E. Jnr. (1959). Geologic History of the Chenier Plain, Southwestern Louisiana. Trans. Gulf Coast Ass. Geol. Soc. 9, 261-270.

GRAYSON, J.F. (1956). The Conversion of Calcite to Fluorite. Micropalaeontology, 2, (1), 71-78.

GUILCHER, A. (1959). Coastal Sand Ridges and Marches and their Continental Environment near Grand Popo & Ouidah, Dahomey. 2nd Coastal Geography Conference, Coastal Studies Institute, Louisiana State University, 189-213.

HAM, W.E. & PRAY, L.C. (1962). Modern Concepts and Classifications of Carbonate Rocks. in Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem. 1, 2-20.

HAY, W.H., TOWE[illegible], K.M. & WRIGHT, R.C. 1963. Ultramicrostructure of some selected foraminiferal tests. Micropalaeontology, 9, 171-195.

HOUBOLT, J.J.H.C. (1957). Surface Sediments of the Persian Gulf near the Qatar Peninsula. Thesis, Univ. of Utrecht, Mouton & Co. - Den Haag. (1-113).

HOYT, J.H. & VERNON, J.H. Jr. (1963). Development and Geologic Significance of Soft Beach Sand (Abstr.). Geol. Soc. Am. Spec. Paper 73, 175.

HYMAN, L.H. (1940). The Invertebrates: Protozoa through Ctenphora. McGraw Hill Book Co., New York, 1-726.

ILLING, L.V. (1954). Bahaman Calcareous Sands. Bull. Am. Ass. Petrol. Geol. 38, (1), 1-95.

ILLING, L.V., WELLS, A.J. & TAYLOR, J.C.M. (1965). Penecontemporary Dolomite in the Persian Gulf. Symposium of Dolomitization and Limestone Diagenesis. Sp. Publ. Soc. Econ. Paleont. Miner. 13, 89-111.

ILLING, L.V. (1966). Personal Statement.

IMBRIE, J. & PURDY, E.G. (1962). Classification of Modern Bahamian Carbonate Sediments. in Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem., 1, 253-273.

JOHNSON, D.W. (1919). Shore Professes & Shoreline Development. John Wiley & Son Inc., New York, 1-548.

KAULBACK, J.A., KENDALL, C.G.St.C., & SKIPWITH, Sir P.A. d'E. (1962). Cyclothems on the Islands of Kharg and Khargu, Persian Gulf. Unpublished Report to the Iranian Oil Exploration & Producing Companies.

KING, C.A.M. (1959). Beaches and Coasts. Edward Arnold, London. 1-403.

KINSMAN, D.J.J. (1964a). The Recent Carbonate Sediments near Halat el Bahrani, Trucial Coast, Persian Gulf. from Developments in Sedimentology, Vol. 1 L.M.J.U. Straatan (Editor). Deltaic & Shallow Marine Deposits, Elsevier Publishing Co., Amsterdam. 185-192.

KINSMAN, D.J.J. (1964 b). Reef Coral Tolerance of High Temperatures and Salinities. Nature. 202, 4939, 1280-1282.

KINSMAN, D.J.J. (1964 c). Recent Carbonate Sedimentation near Abu Dhabi, Trucial Coast, Persian Gulf. Unpublished Ph.D. Thesis, Library of Univ. of London.

KORNICKER, L.S. & PURDY, E.C. (1957). A Bahamian Faecal Pellet Sediment. J. sediment. Petrol. 27, 126-128.

KORNICKER, L.S. & BOYD, D.W. (1962). Shallow-Water Geology & Environments of Alacran Reef Complex. Campech Bank, Mexico. Bull. Am. Ass. Petrol. Geol. 46, 640-673.

KREMPF, A. (1927). La forme des recifs corallien et le regime vents alternanets. Travaux du Service Oceanogiephiques des Peches de l'Indochina. Mem 2, 3-33.

KRUMBEIN, W.C. & PETTIJOHN, F.J. (1938). Manual of Sed. Petrography. Appleton Centuary Co., New York, 1-549.

LADD, H.S., TRACEY, J.I., Jnr. WELLS, J.W. & EMERY, K.O. (1950). Organic Growth & Sedimentation on an Atoll J. Geol. 58, 413-414.

LEIGHTON, M.W. & PENDEXTER, C. (1962). Carbonate Rock Types. in Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem., 1, 33-62.

LOGAN, B.W. (1961). Cryptozoon and Associate Stromatolites from the Recent of Shark Bay, Western Australia. J. Geol. 69, (5), 517-533.

LOGAN, B.W., REYZAK, R. & GINSBURG, R.N. (1964). Classification and Environmental Significance of Algal Stromatolites. J. Geol. 72, (1), 68-84.

MASLOV, V.P. (1961). Algae & Deposition of Carbonates. Izv. Akad. Sci. U.S.S.R., Geol. Ser. 12.

MAXWELL, W.G.H., JELL, J.S. & McKELLER, R.G. (1964). Differentiation of Carbonate Sediments in the Heron Island Reef. J. sediment. Petrol. 34, (2), 294-308

MONTY, C. (1965). Recent algal stromatolites in the windward lagoon, Andros Island, Bahamas. Amm. Soc. Geol. Belgique, T.88, Bull. 6, B269-276.

MURRAY, J. (In Press). Foraminifera of the Persian Gulf. Pt. 4. Khor al Bazam.

NEWELL, N.D., PURDY, E.G. & IMBRIE, J. (1960). Bahamian Oolitic Sand. J. Geol. 68, (5) 481-497.

NEWELL, N.D., RIGBY, J.K., WHITEMAN, A.J. & BRADLEY, J.S. (1951). Shoal Water Geology & Environments, Eastern Andros Islands, Bahamas. Bull. Am. Mus. Nat. Hist. 97, 7-26.

NEWELL, N.D. & RIGBY, J.K. (1957). Geological Studies on the Gt. Bahaman Banks. Symposium of Regional Aspects of Carbonate Sedimentation. Special Publ. Soc. Econ. Paleont. Miner. 5, 15-73.

ORME, G.R. & BROWN, W.W.M. (1963). Diagenetic Fabrics in Avonian Limestones of Derbyshire and North Wales. Proc. Yorks. geol. Soc. 34, (1), 51-66.

PARK, N. & CURL, H.C. Jnr. (1965). Effect of Photosynthesis and Respiration on Electrical Conductivity of Seawater. Nature. 205, 4968, 274.

PHLEGER, F.B. & EWING, G.C. (1962). Sedimentology and Oceanography of Coastal Lagoons in Baja California, Mexico. Bull. Geol. Soc. Am. 73, 145-182.

PLUMLEY, W.J., RISLEY, G.A., GRAVES, R.W., Jnr. & Kaley, M.E. (1962). Energy Index for Limestone Interpretation and Classification. in Classification of Carbonate Rocks. Am. Ass. Petrol. Geol. Mem. 1. 85-108.

PRICE, W.A. (1951). Barrier Islands, not Offshore Bars. Science. 113, 487-488.

PRICE, W.A. (1963). Patterns of Flow and Channelling in Tidal Inlets. J. sediment Petrol. 33, (2), 279-290.

PURDY, E.G. (1963). Recent Calcium Carbonate Facies of the Great Bahama Bank Parts. Parts I & II. J. Geol. 71, (3), 334-355 & 71, (4), 472-497.

RUBEY, W.W. (1933). The Size-Distribution of Heavy Minerals Within a Water-Laid Sandstone. J. Sediment. Petrol. 3(1), 3-29.

SHEARMAN, D.J. & SKIPWITH, P.A.d'E. (1965). Organic matter in Recent and ancient limestones and its role in their diagenesis. Nature 208, 5017, 1310-1311.

SHEPARD, F.P. (1948). Submarine Geology. Harper & Brothers, New York. 1-338.

SHEPARD, F.R. (1952). Revised Nomenclature for Coastal Features. Bull. Am. Ass. Petrol. Geol. 36, 1902-1912.

SHEPARD, F.P. (1956). Marginal Sediments of Mississippi Delta. Bull. Am. Ass. Petrol. Geol. 40, 2537-2623.

SHINN, E. (1963). Spur & Groove Formation on the Florida Reef Tract. J. sediment. Petrol. 33, (2), 291-303.

SHINN, E.A., GINSBURG, R.N. & LLOYD, R.M. (1965). Recent supratidal dolomite from Andros Island, Bahamas. Symposium of Dolomitization and Limestone Diagenesis. Soc. Econ. Palaeontologists & Mineralogists, Spec. Pub. 13, 112-123.

SHEED, E.D. & FOLK, R.L. (1958). Pebbles in the Lower Colardo River, Texas. A Study in Particle Morphogenesis. J. Geol. 66, 114-150.

STEERS, J.A. (1929). The Queensland Coast and Great Barrier Reefs. Geogr. Jour. 74, 232-257, 341-370.

STODDART, D.R. (1962). Three Caribbean Atolls: Turneffe Islands, Lighthouse Reef, and Glover's Reef, British Honduras. Atoll. Res. Bull. 87, 151 p.

STRAATEN, L.M.J.U. Van (1953). Megaripples in the Dutch Wadden Sea and in the Basin of Arcachon (France). Geologie Mijnb n.s. 15, 1-11.

SORBY H.C. (1879). Anniversary address of the President (On the structure and origin of limestones): Proc. Geol. Soc. Lond. 35, 56-95.

SOLLAS, W.J. 1921. On Saccamina Carteri Brady and the Minute Structure of the Foraminifera Shell. Quart. J. Geol. Soc. Lond. 77, 193-212.

STRAATEN, L.M.J.U. Van (1954). Composition and Structure of Recent Marine Sediments in the Netherlands. Leidse Geol. Med. dl. 19, 1-96.

STRIDE, A.H. (1963). Current-swept sea floors near the Southern half of Great Britain. Quart. J. Geol. Soc. Lond. 119, 175-201.

SUGDEN, W. (1963 a). The Hydrology of the Persian Gulf and its significance in respect to evaporite deposition. Am. J. Sci. 261, 741-755.

SUGDEN, W. (1963 b). Some aspects of sedimentation in the Persian Gulf. J. sediment. Petrol. 33, (2), 355-364.

SWINCHATT, J.P. (1965). Significance of Constituent Composition, Texture & Skeletal Breakdown of some Recent Carbonate Sediments. J. sediment. Petrol. 35, (1), 71-90.

TANNER, W.F. (1964). Modification of Sediment Size Distribution J. sediment. Petrol. 34, (1), 156-164.

THORNBURY, W.D. (1954). Principles of Geomorphology. John Wiley & Sons, Inc., New York & London. 1-618.

TIPPER, G.H. (1914). Monazite Sand of Travancore. Sec. Geol. Survey India. 44, 186-196.

