RECENT OOLITES OF THE TRUCIAL COAST, ARABIAN GULF

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ABSTRACT

The Trucial Coast of the Arabian (Persian) Gulf from the Dhabaya Peninsula to Ras Ghanada is characterized by numerous small tidal deltas that are composed mainly of oolite sediments. Examination of the sediments forming the delta between the islands of Abu Dhabi and Al Bahrani reveals that the oolites are generated in situ and distributed within the area by the action of wave and tidal generated currents.

Stereomicroscope and petrographic examination of the Abu Dhabi-Al Bahrani oolites shows them to be composed of a nuclear grain of carbonate or non-carbonate surrounded by a coating of very minute aragonite crystals intimately mixed with gelatinous organic matter of indeterminate origin. Perforating blue-green algae are found both on and within the oolites. The fabric of the coating is made of distinctly laminated material which in some cases is replaced by a non-laminated mixture of aragonite organic matter and algal cells. The non-laminated material appears to have formed in cavities made by perforating blue-green algae.

Grain size analysis of the sediments of the Abu Dhabi-Al Bahrani delta and those of the adjacent inner shelf area showed that most have unimodal and bimodal grain size distributions. Unimodal lognormally distributed sediments are rare. Grain size analysis also showed that all the oolites in the Abu Dhabi-Al Bahrani area were probably derived from a single "mother" population that was generated along the seaward margin of the delta. This "mother" population has been split into a small number of separate populations due to action of wind and tide

induced currents. The aerial distribution of modal populations on the delta and certain superficial characteristics of the oolites in them, indicates that the coarser modes of material are locationally stable while the finer populations move rapidly across the delta surface.

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CHAPTER 1

Introduction

The Trucial Coast embayment lies at the southerly end of the Arabian (Persian) Gulf and its shoreline extends from east of Quatar to the tip of the Oman Peninsula, a distance of some 500 miles (Figure 1). From 1960 on, staff members and students from the Department of Geology, Imperial College, University of London, have been engaged in studying the unconsolidated Recent sediments of the nearshore and coastal plain environments along the Trucial Coast. To date, only the eastern half of the coast has been examined in any detail. In general, the area is one of predominately carbonate deposition, other mineralogic components being present in relatively minor amounts. The most significant non-carbonate components are anhydrite and gypsum. These occur as primary precipitates inter-mixed with the carbonates of the coastal plain (Sabkha). The suite of sedimentary facies, so far delimited in the area outlined in Figure 1 includes coral reefs, subaqueous and littoral accumulations of skeletal and non-skeletal carbonate grains, lagoonal aragonite muds, inter-tidal algal flats with associated calcareous sediments, and the carbonate/anhydrite/gypsum terrestrial sediments mentioned above. Unconsolidated non-skeletal carbonate sediments, principally oolites, have accumulated to form subaqueous tidal deltas at several places along the Northeast trending portion of the coast (Figure 1).

This study is based mainly on the samples and information provided by D.J.J. Kinsman, whose thesis area included the tidal delta

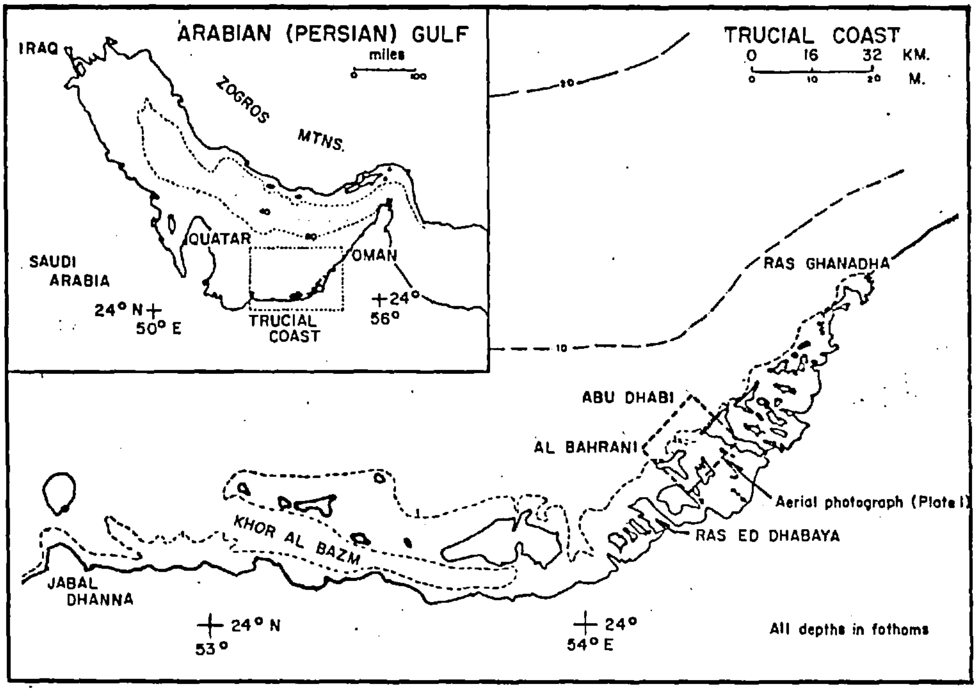


Fig. I. INSET MAP OF ARABIAN (PERSIAN) GULF SHOWING BROARD BATHYMETRY AND ASYMMETRIC CHARACTER IN CROSS SECTION. MAP OF TRUCIAL COAST SHOWING NEARSHORE BATHYMETRY AND DISTRIBUTION OF ISLANDS AND EMBAYMENTS.

between the islands of Abu Dhabi and Al Bahrani (Figure 1). Unless otherwise indicated, all field information (bathymetry, tides, wind, etc.), determinations of the sea water and sediment chemistry are taken from Kinsman's thesis (Kinsman 1964). Additional oolite samples from other areas of the coast were provided by Sir Patrick Skipwith, Christopher Kendall and Dr. Graham Evans. The writer is deeply indebted to the workers mentioned above for sharing their observations of the field conditions under which the oolites are forming and accumulating. Mr. D.J. Shearman suggested the project and supervised this thesis. Special thanks are due to Dr. Kinsman, for without his generosity in providing samples from his thesis area, this study would not have been possible.

Terminology

Two main classes of carbonate grains are being deposited in the shallow marine environment of the delta between the islands of Abu Dhabi and Al Bahrani. These are, using the terminology suggested by Illing (1954), skeletal and non-skeletal grains, and they are defined as follows:

a) Skeletal grains: These are the particles derived from the breakdown of calcareous animals or plants. During life the organisms extracted calcium carbonate from the sea and utilized it to build skeletons or other supporting or protective structures. The grains may be of calcite, aragonite or a mixture of both.

b) Non-skeletal grains: These grains form when a favourable combination of chemical, mechanical and in some cases, organic conditions occur in an aqueous environment. Unlike the skeletal grains, the non-skeletal grains are not the utilitarian products of plant or animal activity. Non-skeletal sediments exist as minute single crystals of calcium carbonate or as aggregates of these crystals. Non-skeletal carbonate is always in the form of aragonite.

Non-skeletal grains make up the bulk of the sediments which form the Abu Dhabi-Al Bharani delta. Of these, oolites are quantitatively the most important. The terms used to describe oolites and genetically related sediments are defined as follows:-

Oolite: An oolite is a non-skeletal carbonate grain consisting of a nuclear grain of carbonate or non-carbonate completely coated with non-skeletal carbonate to an approximately even thickness and with a recognizable boundary between the coating and the nucleus.

Nucleus: A nucleus is a grain around which there is an oolitic coating.

Potential nucleus: A potential nucleus is a grain of such a size as to be capable of becoming a nucleus given the appropriate conditions in a specific environment containing oolites with nuclei of a similar size.

Partly coated potential nucleus: A grain which is partly coated with carbonate and can be shown by association to be an early phase in the process of oolitization is called a partly coated potential nucleus.

It follows from the above definitions that oolitization is the process by which an accretionary coating of non-skeletal carbonate is added to a pre-existing substrate grain. Additional terminology relating to the various characteristics of the oolitic coating itself will be introduced at appropriate places in the text.

Scope of Study and Methods

Figure 2 is a schematic drawing of the sub-aqueous tidal delta between the islands of Abu Dhabi and Al Bahrani. It introduces the terminology used for various parts of the delta and also shows a simplified version of the bathymetry. Since there are certain important differences between those portions of the delta which lie on opposite sides of the axial channel, the delta has been divided into two sections. The area northeast of the axial channel is called the Abu Dhabi section, and that to the southwest the Al Bahrani section.

Kinsman collected some 80 samples from the oolite delta and the nearby shelf area. The samples are about evenly divided between the two sections of the delta, however, since the Al Bahrani section is somewhat smaller in area, the sample density is greater.

Each of the samples was mechanically seived into 21 size fractions, 1/4 phi apart. After weighing, each seive split was examined with a stereoscopic microscope and the percentage oolite was estimated. The surface characteristics of the oolites were recorded for each split and a rough estimate of the proportions between various classes of oolite was made. Classification included such characteristics as surface lustre, degree of algal infestation,

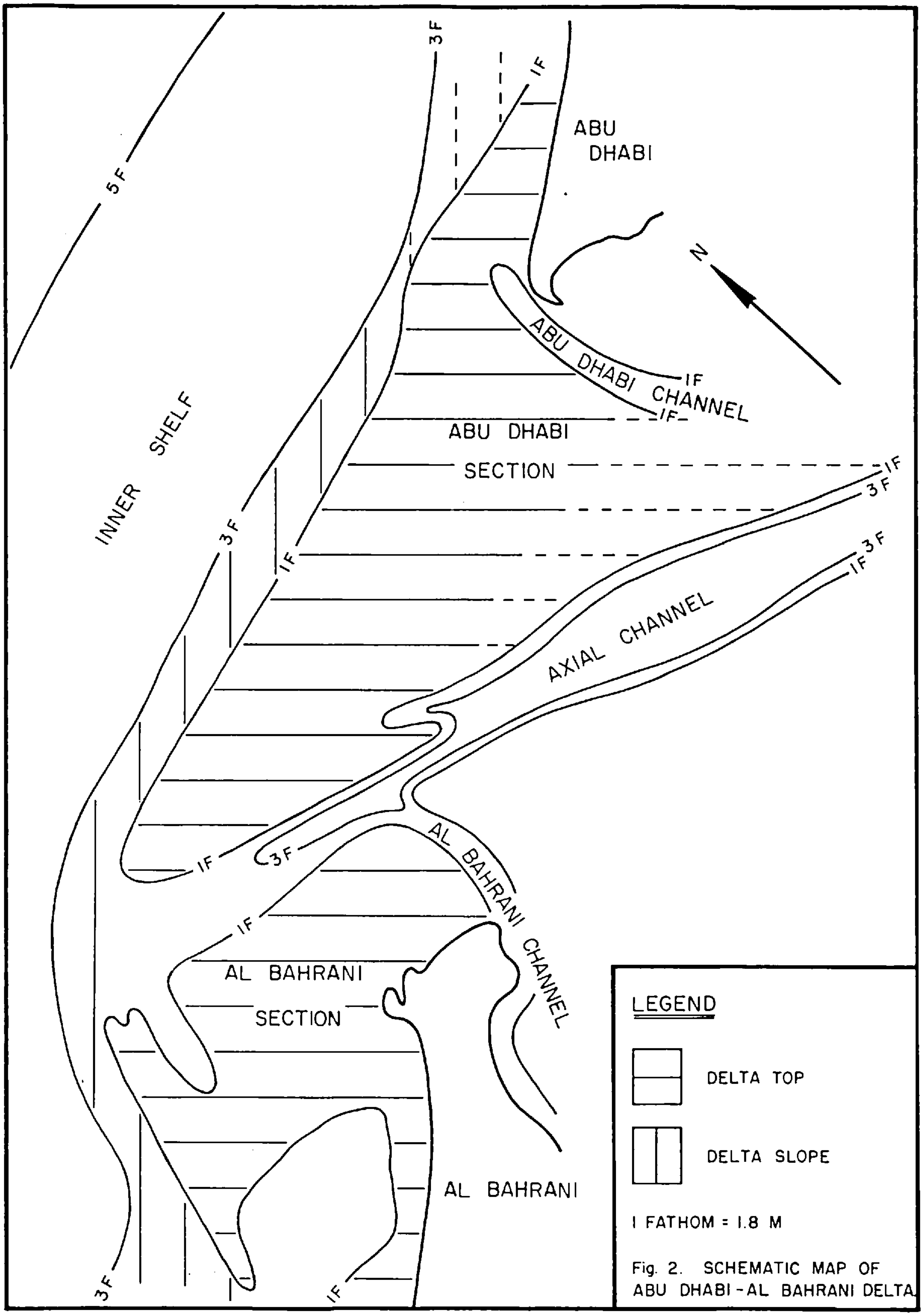


Fig. 2. SCHEMATIC MAP OF ABU DHABI - AL BAHRANI DELTA

smoothness, friability, and colour. Experience showed that, based on surface morphology, there were only two classes of oolite present in the samples. Furthermore, each class was distinct in at least four of the five characteristics mentioned above. Other parameters recorded from each seive split include, presence of non-carbonate grains, percentage of partly coated potential nuclei, nature of skeletal grains, character of any non-skeletal non-oolitic grains. The data obtained by the means outlined above was used to establish a correlation between size and surface properties in the oolites. This correlation proved to be useful when examining thin sections of the oolites. It also provided a means of integrating oolite character into grain size analysis and thereby helped to interpret the depositional pattern of oolites on the delta.

Thin sections of some 70 of the samples were provided by Dr. Kinsman. Detailed descriptions of the petrographic properties of the oolite coating were made for the oolites in each sample. Additional thin sections of selected grains were made to relate surface morphology to the internal fabric of the oolite coating. The types of grains which formed the oolite nuclei was recorded for each sample. This information was found to be of little value as compared to the actual size of the nuclei. By making measurements of the nuclei size from the thin sections it was possible to obtain a grain size distribution which could be compared to that of sediments which might be sources of potential nuclei.

Replicas and small chips of the oolites were examined with the electron microscope. Attempts at obtaining useable photographs of the oolite fabric were unsuccessful. Several good photographs were made of individual and groups of crystals projecting from the edges of chips spalled off the oolite surface. At a fairly late stage in this study it became evident that there was a comparatively large organic component in the oolite coatings. The identity of this material could possibly have been established by electron microscopy, unfortunately the facilities for doing this type of work were not available to the writer at the time when they were required.

The Algae infesting the surface of the oolite grains were identified by Dr. W. Stewart of Westfield College, University of London. Thin section and stereo microscope examination of the samples showed that the algae were responsible for certain characteristics of the internal fabric and surface morphology of the oolites. To separate the effects due to algal infestation and those with other causes, loose samples and thin sections of the oolites were treated with dyes specific to organic matter. It soon became apparent that the oolite coatings contained abundant organic matter throughout. Furthermore, much of the organic matter lacked any evidence of being algal in origin. This material formed an integral part of the coating fabric and was best seen after slow solution of the carbonate. The residue, consisting of the mucoid substance of unknown origin and whatever algal cells were also present, was examined in water using a petrographic microscope. The optical properties of the organic matter, algal and otherwise, were determined from the material in aqueous suspension and from dissolved oolites in thin section. Chemical analysis was not performed on any of the organic matter.

Kinsman (1964) determined the bulk composition of the oolites by X-ray diffraction. His results, based on the dominance of aragonite in the X-ray diffraction pattern, indicated that the oolite coatings were composed of aragonite. X-ray diffraction examination of chips of the oolite coatings performed by the writer served to confirm Kinsman's findings. Attempts at establishing the optical orientation of the constituent crystals of the oolite coatings using X-ray diffraction methods were unsuccessful. The specific gravity of the oolites was measured using a pyc nometer.

The results obtained from mechanical sieving were plotted as cumulative frequency curves and analysed according to the method of Folk & Ward (1957). Raw data and the calculated statistical values are tabulated in Appendix I. Considerable effort was expended in attempting to relate mean size, sorting, skewness, kurtosis and log-normality of the sediments to the hydraulic regime and sedimentary processes on the Abu Dhabi-Al Bahrani delta. Unfortunately, the results did not justify the effort expended. The complexity of the grain size distributions, some of which have five modal sizes, the growth in situ character of the oolite grains, and the sparsity of precise information regarding water movements all contributed to the failure of what was essentially a mathematical approach to the problem. Ultimately a more empirical and less sophisticated method was used and a quite reasonable interpretation emerged. This method employed some of the statistical parameters, the modal classes of the grain size distributions, morphological features of the oolites, and the available hydraulic data.

The insoluble residues from about 100 samples were available from Kinsman's work in the Abu Dhabi area. Some 40 of these were from samples taken on the oolite delta and the nearby shelf. Not surprisingly, along the seaward margin the weight percentage of the delta insolubles was greatest where there were the fewest oolites. Dr. Kinsman's work also showed that the mineralogy of the insolubles was essentially the same for both the shelf and the delta sediments. To further clarify the relationship between the shelf and delta sediments, a few samples of insolubles were mechanically seived and submitted to grain size analysis. This approach, though fruitful in its results, was limited by the large amount of sample required to obtain sufficient material for seiving. As a consequence only one short portion of a single traverse could be analysed.

Summary of Results

Aragonite oolites are the dominant grain type in the sediments which form the sub aqueous tidal delta between the islands of Abu Dhabi and Al Bahrani. An average sample taken on the delta would contain around 70% oolites whereas one taken from the nearby shelf area would consist of skeletal grains and non-carbonate minerals. Evidence provided by a comparison of the grain size characteristics of the oolite nuclei with those of the finer fractions of the unoolitized shelf sediments indicates that the latter grains can be classed as potential nuclei. There is no evidence that the oolites on the delta are other than the product of an indigenous accretionary process.

The initiation of oolitization evidently takes place along the seaward margin of the delta in waters between 1 and 3 fathoms in depth. Here in the frontal zone of the delta the oolites grow to near their maximum size by the addition of a finely laminated coating made up of minute and elongate aragonite crystals embedded in an organic matrix. The aragonite crystals are oriented with their lengths roughly parallel to the plane of the laminations. In general the oolites of the frontal zone of the delta show little evidence of algal infestation, either on their surface or within the layers of aragonite. They have a uniform cream external coloration, and a hard, almost brittle surface. Characteristically, they have a porcellanous lustre, even in those size grades which would appear to be too small to have suffered any degree of abrasion. The sediments of the frontal zone of the delta are typically well sorted and have unimodal grain size distributions.

The seaward margin of the delta is under almost continual attack from the prevailing north-northwesterly waves and as a consequence the finer grades of oolite are rapidly depleted from the zone of oolite generation. In the Abu Dhabi section these sediments are swept into the interior area that lies behind the frontal zone. In the Al Bahrani section however, the prevailing wave approach direction is roughly parallel to the frontal zone and consequently little if any sediment is moved toward the inner part of the bank.

In the interior portion of the Abu Dhabi section, the bulk of the sediment is made up of oolites of slightly coarser size than those of the frontal zone to seawards. These oolites are interpreted as a lag deposit representing the sedimentation during earlier phases in the development of this part of the delta. In character they are quite unlike the oolites of the frontal zone. They have a soft, friable surface, a mottled white coloration and are heavily infested with a perforating type of blue-green algae. Internally their fabric consists of an inner layer which has the fine laminations and oriented crystals as described for the frontal zone oolites, and an outer layer, without laminations, made up of randomly oriented crystals. There is considerable evidence that the outer layers are in large part due to the activities of the perforating algae. Mixed in with the lag oolites of the Abu Dhabi section are porcellanous surfaced oolites, similar in every detail, to the oolites of the Abu Dhabi frontal zone. These oolites form a distinct though partially overlapping size mode finer in size than that of the lag oolites, i.e. the total grain size distribution is bimodal.

The oolites of the interior portion of the Al Bahrani section are predominately of the porcellanous surfaced type described above. Algal infestation is only evident in those sediments which lie in the most southerly part of the interior. The sediments are extremely well sorted, superior in this respect to any other on the delta. Unimodal grain size distributions are characteristic of these sediments and over a large area of the bank their mean size, sorting, etc., varies little between separate samples. Of considerable significance is the fact that the mean size of the oolites in this area is closely comparable to that of the finer mode of oolite in the interior portion of the Abu Dhabi section.

Depletion of fresh surfaced oolites from the frontal zone of the Al Bahrani section leaves the sediment there enriched in grains that are of minor importance in the frontal zone of the Abu Dhabi section. Included in this category are algally infested oolites, lumps and pellets and skeletal grains. This part of the delta receives a certain amount of its skeletal detritus from the coral reefs growing in and along the axial channel. This material is carried seawards on the ebbing tide and after ejection from the mouth of the channel, is drifted along-shore into the frontal zone. It is to be noted that coral detritus from the same source is also deposited on the interior part of the bank that is in proximity to the axial channel.

The pattern of net water movement due to tides and wind generated currents on the Abu Dhabi-Al Bahrani delta is as follows. In the Abu Dhabi section the prevailing north-northwesterly waves back up the flood tide and resist the ebb, consequently the net movement of waters is away from the frontal zone towards the axial channel. Due to this effect the net flow in the axial channel is seawards. Ebb and flow in the Al Bahrani section is roughly perpendicular to the frontal zone, however, this motion is at right angles to the prevailing waves. The result is that whereas the tidal motions cancel out, there is a net movement in a direction roughly parallel to the frontal zone. This is most pronounced in the frontal zone. The interior portion of the Al Bahrani bank lies in the lee of the Abu Dhabi section with respect to the dominant oncoming waves. That part of the Al Bahrani section next to the channel experiences some of the effect of the ebb tide flow insofar as the waters carried by the channel tend to fan out in that direction.

From the pattern of sediment distribution, the characteristics of the oolites that make them up and the water movements that take place on the delta, a reasonable interpretation of the sedimentology can be postulated. The main zone of oolite generation appears to be in the frontal area of the Abu Dhabi section of the delta. Potential nuclei derived from the nearby shelf are kept in the zone of oolitization due to the orientation of the edge of the bank with respect to the prevailing wave approach. As the grains increase in size they become less easily moved by the wave generated currents. Consequently these grains accumulate and the front of the bank advances seawards. During this process there is a high rate of attrition of the finer grades of oolite, particularly during stormy periods. These grains are swept into the interior part of the bank and ultimately, under the impetus of wave generated currents and tidal movements, are deposited in the axial channel. The surface over which these transient oolites move is made up of coarser grained oolites that are relatively stable under the prevailing hydraulic conditions. Their stability is attested to by the high degree of surface alteration due to algal infestation, a condition which is absent in the actively moving sediments on the delta.

The Al Bahrani section of the delta appears to be a subsidiary bank that owes its existance to the fact that it serves as a depository for grains derived from the Abu Dhabi section. The character of the sediments and the nearly parallel alignment to the prevailing waves suggest that the Al Bahrani frontal zone is either not favourable to oolitization or loses its oolites at an early stage in their development. In all probability the frontal zone is actually an extended spit rooted to the seaward apex of the Abu Dhabi section. The sediments that compose the interior portion of the bank consist mainly of oolites derived from the Abu Dhabi section and carried there via the axial channel. Lack of intense algal infestation except in those sediments most remote from the channel in the direction of prevailing wave action suggests that the rate of accumulation must be relatively high.

The petrology of the oolite grains is still not understood even though we may trace their evolution within a specific environment and examine their composition in minute detail. Large quantities of organic matter have to be accounted for, both as to its origin and its possible effect on oolite growth. If, for example, it turns out that an organism is required to initiate and continue oolite growth, then oolitization may be dependent on the appropriate ecologic conditions for that organism, rather than the appropriate conditions for carbonate precipitation as is so often stated. The evidence which will be presented in this study is perhaps insufficient to support any rigorous conclusions regarding the role of organic matter in the formation of oolites. Nevertheless, the presence of an organic component integral with the carbonate of the oolite coating is, in the writer's opinion, a most significant fact. It is the writer's belief that most fruitful approach to the problem of oolite, and probably other non-skeletal grain growth, will in future be through means not employed in this study. That is, by chemical analysis of the organic matter, in vitro studies of the organic matter under varying conditions of carbonate saturation and bacteriologic examination in the field and laboratory.

The Origin of Oolites (A review of the literature)

The purpose of this section is to review the literature which relates to the origin of oolites. In this regard, emphasis has been placed on those works which have relevance to the present study. The writer has not concerned himself with other than carbonate oolites nor with the extensive literature that deals with the stratigraphic implications of oolites in the ancient rocks.

The oolite was recognized as a distinctive grain type as early as 1667. Hooke described it as the chief constituent of a rock made up of minute grains which "....appear to the eye like cobb or roe of herring or some small fishes." Hence the term oolite or roestone. Bakewell (1813, see Challinor, 1961) described roestone as a species of marine limestone, and in 1851, De LaBeche reported Recent oolitic rocks he had observed in the Bahamas.

The first important work on the oolite grains can be said to have commenced with the advent of the thin section as adapted to petrologic study by Sorby (1856). Sorby recognized, as did others who applied this new technique to the study of oolites, that the oolite grains possessed distinctive structural properties viz. a nucleus, not necessarily of carbonate, around which was a carbonate coating that exhibited a variety crystalline fabrics. Sorby (1879), postulated that a large part of the initial growth of oolites was due to the accretion of fine lathlike crystals of aragonite around a rolling nucleus, much in the same way as a snowball increases in size when rolled in the snow. He also suggested that direct precipitation of carbonate might contribute to oolite formation. It is noteworthy that Sorby's views on the origin of oolites included the recognition that some of the textural features of the oolite fabric were due to post-depositional diagenetic changes, for examble the change from aragonite to calcite.