TWYMAN J. (1964). Personal communication.

VALENTIN, H. (1959). Geomorphological Reconnaissance of the North-West Coast of Cape York Peninsula. (Northern Australia). 2nd Coastal Geography Conference. Coastal Studies Institute. Louisiana State University.. 213-233.

VANN, J.H. (1959). Geomorphology of the Guiana Coast. 2nd Coastal Geography Conference. Coastal Studies Institute. Louisiana State University. 153-189.

Van VEEN (1953). Eb-en Vloedschaar Systemen in de Nederlandse Getijwateren. pp. 43 to 66. Waddensymposium. Overdruk van de Mei-Aflereverin 1950. Van Het Tijdschrift Koninklijk Nederlansch Aardrijkskundig Genootschap.

VAUGHAN, T.W. (1909). The Geologic Work of Mangroves in Southern Florida. Smithson Misc. Coll. 52, 461.

VAUGHAN, T.W. (1919 b). Corals and the Formation of Coral Reefs. Smithsonian Rept. 189-276.

WELLS, A.J. (1962). Recent Dolomite in the Persian Gulf. Nature. 194, 4825, 274-275.

WELLS, A.J. & ILLING, L.V. (1964). Present day Precipitation of Calcium Carbonate in the Persian Gulf. from Developments in sedimentology Vol. 1. L.M.J.U. Straaten. (Editor), Deltaic & Shallow Marine Deposits. Elsevier Publishing Company. Amsterdam, 420-435.

WOLF, K.H. (1965a). Petrogenesis and Palaeoenvironment of Devonian algal limestones of New South Wales. Sedimentology 4, 113-178.

WOLF, K.H. (1965b) 'Grain Dimunition' of algal colonies to micrite. J. sediment. Petrol. 35, 420-427.

WOLF, K.H. & CONNOLLY J.R. (1965). Petrogenesis and Palaeoenvironment of limestone lenses in Upper Devonian red beds of New South Wales. Palaeogeography, Palaeoclimatol Palaeoecol., 1, 69-111.

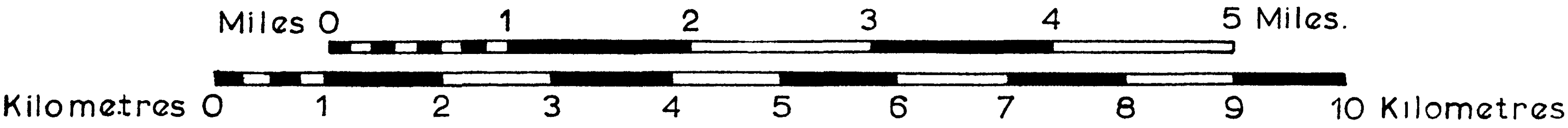
WOOD, A. (1948). The Structure of the Wall of the Test in the Foraminifera: its Value in Classification. Quart. J. geol. Soc. Lond. 104, 229.

WENTWORTH, C.K. (1922). A Scale of Grade and Class Terms for Clastic Sediments. J. Geol. 30, 377-392.

WILLIAMS, W.W. (1960). Coastal Changes. Routledge and Kegan Paul. London. 1-220.

VARIATION DIAGRAMS KEY.

────────	Mollusc tests & fragments.
━━━━━━━━	Unidentifiable grains.
··················	Aggregates.
••••••••••••••••	Ostracod tests.
- - - - - - - - - -	Foraminifera tests.
— — — — — — —	Calcareous algae.
o o o o o o o o o o o	Bryozoan.
+ + + + + + + + + +	Quartz grains.
o–o–o–o–o–o–	Pellets.
o+o+o+o+o+o+o+o	Sugary brown grains.
+·+·+·+·+·+·+·	Heavy mineral grains.
·—·—·—·—·	Gypsum crystals.

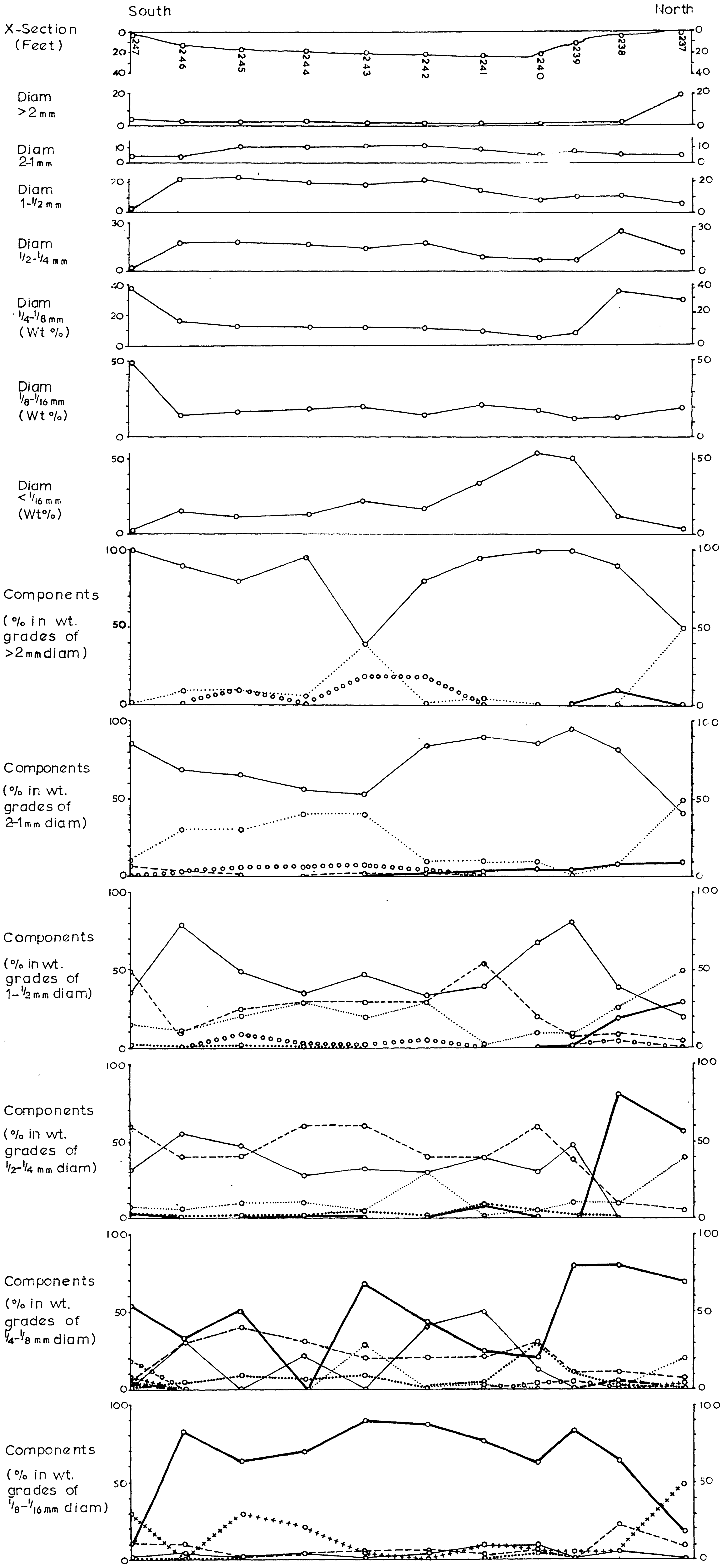



WEST KHOR AL BAZAM
GEOMORPHOLOGY & SAMPLES.
SHEET 3.
Tertiary hills.
Outwash fans.
Sabkha.
Beach ridges.
Offshore sand shoals.
Algal flats.
Mangrove clumps.
Coral reefs.
Seaweed patches.
Shallow water shelf.
Deep water.
Break in slope.
Long axes of sand bodies.
N
HAIL
Multiple delta
Longitudinal megaripples
Levees
Grooved reef
Coral spurs
Old coral fronts
Delta
Longitudinal megaripples
Lines of old reefs
Scoured sand covers coral
Lineation of weed & rhomboid sand streaks.
Compound spit
MARAWAH
Linguoid megaripples
Linguoid megaripples fixed by coral
Longitudinal megaripples
Double ended delta with weed streaks
Delta
Compound spit
RAS AL SEHAMA
Deltas
MAHMEEM
Rilled area
Rills
Cusped beach ridges
JANANA
Coral front
Beach barrier
Linguoid megaripples
Delta linguoid megaripples
Rhomboid sand streaks on weed
Weed infected channels
Old coral lines exposed by channels
Double reef front
Small deltas
Lines of old reefs
Rhomboid sand streaks on weed
Weed covered coral
SALAHA
Weed lined channel
KHOR AL BAZAM
Break point bar
Coral front
Transverse megaripples on weed covered platform
Angled runnels & bars
Winged headland
Angled runnels & bars
Complex of old beach lines and wind blown sediment
Runnels & bars
JABAL MIRFA
T1 T2 T3 T4 T5 T6 T7
Scale 1:40,000
Based on an uncorrected mosaic from Iraq Petroleum Company aerial photographs. Interpreted by Christopher G. St.C. Kendall 1965.
Miles 0 1 2 3 4 5 Miles.
Kilometres 0 1 2 3 4 5 6 7 8 9 10 Kilometres.
South
North
Feet
Vertical exaggeration X66. Cross sections uncorrected for tide
Wind rose for Abu Dhabi (after Kinsman 64).
N E S W
Location map.
Abu Dhabi
Zubaiya
Abu al Abyad
Khor al Bazam
Jabal Dhana
Miles 0 10 20 30 40

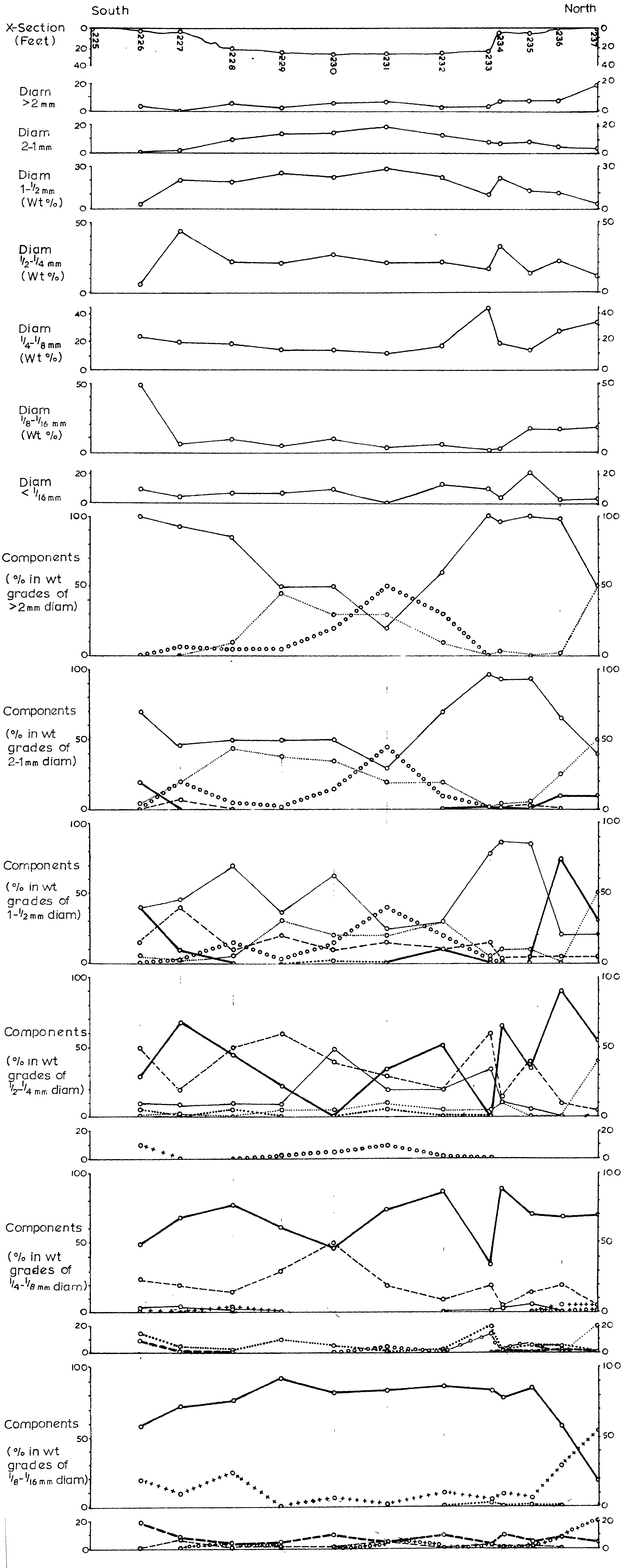

WEST KHOR AL BAZAM
GEOMORPHOLOGY & SAMPLES.
SHEET 2.
☐ Tertiary hills.
☐ Outwash fans.
☐ Sabkha.
☐ Beach ridges.
☐ Offshore sand shoals.
☐ Algal flats.
☐ Mangrove clumps.
☐ Coral reefs.
■ Seaweed patches.
☐ Shallow water shelf.
☐ Deep water.
Break in slope.
Long axes of sand bodies.
N
Grooved reef front
Beach barrier partially fixed by coral
Transverse megaripples on weed
Longitudinal megaripples
Coral pinnacles
BAZAM AL GARBI
Tailed coral pinnacles
Cusped spit
Linguoid megaripples
Rhomboid sand streaks on weed
Rhomboid sand streaks on weed
Longitudinal megaripples
Delta
FIYA
Weed on rock platforms
Coral pinnacles & spurs
Line of old reef front
Transverse megaripples
Angled runnels & bars
MARAWAH
Weed on rock platform
Transverse megaripples on weed
KHOR AL BAZAM
Transverse megaripples on weed covered platform
Weed covered coral front
Crescentic bars and runnels & bars
Deltas
Angled runnels & bars
RAS AL AISH
Break point bars
Transverse megaripples on weed covered platform
KHUSAIFA
Washout delta
Complex of old beach lines and wind blown sediment
T6 T9 T8 T7
Scale 1:40,000
Based on uncorrected mosaic from Iraq Petroleum Company aerial photographs. Interpreted by Christopher G. St.C. Kendall 1965.
Miles 0 1 2 3 4 5 Miles
Kilometres 0 1 2 3 4 5 6 7 8 9 10 Kilometres
South
North
Feet 0 1 0 2 0 3 0 4 0 5 0 6 0
Vertical exaggeration x66 Cross-sections uncorrected for tide.
Wind rose for Abu Dhabi (after Kinsman 64).
N E S W
Location map.
1. 2. 3. 4.
Khor al Bazam
Abu al Abyad
Zubaiya
Abu Dhabi
Miles 0 10 20 30 40


WEST KHOR AL BAZAM
GEOMORPHOLOGY & SAMPLES.
SHEET 1.
☐ Tertiary hills.
☐ Outwash fans.
☐ Sabkha.
☐ Beach ridges.
☐ Offshore sand shoals.
☐ Algal flats.
☐ Mangrove clumps.
☐ Coral reefs.
■ Seaweed patches.
☐ Shallow water shelf.
☐ Deep water.
Break in slope.
Long axes of sand bodies.
N
Area not covered by I.P.C. photographs.
Old reef front
Coral spur
127
126
125
124
123
122
121
120
119
118
117
116
DAGALLAH
Deltas
Transverse megaripples on weed covered platform
Weed covered coral front
449
450
451
452
453
454
455
456
QUALA
THIMAIRIYAN
BU SHIYARAR
Sand cays
Runnels & bars
Gullies
Old delta
Delta
Levee
Runnels & bars
Longitudinal megaripples
Angled runnels & bars
Angled runnels & bars
Winged headland
Washout gullies
Scale 1:40,000
Based on an uncorrected mozaic from Iraq Petroleum Company aerial photographs. Interpreted by Christopher G. St.C. Kendall 1965.
Miles 0 1 2 3 4 5 Miles.
Kilometres. 0 1 2 3 4 5 6 7 8 9 10 Kilometres.
South
North
Feet 0 10 20 30 40 50 60
0 Feet. 10 20 30 40 50 60
116 117 118 119 120 121 122 123 124 125 126 127 128 129
Vertical exaggeration x66. Cross sections uncorrected for tide
Wind rose for Abu Dhabi (after Kinsman 64).
N E S W
Location map.
N
Abu Dhabi
Zubaiya
Abu al Abyad
Khor al Bazam
Jabal Dhana
1. 2. 3.
Miles 0 10 20 30 40

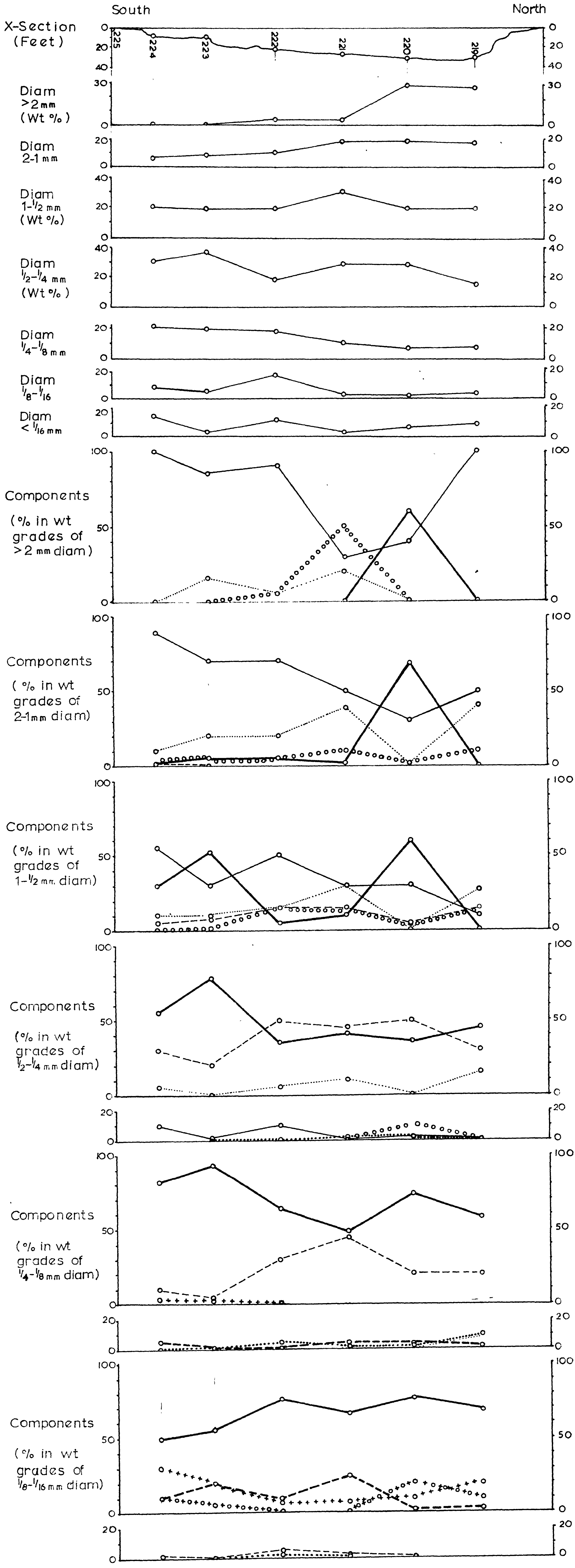
SHEET 4


South
North
X-Section (Feet)
0
20
40
247
246
245
244
243
242
241
240
239
238
237
Diam >2 mm
20
0
Diam 2-1 mm
10
0
Diam 1-½ mm
20
0
Diam ½-¼ mm
30
0
Diam ¼-⅛ mm (Wt %)
40
20
0
Diam ⅛-1/16 mm (Wt %)
50
0
Diam <1/16 mm (Wt%)
50
0
Components (% in wt. grades of >2 mm diam)
100
50
0
Components (% in wt. grades of 2-1 mm diam)
100
50
0
Components (% in wt. grades of 1-½ mm diam)
100
50
0
Components (% in wt. grades of ½-¼ mm diam)
100
50
0
Components (% in wt. grades of ¼-⅛ mm diam)
100
50
0
Components (% in wt. grades of ⅛-1/16 mm diam)
100
50
0