Wethered (1890) noted that Sorby had failed to observe the abundant evidence in oolites from the Silurian to Jurassic inclusive, that suggested an algal origin. Although he is not explicit on the point, Wethered implied that the entire oolite grain, excepting the nucleus, was originally composed of the alga Girvanella. These, he felt, were largely obscured by subsequent calcification, however in some cases the form of the algal tubules and their felted habit showed up quite clearly. An early worker, (Harris, 1895) noted the cross-cutting of the concentric layers of recent Bahaman oolites by tubular borings. It has been demonstrated (Illing, 1954) that these borings are due to the activities of a perforating type of blue-green algae and Illing (1954, p.44) has suggested that algae play a destructive rather than a constructive role in oolite development. Dangeard, while cognizant of the destructive role played by some algae, (Dangeard, 1936, p.240) considers that the enveloping forms are important in oolite formation (Dangeard, 1952).

Rothpletz (1892) extracted living colonies of the blue-green algea Gloeocapsa and Gloeotheca from oolites forming in Great Salt Lake. He felt that these algae were capable of secreting carbonate and postulated that the Great Salt Lake oolites were the product of algal activity. Rothpletz compared these oolites to those forming in the Red Sea and ancient oolites and concluded that the majority of marine oolites with zonal or radial structure were produced by lime secreting blue-green algae.

In contrast to the views of Wethered and Rothpletz, Linck (1903), working mainly from experimental data, considered that oolites are the product of physico-chemical precipitation induced by decaying organic matter. He suggested that two of the products of organic decay, ammonia and sodium carbonate, are produced in sufficient quantities in tropical seas to cause calcium carbonate to come out of solution. Linck envisioned the oolite nuclei as the initial centres of attraction for the precipitating crystals. He suggested that the nuclei would only be effective in attracting crystals when they were suspended in the precipitating waters. Once the oolites became too large to be placed in temporary suspension, growth would cease.

A bacterial origin for oolites was proposed by Vaughan (1914). He maintained that the activities of dentitrifying bacteria released sufficient ammonia to elevate the pH of sea water and thus effect carbonate precipitation therefrom. The crystals so precipitated would then collect together to form oolite nuclei 4-6 microns in diameter. Once the nuclei had been created they serve as centres of attraction and would be expanded to oolite dimensions by what he describes as chemical agencies. It is interesting to note that Vaughan worked mainly on the oolites of Florida and the Bahamas. According to Illing (1954, p.46), non-carbonate grains are extremely rare in the Bahaman sediments and consequently the oolite nuclei are dominantly calcareous grains, commonly structureless pellets. Frequently it is difficult to draw a sharp line between the nucleus and the oolitic coating (Illing, 1954, p.40) however, this condition only serves to emphasize the differing origins of the various grains that become oolitically coated. Had Vaughan recognized these facts he would probably not have emphasized the importance of the bacterial creation of minute spherulitic nuclei as a pre-requisite to oolite formation.

Bucher (1918) stated that oolites formed by at least one constituent substance changing from the emulsoid state to that of a solid. He suggested that oolites developed in a gelatinous mass, growing out from centres of nucleation within that mass. Bradley (1929A) also maintained that a colloidal component was necessary in oolite formation. He suggested that this colloidal component could be algal in origin. Coalescence of dispersed algal colloids provided the mechanism by which suspended calcium carbonate was enmeshed and formed oolite grains. Bradley's conclusions were based on his observations of oolites contained in the Tertiary Green River formation which is a lacustrine deposit. He found abundant evidence that the Green River pisolites were formed by the enrobing of action of algae. He was unable to find any convincing evidence that the oolites present had a similar origin. Interestingly enough, later experimental work by Bradley (1929B) tended to suggest that the algae played some role in oolite formation. In his experiments, Bradley immersed colonies of the blue-green algae <u>Nostoc caerulium Lyngbe</u> in a carbonate rich medium. After one year, thin sections revealed that the original colony and the new growth had both been calcified. He offered no explanation of this phenomena. It is worth noting that <u>Nostoc</u> forms a felted mass of tubules in a common mucilage and that their calcified remains bear a strong resemblance to Wethered's <u>Girvanella Incrustans</u> (Bradley, 1929B).

Mathews (1930) concluded that the oolites of Great Salt Lake formed independantly of the action of blue-green algae. Based in part on what he mistakenly believed to be soot particles entrapped within the oolites, he proposed a theory of terrestrial origin, according to which, oolites formed at the shore margin in the zone of capillary action. Repeated evaporation of the film of water surrounding each grain caused carbonate to be deposited in layers. As the grains were thus being coated, they moved inland under the impetus of the prevailing wind. Mathew's idea regarding carbonate precipitation due to evaporation of capillary waters may apply in the case of marine oolites present in an intertidal zone (Sugden, 1963), however, as pointed out by Eardley (1938), there are abundant oolites present in the shallow nearshore waters in Great Salt Lake.

From his work on the oolites of Great Salt Lake, Eardley (1938) came to the conclusion that they were the product of purely physico-chemical factors, acting in conjunction with the presence of nuclear grains. He reasoned that in the surface layers of the nearshore waters, evaporation and agitation would have their greatest effect and carbonate precipitation would take place. Once precipitated the carbonate crystals would sink and redissolve in the less saturated waters at the sediment/water interface. Simultaneous with the solution of the crystals, an equivalent number of carbonate molecules would come out of solution on the surface of nuclei and oolites. Eardley's explanation for this phenomenan is that the minute (less than 2 microns) crystals precipitated at the surface are far more soluble than grains of oolite or nuclei size and therefore a solution which is saturated with resepct to the smaller grains is supersaturated with respect to the larger. From observations made by the writer and those made by Illing (1954, p.36) and others it is evident that the aragonite crystals that make up oolitic coatings in recent deposits are of submicroscopic dimensions. If the crystals composing the Great Salt Lake oolites are equally small, then it may be that Eardley made a fallacious assumption in regarding the nuclei and oolite diameters as the effective diameters in any chemical reaction at the sediment/water interface.

Cayeux (1935) in his work on carbonate rocks, provided excellent petrographic descriptions of oolites from a great variety of sources. The conclusions he drew from his observations have a decidedly modern character and in this sense he represents the beginning of the phase of carbonate petrography that extends up to the present day. With regard to the genesis of oolites, Cayeux considered them to be concretionary bodies whose structural form may have been somewhat modified by organic agents. He felt that the role of rotting organic matter, algae and bacteria in the formation of oolites was to augment already favourable conditions in the environment of carbonate precipitation.

The work of Black (1933) on the sediments of the Bahama banks yielded the so called classical theory of oolite origin that is adhered to by several workers today (Illing, 1954; Newell et al, 1960: Cloud, 1962). According to Black, oolites are the product of purely physico-chemical processes. Cool waters, saturated with calcium carbonate, in passing onto shoals or banks become warmed up and subsequently concentrated by evaporation. Evasion of CO_2 due to warming and agitation of the waters causes precipitation to take place. Aerially coincident with the zone of agitation are well winnowed sediments which provide suitable oolite nuclei. The nuclei serve to encourage precipitation and as a consequence themselves become coated with carbonate.

Nesteroff (1956A) in his study of the Great Salt Lake oolites ascribes an important role to the blue-green algae but differs with Rothpletz (1892) as to the extent of their function in oolite genesis. Nesteroff believes that the algae form an organic substrate whose presence is necessary in order that the initial layer of carbonate be deposited. He calls this initial layer biogenic carbonate. Once the biogenic carbonate layer has been deposited around the nuclei, the grain becomes enlarged by physico-chemical precipitation. In applying this theory to the formation of other non-skeletal grains and the cementation of beach rock, Nesteroff (1956B) describes the organic substrate as a homogenous organic web. He believes that bacteria are present in this web and that it is their activities that are responsible for the precipitation of the initial layer of carbonate. In summary, Nesteroff's theory of oolite origin can be called the algal, bacterial, physico-chemical theory.

CHAPTER 2

The Environment and Physiography of the Abu Dhabi-Al Bahrani Delta.

Regional Setting

The Trucial Coast between the Dhabaya peninsula and Ras Ghanada, a distance of about 50 miles (80 km.), is characterized by numerous nearshore islands and shallow tidal lagoons (Figures 1&3). The open portion of the coast trends southwest/northeast and is comprised of the seaward facing coasts of several of the islands. Between the islands with open coasts are large, generally deep tidal channels which connect with and extend into lagoons behind. At the seaward ends of these channels are subaqueous tidal deltas. These deltas extend seawards of the open coasts, usually to a distance of about 3 miles (4.8 km.), and laterally along the island fronts. Behind the tidal deltas and the adjacent islands, are broad lagoonal areas containing many islands and largely intertidal during periods of low spring tides. The gently shelving intertidal zone of the lagoons passes without break into the coastal plain surface. The coastal plain extends inland of the inner coast of the region to distances of up to 15 miles (24 km.).

The Abu Dhabi-Al Bahrani Area

The sub-aqueous delta that was examined in this study, lies between the islands of Abu Dhabi and Al Bahrani (Figure 3). With the exception of these two islands practically all the descriptive details that are given below, concern the marine portion of the area. The reader is referred to Kinsman (1964) for detailed descriptions of

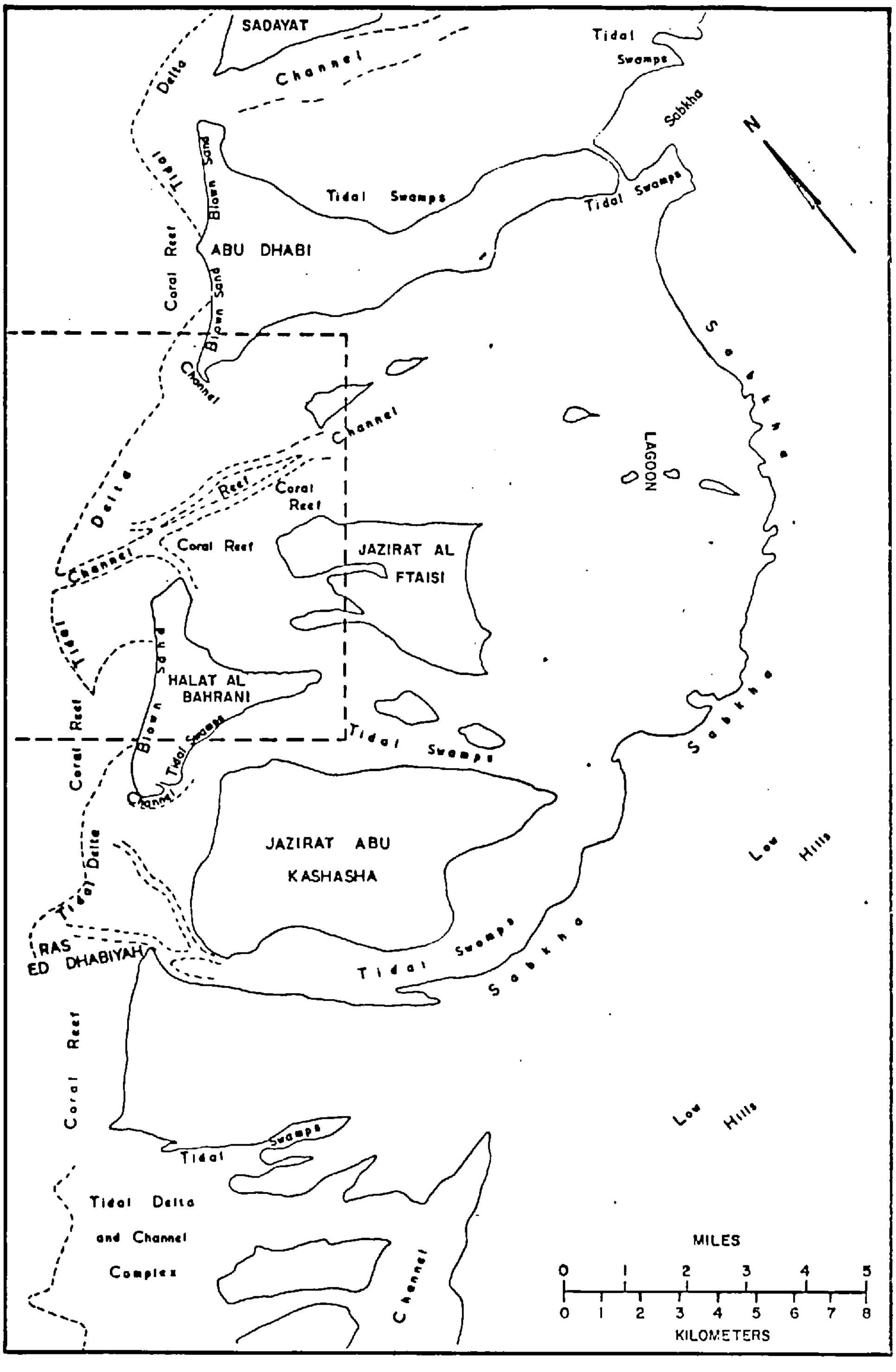


Fig. 3. MAP SHOWING SALIENT FEATURES OF NORTHEAST TRENDING PORTION OF TRUCIAL COAST FROM THE DHABIYA PENINSULA TO THE ISLAND OF SADAYAT. INSET AREA CONTAINS THE ABU DHABI - AL BAHRANI OOLITE DELTA. DASHED LINE IS ONE FATHOM CONTOUR.

the several islands in the lagoon and of the mainland coast.

The islands of Abu Dhabi and Al Bahrani are mainly composed of uncemented Recent carbonate sediments. Erosional remnants of recent and possibly Quaternary age, crop out at a few places on the islands and Kinsman (1964) has suggested that the loose sediments have accreted around a core of consolidated rocks. There is some evidence that present day cementation is taking place, particularly in the splash zone on the open coast. The islands are in general of very low relief along their seaward coasts, where dune ridges, parallel to the shore, reach a height of 30 feet (9 m.). Normally the beaches of the islands dip rather steeply seawards but where the delta is present the gradient is small and sediments move onshore with greater rapidity. Since the delta itself is chiefly composed of oolites, it is not surprising that the dunes in these areas have a high oolite content. The areas behind the frontal dunes are characterized by low hummocky dunes and a certain amount of sparse vegetation. The prevailing wind is onshore and under its impetus, dune materials derived to seawards are being moved in a generally south-easterly direction. Near the northeast and southwest tips of the islands, the loose sediments have a relatively short distance to travel before they reach the edge of the land area (Figure 3). In these localities, significant amounts of sediment are being dumped into the lagoon or into the channels where the latter are next to the shore. The Abu Dhabi-Al Bahrani Delta lacks the well developed symmetry that characterizes most of the other tidal deltas in this part of the Trucial Coast. The somewhat smaller delta to the northeast, between the islands of Abu

Dhabi and Sadayat, is symmetrical with respect to its tidal channel and to the islands themselves. In contrast, the Abu Dhabi-Al Bahrani Delta is asymmetric with respect to the islands between which it lies and different in shape on either side of its axial channel. The Abu Dhabi section is roughly triangular in shape and the Al Bahrani section is approximately square (Figure 3). The axial tidal channels of all the deltas northeast of Abu Dhabi (Figure 1) are aligned perpendicularly to the open coast and it may be that the slightly oblique orientation of the Abu Dhabi-Al Bahrani axial channel has in part determined the shape of the delta. Kinsman (oral communication) has suggested that the anomalous orientation of the channel may be due to the presence of a structural lineament in the underlying bedrock.

Bathymetry

The detailed bathymetry of the Abu Dhabi-Al Bahrani delta, hereafter referred to as the delta, and of the seaward shelf and lagoon areas is shown in Figure 4. The bathymetric data are a combination of surveys made by H.M.S. Dalrymple and field observations by Kinsman (1964). All depths shown have been corrected for tidal differences and related to low water spring tides. Mean sea level is four feet (1.2 m.).

The boundary between the open shelf and the delta coincides in most places with the 3 fathom contour. Seawards of this line the bottom shelves very gradually and at 2 miles (3.2 km.) out is only 2 fathoms deeper, i.e. a slope of less than 1 in 400. Along the front of Abu Dhabi island, the 3 fathom contour moves seawards instead of paralleling the delta and the inner edge of the shelf approaches the

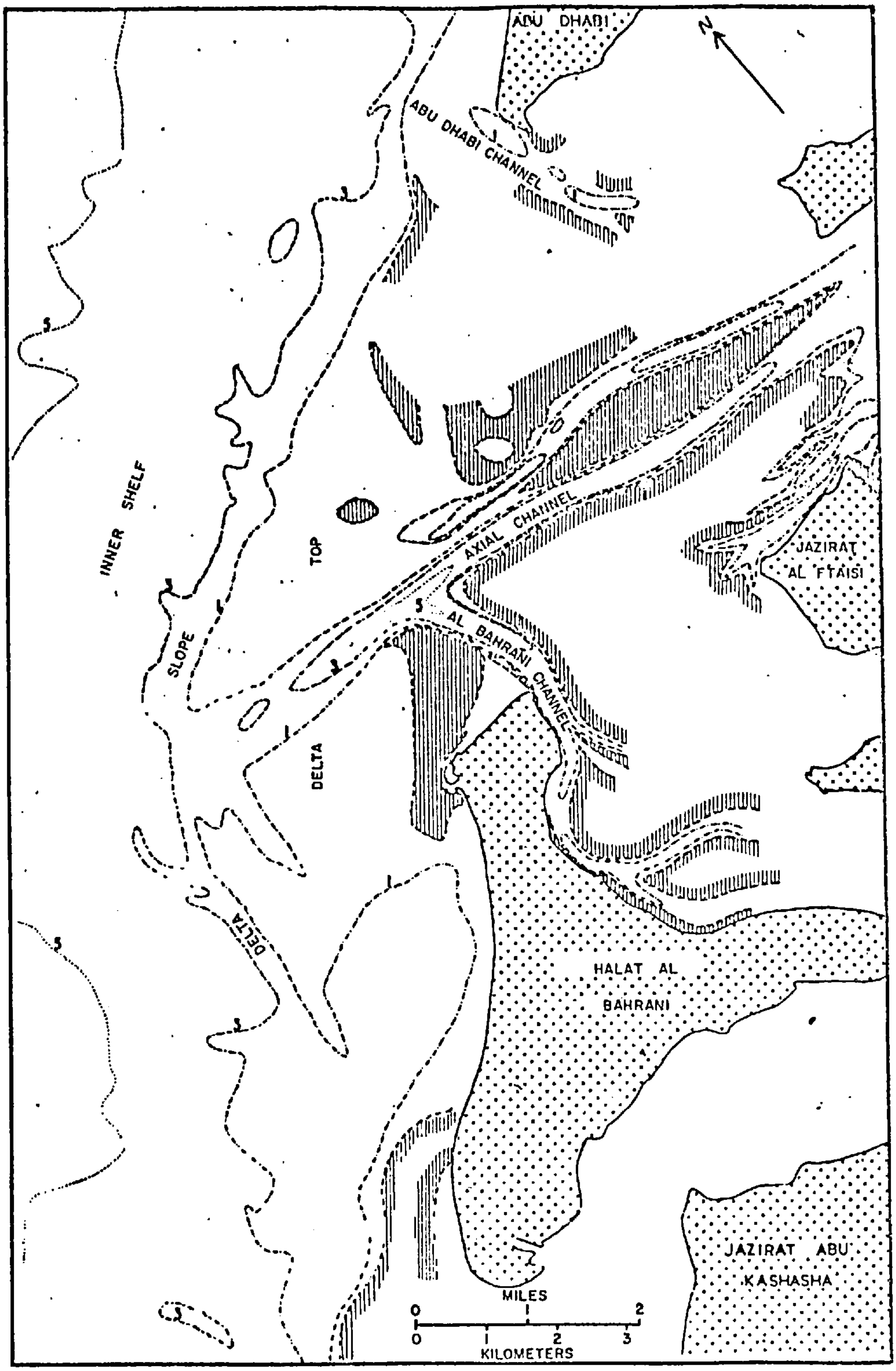


Fig. 4. THE HALAT AL BAHRANI - ABU DHABI REGION OF THE TRUCIAL COAST, SHOWING LAND AREAS, (SOLID LINE), INTERTIDAL AREAS (SHADED), AND DETAILED BATHYMETRY. ALL DEPTHS ARE ACCURATE TO WITHIN 1 FT.

shore. A similar divergence occurs along the front of Al Bahrani island. The form of the front edge of the delta is best defined by the 1 fathom contour. This contour coincides with the break in slope between the delta slope zone enclosed by the 1 and 3 fathom contours and the shoal delta top area. The delta slope, as defined above, extends almost uninterupted from near Abu Dhabi to where the 1 fathom contour swings seawards. The inclination of the delta slope is about 1 degree.

The shoreward half of the delta top in the Abu Dhabi section of the delta is intertidal in character. In the Al Bahrani section only a small area just north of the island is exposed during low water spring tides. It is interesting to note that the seaward boundary between the intertidal and tidal areas of the two sections of the delta falls along a common line parallel to the fronts of the islands.

The axial channel which forms the boundary between the two sections of the delta varies considerably in depth along its length. Just north of Al Bahrani island where it is joined by a subsidiary channel entering from the south, it is 44 feet (13.4 m.) deep. This appears to be a local deepening however, and lagoonwards the channel depth averages around 3 fathoms. To seawards of the same point the channel becomes progressively broader and shallower. At its mouth it is only 1/2 fathom deeper than the adjacent sections of the delta.

The shallow channel just off the western tip of Abu Dhabi island evidently carries a sufficient amount of water to cause a small subsidiary delta to be built at its mouth. The building out of this minor delta appears to be responsible for the abnormal steepness of the delta slope at this point.

The data given above serve to define the principal physiographic features of the sub-aqueous tidal delta (Figure 4). These features are summarized as follows:

a) Delta slope: The delta slope is the portion of the delta that bounds on the open shelf and lies between the 3 and 1 fathom contours.

b) Delta top: The delta top is the area inside the 1 fathom contour. In the Al Bahrani section the lagoonward boundary of the delta top is formed by the island shore and the subsidiary channel that enters the axial channel from the south. In the Abu Dhabi section, the inner boundary of the delta top is roughly coincident with the lobate edge of its intertidal zone. Kinsman (1964) has noted that the oolite sediments along this edge dip off into the slightly deeper water at what appears to be their angle of repose.

c) Axial channel: The axial channel is the principal drainage feature of the area. It strikes roughly east-southeast and forms the boundary between the two sections of the delta.

d) Abu Dhabi channel: The Abu Dhabi channel is the subsidiary drainage channel that lies at the western tip of Abu Dhabi island.

e) Al Bahrani channel: The Al Bahrani channel is the channel that lies behind the island of Al Bahrani and extends northward to join the axial channel.

Wind, Wave and Tidal Regime

The morphology of the delta is in part determined by the dynamic forces acting upon it. These forces are of two principal origins; wind and tides. The wind generates waves and these in turn create water turbulence and currents, the two main agents of sediment movement. It is to be noted that variations in water depth due to tides has a considerable effect on the influence of the waves. The vertical rise and fall of the sea surface due to tidal forces has as its main effect, the creation of tidal currents.

Wind

The prevailing wind is the regional "Shamal" wind which blows from the north-northwest. The Shamal is light and variable most of the time, however, during the winter months strong and gale force Shamals are fairly common. Occasionally strong southerly winds blow from the land. Although the southerlys are not common, they are important insofar as they are capable of carrying large volumes of airborne material seawards. Diurnally developed winds, offshore in the morning and onshore as the land warms up, oppose or back up the prevailing regional winds. In the absence of any regional air movement, the onshore winds are in themselves strong enough to raise appreciable waves at sea.

Waves

Since the height of the waves is in part related to the fetch of the wind, it is not surprising that in the delta area, waves in excess of 3 feet (1 m.) have a pronounced modal orientation to the north-northwest, the direction of the regional Shamal. Waves less than 3 feet (1 m.) in height may occur with any orientation. The maximum height of waves recorded in the nearshore area is 9.5 feet (3 m.).

A line of breakers is developed where the prevailing north-northwest Shamal generated waves encounter the frontal edge of the delta. The breaker zone roughly straddles the 1 fathom contour and moves seawards or landwards depending on the state of the tide. Breakers are present along the front of the delta during all but the calmest periods. The two sections of the delta differ in the degree to which a breaker zone is developed. In the Abu Dhabi section the delta edge is approximately perpendicular to the direction of the oncoming waves. Here the waves impinge on the delta slope and pass relatively quickly into a state of disequilibrium that results in breakers. The frontal edge of the Al Bahrani section is aligned almost parallel to the direction of the oncoming waves. The shoaling waves dissipate their energy over a longer distance relative to those in the Abu Dhabi section. This effect is due to the tendency of the wave fronts to swing in parallel to the delta edge. The net effect is to lessen the height of the breading waves and consequently diminish their force.

Due to the loss of energy in the breaker zone, wave activity on the delta top, though intense, is much diminished in vigour. Nevertheless, the waves on the delta top are extremely persistent, as persistent as the Shamal wind which generates them. For this reason these waves must be reckoned to be the most important agents, other than tides, capable of effecting sediment movement on the delta top.

Tides

There are two major components of vertical tidal movement on the Trucial Coast. The diurnal tides, one high and one low tide per lunar day, and the semi-diurnal tides, two high and two low tides of approximately equal magnitude per lunar day. The interaction of the diurnal and semi-diurnal tides produces mixed tides which are characterized by two high and two low tides per lunar day, each successive high and each succesive low tide being of quite different heights. The tides of maximum rise and fall are the spring tides which occur about twice per lunar month. Lower than normal or neap tides occur four times per lunar month. The spring and neap tides are about 20% greater or smaller than the mean tidal range.

The maximum tidal range on the delta is about 7 feet (2 m.). During low spring tides, large areas of the delta top are exposed. Detailed information is lacking as to how much of the delta top is exposed during periods of normal (5 feet-1 1/2 m.) tides.

Tidal Currents (Figure_5_).

Tidal currents are the horizontal component of the tidal wave. In the area off the front of the delta tidal currents set east-west, reversing direction roughly in phase with the tides. Since they are reversible, the net effect on the longshore movement of sediments is probably negligible. The tidal movement of water on the delta does not conform to the simple pattern of reversible flow that characterizes the nearby shelf area. During the flood portion of the tidal cycle, water moves in over the delta top in a direction roughly perpendicular to the delta edge in each section. These waters converge

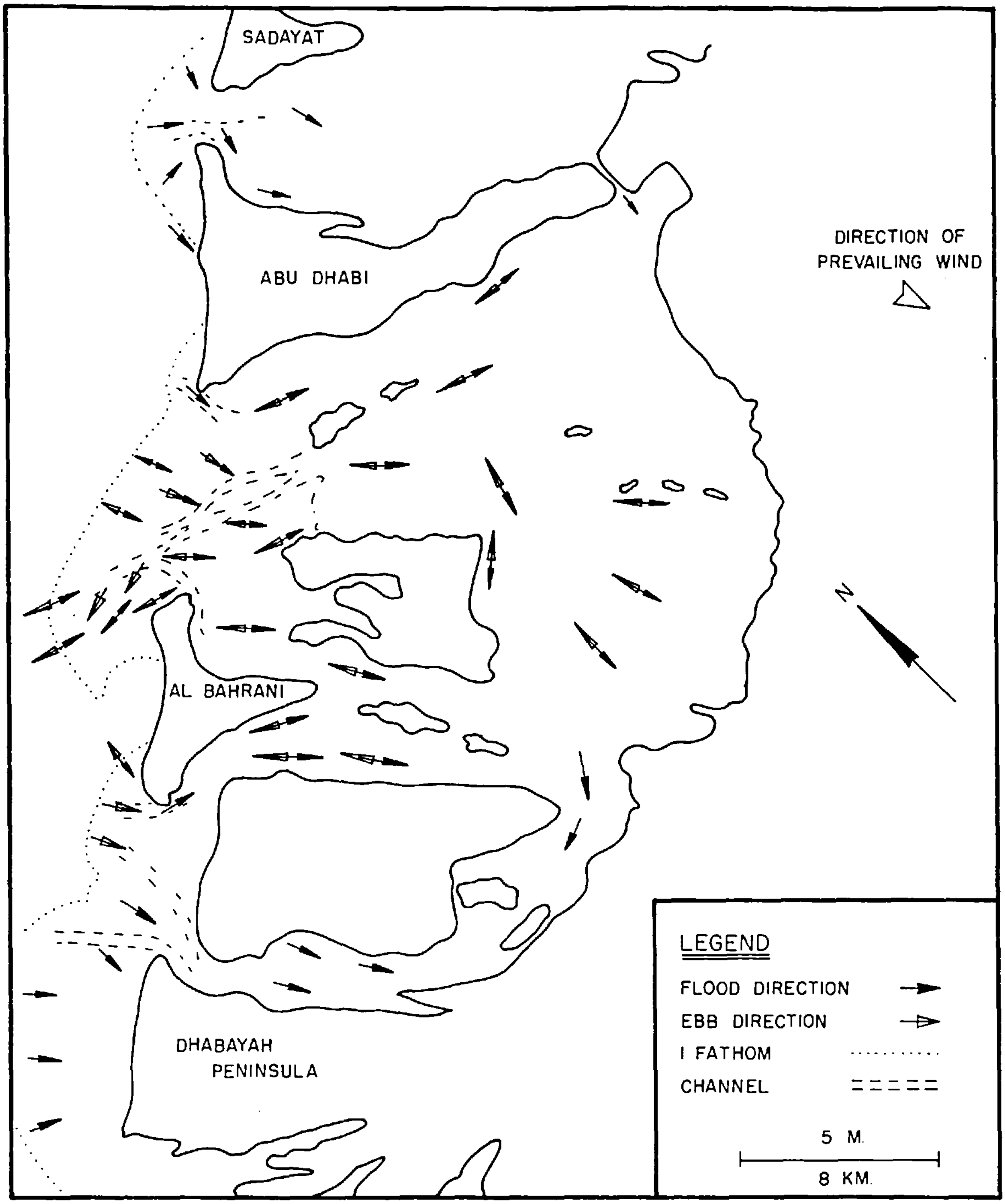


Fig. 5. MAP SHOWING THE FLOW DIRECTIONS OF THE FLOOD AND EBB TIDES IN THE ABU DHABI - AL BAHRANI AREA.

on the axial channel and augment the flow of water which it is carrying towards the lagoon. The flow of water in the channel is much more turbulent and of a higher velocity that that on the shoal delta top. This is particularly evident during ebb tidal flow. On the ebb, water does drain off the delta top in a direction opposite to the flood, however, this is only so along the seaward perimeter of the delta and on the southern half of the Al Bahrani section. Elsewhere the drainage is towards the axial channel. This effect appears to be due to the high rate of flow in the channel which tends to draw in water from the adjacent delta top area. A similar drainage pattern is associated with the small subsidiary channel off the western tip of Abu Dhabi island. Near the mouth of the axial channel, shallowing depth causes the ebb waters it carries to fan out over the adjacent delta top, consequently, drainage in this area is normal viz. in a reverse direction to that of the flood. It is to be noted that the pattern of dispersal appears to be somewhat assymetric with respect to the axis of the channel. This appears to be due to the fact that the water that is turned onto the Abu Dhabi section is met by the oncoming prevailing waves whereas that moving onto the Al Bahrani section is virtually unopposed in this respect.

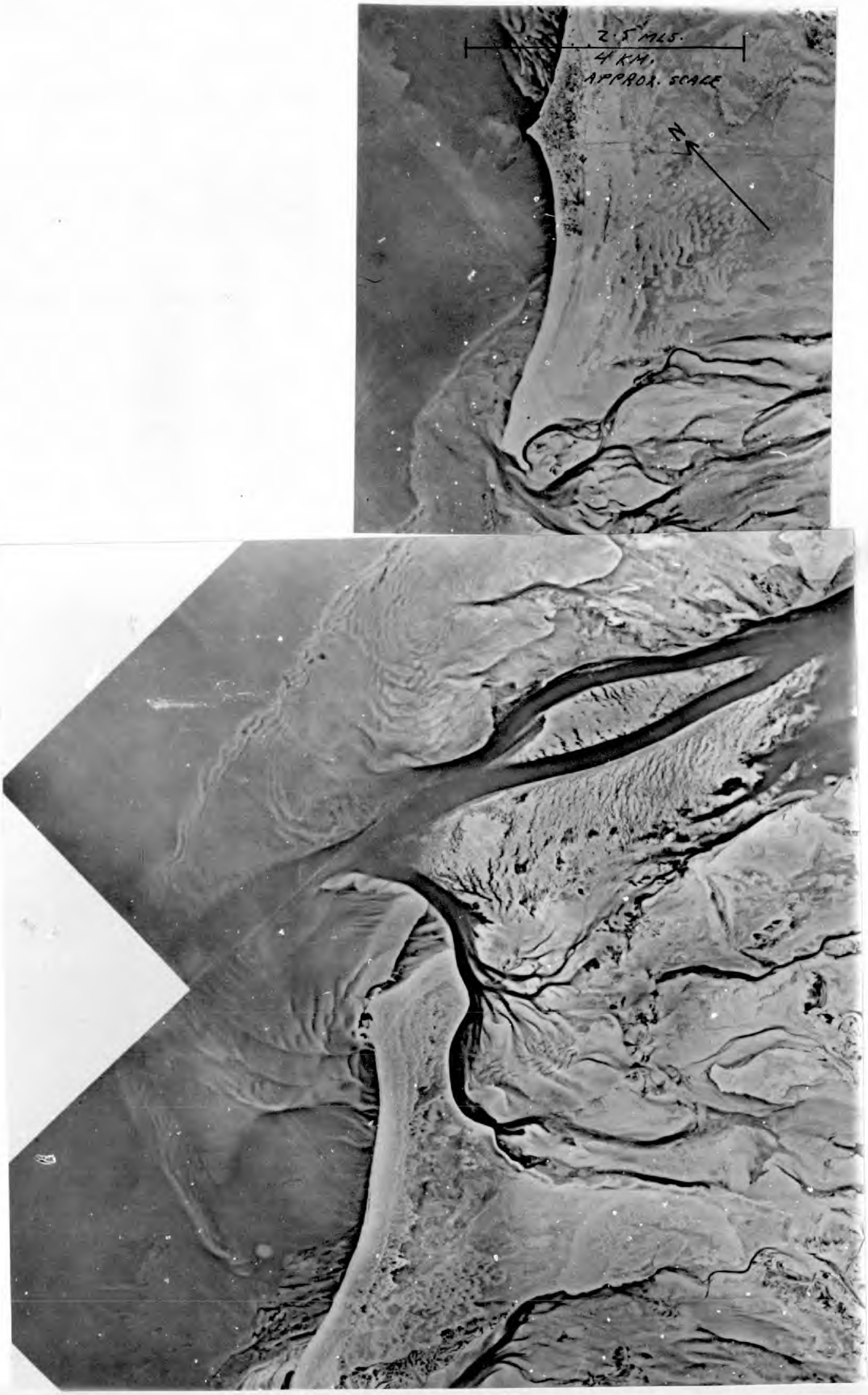
Morphological Features of the Delta

The description of the bathymetry and of the current regime as given above undoubtedly greatly oversimplifies conditions as they actually exist. This is immediately apparent when one examines an aerial photograph of the delta area (Plate 1). The delta top itself is marked by numerous systems of straight, curved and in some

Plate 1

Uncontrolled aerial photomosaic

The island of Abu Dhabi lies at the top of the picture and the island of Al Bahrani at the bottom. The visible seaward limit of the oolite delta marks the approximate position of the one fathom bathymetric contour.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cases mutually interfering bar-like features. In addition, there are spits, gullies and many other morphologic features for which there is no specific name. All reflect the effects of water movement on the unconsolidated sediments, however, in most cases we can only speculate as to why they have formed at various locations on the delta top.

Tonal differences in the aerial photograph serve to indicate the relative depths of water over the delta. For example, in the Abu Dhabi section there is a difference in tone between the seaward edge of the delta top and the lagoonward portion. The lobate lagoonward portion is a lighter shade of grey, indicating a shallower depth of water. The extent of this shallower area correlates well with our knowledge of the delta bathymetry and in fact corresponds quite closely to that of the Abu Dhabi section intertidal zone shown in Figure 4.

Figure 6 is a tracing made from the aerial photo-mosaic and it illustrates the lineations formed on the delta surface by those features of surface relief that are sufficiently large to be apparent in the photographs. Each of these features will be discussed in turn according to the system of lettering used in the tracing.

A-A': Breaker Zone Bars

A system of large scale sandbars is developed along the seaward edge of the delta top. These bars have a parallel to sub-parallel alignment to each other and to the general directional trend of the delta edge. Echo-sound profiles indicate that on average, the bars have wave lengths of several hundred feet (200-300 m.) and amplitudes

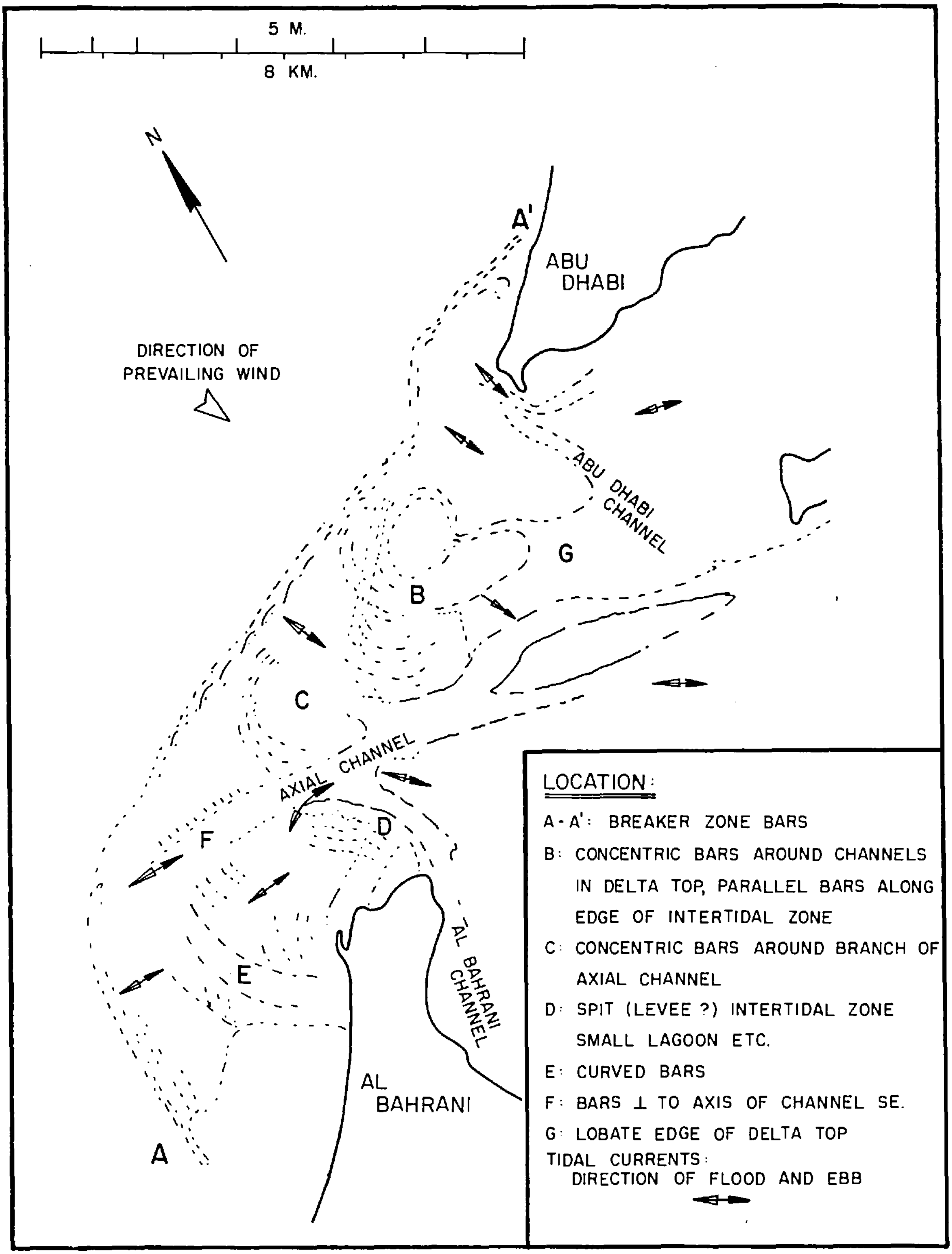


Fig. 6. TRACING FROM AERIAL PHOTOGRAPH (PLATE I) OF SURFACE FEATURES ON THE ABU DHABI-AL BAHRANI DELTA.

of 2-4 feet (0.6-1.2 m.). The area of occurrence of this bar complex closely coincides with that of the breaker zone and it is probable that the bars are developed in response to breaker activity. According to Dr. Graham Evans, there is a profuse growth of seaweed in the troughs between the bars suggesting that the bars are relatively stable features of the delta topography. It is interesting to note that the bars along the front of the Al Bahrani section tend to be far less well developed than those in the Abu Dhabi section. They are also straighter and more continuous laterally. These differences are probably due to the sub-parallel alignment of the Al Bahrani delta edge with respect to the oncoming prevailing wave attack. Significantly enough , the Al Bahrani bars extend southwards beyond the delta top to form a curving spit, a feature that suggests the presence of a longshore current following in the track of the waves.

B: Concentric and Parallel Bars and Delta Top Channels

The Abu Dhabi delta top in the vicinity of B, shown on Figure 6 , is marked by systems of inter-secting concentric and parallel bar-like features whose size is comparable to, or greater than that of the breaker zone bars discussed above. Associated with these bar systems are two narrow and shallow channels which extend into the unconsolidated sediments of the delta top. It is difficult to determine whether the bars on the delta top are in any way genetically related to the presence of these delta top channels. The evidence, though spare, suggests that the channelways have played a role, however, this conclusion is necessarily tentative. The reader will note (Plate 1) the channels are rimmed by much lighter coloured areas. These are interpreted as being channel edge bars. There is only one way in which such features could be built under the tidal regime existing on the delta. Seaward flow along the minor channels during the ebb portion of the tide cycle must be strong enough to overcome the effect of the oncoming waves and exceed in force the flow during flood water movement. Were this not so the net movement of sediment would be into the channel and no channel edge bars would be built. The reader will note (Plate 1) that channel edge bars are not uncommon along other channels on the delta. It is assumed that the reasoning given above is equally applicable at other localities.

One may think of the areas immediately surrounding the seaward ends of the minor channels as deltas within the delta top. It is worth noting that these areas have some slight relief above the portion of the delta top that lies to seaward. They are in fact intertidal. The break in slope that marks the boundary between the tidal and the inter-tidal zone closely coincides with the system of parallel bars that in places cut across curved bar developments. It is possible that the parallel bars are in fact breaker zone bars which have developed during some earlier period of the delta's history or alternatively are presently being formed during periods of high tide. Based solely on the evidence provided by the aerial photograph, the writer favours the latter of these two possibilities. Where the troughs of parallel bars cut across the curved bars the latter are cut into short segments which are of approximately the same width as that of the parallel bars where no intersection takes place. This suggests that the parallel bars post date the curved bars. This relationship, which the reader will note is associated with the bars near the smaller of the two channels, suggests that the curved bars are relicts of earlier sedimentological conditions during the deltas development. One must add however, that it is probable that the flow of water seawards along the larger channel is still having some effect on the pattern of bar formation.

C: Concentric Bars around a Branch of the Axial Channel

The concentric bars at C in Figure 6 appear to be associated with the presence of broad and relatively shallow branch of the axial channel that extends seawards for a short distance across the delta top. Except for the curved bars, this portion of the delta top is practically featureless landwards of the breaker zone. This is not surprising since within the breaker zone the waves lose much of their energy. Furthermore, the area is nearly flat and lacks any feature of positive relief where high tide breaker zone bars, such as the ones postulated above, could develop. It therefore seems probable that the curved system of bars has formed in response to the seaward flow of waters diverted onto the delta top. ~~via the~~ Bar ORIENTATION with respect to the channel around which they are formed raises a general point of some interest. The channel with which we are presently concerned shallows to seawards, much in the same way as the axial channel decreases in depth as it passes out between the two sections of the delta. The consequence of this fact is that the channel becomes steadily wider until at some point it loses its identity. This phenomenon occurs because, in order to maintain its carrying capacity, the channel must maintain its cross sectional area and on the delta it appears that the only way it can do this is by becoming wider. The fanning out of the channel can also be viewed in terms of the velocity of the waters which it is carrying. If one were to draw a series of isovelocity contours using values taken during the seaward surge of the ebb tide, they would by their spacing, reflect the rate of shallowing in the channel and the contours themselves would appear as concentric arcs convex in the direction of the flow. This latter observation follows logically from the fact that the waters suffer a lateral displacement as the channel broadens. If this synthesis is correct it would seem more than coincidental that we find a system of convex seawards concentric bars in close association with a shallowing and broadening channel.

D: Channel Edge Bar, Intertidal Zone Bank, Small Lagoon

A prominent channel edge bar is developed on the west side of the Al Bahrani channel. To judge from its light colour (Plate 1), which is in marked contrast to that of the adjacent delta top area, this feature was nearly emergent at the time the aerial photograph was taken. The channel edge bar appears to be rooted to the intertidal zone bank (light coloured rectangular area) and it is quite likely that its formation and development to its present size has in part depended upon a supply of material from the bank. Note how much narrower the channel edge bar is that runs from the tip of the island to the corner of the inter-tidal zone bank.

The inter-tidal zone bank appears to be due to a piling up of sediment over a relatively narrow strip north of Al Bahrani Island. Precisely why this should happen is not clear. Its front is sub-parallel to the prevailing wave approach over the open shelf, however, this may simply be due to deflection of the waves as they pass over the delta. There appears to be a slight tonal lightening from its seaward to Al Bahrani channel side which would suggest that the bank is wedge shaped in section. Kinsman, (oral communication) has reported that the channelward edge of the bank is a fairly steep slip slope. This would account for the sharp channelward edge that appears on the photograph. The small triangular lagoon enclosed between the inter-tidal zone bank and the channel edge bar, was apparently somewhat larger at one time. At the island end of the bank there are several small and separated or nearly separated deeps between the bank and the island suggesting that the bank sediments have been actively infilling the lagoon.

Within the area enclosed by the front edge of the inter-tidal zone bank and the large spit-like channel edge bank, the delta top is marked by a number of linear bars(?). A close inspection of the photograph reveals that the lineations of these features can be traced without break onto and across the bank. On the bank however, they tend to curve very slightly towards the tip of the island. At first it was thought these bank top lineations were a palimpsest of the delta top bars now lying buried under the bank sediments. Their slight curvature would however, be consistent with the effect that, difference in elevation between the bank and the adjacent delta top would have formed on bars due to the pressure of flood tide water movement.

E: Curved and Branching Bars

The Al Bahrani delta top is marked by three major curved bars, roughly concentric, evenly spaced and convex toward the axial channel. Closely associated with these major features are a number of shorter bars, some of which branch towards the axial channel, almost at right angles to the main bar trend. The major bars, being convex toward the axial channel, have probably developed in response to the fanning out of ebb tide waters due to the progressive seaward shallowing of the axial channel. In this regard it is noteworthy that their curvature is parallel to that of the series of shorter bars that lie close to the axis of the channel. It is also interesting to note that radii projected from any of the above bars intersect over the deep formed where the Al Bahrani channel enters the axial channel viz. at the point, seawards of which the channel becomes progressively shallower. It is possible that the three major bars represent separate phases in the development of this section of the delta. Kinsman (1964) has found considerable evidence that the lagoonal area which lies behind the delta is being infilled by sedimentation. A decrease in the size of the lagoon results in a decrease in the amount of water which flows from it during ebb tide. Perhaps each major curved bar is in effect the sedimentational resultant of separate steps in the infilling of the lagoon and of the consequent dimunition of ebb tidal flow. The writer can offer no explanation for the channelward-branching bars. These are peculiar features indeed. They are best developed near the innermost of the three major curved bars. Here they occur as distinctly elongate features that appear to coalesce with the major curved bar at their one end and die out channelwards at the other. One of them, for some inexplicable reason, splits in two about halfway along its length, however, the two parts rejoin a little further on.

F: Lobate Lagoonward Edge, Abu Dhabi Section

The lagoonward edge of the delta top in the Abu Dhabi section is formed by three prominent lobes of sediment arranged side by side and separated from one another by narrow channels. Between this lobate edge and the axial channel there is broad and fairly flat area of somewhat irregular texture. It is apparent on the photograph that the edge of the delta top, both along the minor channels and where it faces the axial channel, is marked by a relatively sharp drop-off. Kinsman, in discussions with the writer has confirmed this fact and has described the entire delta top edge in this vicinity as a slip slope. Evidently if the sediments on the slope are disturbed, as for example, during sampling, they avalanche down to its base. The occurrence of slip-slope conditions along this edge of the delta top strongly suggests that the delta is building out towards the axial channel. The surface of the broad area between the axial channel and the delta edge dips slightly seawards. This is not apparent on the photographs, however, the bathymetric data (Figure 4) shows that there is a narrow tidal zone that runs along the front of the lobate delta edge and extends up the minor channels.

Climate

The climate in the Abu Dhabi area can be summed up with two words, dry and hot. The annual rainfall is neglible during most years. About every five years torrential rains occur during the winter, however, their effect is climatically insignificant and in general the area is one of extreme aridity. Curiously enough the area is fairly humid, 75-80% in the winter and around 60% during the summer. This is due to the fact that the Gulf region is one of net evaporation. Rates of evaporation up to 165 cm./year have been recorded in the open gulf. One consequence of the humidity is that heavy dews are a common phenomenon in the coastal areas. The hottest months of the year are July, August and September. Kinsman recorded a land temperature of 47°C. (116°F.), during the month of August, 1963. The maximum diurnal variation in the Abu Dhabi area is around 11°C.(19.8°F.).

Sea Water Temperatures and Chemical Parameters

Sea surface temperatures in the open Gulf off Abu Dhabi range from a maximum of 35°C (95°F.) to a minimum of 22°C. (71.6°F). The temperature in the water remains roughly the same as its surface temperature down to a depth of 8-10 fathoms. Nearshore temperatures in the vicinity of the delta edge are about 2°C. (3.6°F.) higher than those in the open Gulf.

The salinity of the open sea off Abu Dhabi ranges from 42-43°/oo, a slightly greater range and a higher maximum, but not significantly so. This undoubtedly reflects the effectiveness of the tidal interchange between the water overlying the oolite banks and that of the open shelf. In the mid areas between the delta and the lagoon, the salinity ranges from 42°/oo to 47°/oo. Once within the lagoon proper, salinities increase rapidly and at its landward edge reach 67°/oo.