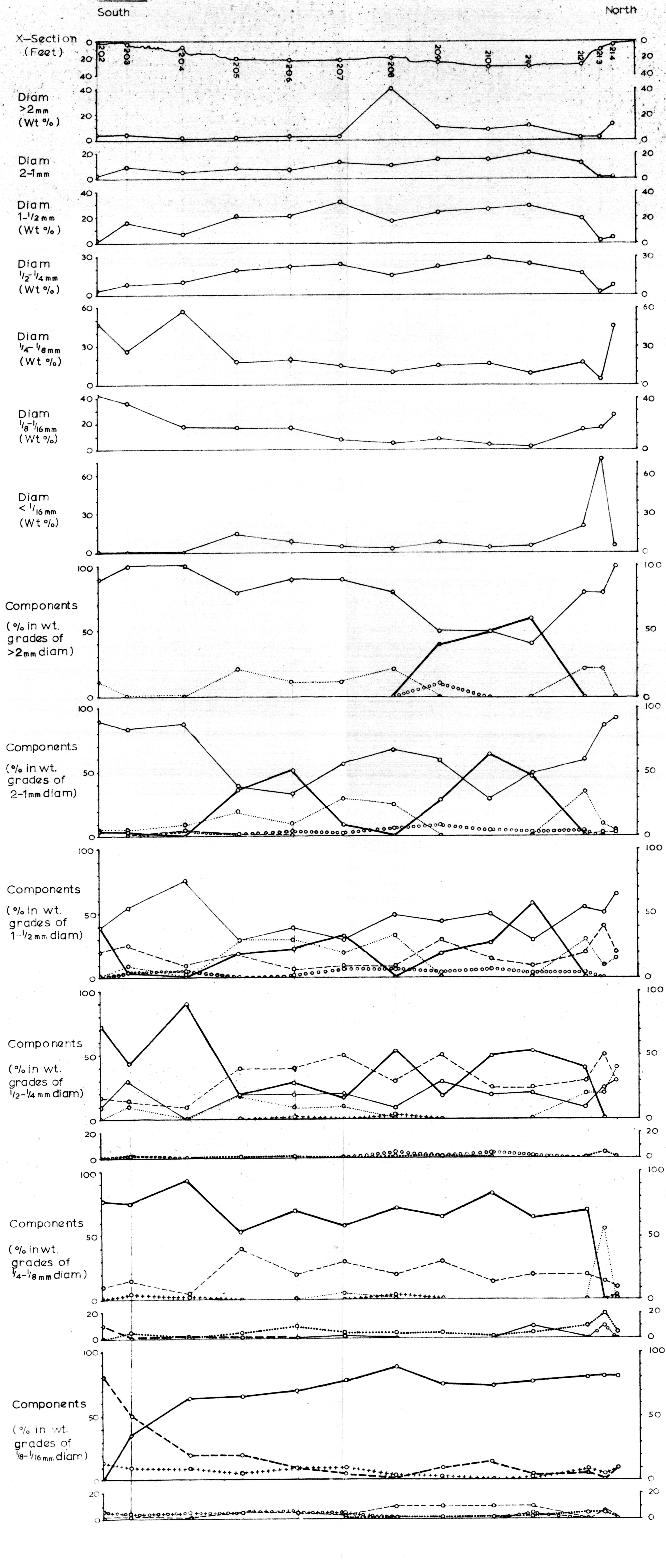
SHEET 5


South
North
X-Section (Feet)
0
20
40
225
226
227
228
229
230
231
232
233
234
235
236
237
Diam >2 mm
Diam 2-1 mm
Diam 1-1/2 mm (Wt %)
Diam 1/2-1/4 mm (Wt %)
Diam 1/4-1/8 mm (Wt %)
Diam 1/8-1/16 mm (Wt %)
Diam < 1/16 mm
Components (% in wt grades of >2 mm diam)
Components (% in wt grades of 2-1 mm diam)
Components (% in wt grades of 1-1/2 mm diam)
Components (% in wt grades of 1/2-1/4 mm diam)
Components (% in wt grades of 1/4-1/8 mm diam)
Components (% in wt grades of 1/8-1/16 mm diam)
10
20
30
40
50
100

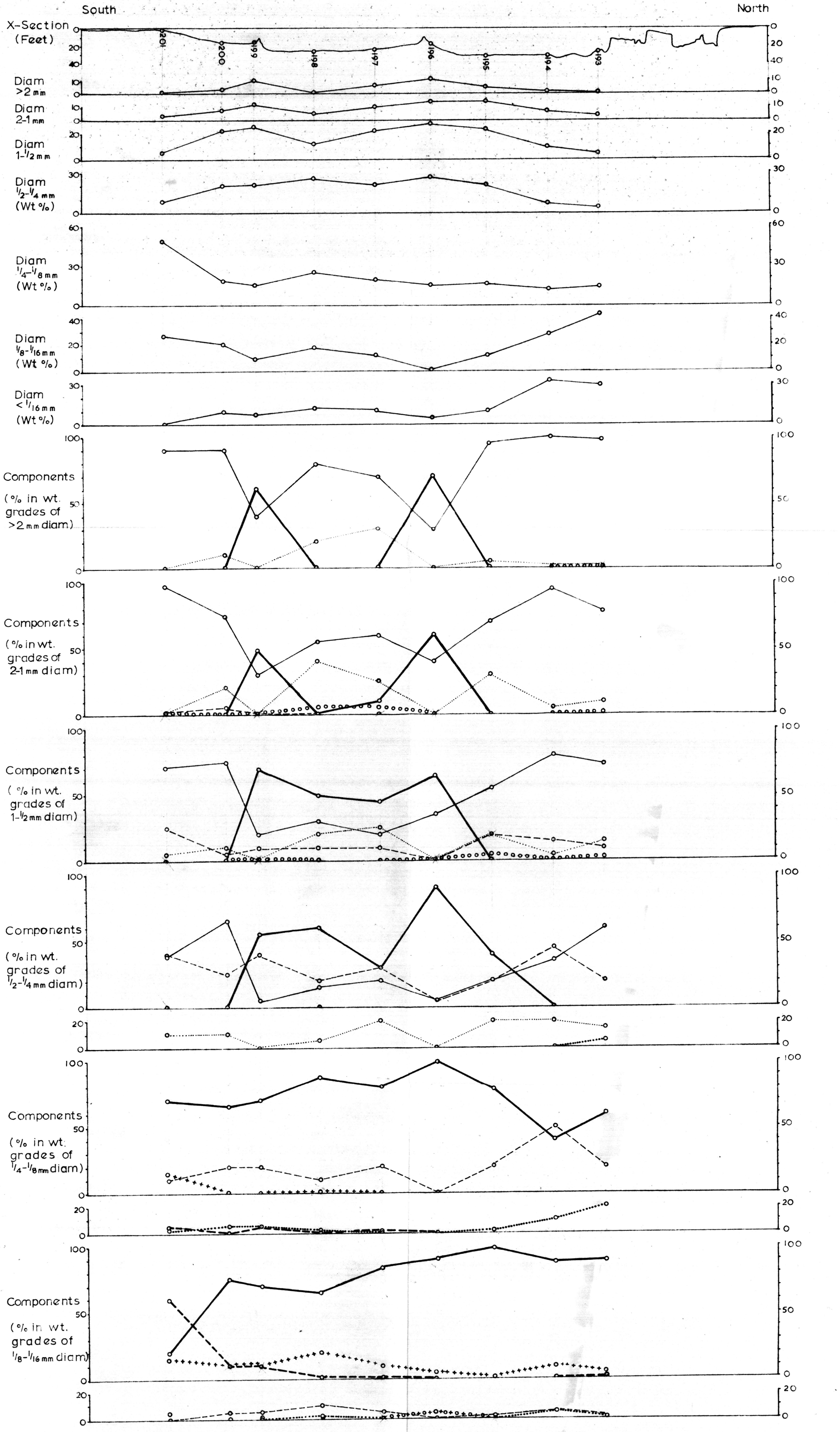
SHEET 6


South
North
X-Section (Feet)
0
20
40
225
224
223
222
221
220
219
Diam >2 mm (Wt %)
30
0
Diam 2-1 mm
20
0
Diam 1-1/2 mm (Wt %)
40
20
0
Diam 1/2-1/4 mm (Wt %)
40
20
0
Diam 1/4-1/8 mm
20
0
Diam 1/8-1/16
20
0
Diam <1/16 mm
20
0
Components (% in wt grades of >2 mm diam)
100
50
0
Components (% in wt grades of 2-1mm diam)
100
50
0
Components (% in wt grades of 1-1/2 mm diam)
100
50
0
Components (% in wt grades of 1/2-1/4 mm diam)
100
50
0
20
0
Components (% in wt grades of 1/4-1/8 mm diam)
100
50
0
20
0
Components (% in wt grades of 1/8-1/16 mm diam)
100
50
0
20
0

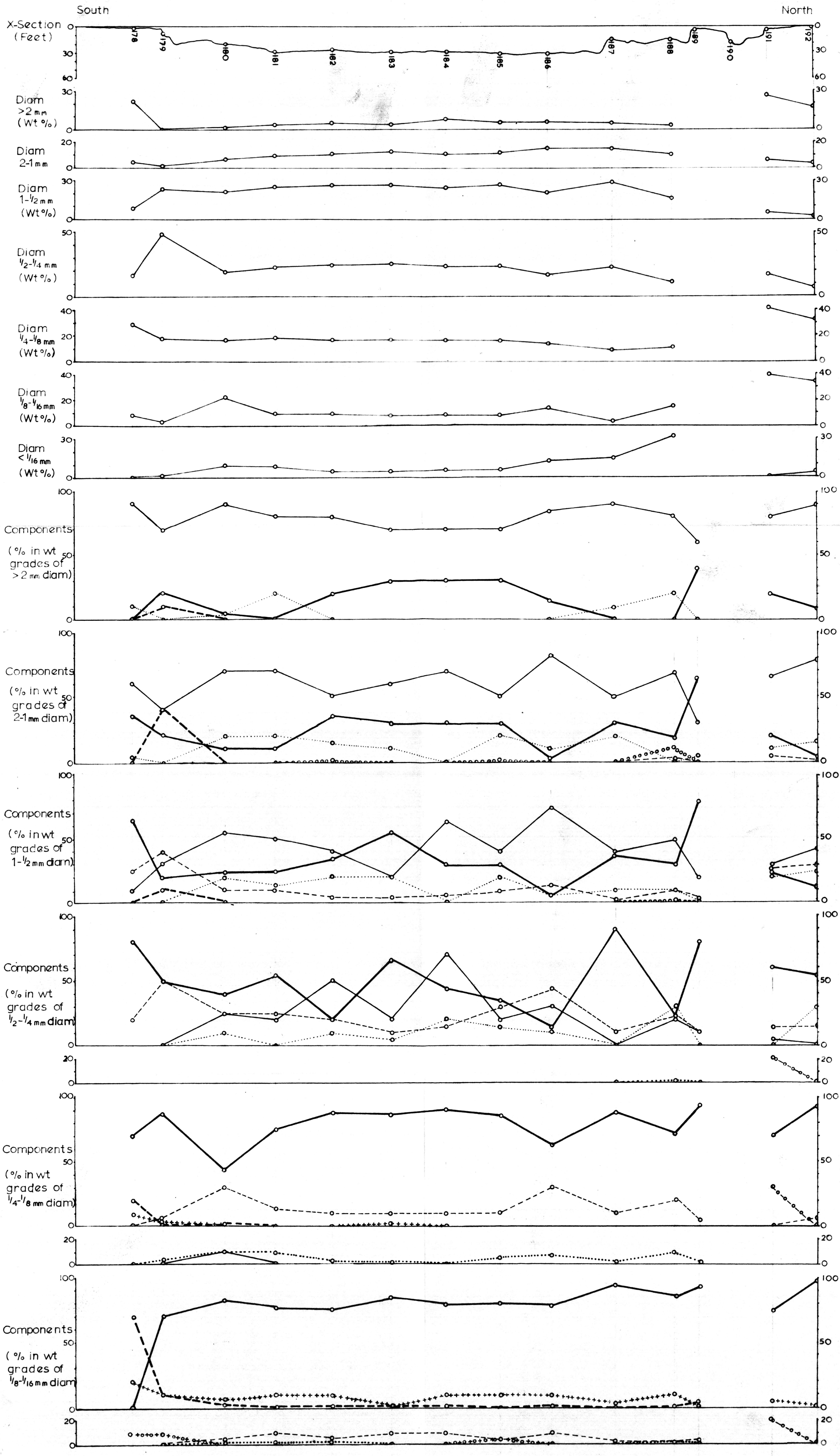
SHEET 7


South
North
X–Section (Feet)
0
20
40
202
203
204
205
206
207
208
209
210
211
212
213
214
Diam >2mm (Wt %)
Diam 2–1mm
Diam 1–½mm (Wt %)
Diam ½–¼mm (Wt %)
Diam ¼–⅛mm (Wt %)
Diam ⅛–1/16mm (Wt %)
Diam <1/16mm (Wt %)
Components (% in wt. grades of >2mm diam)
Components (% in wt. grades of 2–1mm diam)
Components (% in wt. grades of 1–½mm diam)
Components (% in wt. grades of ½–¼mm diam)
Components (% in wt. grades of ¼–⅛mm diam)
Components (% in wt. grades of ⅛–1/16mm diam)
0
30
50
60
100

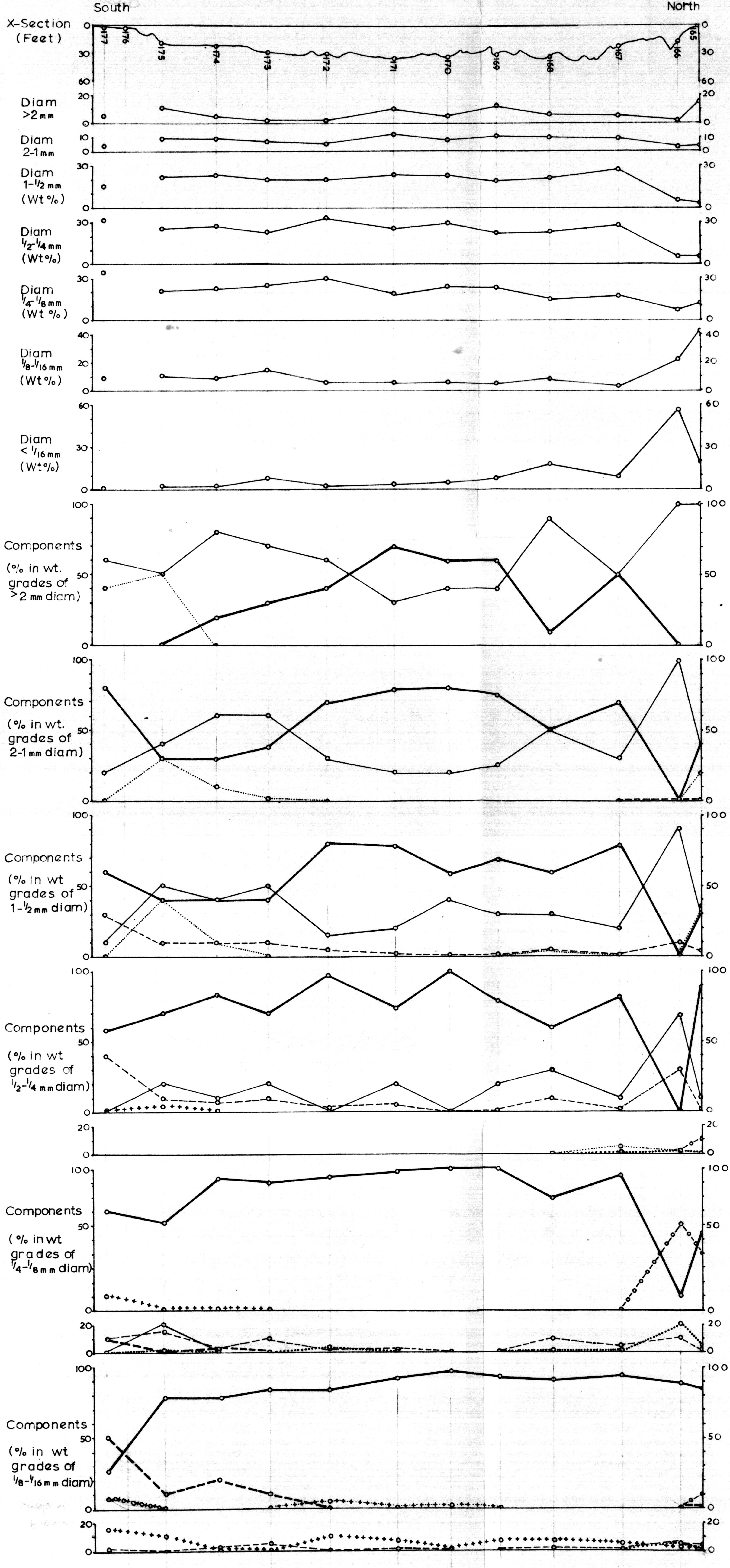
SHEET 8


South
North
X-Section (Feet)
0
20
40
201
200
199
198
197
196
195
194
193
Diam >2 mm
10
Diam 2-1 mm
Diam 1-½ mm
Diam ½-¼ mm (Wt %)
Diam ¼-⅛ mm (Wt %)
Diam ⅛-1/16 mm (Wt %)
Diam <1/16 mm (Wt %)
30
60
40
Components (% in wt. grades of >2 mm diam)
Components (% in wt. grades of 2-1 mm diam)
Components (% in wt. grades of 1-½ mm diam)
Components (% in wt. grades of ½-¼ mm diam)
Components (% in wt. grades of ¼-⅛ mm diam)
Components (% in wt. grades of ⅛-1/16 mm diam)
100
50

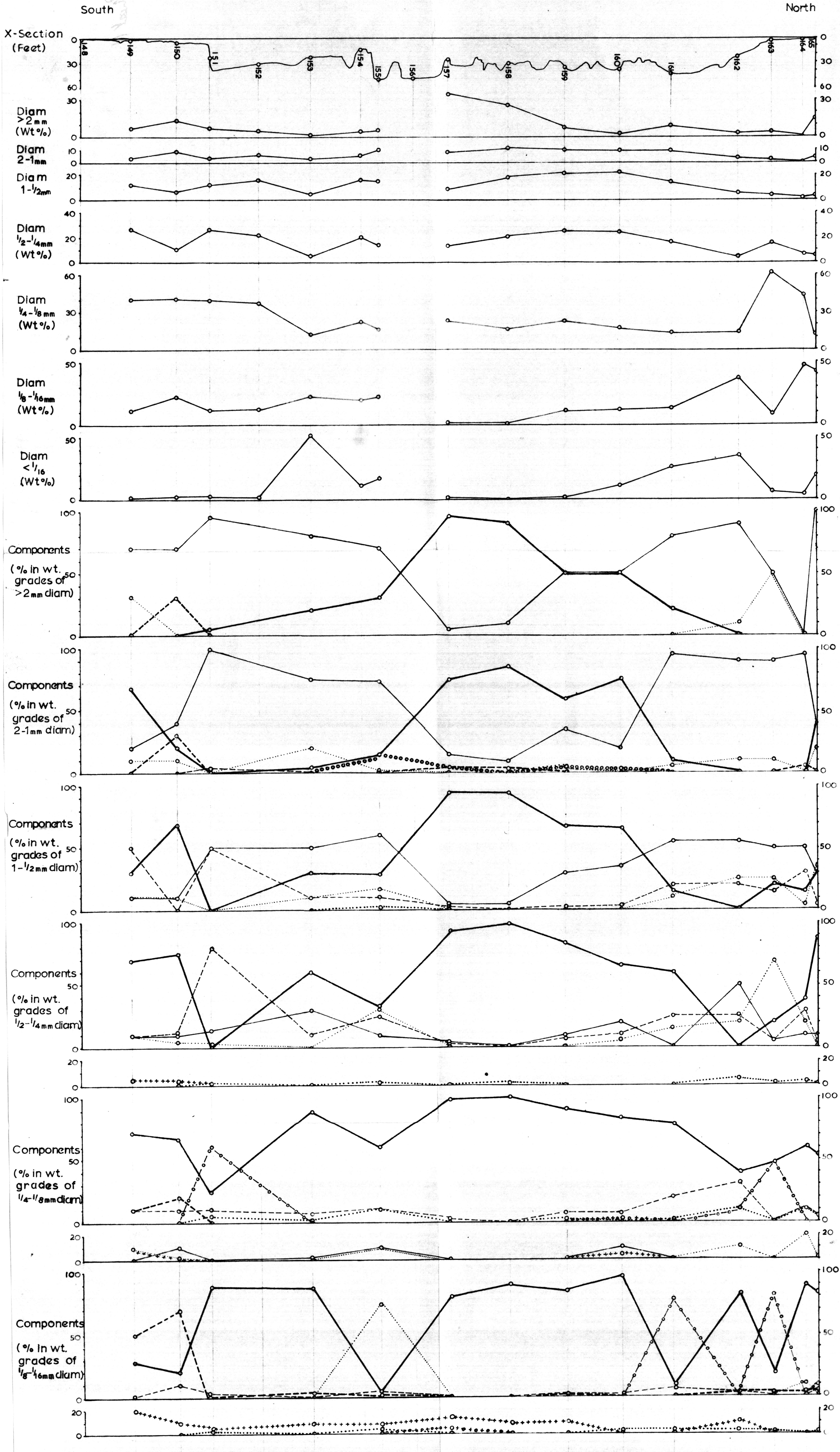
SHEET 9


South
North
X-Section (Feet)
0
30
60
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
Diam >2 mm (Wt %)
Diam 2-1 mm
Diam 1-1/2 mm (Wt %)
Diam 1/2-1/4 mm (Wt %)
Diam 1/4-1/8 mm (Wt %)
Diam 1/8-1/16 mm (Wt %)
Diam <1/16 mm (Wt %)
Components (% in wt grades of >2 mm diam)
Components (% in wt grades of 2-1 mm diam)
Components (% in wt grades of 1-1/2 mm diam)
Components (% in wt grades of 1/2-1/4 mm diam)
Components (% in wt grades of 1/4-1/8 mm diam)
Components (% in wt grades of 1/8-1/16 mm diam)
0
20
40
50
100