Kinsman (1964) found that the highly saline waters of the lagoon are not ejected seawards during the ebb tidal flow and tended to show only a slight inclination to proceed in that direction. The slightly greater salinity range of the delta waters as compared with those of the open shelf may be due to the incursion of mid-area waters (42°-47°/oo) during the ebb tidal surge. It is worth noting that this effect would probably be greatest in the inter-tidal area of the Abu Dhabi section since it is both shallow and in close proximity to the mid-area waters. The pH of the waters overlying the oolite delta ranges from 8.1 to 8.4.

Kinsman (1964, p.167) analysed sea water samples taken on traverses running from the open shelf onto the oolite delta. He was able to show that the waters overlying the delta top have had some of their calcium content removed. He was also able to demonstrate that this depletion in calcium takes place on the delta top. Since the faunal population on the oolite delta is sparse, Kinsman concluded that the calcium loss was due to the chemical precipitation of calcium carbonate in the form of aragonite. He supported this conclusion with additional evidence based on the strontium content of the oolite coatings. In sea water when calcium carbonate precipitates in the form of aragonite, strontium is absorbed into its lattice. Kinsman found that over the delta top, the calcium/strontium ratio of the waters stayed constant. This means that strontium as well as calcium had been withdrawn from the waters. He found that the strontium content of the oolite coatings, expressed as strontium carbonate, is 1.28%, a value which falls within the range expected for aragonite chemically precipitated under the temperature conditions of the area. The reader is referred to Kinsman (1964, p.176) for details regarding the temperature dependence of the strontium content in chemically precipitated aragonite. The writer has not undertaken any studies of the sea water chemistry involved in the process of oolitization.

It is generally agreed that the seas are approximately saturated with calcium carbonate (Revelle and Fairbridge, 1957). In tropical waters however, it is probable that a significant degree of supersaturation is attained, particularly with respect to aragonite. Recent work by Broeker and Takahashi (1966) has shown that the waters flowing onto the Bahama Banks from the adjacent open ocean have a twofold supersaturation with respect to aragonite.

At present there is no data available on saturation conditions in the waters of the Arabian (Persian) Gulf. The water which enters the Gulf through the Straits of Hormuz has a salinity of around 36°/oo and a temperature in the order of 24°C, (73°F.)(Emery, 1956). Within the Gulf these waters achieve concentrations in excess of 40°/oo and temperatures above 30°C. (86°F.) are not uncommon. The amount of $CaCO_3$ which can be maintained in solution in the sea is directly proportional to the amount of CO_2 present in solution which in turn varies directly as the water temperature (Miller, 1952). If we allow that supersaturation is possible and assume that the incoming waters are at least saturated with respect to calcium carbonate, then it is probable that, due to increased water temperature alone, some degree of supersaturation is attained within the Gulf. Another means of removal of CO_2 from solution is photosynthesis. According to Emery (1956) the greatest concentration of planktonic life in the Arabian Gulf is found in the Straits of Hormuz. It may well be that even before the waters which enter the Gulf have lost CO_2 due to increased temperature, photosynthesizing plankton will have effected a partial removal. The principal source of CO_2 in the sea is the atmosphere. In general there is a tendency for the CO_2 saturation of the sea's surface layers to attain equilibrium in this respect. The transfer of CO_2 between the atmosphere and the sea is quite slow (Broeker & Takahashi, 1966) and it is therefore probable that the effects of biological extraction of CO_2 on saturation conditions are extremely persistent.

The maximum supersaturation with respect to aragonite that can be attained in the surface layers of the sea is not known. It is self evident that the higher the degree of supersaturation, the more critical will be conditions in the waters and the more easily will precipitation be initiated. Although the rate of precipitation is apparently directly proportional to the degree of supersaturation (Broeker & Takahashi, 1966), precipitation will also take place at fairly low supersaturations providing the appropriate conditions exist. For example, in the Bahamas, precipitation takes place over a range of supersaturations from 100 to 15 percent (Broeker & Takahashi, 1966).

Generally speaking, in any system which is capable of attaining supersaturation, the introduction of nuclei of some sort will result in precipitation. The high degree of supersaturation achieved in the open waters off the Bahama Banks, supports the contention of Rankama and Sahama (1950) and others that nuclei are relatively rare in the surface layers of the open ocean. In shallow waters, such as those on the Bahama Banks and nearshore along the Trucial Coast, nuclei can be provided by resuspension of submicroscopic carbonate detritus. From their work on the aragonite needle mud area, lying to the west of Andros Island, Broeker and Takahashi (1966) concluded that resuspended material was the principal cause of precipitation from the overlying waters.

In laboratory experiments, precipitation from a supersaturated solution will occasionally take place first on the walls of the container rather than in the body of the fluid. This phenomenon appears to be due to the presence of minute dirt particles adhering to the container walls, which while not free in the sense that suspended material is free, effectively serve as centres of crystallization. The gelatinous coating found on non-skeletal grains (Newell, Purdy & Imbrie, 1960) is probably a very unclean surface in the chemical sense, and while not explaining the reason why the growth of these grains is initiated, certainly suggests why they may act as loci of precipitation.

The concept that surfaces may provide centres of nucleation is well supported in evidence from studies of both organic and inorganic materials. In these cases however, nucleation is due to certain physico-chemical properties of the surfaces and not to adhering particulate matter. That such properties may be relavent to the problems of carbonate precipitation has largely been overlooked. Watabe and Wilbur (1960) have demonstrated experimentally that pieces of de-calcified protein matrix extracted from a variety of shells act as a substrate upon which crystallization preferentially takes place when the organic material is in contact with a saturated solution of calcium carbonate. They also found that aragonite was never deposited on substrates other than those from aragonite shells. Their findings show that not only may a different material provide a suitable surface for nucleation but also that the nature of the substrate may determine the form of calcium carbonate that is deposited.

CHAPTER 3.

Sediments of the Abu Dhabi-Al Bahrani Delta

Figure 7 shows the location of the samples that were used in the writers study of the sediments of the delta and adjoining shelf area. Each sample was mechanically seived (see grain size analysis for details of method) through 21 seives covering a size range of from 2.00 mm to 0.07 mm (very coarse to very fine sand). Each seive split was examined using a stereoscopic microscope. To facilitate identification of oolites in the samples, a few grains from each split were crushed in a small agate mortar.

The samples examined were found to be composed of mixtures, in various proportions, of four principal types of grains. These are oolites, skeletal grains, acid insolubles and carbonate grains of uncertain origin. The latter category includes non-oolitic non-skeletal grains. The size relationships between these four main groups is illustrated in Figure 8. Of lesser importance quantitatively, are the partly coated potential nuclei. Due to their significance with regard to oolitization, their size range is also shown in Figure 8. It is to be noted that the size range shown does not define the range of oolite nuclei but only indicates the sizes that are most commonly seen in the samples.

General Sediment Composition of the Delta and the Adjoining Shelf

The delta and the adjoining shelf comprise the two major subdivisions that can be made on the basis of sediment composition. The delta is composed mainly of oolites, whereas the nearby shelf

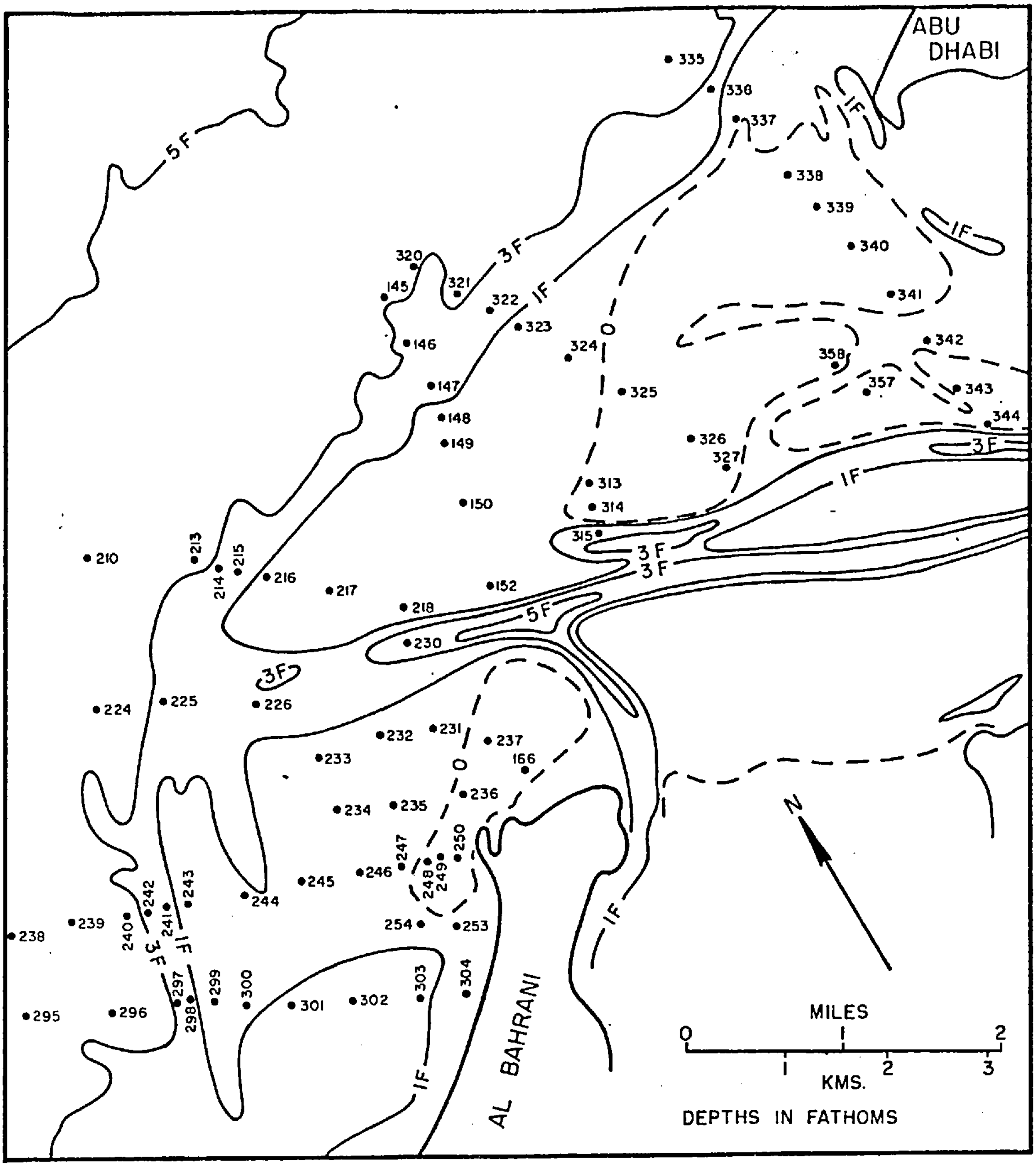


Fig. 7. MAP SHOWING SAMPLE LOCATIONS ON THE ABU DHABI – AL BAHRANI DELTA AND ADJACENT INNER SHELF.

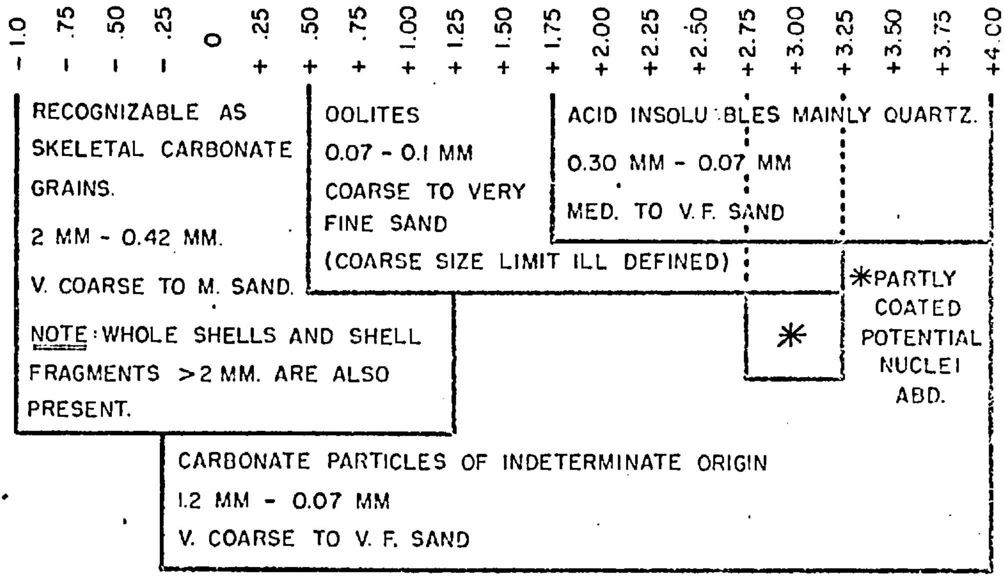


Fig. 8. TABLE SHOWING SIZE RANGES OF SEDIMENT GRAINS FOUND ON THE ABU DHABI - AL BAHRANI DELTA.

sediments consist of skeletal grains and acid insolubles. Transitional between these two facies are the sediments of the delta slope. Figure 9 illustrates the distribution of the three facies mentioned above. It also shows the location of the coral reefs on the shelf, the delta top and along the axial channel. The nature of the lagoonward sediments and the extent of the reef flanking the channel are taken from a similar figure in Kinsman's thesis (1964). Detailed descriptions of the various types of oolites and their areal distribution are not included under the headings that follow. These will be dealt with in a subsequent portion of the thesis.

Inner Shelf Facies

The inner shelf is defined as the area adjacent to the delta slope and bounded by the 5 and 3 fathom bathymetric contours. The sediments of the inner shelf consist of whole and broken shells, mainly lamellibranch valves, fine acid insoluble grains, principally quartz, and fine carbonate particles of indeterminate origin. An average inner shelf sample contains about 80% by weight of the latter two consituents, non-skeletal grains are not present in any significant quantity. Bottom topography appears to control the proportion of shells and shell fragments, an increase taking place on highs due to winnowing out of the fines. Similarly, variations of the percentage insolubles in the inner shelf sediments is mainly a reflection of varying shell content since the proportion between acid insolubles and fine carbonate grains is fairly constant (see grain size analysis).

Delta Slope Facies

The facies of the delta slope is distinguished from those of the

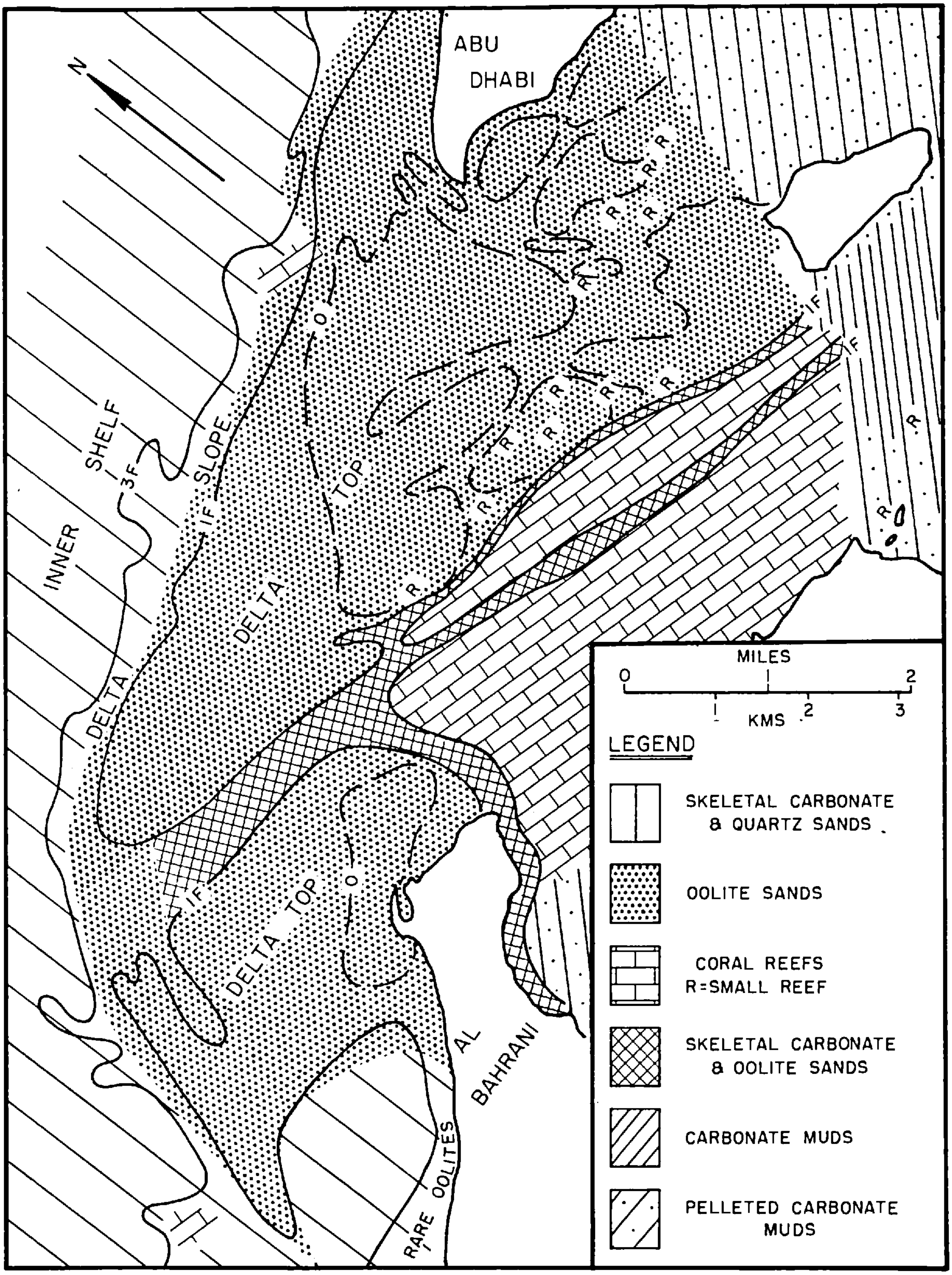


Fig. 9. FACIES MAP OF THE ABU DHABI - AL BAHRANI DELTA AND NEARBY AREAS.

inner shelf and delta top for the following reasons:

1) Oolitization commences on the delta slope.
2) The nuclei of the oolites on the delta belong both mineralogically and in size to the generally dominant fine grained portion of the inner shelf sediments viz. the acid insolubles and the carbonate particles of indeterminate origin (see grain size analysis).
3) Skeletal remains are scarce on the delta top, much more so than on the inner shelf. The transition between the inner shelf and the delta top is marked by a progressive decrease in skeletal grains up the delta slope.

The dominant characteristic of the delta slope sediments is the progressive increase of the oolite content in an upslope direction.

Delta Top Facies

The sediments of the delta top are composed mainly of oolites. Where large amounts of non-oolitic material present in the samples, it is invariably coral debris. On the Abu Dhabi section this debris comes from the several small reefs along the southeast edge of the delta top. Distribution of detritus from these reefs is very limited in areal extent. On the Al Bahrani section, fine coral fragments appear to have been carried there by the flow of water along the axial channel since there is no local source on the delta top. The most probable source is the large area of coral reef through which the channel flows along the greater part of its length (Figure 9). Other grain types which serve to dilute the oolite content of the delta top sediments are shell fragments, non-skeletal lumps and pellets, carbonate grains of indeterminate origin and acid insoluble grains, chiefly quartz. These grains rarely account for more than 20% of any sample.

Sediment in the Axial Channel

The axial channel is floored with a coarse lag deposit composed mainly of coral debris. Finer pieces of coral, shell fragments and oolites occupy intersitial positions in the coarse framework. The vigorous flow along the channel appears to prohibit the accumulation of any of the finer grades of sediment.

The Oolite Content of the Sediments

Kinsman (1964) found that within the area bounded by the one fathom contour, the sediments of the delta consisted of 60% or more oolites. He estimated the composition of the sediments by examining the bulk samples with a stereoscopic microscope and from thin sections of selected samples. In the present study, the percentage of oolite was estimated visually for each seive split and a weight percent oolite content derived for each sample. For example, if a seive class contained 40 weight percent of the size distribution and 4/5 of the grains were oolites then the weight percent oolite contained in that split would be 32% and so on for each split obtained from seiving the sample.

Figure 10 shows the weight percent oolites obtained for samples from the delta and the adjacent shelf area. Oolites were found to be absent or in small amounts in all but one of the samples that were collected from the inner shelf area. Between the 3 and 1 fathom contours (delta slope) the oolite content ranges from neglible to 64% with and overall average of around 35%. Just inside the 1 fathom

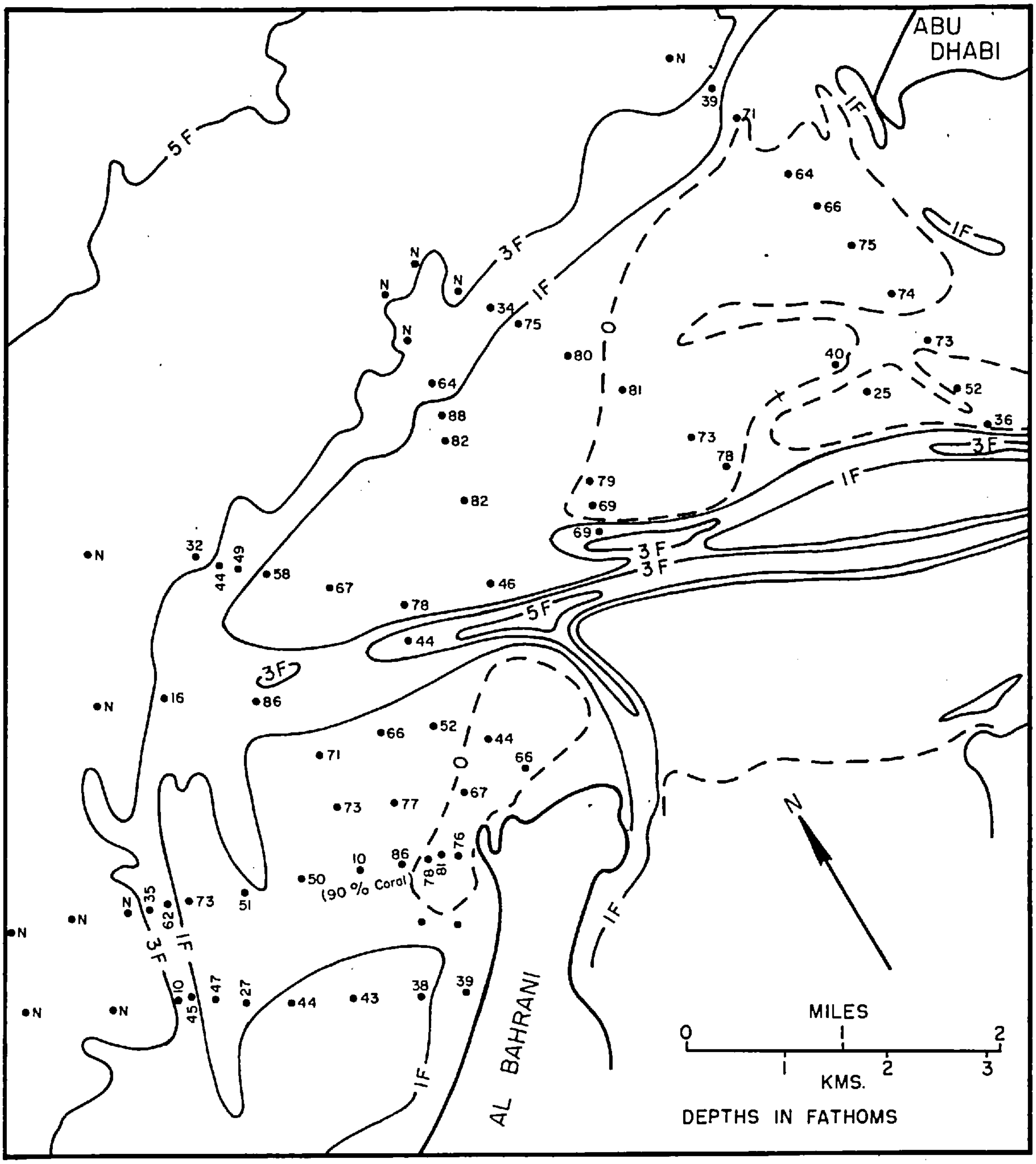


Fig. 10. MAP SHOWING WEIGHT % OOLITES IN THE SEDIMENTS OF THE ABU DHABI - AL BAHRANI DELTA AREA. NEGLIGIBLE AMOUNT OF OOLITES IN SAMPLE IS SHOWN AS "N".

contour there is an increase in the oolite content of the sediments. The overall average for the delta top is approximately 71%. It is interesting to note that whereas the proportional increase in overall oolite content between delta slope and delta top sediments is twofold, the oolite content of the delta slope sediments is at least ten times that of those on the inner shelf.

As shown in Figure 10, the oolite content of the delta top sediments tends to be somewhat lower in those areas that are adjacent to the channels. This is probably due to a dilution of oolite content by materials carried there and deposited during ebb tidal flow. In the southeast corner of the Abu Dhabi delta top the small coral reefs contribute detritus to the adjacent area and the oolites, though abundant, serve to dilute what is basically a skeletal grain sediment. On the delta slope and delta top of the Al Bahrani section, there is a general decrease in oolite content as one proceeds from the axial channel in a southerly direction. The lower oolite content is usually due to an abundance of mollusc fragments, however, in one sample taken near the geometric centre of the delta top, almost 90% of the non-oolitic material was coral debris. Since there are no coral reefs on the delta top, it is safe to assume that currents have carried this material from a nearby source (probably the reefs in the axial channel) and for some reason, deposited it in one small area of the delta top. Samples taken adjacent to the above location were found to contain a maximum of 10% coral debris.