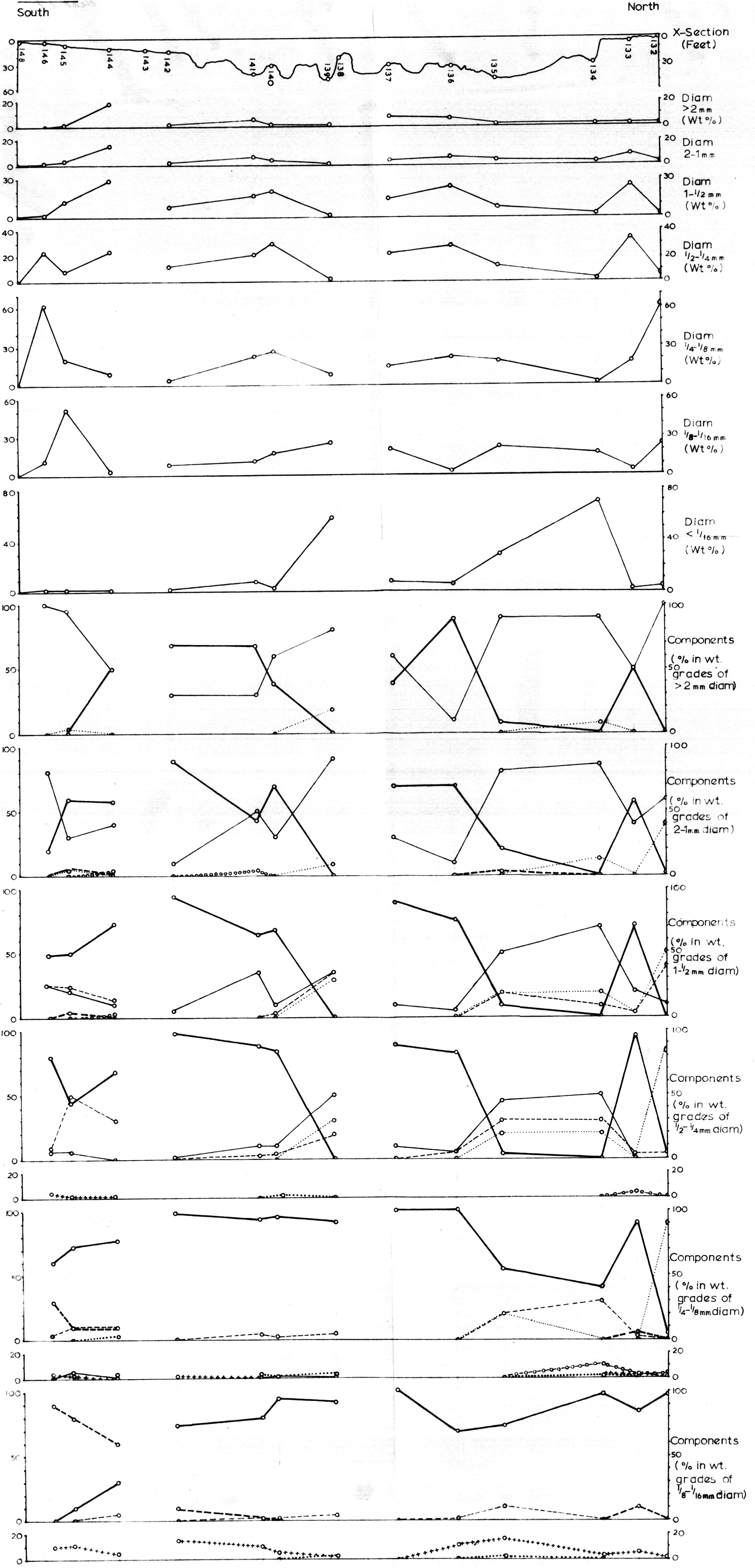
SHEET 10


South
North
X-Section
(Feet)
0
30
60
177
176
175
174
173
172
171
170
169
168
167
166
165
Diam
>2 mm
20
0
Diam
2-1 mm
10
0
Diam
1-1/2 mm
(Wt%)
30
0
Diam
1/2-1/4 mm
(Wt%)
30
0
Diam
1/4-1/8 mm
(Wt %)
30
0
Diam
1/8-1/16 mm
(Wt%)
40
20
0
Diam
< 1/16 mm
(Wt%)
60
30
0
Components
(% in wt.
grades of
>2 mm diam)
100
50
0
Components
(% in wt.
grades of
2-1 mm diam)
100
50
0
Components
(% in wt
grades of
1-1/2 mm diam)
100
50
0
Components
(% in wt
grades of
1/2-1/4 mm diam)
100
50
0
20
0
Components
(% in wt
grades of
1/4-1/8 mm diam)
100
50
0
20
0
Components
(% in wt
grades of
1/8-1/16 mm diam)
100
50
0
20
0

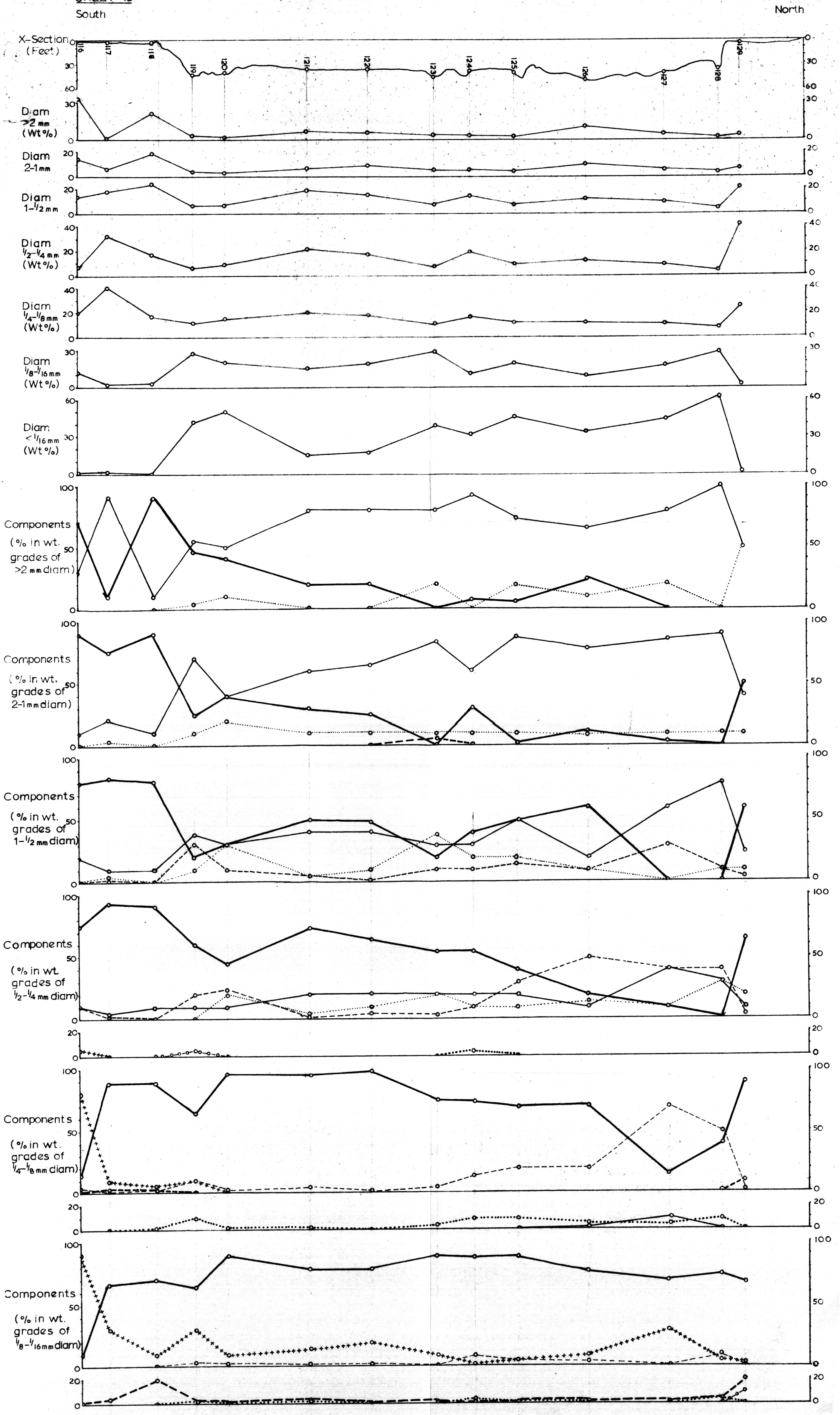
SHEET 11


South
North
X-Section
(Feet)
0
30
60
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
Diam
>2mm
(Wt%)
Diam
2-1mm
Diam
1-1/2mm
Diam
1/2-1/4mm
(Wt%)
Diam
1/4-1/8mm
(Wt%)
Diam
1/8-1/16mm
(Wt%)
Diam
<1/16
(Wt%)
Components
(% in wt.
grades of
>2mm diam)
Components
(% in wt.
grades of
2-1mm diam)
Components
(% in wt.
grades of
1-1/2mm diam)
Components
(% in wt.
grades of
1/2-1/4mm diam)
Components
(% in wt.
grades of
1/4-1/8mm diam)
Components
(% in wt.
grades of
1/8-1/16mm diam)
0
10
20
30
40
50
60
100