The Shapes of the Oolite Grains (Figure 11).

Most of the oolite grains found in the sediments of the delta are

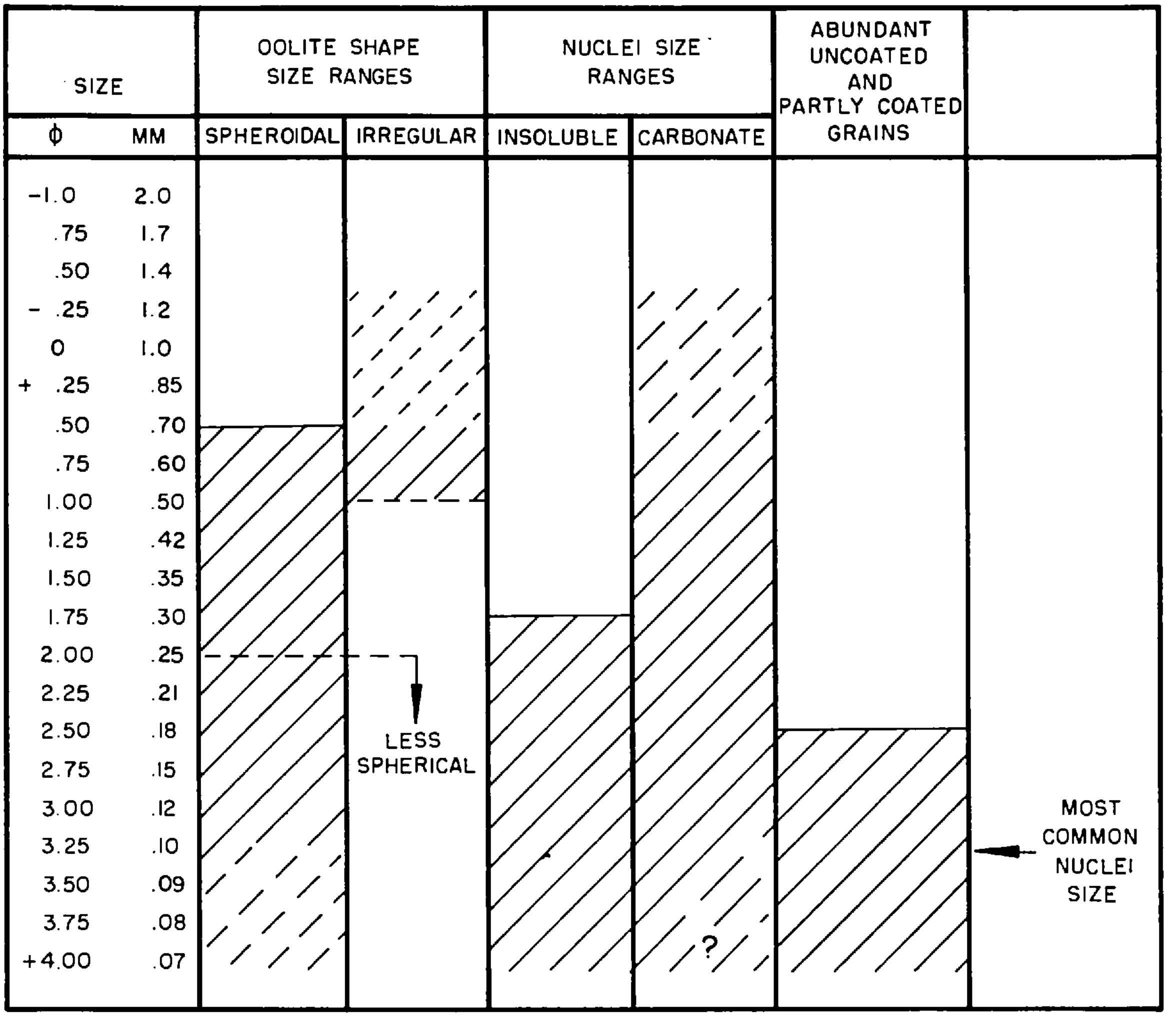


Fig. 11. TABLE SHOWING SIZE RANGES OF SPHEROIDAL AND IRREGULARLY SHAPED OOLITES, AND INSOLUBLE AND CARBONATE NUCLEI. TABLE SUMMARIZES DATA FROM STEREOSCOPIC MICROSCOPE EXAMINATION OF 1600 SEIVE SPLITS.

spheroidal in shape and have diameters which lie between 0.7mm (+0.5 phi) and 0.1mm (+3.25 phi), i.e. coarse to very fine sand grades. In examining the sediments it was observed that the oolites with diameters of 0.25mm (+2.00 phi) or less, i.e. fine to very fine sand grades, tended to be slightly irregular in shape. This change in character with decreasing size appears to be related to the fact that approximately 75% of the oolites (see grain size analysis) have nuclei with diameters of 0.18mm (+2.50 phi) to 0.10mm (3.25 phi). For this reason the finer oolites, having thinner coats, tend to reflect the shape of their nuclei.

The influence of the shape of the nuclei is also apparent in the very coarsest oolites which are generally composed of a very thin oolitic veneer covering an angular skeletal fragment. The size of these particular oolites cannot be defined by any single measurement. They most commonly occur in the sieve fractions coarser than 0.5mm (+1.00 phi) along with uncoated skeletal debris. In this regard it is noteworthy that one of the most commonly occuring changes in the character of the sediment grains contained in the seive fractions is the appearance of abundant, partly coated potential nuclei in the fractions finer than 0.20mm (+2.25 phi).

Superficial Features of the Oolite Grains

The most consistent distinguishing superficial property of the oolites found on the delta is the hardness (friability) of their surface. Within fairly narrow limits, the following relationship occurs between hardness and other superficial properties:

	Hard surface	Soft surface
Colour:	cream	white
Lustre:	sub-vitreous	dull
Texture:	smooth	rough

This distinctive association of surface properties serves to classify the two dominant classes or types of oolites that can be distinguished by means of examination with a steroscopic microscope. The hard and soft surfaced oolites, though generally the dominant types in the samples examined, appear to be the end members of a process which transforms the former into the latter. The intervening stages in this process are represented not by a progressive and uniform softening, but by an increasing abundance and eventual coalescence of soft patches on the oolite surface. Oolites possessing this characteristic have a mottled appearance that is equally as distinctive as that of the hard and the soft surfaced types. The writer has called these oolites mixed surface oolites.

The soft patches on an oolite with a mixed surface can easily be crushed or removed with the point of a needle. By so doing, it was found that the soft patches do not overlie the adjacent hard surface but occupy shallow pits in that surface. The under-surface upon which the soft patches lie was found to be hard but not smooth. Equally common, were cases where between the soft carbonate and the hard rough surface there was a thin layer of algal cells, clustered together as a very fine botryoidal mass. The presence of a layer of algal cells appears to increase the softness of the dull white carbonate patches. The algae are a species of blue-green, <u>Entophysalis</u>

deusta (Menegh), Drouet and Daily. These are known to be a perforating type (Drouet and Daily,1956), that grow as strata or cushions and put down a profusion of perforating filaments into carbonate substrate. The fact that the algae are overlain by a layer of carbonate and enclosed in pits in the hard oolite surface indicates that the soft patches postdate algal infestation. More conclusive proof of this relationship, which includes those cases where no algal cells are evident, is provided in the section on the petrography of the oolites.

Algae of the same species discussed above are also found occupying uncovered pits in the surface of the oolites. In some cases the pitting, due to the presence of a few large aggregates of algal cells, is so severe that approximately half of the oolite surface will be eaten away. This extreme form of algal infestation is almost exclusively found in oolites with a predominantly soft surface. Algal infestation of varying degrees is very common in the mixed surface oolites.

By treating the oolites with methylene blue dye, the presence of organic matter can readily be detected. It is to be noted that this technique cannot be applied in those cases where the grains are immersed in an acid solution as the acid tends to bleach the dye. Completely hard surfaced oolites stain only faintly when treated with methylene blue. If there are algal cells on the oolite surface or in pits they take on a vivid colouration that is in marked contrast to the surrounding uninfested areas. In contrast, entirely soft surfaced oolites stain an intense blue colour all over and little contrast can be observed between the surface and any exposed algae. The character of the staining achieved by the soft surface oolites provides corroborative evidence of the presence of a substrate of algal material underlying the surface carbonate. It also suggests that the soft carbonate coating is relatively porous.

Hard and soft surfaced oolites were found to react quite differently when treated with diluted hydrochloric acid. Hard surfaced oolites react vigorously the instant they are immersed in acid and in general continue to do so until all of the carbonate is dissolved. Soft surfaced oolites of the same size, react with vigour for a few seconds, almost cease reacting, then continue dissolving in the same manner as before. It would appear that the layer of algal cells underneath the superficial carbonate serves as a temporary barrier to solution. Oolites with mixed surfaces show a similar differentiation of staining intensity as is observed between hard and soft surfaced oolites. In the case of solution behaviour, it is impossible to detect any differences except in those cases where one or the other of the surface characteristics is dominant.

Surface Lustre

Hard surfaced oolites were found to possess a characteristic glossy lustre regardless of their size, viz from 0.7mm (+0.50 phi) to 0.1mm (+4.00 phi). The sediments which most clearly demonstrate this uniformity of lustre are those from the highly turbulent zone at the boundary between the delta slope and the delta top. Newell, Purdy and Imbrie (1960) concluded that mechanical polishing was responsible for the bright lustre found on some of the oolites on the Bahama Banks.

Their conclusions were based upon the results of tumbling dull surfaced oolites under laboratory conditions and the occurence of highly lustrous oolites in zones of turbulence. Illing (1954) suggested that the high surface lustre found on Bahaman oolites was due to active oolitization and when oolites were removed from the zone of oolitization, they lost their lustre.

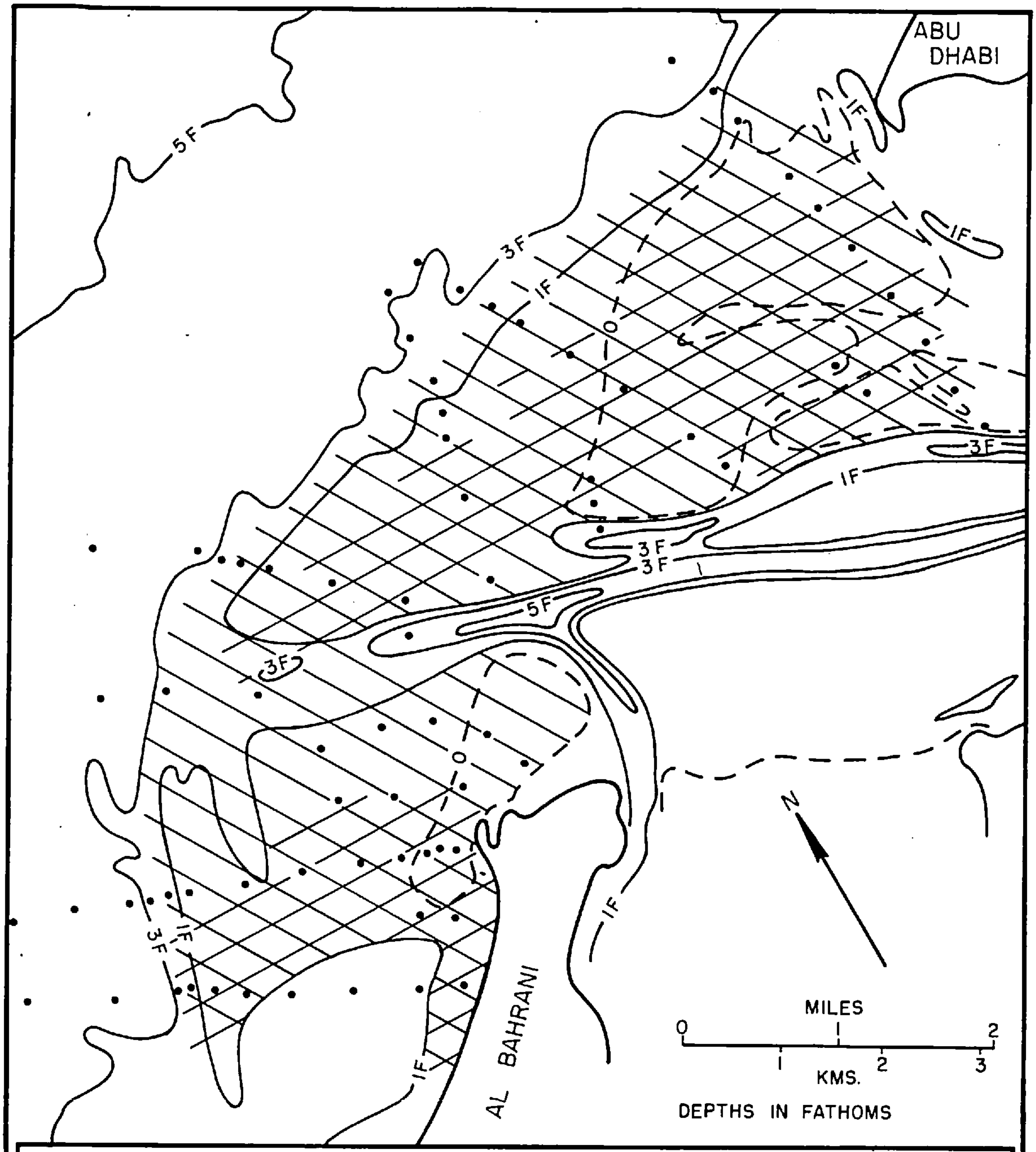
Twenhofel (1945) in a study of the rounding of sediment grains in natural environments concluded that the abrasion of quartz grains with diameters less than 0.5 mm (+1.00 phi) is neglible. A similar conclusion was drawn by Kuenen (1959) from experimental evidence. Both Twenhofel and Kuenen pointed out that carbonate grains are considerably more vulnerable to abrasion than quartz. The size at which abrasion becomes negligible on on carbonate grains is not known. Kuenen (1964) states that the rate of abrasion of a 0.4mm (+1.25 phi) limestone cube is roughly equal to that of a 2.5mm quartz grain. He also found (Kuenen, 1959) that if a 2.00mm (-1.00 phi) quartz grain is initially well rounded, it will suffer no appreciable abrasion regardless of the distance it travels. It is to be noted that Kuenen uses the term travel to mean stationary rotation or rotation in translation. These findings suggest that well rounded carbonate grains, such as oolites, of approximately 0.3mm (1.75 phi) or less, suffer very little abrasion.

There is no perceptible difference between the lustre of the largest and the smallest hard surfaced oolite , which one might expect to be present if polishing due to abrasion were responsible for this characteristic property. The difference in lustre between the hard and soft surfaced oolites appears to be related to some fundamental difference in the process by which carbonate accretion is taking place viz. the absence or presence of prior infestation by algae. The concept that surface lustre is related not to abrasion, but to the accretionary process will be discussed in connection with the petrography and organic content of the oolites.

The Pattern of Distribution of Oolite Surface Types

The following description and discussion presents, in a very general way, the areal distribution of oolites with different types of surface characteristics. A rough estimate was made of the relative proportion of each type that was present in the individual seive splits from each sample. From these estimates, the general character of the sample was derived, i.e. dominantly hard surfaced oolites with rare mixed surface oolites. The distribution of the various surface types determined by the method outlined above is shown in Figure 12.

If the mixed surfaced oolites are included with the soft surfaced oolites, certain distinctions can be made between the size ranges of these types and that of the hard surfaced oolites. In the Abu Dhabi section, the range of size of the soft (soft and mixed) surfaced oolites is restricted at a lower limit of 0.2mm (+ 2.25 phi) and only very rarely are oolites of this type found in the finer fractions of the sediments. In examining the seive fractions, proceeding from coarse to fine, the disappearance of soft surfaced oolites is strikingly abrupt and usually complete over a single seive interval (1/4 phi). The boundary defining this lower limit of 0.2mm (+2.25 phi)



OOLITE SURFACE TYPES

▧	▨	▩
HARD	SOFT & MIXED	HARD + SOFT & MIXED

SIZE RANGES

	ABU DHABI SECTION	AL BAHRANI SECTION
HARD:	0.7 - 0.07 MM (+0.5 ϕ - 4.00 ϕ)	0.7 - 0.07 MM (+0.5 ϕ - 4.00 ϕ)
SOFT & MIXED:	0.7 - 0.20 MM (+0.5 ϕ - 2.25 ϕ)	0.7 - 0.07 ? MM (+0.5 ϕ - 4.00 ϕ)

Fig. 12. MAP SHOWING AERIAL DISTRIBUTION OF HARD, SOFT AND MIXED SURFACED OOLITES ON THE ABU DHABI - AL BAHRANI DELTA.

was fairly consistent throughout the samples examined. Where variations did occur, the boundary was always displaced towards coarser sizes. The hard surfaced oolites that are mixed with soft surfaced types are unrestricted in terms of the range of oolite sizes.

In the Al Bahrani section, much of the oolite sediment is exceptionally well sorted, about mean sized from 0.18mm (+2.50 phi) to 0.20mm (+2.25 phi), and as a consequence, both the largest and smallest oolite sizes are often absent. The less well sorted sediments tended to have a relatively low oolite content. Good sorting or low oolite content both made it difficult to determine if the average smallest size of soft surfaced oolite was the same as that found on the Abu Dhabi section of the Delta.

Hard surfaced oolites of all sizes and essentially unmixed with other types occur near the one fathom bathymetric contour along the seaward edge of the Abu Dhabi delta top. These sediments lie in a zone of considerable turbulence which is caused by the breaking of waves as they move into the shallower water of the delta top. Sediments composed of a mixture of hard, soft and mixed surface oolites lie in the quieter waters behind this zone of turbulence and in general are characteristic of the delta top area. The proportion of soft surfaced oolites increases as one proceeds from the seaward edge of the delta towards the axial channel. The nature of the size ranges of the hard and soft surfaced oolites (hard: all sizes, soft: down to o.2mm, 2.25 phi) suggests that on the Abu Dhabi delta top, the coarser oolites are sufficiently stationary under the prevailing conditions of water movement to allow extensive infestation by algae and subsequently the development of soft surfaces. The finer oolites, being more mobile, escape infestation, and thus retain their hard surfaced character. The net lateral movement of currents on the Abu Dhabi delta top appears to be towards the axial channel. This motion would maintain the supply of hard surfaced oolites, carrying them from the turbulent zone near the one fathom contour into quieter waters. Turbulent motion appears to play some role in the inhibiting of extensive algal infestation. Whether it inhibits infestation by constantly stirring up and turning over the sediments or by some other means affects the suitability of the environment to algae is not known. Whatever the cause, the oolites of the turbulent zone are characteristically almost devoid of algae. In quieter waters turbulence is relatively slight and cannot be considered as a possible cause of inhibited algal growth. Differing rates of lateral movement of the various sizes of oolite appears to be one possible explanation for the size selective infestation by algae that precedes the development of soft surfaces.

The Al Bahrani section of the delta has a quite different pattern of distribution of oolite surface types than that found on the section just discussed. Here, hard surfaced oolites cover a considerable part of the delta. Their position, unlike that of similar oolites on the Abu Dhabi section, does not coincide with the zone of turbulence caused by breaking waves. Hard surfaced oolites occupy approximately two-thirds of the Al Bahrani delta top from the axial channel south. Hard surfaced oolites do occur in the frontal turbulent zone, however, they are mixed with many more soft and mixed surfaced oolites than are present in the "pure" hard surfaced oolite sediments found at a comparable location in the Abu Dhabi section. In the southerly third of the delta top a mixture of hard, soft and mixed surfaced oolites are found. There is, however, no apparent differentiation of size between the various types and the range of sizes is not markedly different from that of the dominantly hard surfaced oolite sediments lying in proximity to the axial channel.

The absence of algal infestation on the hard surfaced oolites bordering the axial channel may in part be due to turbulence produced during ebb and flow of tidal waters. Wave action in this zone is not sufficiently strong to produce turbulence comparable to that found along the delta front. An alternate explanation is that the hard surfaced oolites on the Al Bahrani delta top have been derived from the Abu Dhabi section and deposited at a rate which exceeds the rate at which they can be transformed. The idea that the Al Bahrani oolites are largely derived from elsewhere will be discussed further in the section on grain size analysis.

Algae

Dr. W. Stewart of Westfield College, University of London, identified Entophysalis deusta (Menegh.), (Drouet and Daily, 1956) as being the dominant alga infesting the surfaces of the delta oolites. He was able to determine that other blue green algae, species of Lyngbya or Phormidium, though also present are rare in comparison to Entophysalis deusta. It is noteworthy that Entophysalis deusta is one of the species of algae associated with the Bahaman oolites (Newell, Purdy and Imbrie, 1960).

The presence or absence of E. deusta on the surface of oolite grains is easily determined with a stereoscopic microscope. If it is present it shows up clearly due to its deep green colour and the characteristic fine botryoidal nature of its aggregated form (Plate 2).

The possibility that other algae may be present that are less apparent than E.deusta, could not be directly assessed by examination with the stereoscopic microscope. For example, many of the hard surfaced oolites show no direct evidence of algal infestation except a few scattered faint white vermicular markings that could possibly be due to very fine scale algal boring. To investigate these problematic markings the following technique was employed. By treating carbonate grains with hydrofluoric acid, the aragonite or calcite is replaced by fluorite. The normal use of this method is in the examination of forams. Glover and Sippel (1962) have reviewed the literature on this method and examined the chemical mechanism involved. By treating oolites with 40% hydrofluoric acid for five minutes, a thin (approximately 0.05mm) layer at the surface of each oolite is replaced by fluorite. After solution of the remaining carbonate in diluted hydrochloric acid, the thin fluorite shell is released. This shell is perfectly transparent and can be examined in transmitted light with a petrographic microscope. Best results are obtained if the fluorite shell is immersed in water.

By employing the method outlined abo ve, it was found that the hard surfaced oolites commonly possess numerous surficial markings whose organization is suggestive of algal boring (Plate 3).

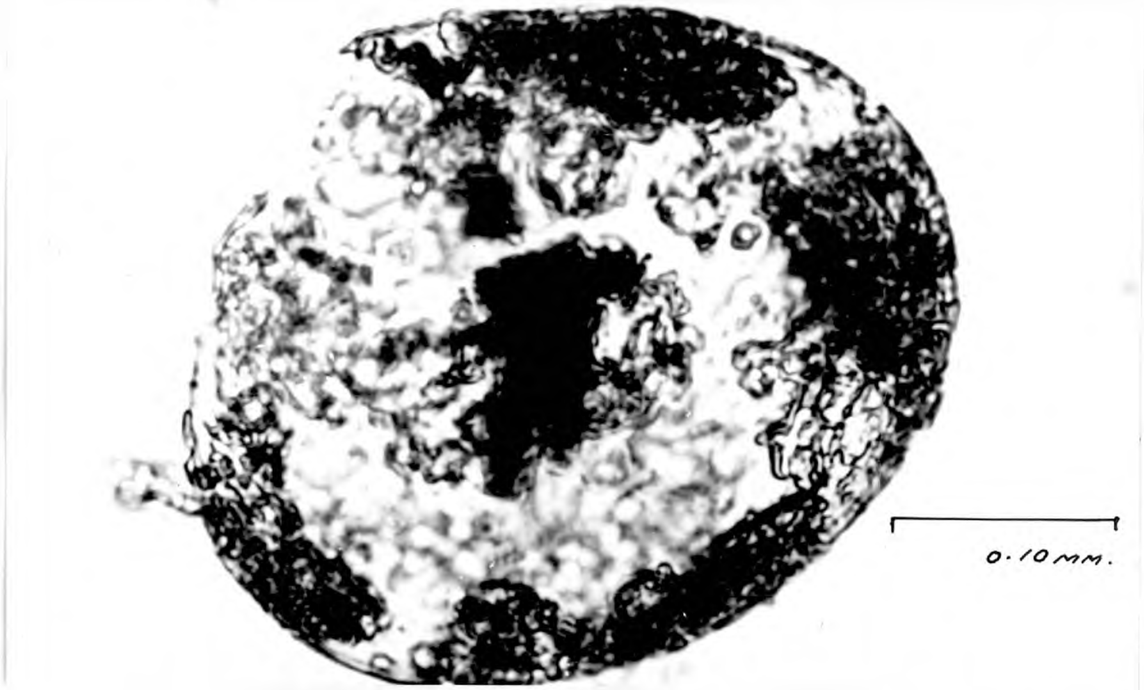
Plate 2

Upper (Plain polarized light.)

Water mount of a fluorite pseudomorph of an aragonite oolite (see text). Colonies of the blue-green algae Entophysalis deusta appear as dark masses clinging to and projecting below the surface of the spherical fluorite shell. Spherical nature of the individual algal cells is typical.

Lower (Plain polarized light.)

Water mount of an agglomeration of algal cells, principally of the blue-green algae Entophysalis deusta. Texture viewed here is typical of what one usually sees when algae are observed in the fabric of a thin-sectioned oolite.


0.10 mm.


0.10 mm

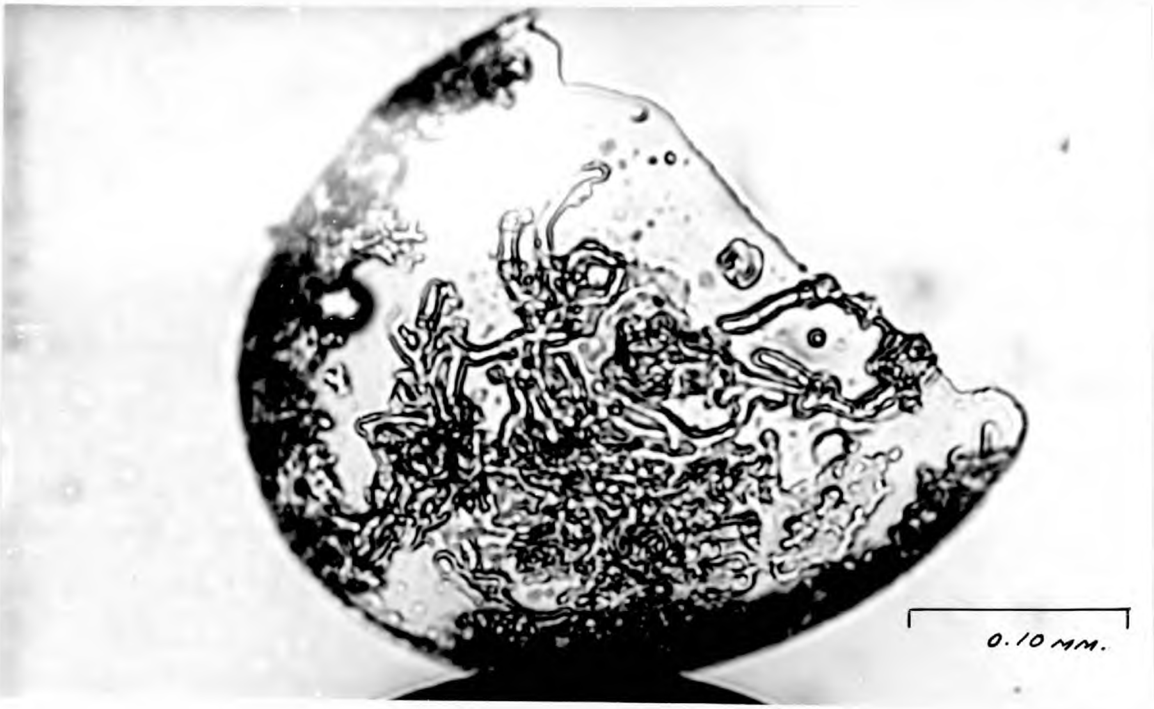
Plate 3

Upper (Plain polarized light.)

Water mount of a fluorite pseudomorph of the surface layer of an oolite. No algal colonies apparent. The markings on the oolite surface were probably made by perforating filamentous algae that bored into the oolite sub-parallel to the grain surface. The algae appear to have been present as several colonies, each with a central aggregation of cells and each radiating out discrete perforating filaments.

Lower (Plain polarized light.)

Water mount of a fluorite pseudomorph of a shell fragment. Surface of the grain shows innumerable borings, most probably of algal origin.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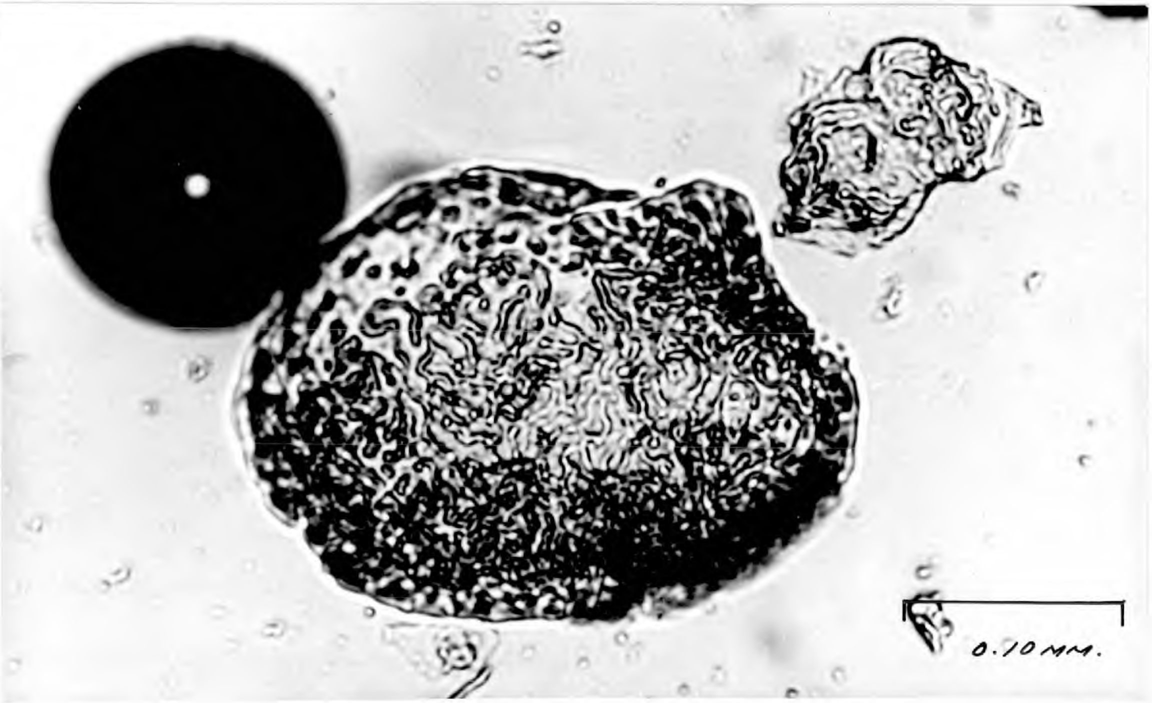

0.10 MM.

Superficially these perforations resemble the penetrating threads of Hyella caespitosa (Born and Flah.) shown in Figure 318, Page 828 of Fritsch (1945). Considering the general abundance of Entophysalis deusta in the delta sediments it is interesting to note that Drouet and Daily (p103, 1956) believe that some varieties of Hyella caespitosa are actually growth forms of E.deusta. Whether or not algae are actually responsible for the markings found on the hard surfaced oolites is difficult to say. Careful examination of both treated and untreated oolites failed to reveal any live algae associated with the perforations.

Organic Matter in the Oolites

In addition to algal cells, another form of organic matter is intimately associated with the skeletal and non-skeletal grains found in the delta sediments. This material is gelatinous, transparent (Refractive Index + 1.470), faint yellowish brown in colour and possesses a very fine grained vermicular texture (Plate 4). In 5% hydrochloric acid carbonate grains dissolve moderately slow and the organic matter remains after solution as a thin gelatinous replica of the outer shape of the grain. Many grains, particularly the larger skeletal fragments, appear to have ohly a partial coating of organic matter. This is, however, rarely true in the case of the oolites.

When the oolites are dissolved in extremely dilute acid, the gelatinous material remaining after solution forms a pseudomorph of the grain and not just a replica of its external form (Plate 5). In those cases where a non-carbonate grain has served as a nucleus

Plate 4

Plain Polarized Light

Water mount of a fragment of gelatinous organic matter. The fragment came from the surface of a hard surfaced oolite that showed no evidence of algal infestation. The organic matter is colourless to very pale brown. It stains only faintly with methylene blue. Quartz silt and other transparent insolubles show up as bright objects with dark rims. Close examination reveals that the vermicular texture of the organic matter can be resolved into individual cell-like objects, each roughly circular in outline and possessing a minute dark nucleus. The cell-like objects are roughly 4-6 microns (.004 to .006 mm.) in diameter and their nuclei are roughly 2 microns (.002 mm.) across. Similar objects are apparent in the laminated fabric type of oolite coating (see Plate 7:L). It is to be noted that the individual laminae of the coating are about 2 microns (.002 mm.) thick, and in some instances exhibit a pinch and swell texture. These sausage-like structures may well be the "objects" of the gelatinous organic matter seen on edge.

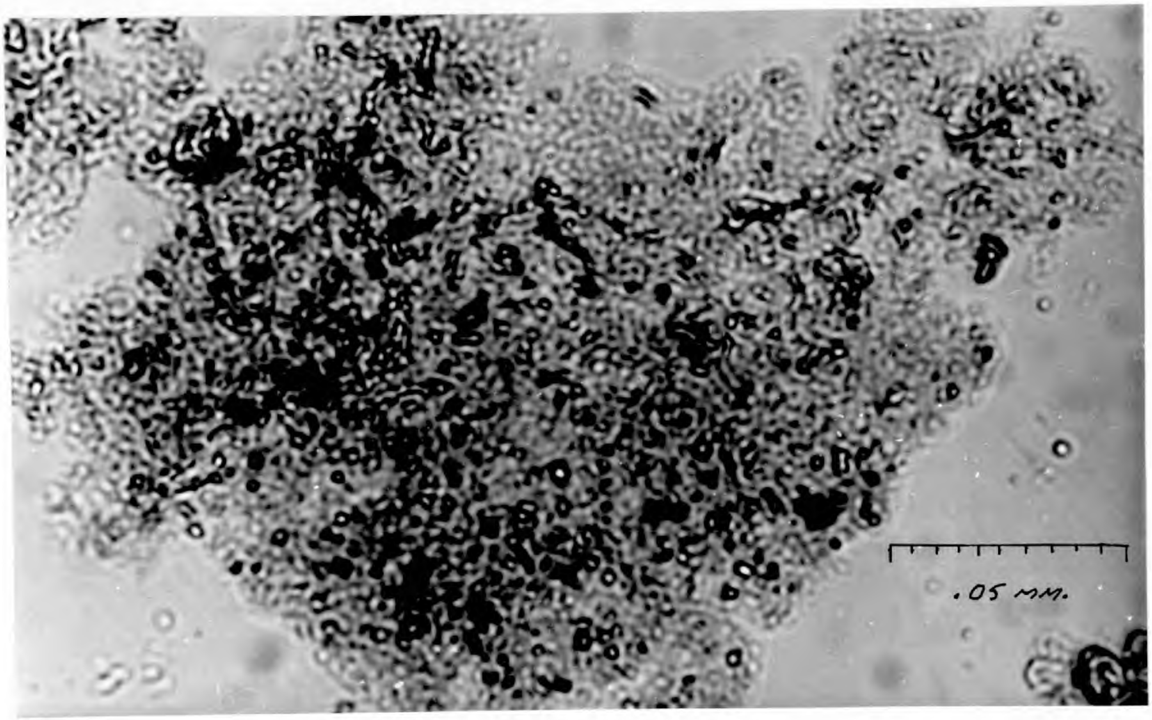

.05 MM.

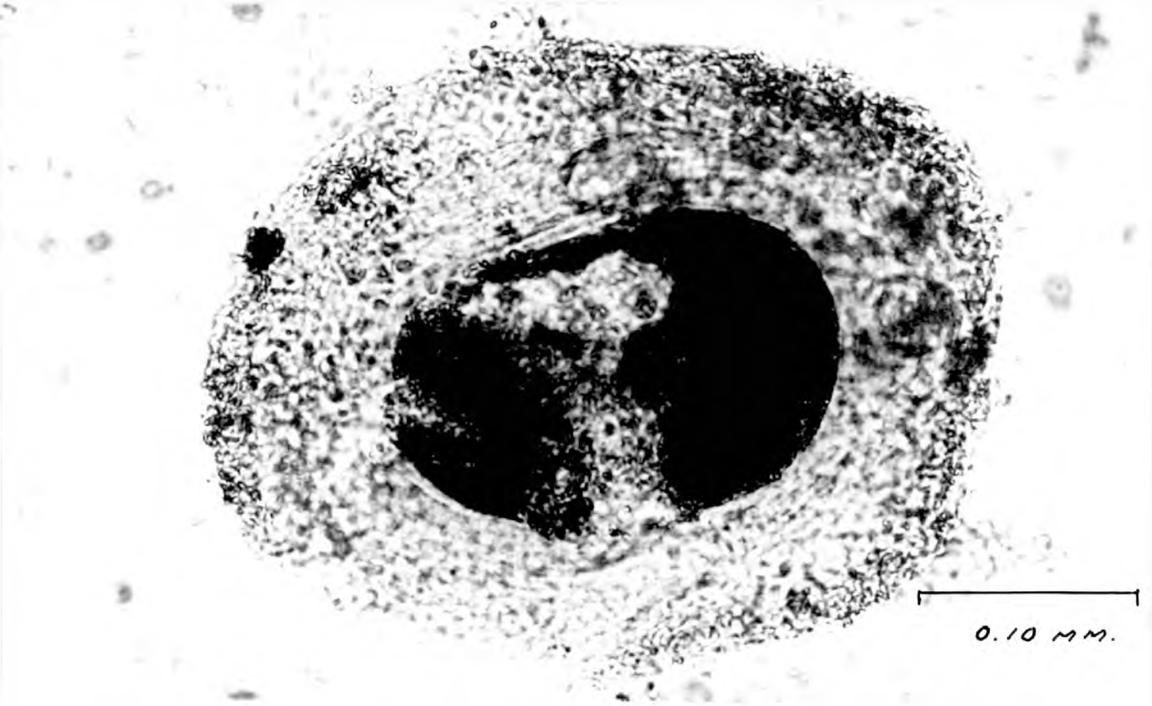
Plate 5

Upper (Plain polarized light.)

Water mount of the gelatinous organic residue left after extremely slow solution of an oolite. Nucleus is enclosed in organic matter. The nucleus appears to be a quartz grain with some undissolved carbonate remaining on its surface. Colour of the organic matter is very pale brown. The fine laminations in the organic matter are of the same thickness as those in the oriented fabric type of coating. Areas of the organic matter with cellular texture are encapsulate algae.

Lower (Plain polarized light.)

Water mount of the gelatinous organic matter left after extremely slow solution of an oolite. Live colonies (still green coloured) of the algae Entophysalis deusta cover the outer surface of the organic pseudomorph and thus obscure any internal structures that may be present. The abundance of algae suggests that the original oolite was probably uniformly soft surfaced type.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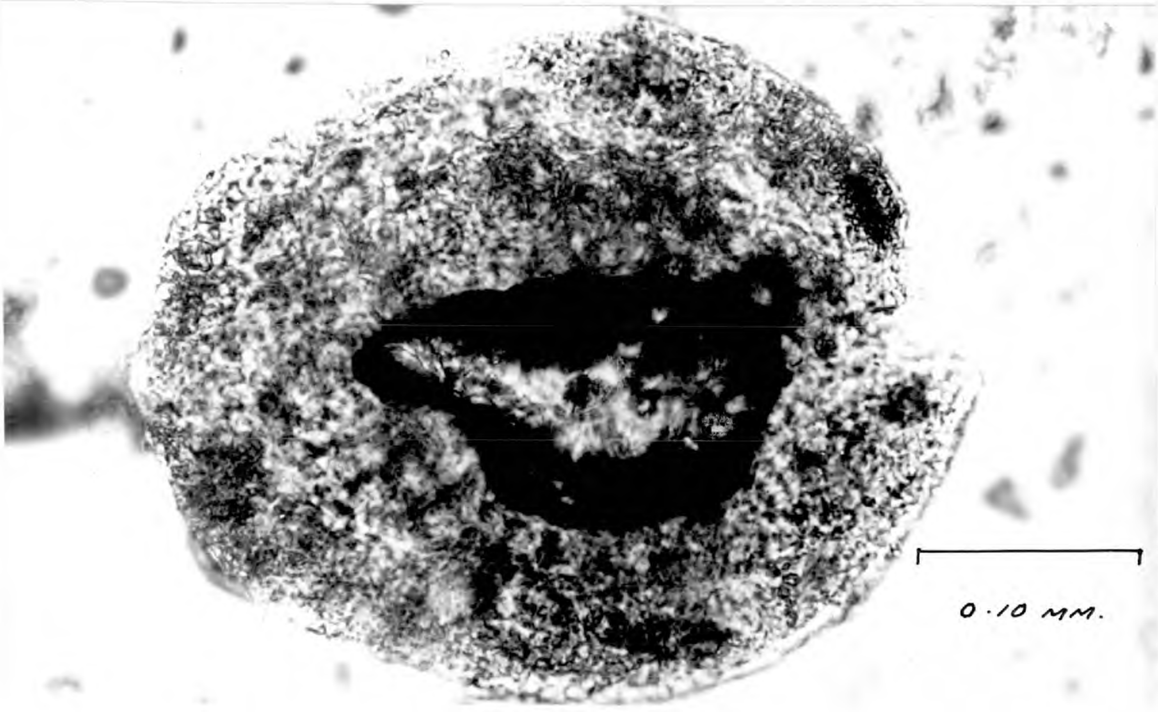
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for the oolite, it will be present, more or less in its original position, suspended within the mass of organic material. The gelatinous pseudomorph possesses an internal lamination that is parallel to its outer surface. The scale of these laminations is very similar to those observed in thin sections of the carbonate oolites (compare Plates 5 and 7). Scattered throughout the organic matter are algal cells and minute non-carbonate particles. In the case of soft surfaced oolites, the cells of Entophysalis deusta are present in abundance at the surface of the organic pseudomorph and obscure the internal laminations (Plate 5).

There is no visible evidence that the organic material contained in the inner parts of the oolites is different from that found at their surfaces. Nor does it appear to be at all dissimilar to the thin organic coatings found on other non-skeletal grains and on skeletal fragments.

Newell, Purdy and Imbrie (1960) found organic masses, similar but devoid of laminations, remaining after solution of Bahaman oolites. They favoured the view that the organic matter was detritus that adhered to the oolite surface and became incorporated within the oolite during its growth. The cohesive nature of the organic matter extracted from the Abu Dhabi-Al Bahrani oolites makes it seem unlikely that it is made up of detrital particles. ~~The fact that it is made up of detrital particles.~~ The fact that it is associated with all the oolites, including those from the highly turbulent zone along the delta front, also tends to discount the idea that the organic matter is detrital in origin.

Newell, Purdy and Imbrie (1960) rejected the possibility that the gelatinous material present in the Bahaman oolites was a secretion of the blue-green alga Entophysalis deusta on the grounds that the shape and distribution of the algal colonies was far too irregular to have produced the characteristically uniform properties observed. This argument seems to be equally applicable to the delta oolites and in fact is strengthened by the even laminated character of the organic matter. The fine filamentous perforations associated with the hard surfaced oolites, if algal in origin, demonstrate that the colonies were rather widely scattered. Assuming that such algae did actually secrete a mucoid substance, the general lack of contact between colonies would prohibit the formation of a continuous organic coating.

The refractory nature of the gelatinous organic matter associated with the carbonate sediments of the delta is evident from its preservation in juxtaposition with the nuclei of well developed oolites. Drouet and Daily (p.7, 1956) point out that the accumulation of large quantities of the mucilage secreted by blue-green algae is inhibited by its tendency to be rapidly hydrolyzed. Without chemical tests to establish the composition of the observed organic matter and subsequently its susceptibility to hydrolization under the conditions prevailing on the delta, one cannot assume that preservation is a criteria of non-algal origin.

Ginsburg (1963) in reviewing the importance of bacteria as a causative agent in the precipitation of calcium carbonate concluded that in sand sized carbonate sediments such as the Bahaman oolites, bacteria are too scarce and their metabolic rate too low for them to be an effective influence. If bacteria are as scarce in these sediments as Ginsburg suggests, it seems improbable that they are responsible for the ubiquitous organic slime that coats the carbonate grains of the Abu Dhabi-Al Bahrani delta.

The nature of the environment typified by the deposition of sand sized carbonate grains, though inhospitable to bacteria due to excessive aeration and exchange of interstitial waters (Ginsberg, 1963), is eminently suited to the development of algae. The organic matter associated with the oolites does not however, show clear evidence of being algal in origin. One might expect there to be abundant living algal cells embedded in the mucilage and readily apparent if only by their colour.

There appears to be no clear cut evidence that points to a single agency that produces the ubiquitous organic material associated with the sediments of the Abu Dhabi-Al Bahrani delta. Algae would appear to be the prime candidate for such a role, yet the absence of any abundance of live colonies on the grains in certain environments is disturbing. Possibly it takes a considerable amount of time to build up a complete coating, and few of the countless generations of algae that have contributed mucilage are evident at the moment of examination. Bacterial infestation may take place even though the environment appears unsuitable. Perhaps some type of facultative anaerobe exists on the surface of the grains, feeds on algal secretions and leaves a slime of dead cells. All the above possibilities are highly speculative. To solve the problem requires the combined efforts of a bacteriologist, an expert in algae and a biochemist.

The role of organic matter in the formation of oolites cannot be established without a better understanding of how the organic matter was formed. The action of organisms at the surface of grains may well determine whether carbonate is precipitated on that surface. Previous workers (see section on oolite literature) have made numerous suggestions as to the importance of algal activity, bacterial activity, the chemical products of decay and so forth, yet there has been little if any laboratory work that would substantiate their claims. In this regard, the work of Watabe and Wilbur (1960) appears to be of especial importance. As previously mentioned, they were able to show that a substrate of organic material not only could determine the form in which calcium carbonate was deposited but could actually cause nucleation and crystal growth to take place. In the writer's opinion, these may be the very factors that could connect the organic coatings and the process of oolitization. Where the organic coating was present, crystal growth would take place on or within that coating, where the coating was absent no oolitization would be possible.

CHAPTER 4

Petrography of the Abu Dhabi-Al Bahrani Oolites

The oolites of the Abu Dhabi-Al Bahrani delta are composed of a nuclear grain with a coating of aragonite and gelatinous organic matter. In thin section the oolite coating is seen to have concentric laminations, bands and patches without laminations, algal colonies enclosed within it and perforations that extend down from it's surface. These and other features make up the fabric of the oolite coating and their characteristics, inter-relationships and origins form the subject of this chapter.

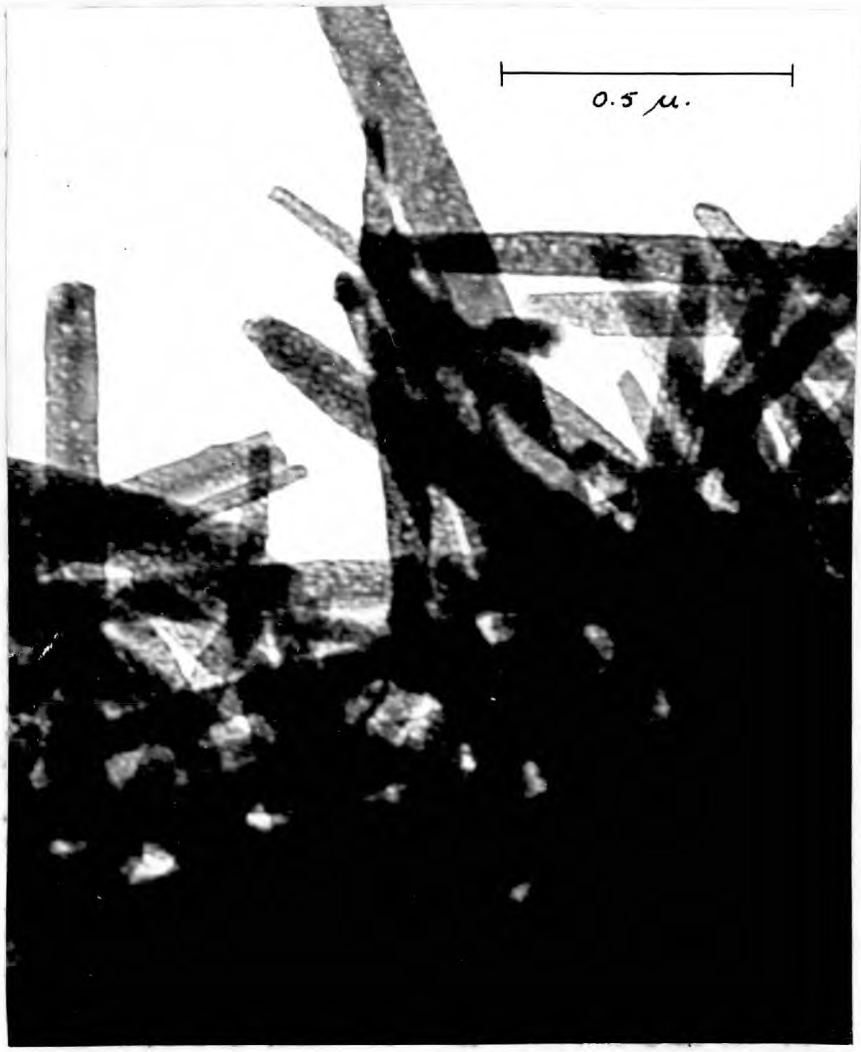
Form of the Aragonite (Plate 6)

The aragonite crystals in the oolite coating cannot be clearly seen with a petrographic microscope. This is partly because of the of the extremely small size of the crystals. Measurements made from electronmicrographs of chips spalled are 1-2 microns (.001 to .002 mm.) in length and about 0.2 microns (.0002 mm.) in width. The aragonite crystals are distinctly lathlike in appearance. Attempts to determine the optic orientation of the crystals with respect to theirelongation were unsuccessful. Due to the arrangement of it's lattice, aragonite tends to occur in the form of slightly elongate prisms whose prism faces are parallel to the c-optic axis. As pointed out by Bunn (1948, p.42), elongate forms are emphasized by rapid growth. It seems safe to assume that the small size and needle-like form of the aragonite crystals in the oolite coating are indicative of rapid growth and that the direction of elongation is parallel to the c-optic axis.