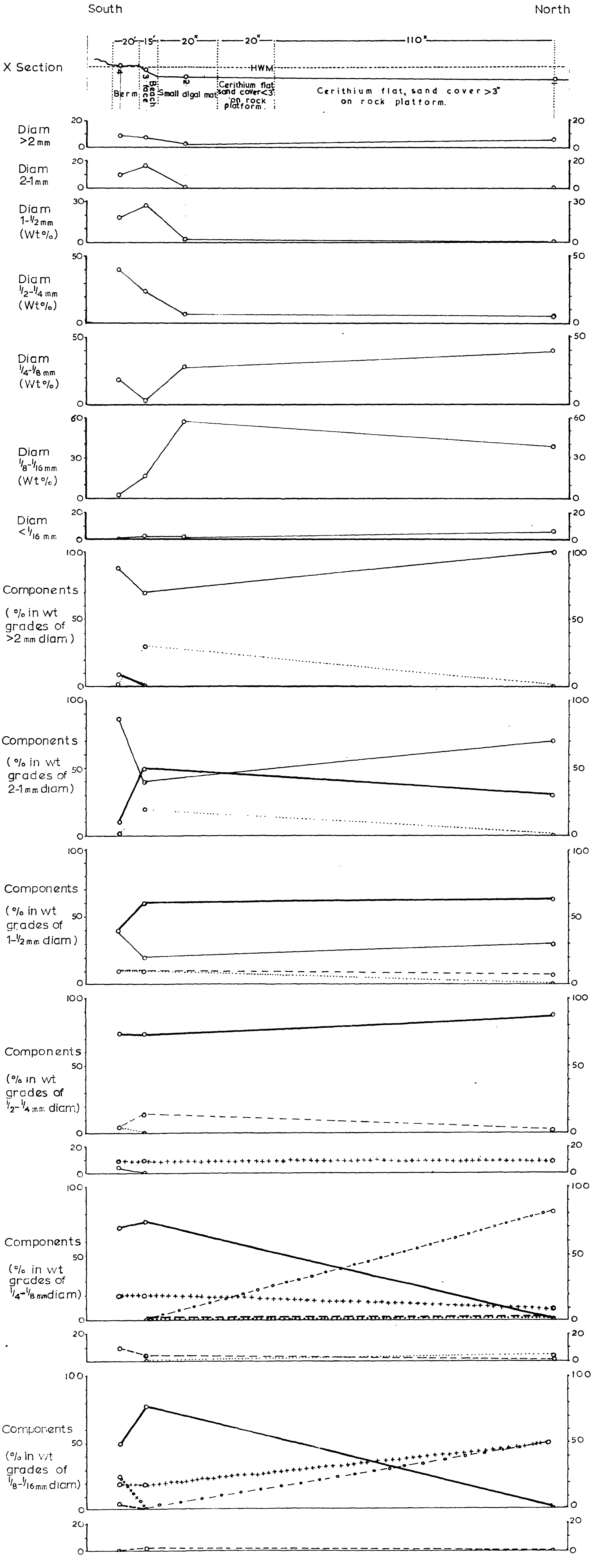
SHEET 12.


South
North
X-Section (Feet)
0
30
60
148
146
145
144
143
142
141
140
139
138
137
136
135
134
133
132
Diam >2 mm (Wt %)
20
Diam 2-1 mm
Diam 1-1/2 mm (Wt %)
Diam 1/2-1/4 mm (Wt %)
40
Diam 1/4-1/8 mm (Wt %)
Diam 1/8-1/16 mm (Wt %)
Diam <1/16 mm (Wt %)
80
Components (% in wt. grades of >2 mm diam)
100
50
Components (% in wt. grades of 2-1 mm diam)
Components (% in wt. grades of 1-1/2 mm diam)
Components (% in wt. grades of 1/2-1/4 mm diam)
Components (% in wt. grades of 1/4-1/8 mm diam)
Components (% in wt. grades of 1/8-1/16 mm diam)

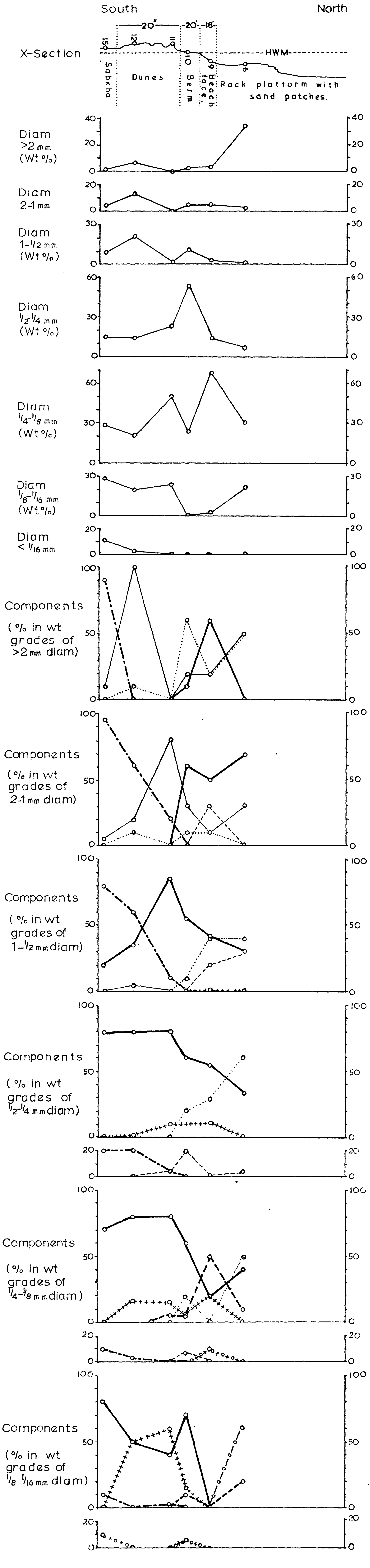
SHEET 13


South
North
X-Section (Feet)
0
30
60
116
117
118
119
120
121
122
123
124
125
126
127
128
129
Diam >2 mm (Wt %)
Diam 2-1 mm
Diam 1-1/2 mm
Diam 1/2-1/4 mm (Wt %)
Diam 1/4-1/8 mm (Wt %)
Diam 1/8-1/16 mm (Wt %)
Diam <1/16 mm (Wt %)
Components (% in wt. grades of >2 mm diam)
Components (% in wt. grades of 2-1 mm diam)
Components (% in wt. grades of 1-1/2 mm diam)
Components (% in wt. grades of 1/2-1/4 mm diam)
Components (% in wt. grades of 1/4-1/8 mm diam)
Components (% in wt. grades of 1/8-1/16 mm diam)
0
20
30
40
50
60
100

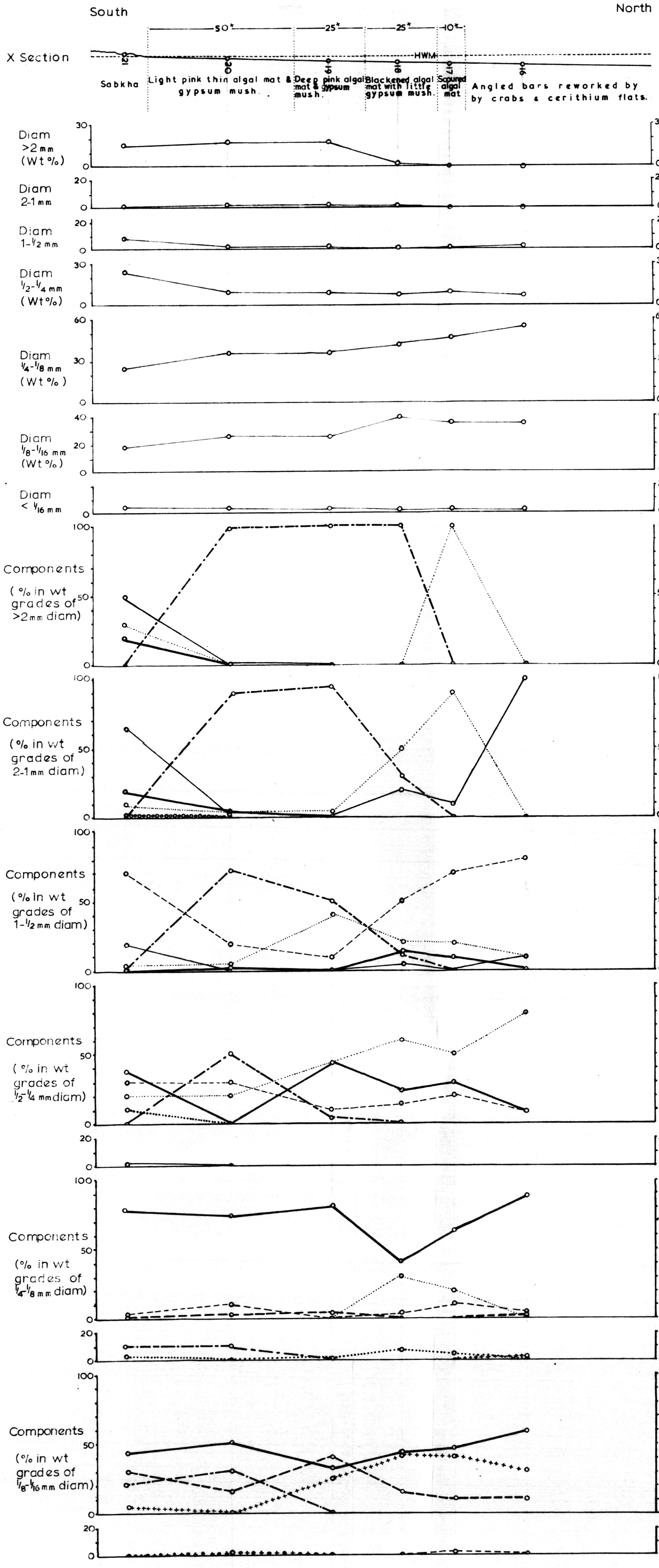
SHEET 14 Traverse 1



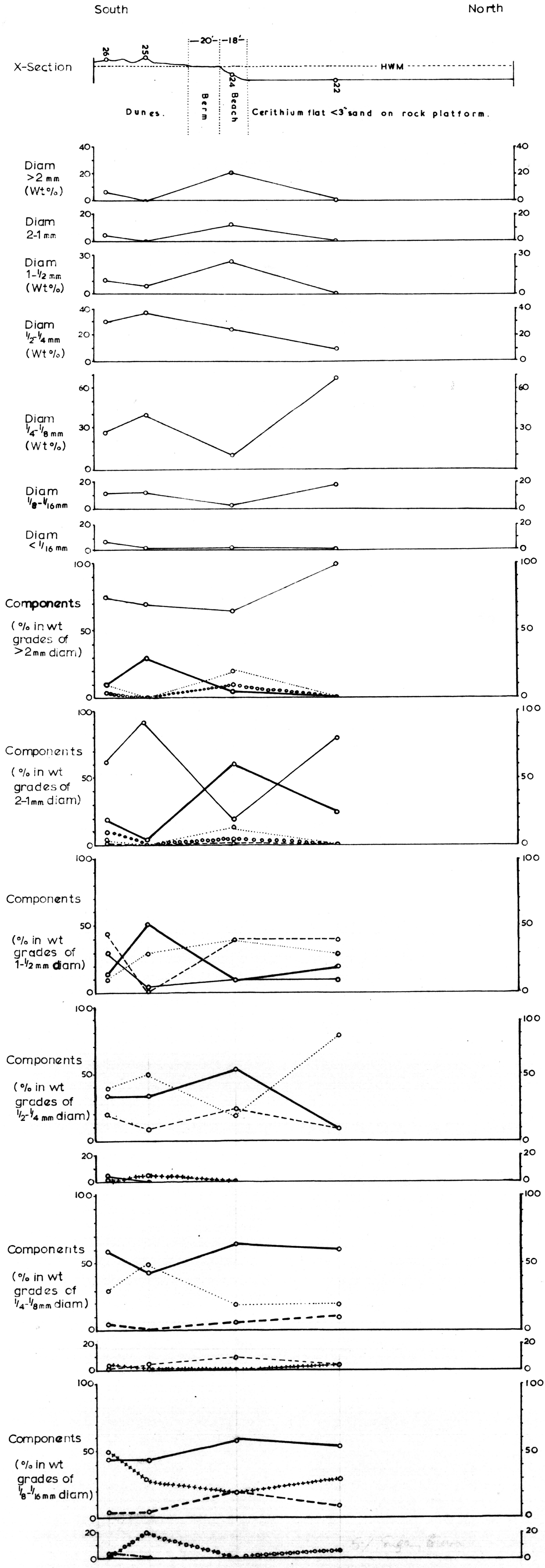
SHEET 15 Traverse 2.