Plate 6

Electronmicrograph

The picture shows the aragonite crystals at the edge of a fragment spalled off the surface of an oolite. The orientation of the long axis of the crystals with respect to the oolite nucleus is tangential.


0.5 μ.

Characteristics of the Oolite Coating

Thin section examination of the oolites reveals that the coating is made up of two distinctive fabric types that occur either singly or in combination. One, which shall be called the oriented fabric, has fine laminations concentric to the oolite nucleus. Between crossed nicols, this fabric exhibits unit extinction parallel to the planes of polarization and when the fabric is continuous around the nucleus, a pseudo-uniaxial black cross is produced. The orientation of the aragonite crystals in this fabric appears to be that they have their long axis parallel to the surfaces of lamination. The other fabric is called the unoriented fabric. It exhibits random extinction under crossed nicols. It's constituent crystals appear to have no preferred orientation. This fabric possesses no internal laminations. Newell, Purdy and Imbrie (1960) have described similar fabric types found in Bahaman oolites as oriented aragonite lamellae and unoriented cryptocrystalline aragonite.

In thin section the oriented fabric appears slightly brownish in colour when observed using ordinary light. The lamellae belie their composite nature, in most cases appearing to be an almost textureless glass-like substance forming successive layers around the oolite nucleus. This somewhat deceptive appearance is almost certainly due to the presence of organic matter in the coating. Careful solution of the oolites releases some organic matter that has fine concentric laminations (see Plate_5_) on the scale of those observed in this section. There is little doubt that this material comes from the oriented portion of the oolite coating since the unoriented fabric exhibits no internal laminations whatsoever. The oriented fabric type of coating always forms the initial layers overlying the oolite nuclei. Thus it is common for the smaller sizes of oolite to have their entire coating of the oriented fabric type. Continuity of the lamallae is typical for the oriented fabric except for the layers close to an irregularly shaped nuclei. It is characteristic of oolitic coating that the shape of the nuclei is further obscured with each successive layer of coating and as the irregularities are covered up, the layers become more continuous. An essential feature of the oriented type of coating is that it never developes in semi-enclosed spaces, such as pits or pores in the surface of a nuclei. Such features, where infilled, contain unoriented aragonite.

The unoriented fabric is slightly darker in colour than the oriented fabric, and also tends to be less transparent. The constituent crystals of the unoriented fabric can in some instances be seen in thin section. This would suggest that the constituent crystals of the unoriented fabric are larger than those in the oriented fabric and/or there is less organic matter obscuring the view. No laminations or other orderly structure is present in the unoriented fabric. A faint clotted texture is sometimes present but in most cases the fabric appears homogenous. It is safe to say that the unoriented fabric in the oolite coatings only occurs in combination with the oriented type of coating and rarely by itself. In all the thin sections examined, perhaps three or four oolites were found that possessed coatings made up entirely of the unoriented fabric type of material. The unoriented portions found in combination with the oriented type are none the less quantitatively important, and in fact, volumetrically, the unoriented fabric may be more important since it always occupies positions separated from the nucleus by a layer of the oriented fabric type.

Algae and the Oolite Coating

In thin section, algal colonies are readily apparent where they occupy pits in the oolite surface and where they extend downward from the surface in clusters of thread-like chains of cells that cut across the laminations of the coating. Oolites whose outer-most layer possesses an unoriented fabric often contain colonies of algae but these can only be seen when the aragonite of the coating is dissolved away. Careful solution of the thin section reveals that algae form a continuous ring occupying the same position as the outermost portion of the unoriented layer. Unoriented fabric layers deeper within the oolite coating do not appear to contain algal cells even though their texture is apparently the same as that of the outer layers from which algae are released. It may be that within the older layers, algal cells, though present originally, have decayed away or alternately have become less cohesive with time and are broken up and dispersed during solution of the carbonate.

It is of interest to note one possible effect that the presence of algal cells may have on the appearance of the oolite coating when it is viewed in thin section. The cell walls of the blue-green algae Entophysalis deusta are slightly anisotropic. Although there does not appear to be any development of small scale convolutions on the surface of fresh cells, it is possible that crinkling of the cell surface might be caused by dessication during thin sectioning. This crinkling, in combination with the slight birefringence of the wall material, could easily create the impression of small aragonite crystals when in fact, none were present. By itself, the effect would probably not be too important but if aragonite crystals were also there, the presence of the algae would not be readily apparent. Conversely, the crinkled algal material, like other organic matter in the coating, would serve to obscure the shape of the aragonite crystals.

The relationship between the soft-surfaced oolites and the blue-green algae has been discussed in a previous section. Thin section examination confirms the presence of algae within the outer layers of the oolites and suggests that oolites whose outermost layers are composed of a coating with an unoriented fabric would be classed as soft-surfaced oolites. To confirm this view, separate thin sections were made from selected hard and soft-surfaced oolites. It was found, not unexpectedly, that the hard-surfaced oolites had an outermost layer with an oriented fabric, sometimes extremely thin, and that the soft-surfaced oolites had outermost layers with an unoriented fabric.

Textural Relationships in the Oolite Coating

The textural relationships and the morphological characteristic of the fabrics that make up the oolite coating are best described with reference to the photomicrographs (Plates 7 to 12 inclusive). Each plate is preceded by a front sheet giving pertinent details of the petrography and a short discussion of the petrology. A summary discussion of the petrography follows at the end of this chapter.

Plate 7

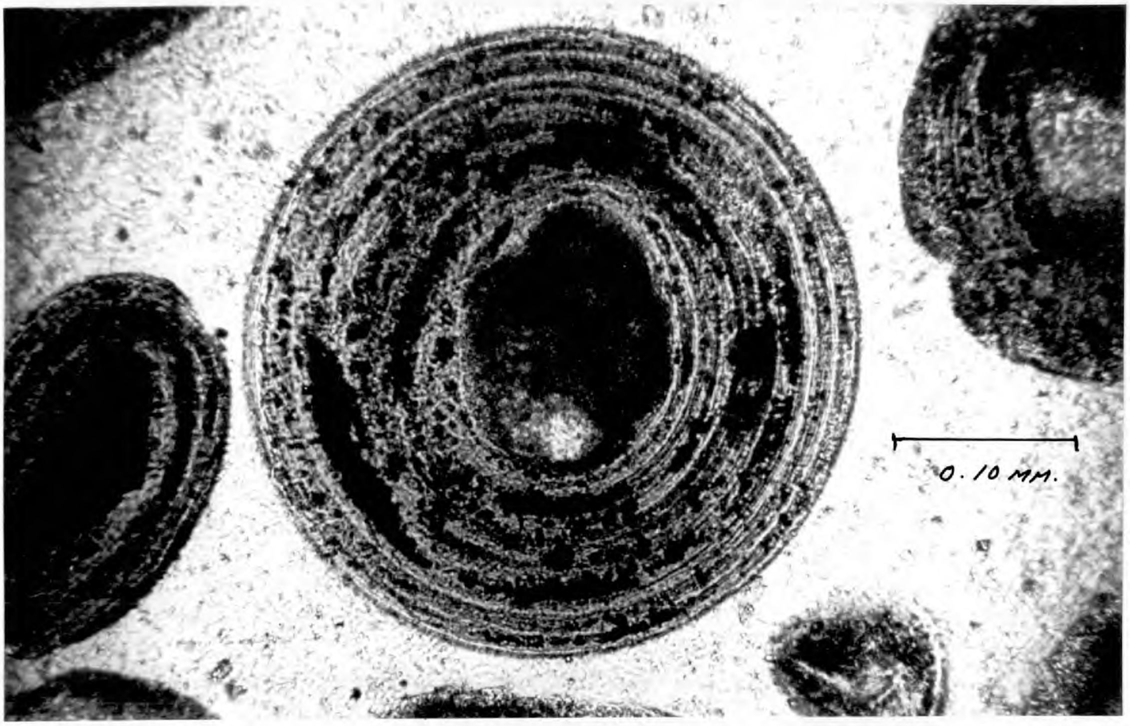
(Plain polarized light.)

Upper

Oolite with a quartz grain nucleus. Shows the fine laminations and typical degree of perfection achieved by the oriented fabric type of coating. There is almost always some portion of this type of coating in which the banding is replaced by dark, nearly opaque patches of organic(?) matter or small areas of unoriented fabric. The parallelism of the upper boundaries of the dark patches with respect to the laminations is typical.

Lower (Note; This is not a detail of the upper picture.)

Oriented fabric type of coating around a quartz(?) nuclei. Note that only a few laminae parallel the surface irregularities of the nuclei. The individual laminae are about 2 microns (0.002mm.) thick. Some of the bands exhibit a distinct "pinch and swell" texture. The segments of which have dark centres where the banding is coarsest. Pinch and swell texture and dark centres are typical of the organic matter shown in plates 4 and 5U. It is felt that the above similarities are sufficient proof of the importance of the organic matter as a contributor to the texture of the oriented type of fabric.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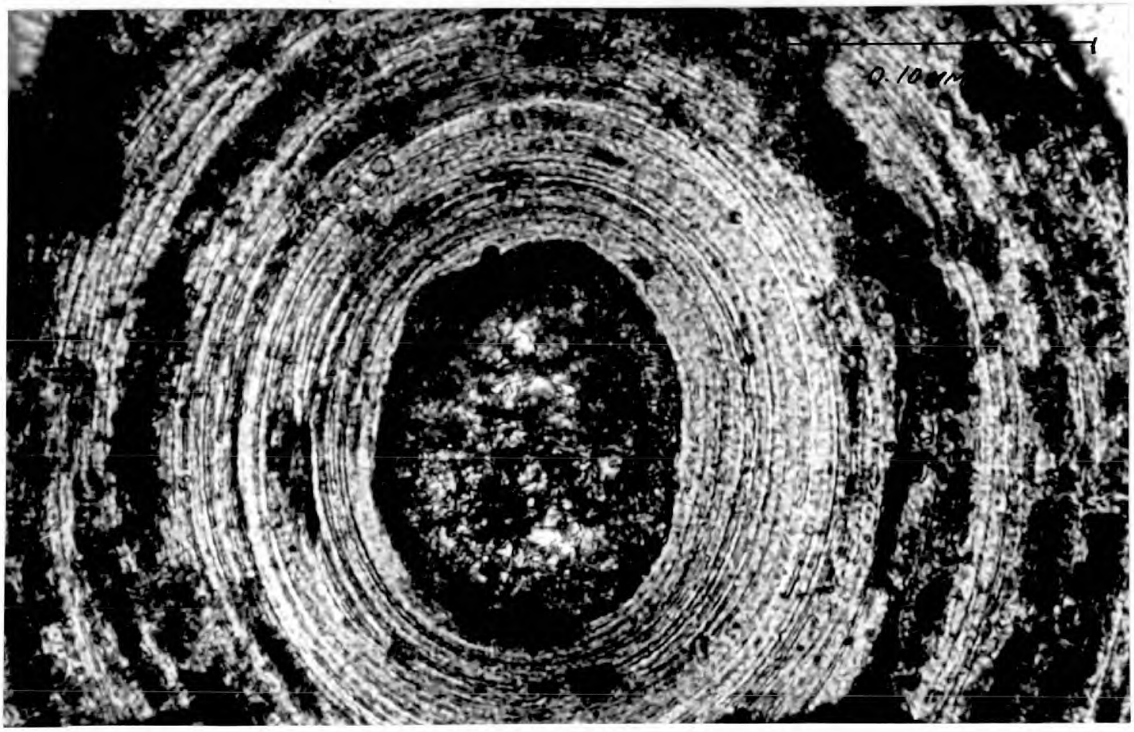
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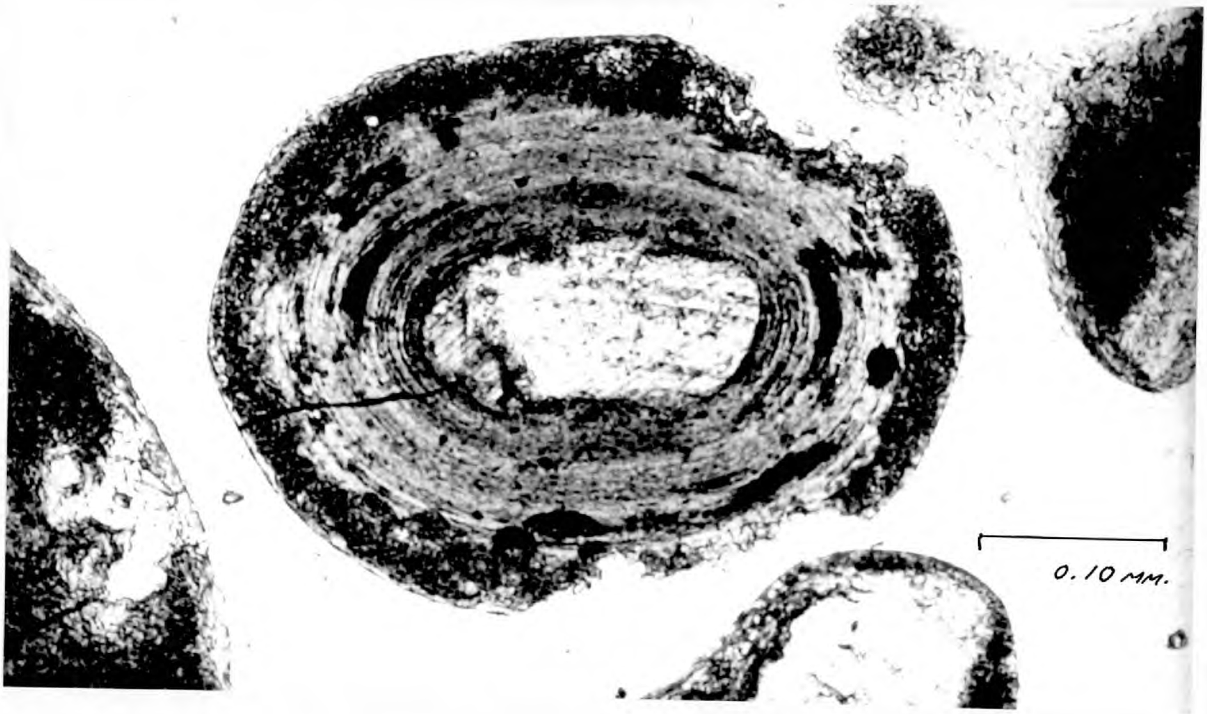
Plate 8

Upper (Plain polarized light.)

Oolite whose outermost layer is of the unoriented fabric type. Profile of the grain is typical of those bored by algae. The unoriented fabric material has a somewhat vermicular texture that is suggestive of included algae. Note also the small circular objects with dark centres that form part of the coating. Like the patches of unoriented fabric shown in Plate 7, the outer layer has a smooth outer surface and an irregular inner surface that cuts across the laminations.

Lower (Crossed Nicols.)

Outer unoriented layer of an oolite similar to that shown in the picture above. The dark area at the bottom of the picture is an oriented fabric layer that has gone into extinction. The outer layer shows random extinction. The pit on the right is an algal boring. Note the similarity between it's curvature and that of the lobes in the boundary between the unoriented and oriented fabric layers. One interpretation would be that the unoriented fabric formed by infilling of a succession of algal borings that penetrated and destroyed the laminated substrate. The generally spotty extinction of the unoriented fabric layer suggests that abundant organic matter may be present.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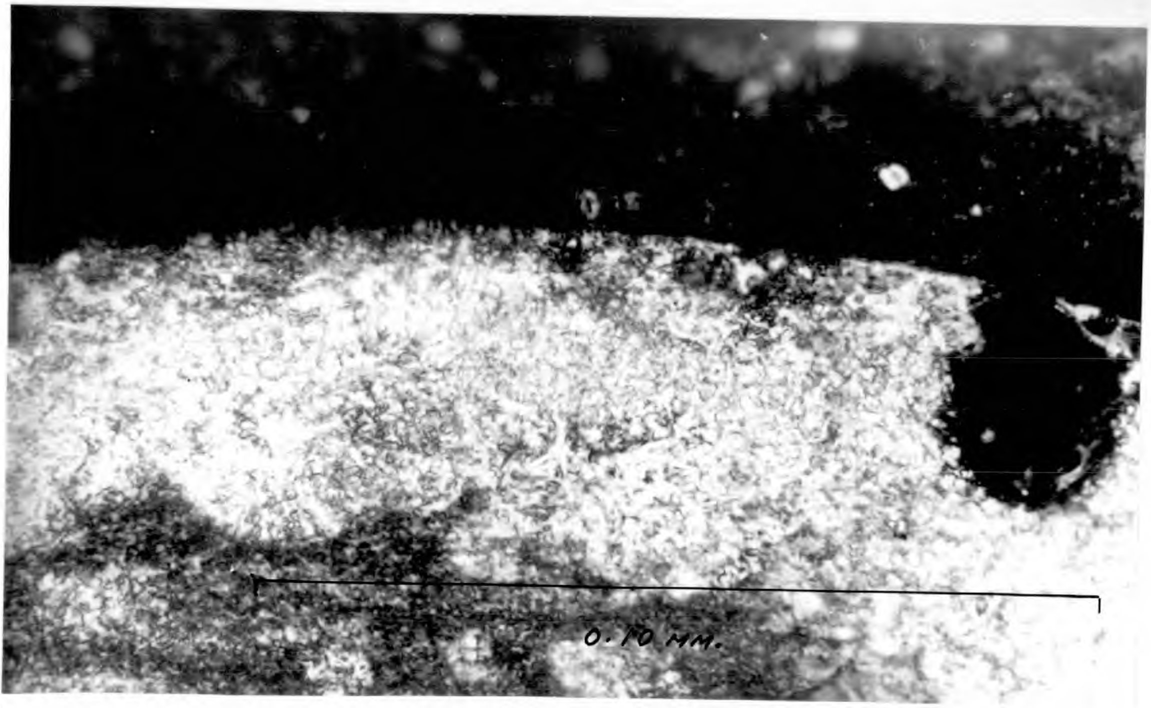
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Plate 9

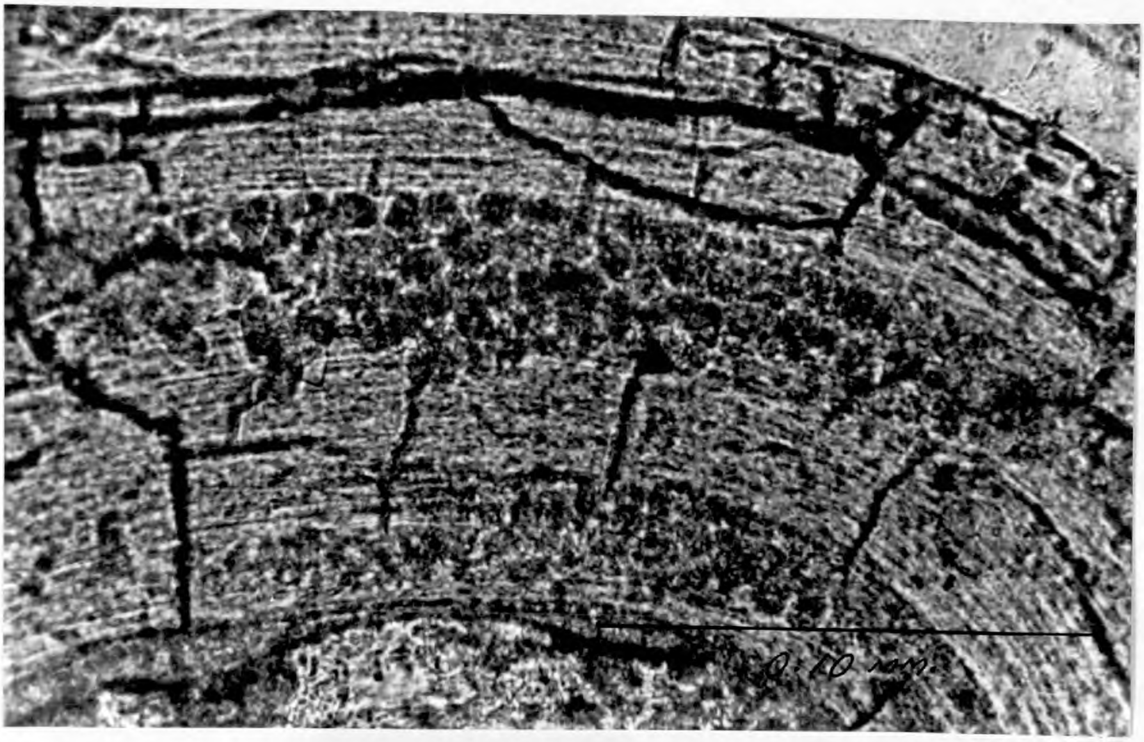
(Plain polarized light.)

Upper

Dark lines parallel and perpendicular to the laminations are cracks in the thin section. Median layer of unoriented fabric type exhibits a reticular texture that outlines roughly circular areas whose size and arrangement are practically identical to that of the algal colony shown in Plate 5 (lower). The unoriented area also shows the typical smooth upper and lobate lower surfaces. Almost certainly these are the remains of an algal colony now largely replaced by aragonite.

Lower

This oolite shows two distinct sequences of generation marked by a colour difference. The inner and darker coloured phase deposited an oriented fabric type of coating whose outer boundary is marked by the emplacement of patches of the unoriented type of fabric. The outer phase shows a similar sequence but with greater areas of unoriented fabric coating. A third, outermost, laminated layer is also apparent. The unoriented fabric layers in each case have a cross-cutting relationship with the underlying laminated layers.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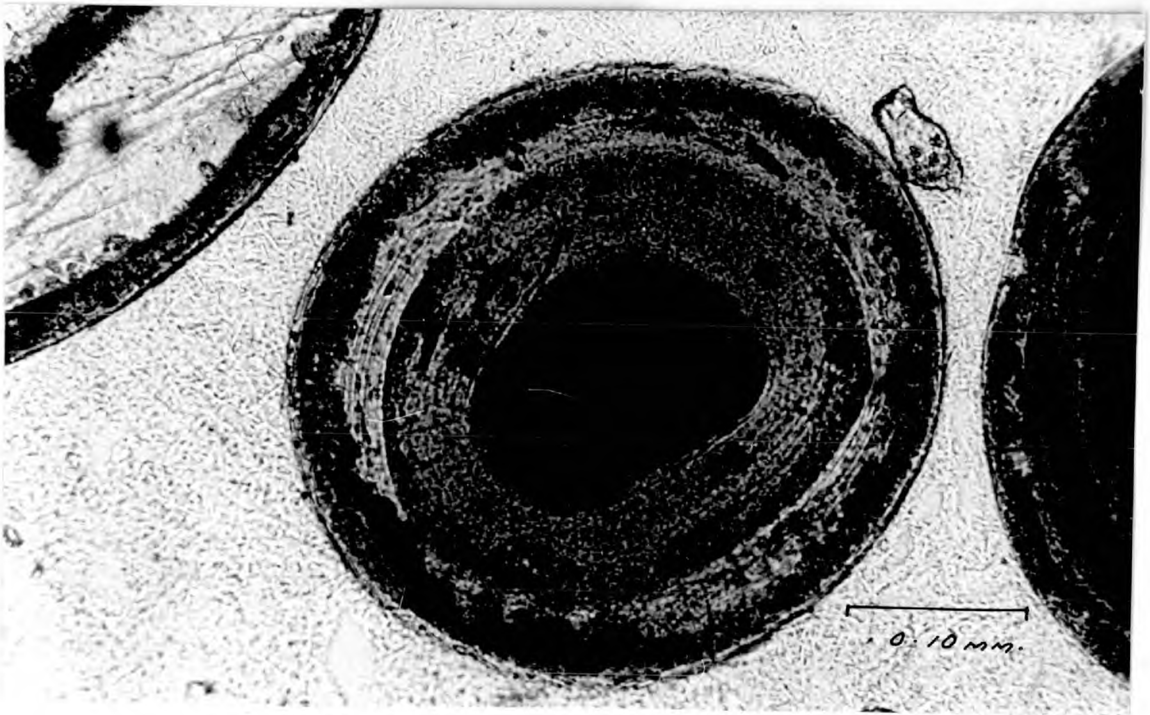
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Plate 10

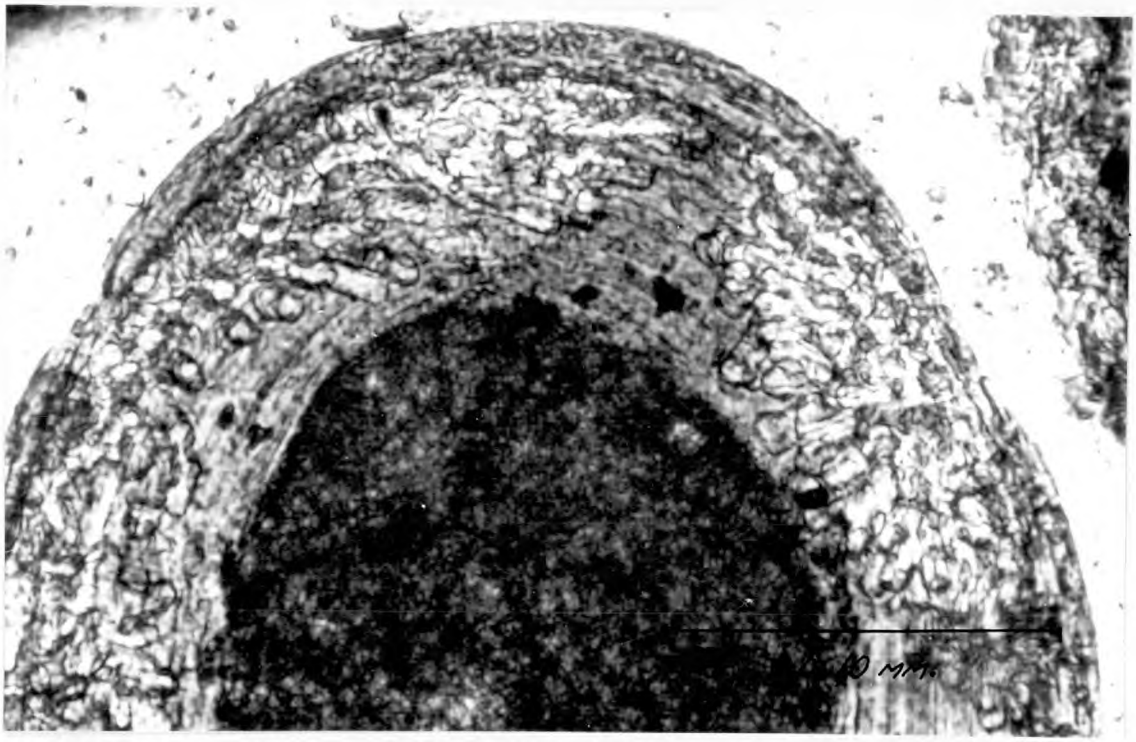
Upper (Plain polarized light.)