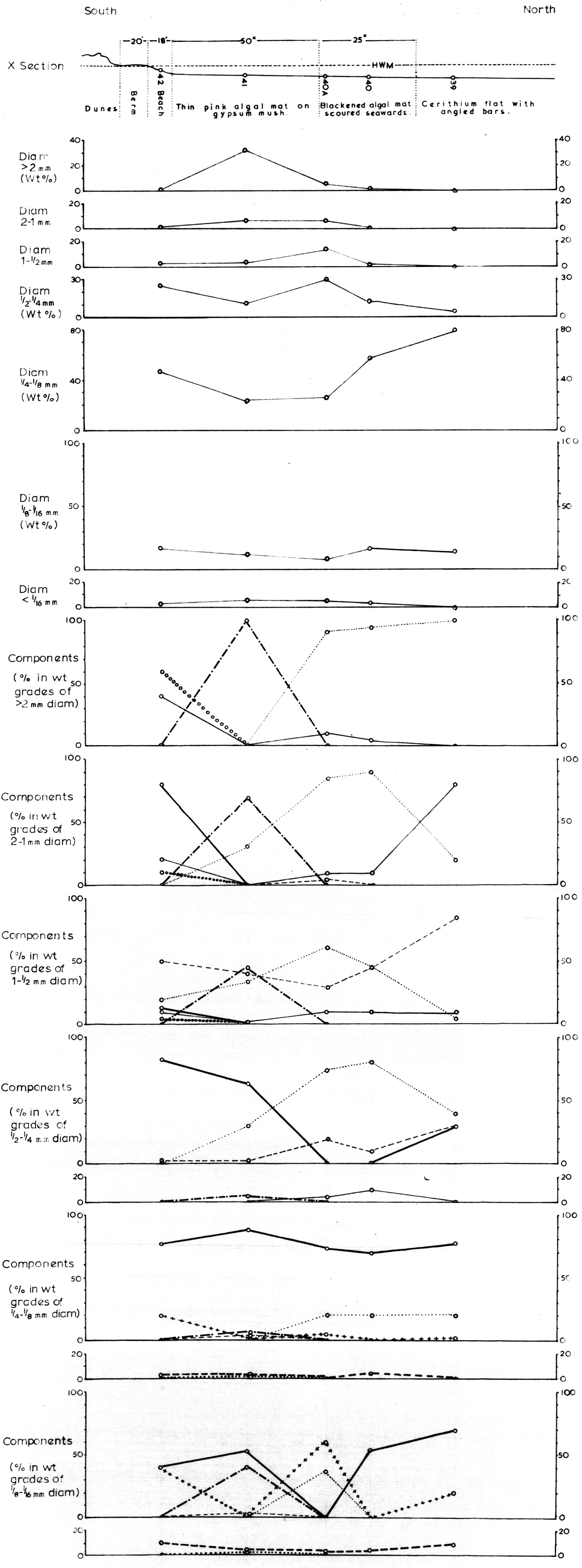
SHEET 16 Traverse 3



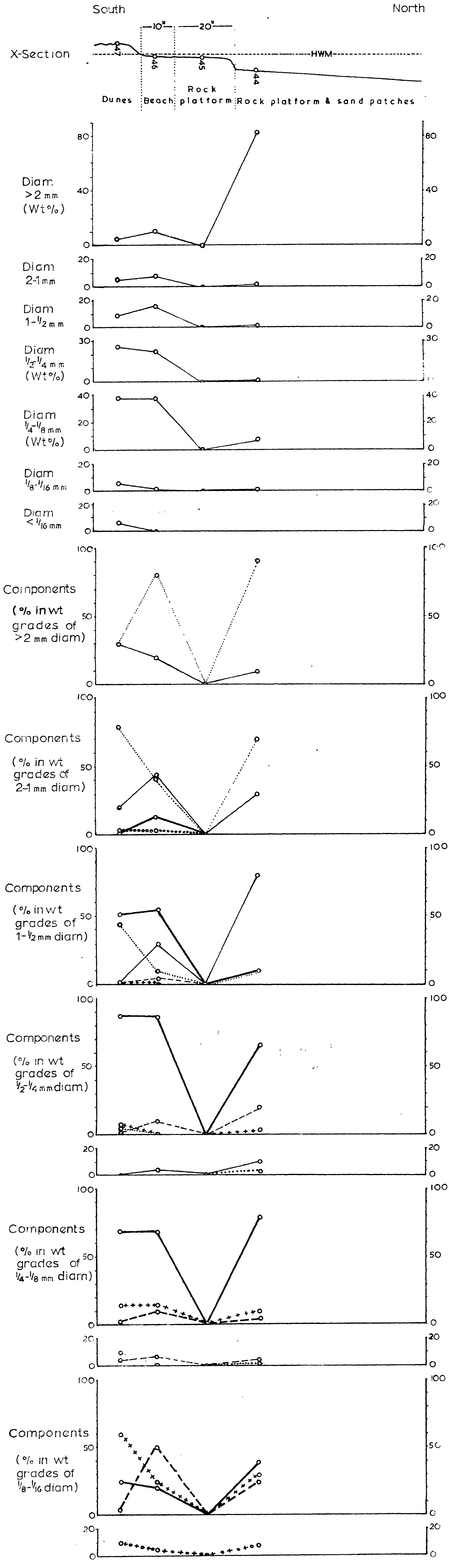
SHEET 17 Traverse 4



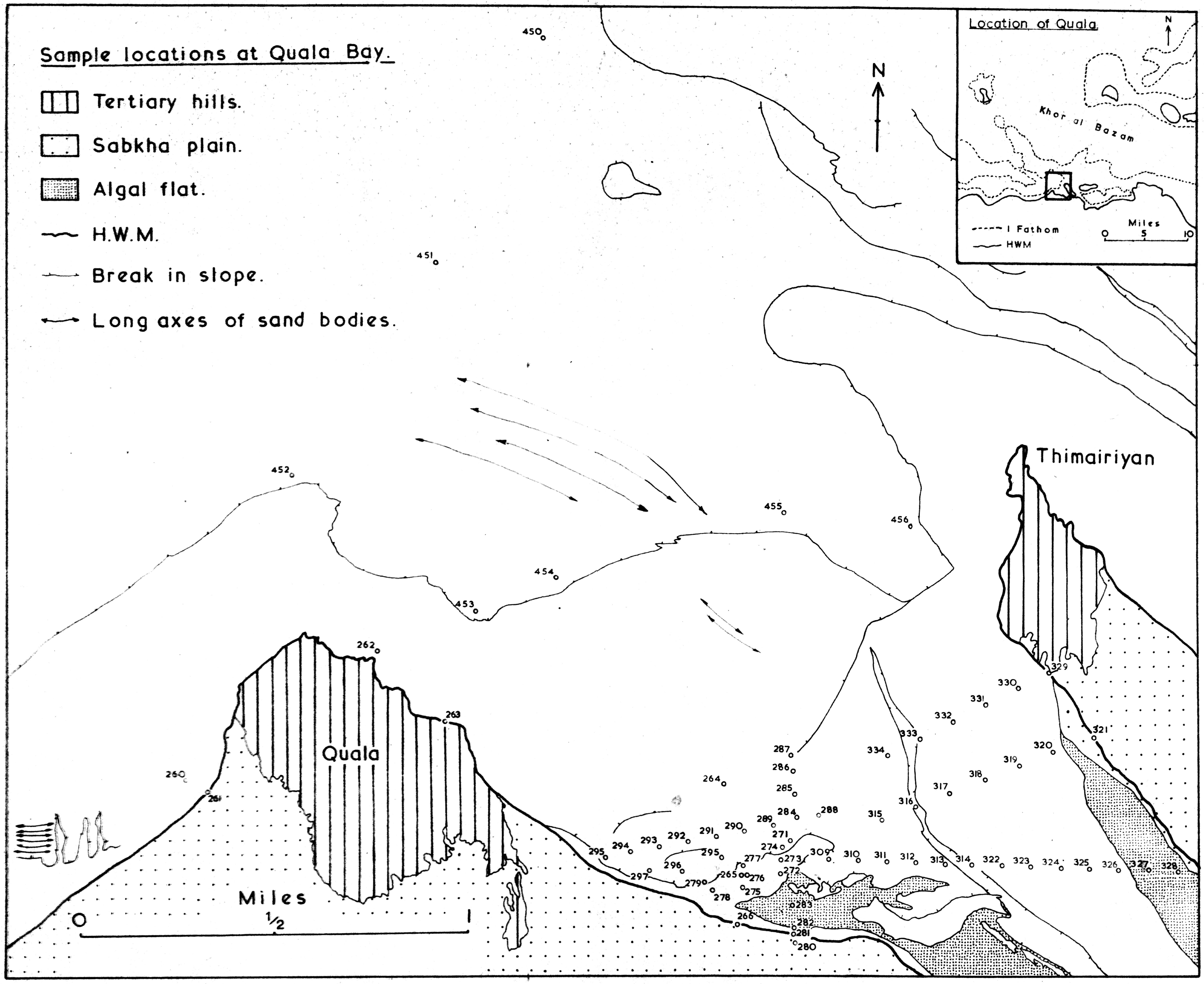
SHEET 18 Traverse 5



SHEET 19 Traverse 6



Sheet 20


Sample locations at Quala Bay.
Tertiary hills.
Sabkha plain.
Algal flat.
H.W.M.
Break in slope.
Long axes of sand bodies.
N
Location of Quala
N
Khor al Bazam
1 Fathom
HWM
Miles
0 5 10
Thimairiyan
Quala
Miles
0
1/2
1
450
451
452
453
454
455
456
260
261
262
263
264
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266
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