Oolite with a dark coloured pellet nucleus and an oriented fabric coating. The oolite coating contains two colonies of boring algae whose perforating threads radiate out from slight depressions near the surface of the grain. The upper surfaces of the colonies lie along a sharply delimited common boundary and in places the laminated coating has been destroyed down to the edge of the nucleus. The algal colonies appear to have maintained a connection with the outside through small windows in the laminated coating that overlies them. Note that the external outline of algal colonies is precisely that of the unoriented fabric areas observed in the previous plates.

Lower (Crossed Nicols.)

Detail of the right hand colony is upper picture. The algal cells show up as vaguely luminous bodies of no apparent textural complexity. They appear to be slightly anisotropic, however, part of their appearance may be due to the cells acting as lenses. Since the algal colony is a hemispherical aggregate convex toward the nucleus, it is likely that the optical effects observed are entirely due to the algae and not to layers of carbonate lying beneath them in the plane of the thin section.

Pl 10



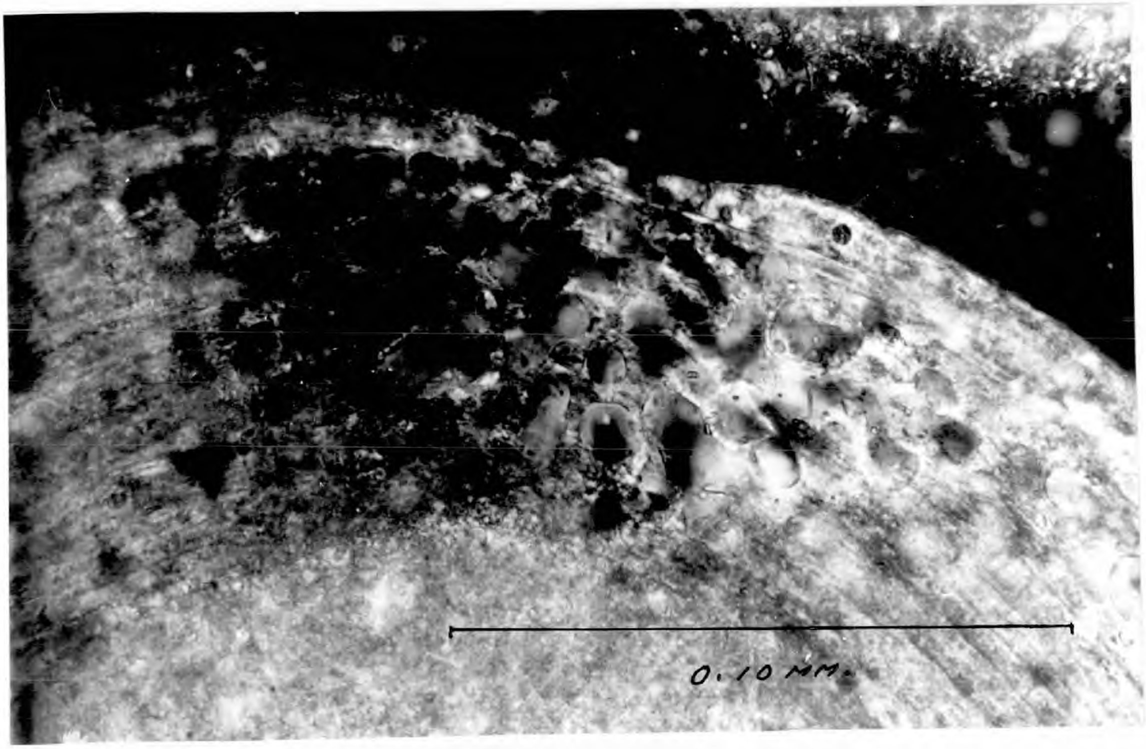


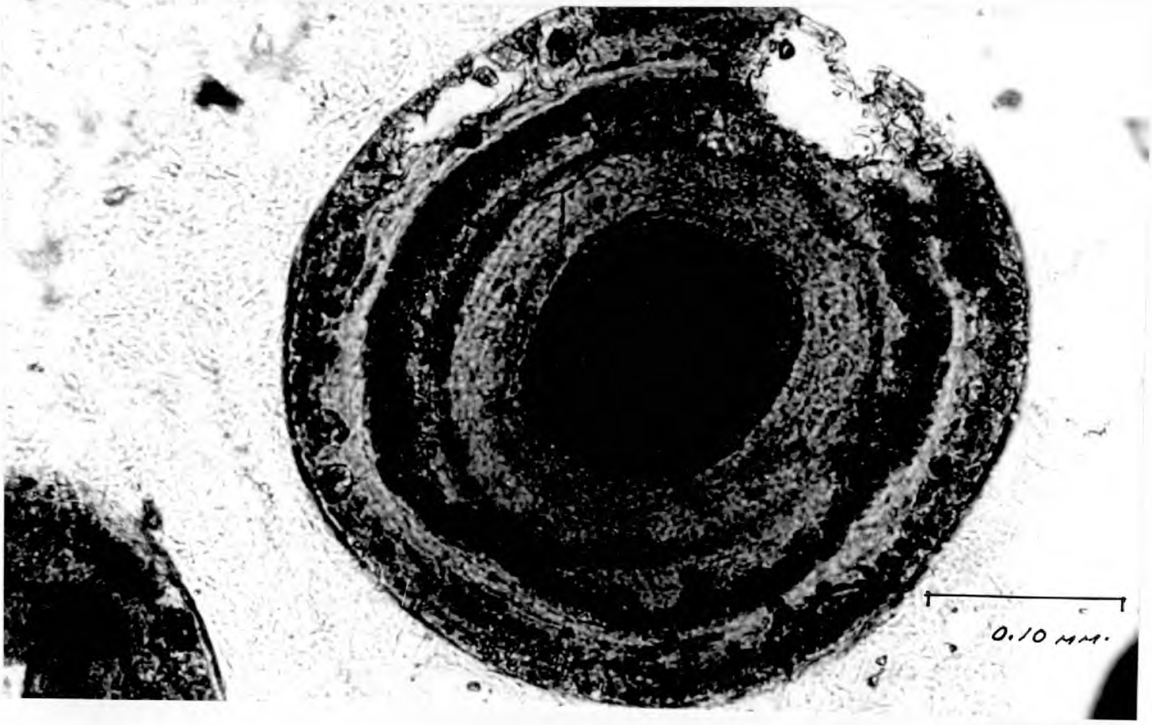
Plate 11

Upper (Plain polarized light.)

Oolite with a dark coloured pellet nucleus. Coating is principally of the oriented fabric type. A relatively narrow band of the unoriented fabric type occupies a middle position in the coating. It shows the typical smooth upper and lobate lower boundaries. The outer oriented fabric layer has numerous circular and elongate cellular patches of included algae.

Lower (Crossed Nicols.)

Detail of upper picture. The inner and outer oriented fabric layers are in extinction along a vertical zone. Clusters of algal cells extend into the unoriented fabric layer from the base of the pit at the right hand side of the picture. The smooth upper boundary of the colony suggest that the algae emplaced themselves before the outer oriented fabric layer was laid down. The layer of unoriented fabric material possesses a vaguely cellular texture of a size scale similar to that of the algal colony.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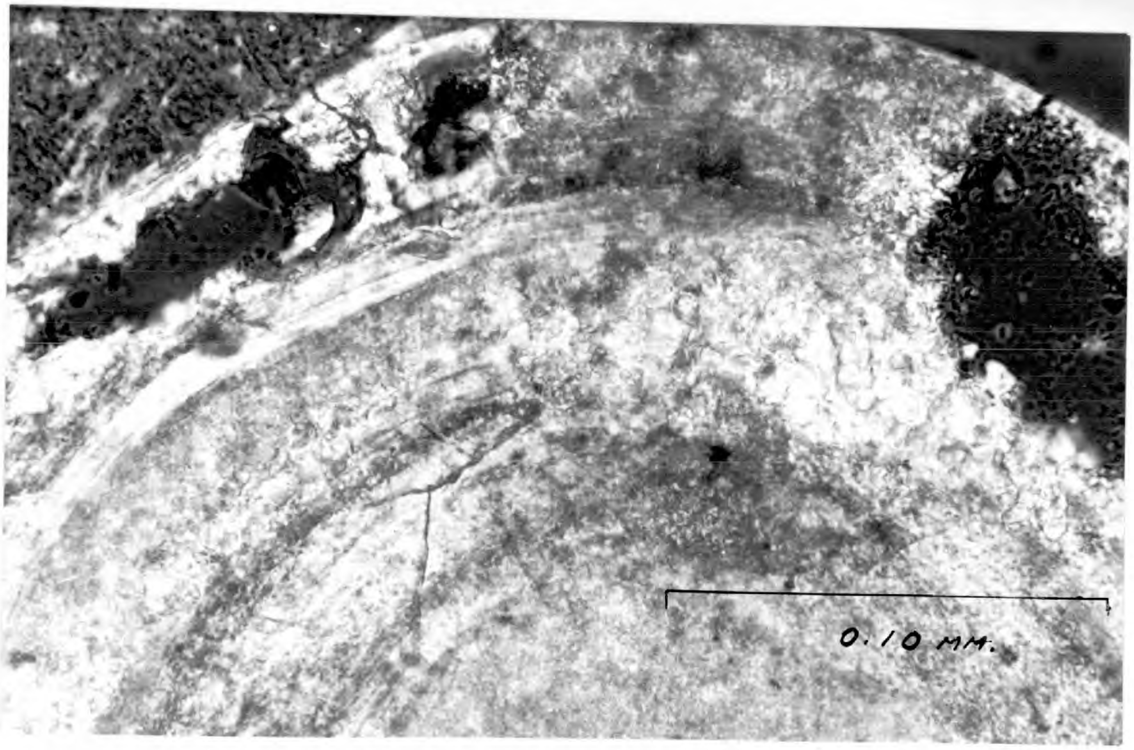
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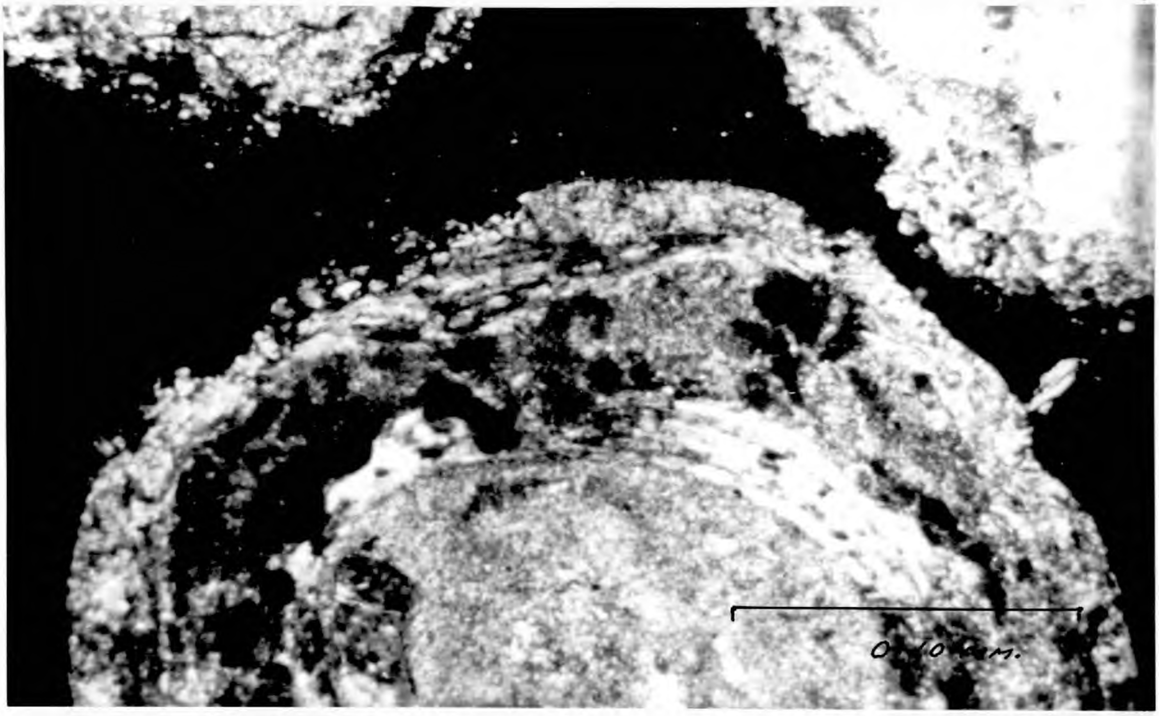
Plate 12

Upper (Crossed Nicols)

In this oolite there is an innermost layer of oriented fabric material whose laminations parallel the curvature of the pellet nuclei. This layer is irregularly developed around the nuclei and appears to have suffered extensive boring by algae. The overlying layer of unoriented fabric coating contains numerous dark patches which are probably algal cells. The laminated portion of the outermost layer does not show any parallelism with the nuclei but rather appears to follow the contours of a new surface that probably developed after intense algal infestation.

Lower (Plain polarized light.)

When an extremely thin thin-section is made of grains which have included algal colonies, only the cell walls remain as evidence of algal infestation. The cell walls appear as a reticulate network of fairly uniform thickness surrounding roughly spherical spaces of widely varying diameters. Note that the thickness of of the cell walls is about the same as that of the individual laminations in the oriented fabric coating of the oolites.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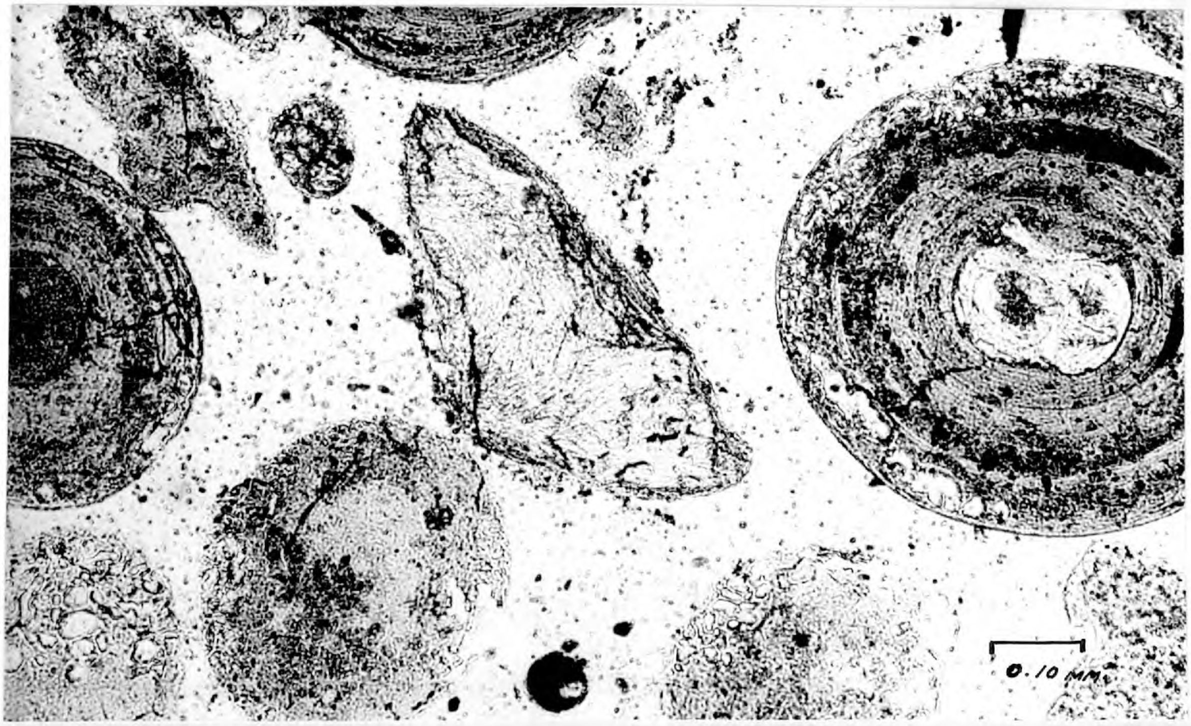
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Summary Discussion

The aragonite component of the oolitic coating consists of extremely minute lath-like crystals that are practically irresolvable with an optical microscope. As implied, these crystals are only part of the coating, the remainder being made up of organic matter of indeterminate origin. Included within the coating are living algal cells occupying pits and burrows of their own making and remnants of algal colonies and individuals that lived during earlier phases of grain growth. The gross fabric of the oolite coating consists in most instances of fine concentrically laminated (oriented fabric) material that contains patches and/or layers of non-laminated (unoriented fabric) material.

The oriented fabric portion of the coating has laminae that are about 2 microns (.002mm.) thick. The individual laminae form continuous layers when they are not interrupted by patches of unoriented fabric material or algal borings. In many instances, slow solution of oolites, releases a laminated organic pseudomorph whose laminations are of the same thickness and character as those observed in the oriented fabric type of coating. There is little doubt that this organic matter is an integral part of the oriented fabric type of coating, however, the precise physical relationship between the organic matter and the aragonite portion of the coating is readily not apparent in thin section. Some of the laminae appear to possess characteristics close to those of the fragments of organic matter released from the surface of the oolites, whereas other laminae do not. As a tentative hypothesis it is suggested that the oriented fabric coating is made up of layers of gelatinous organic matter and layers of aragonite crystals whose long axis are parallel to the plane of the laminations.

Furthermore, that the succession begins with a layer of organic matter. In support of this hypothesis is the observed fact that nearly all grains on the delta and inner shelf have a gelatinous organic coating, whereas not all have an oolitic coating. One may therefore logically conclude that the oolite nuclei would have been coated with organic matter before any aragonite crystals were laid down on their surface. It is of interest and importance to note the observed, but not illustrated, fact that the coating in juxtaposition with the nucleus of an oolite is always of the laminated oriented fabric type.

The most characteristic feature of the unoriented fabric portions of the oolite coating, aside from their lack of laminations, is the consistent physical relationship exhibited by their boundaries with respect to the enclosing laminated material. The lower boundary of an unoriented fabric patch or layer is always a lobate or simple curved surface that cuts across the laminations of the oriented fabric substrate. The upper boundary of the unoriented fabric layer is parallel to the overlying laminations and exhibits no truncation of the laminations. Similarly, where unoriented fabric material forms part or all of the outermost layer of the coating, it's lower surface is lobate and it's upper surface is parallel to the surface of the grain.

Associated with the unoriented fabric material, particularly where it occurs at or near the surface of the oolite, are algal colonies and single algal cells. These are often so intimately a part of the fabric that they are only detectable when the aragonite of the coating has been dissolved away. Occasionally, the presence of algal remains implied by the presence of a faint reticulate texture in the unoriented material. The implication that algae are involved in the creation of the unoriented fabric is strengthened by the similarity between the shape of live algal colonies that have bored into laminated layers at the surface of the grains and that of the patches and layers made up of unoriented fabric material. This similarity includes the fact that the lobes of the lower boundary of unoriented patches have curvatures that are practically identical to that of the distal cells of the observed perforating algae.

In the Recent oolites of the Bahama banks, the origin of the unoriented fabric portions of the oolite coating has been given a variety of explanations. Illing (1954) suggested that an unoriented fabric was produced by recrystallization of oriented fabric material, the change being aided by the presence of bacteria. Purdy (1963A,1963B), stated that recrystallization was responsible for textural changes observed in skeletal carbonate grains and he deduced that the same process was responsible for the unoriented fabric layers in oolites. Purdy felt that recrystallization was a reaction of the aragonite crystals to waters with below normal supersaturations. Illing and Purdy both noted that the process is often confined to the oolite surface. Newell, Purdy and Imbrie (1960) pointed out the two main types of internal relationship between the oriented and unoriented fabrics. The small blebs that transect the oriented layers and the intercalated layers and lenses. The first they considered to be the product of recrystallization induced by the presence of decaying boring algae. The second, as the result of the crystallization of aragonite within adhering organic detritus attached to the oolite surface during periods of little water agitation. Sugden (1963) in a study of some sediments of the Arabian (Persian) Gulf, found oolites with unoriented fabric outer jackets in the intertidal zone. He concluded that the unoriented fabric material was added by evaporation-induced precipitation when the sediments were exposed at low tide.

The prevailing opinion with regard to the origin of the unoriented fabric patches and layers found within the coatings of Recent Bahaman oolites is that they are the product of some sort of recrystallization process that acts to transform the character of the laminated oriented fabric material. It is assumed that by recrystallization, the above mentioned authors refer to a process which involves solution and reprecipitation without any addition of material. Petrographic and other evidence strongly suggest that in the case of the Abu Dhabi-Al Bahrani oolites, the unoriented fabric portions of the oolite coating are primary features whose origins are closely related to phases of infestation of the grain surface by perforating blue-green algae.

The sequence of events in the formation of the unoriented fabric material of the coating appears to be as follows.

1. The initial layers that surround the oolite nuclei are always of the oriented fabric type of material. This type of coating appears to form in a highly agitated environment. Algal infestation is minimal. In fact algae, particularly in colonial form, and the laminated oriented fabric type of coating are practically mutually exclusive.
2. When an oolite grain moves into a quiet water environment it

becomes infested by perforating blue-green algae. The degree of infestation varies from a few colonies in scattered pits to almost total destruction of the original surface by numerous active colonies. The activities of the perforating algae produce characteristically shaped pits in the oriented fabric substrate. Laterally extensive boring produces an irregular surface that is lobate (convex toward the nuclei) in section.

3. During the stage of active perforation (carbonate dissolving phase) the algal colonies are unfavourable sites for carbonate deposition. Once a colony has ceased to be active or died, carbonate can be deposited on the surfaces of the cells and in the spaces between the cells. At a later stage the cells become breached by decay and infilled with carbonate.
4. The return of the grain to an agitated environment leads to the development of a skin of gelatinous organic matter over the new calcified algal colonies and the further deposition of oriented fabric material.

The sequence of events given above presents a very much simplified version of how the unoriented portions of the oolite coating develops. One aspect which may have important effects is the possibility of re-boring of previously developed unoriented fabric layers. Another unspecified problem concerns the implication that carbonate precipitation is taking place in the quiet water environment. It is the writer's belief that favourable conditions for precipitation probably exist at many spots on the delta. The significant distinction is not so much between areas of precipitation or non-precipitation but between areas where an oriented fabric coating develops and where this coating is partially destroyed by perforating algae that are themselves ultimately calcified to form the unoriented fabric patches and layers. It is interesting to note that the type of fabric that develops may be correlated to the form of the organic matter that is present. Where a thin even skin of gelatinous organic matter forms the substrate the evenly laminated oriented fabric develops. Where the substrate consists of an irregular mass of algal cells and algal mucilage an unoriented fabric type of material is produced.

As previously mentioned in the section on the surface luster of the oolites (see page 76 on), it is the writer's belief that the high degree of surface luster of some oolites is not necessarily due to polishing by abrasion. It seems rather more likely that the thin skin of organic matter, which characteristically coats nearly all grains in the environment, acts like a coat of varnish to make the oolite grains shiny.

CHAPTER 5

Grain Size Analysis and Interpretation

The Abu Dhabi-Al Bahrani delta has been described in terms of its physical shape, topographic characteristics, bathymetry, and hydraulic regime. In addition, the nature of the sediments of which the delta is composed has been examined in some detail. The purpose of this chapter is to describe the delta in terms of the size characteristics of its sediments and to attempt to integrate these findings into the already established physical and petrographic framework.

The oolite grains account for the bulk of the sediment making up the delta and it is evident that they are the product of a process that is indigenous to the nearshore area between the islands of Abu Dhabi and Al Bahrani. Because of this fact we are confronted with two separate but related problems when interpreting the grain size characteristics of the sediments. Firstly, there is the problem of the significance of the various kinds of grain size distributions as indicators of the effects caused by the movement of water on the delta. Secondly, there is the problem of determining to what extent the process of oolitization is per se responsible for the grain size characteristics that are possessed by the oolite sediments. The nature of the difficulties encountered and the inter-relationship between the two problems is well illustrated by the following example. Miller and Zeigler (1958) have demonstrated that in an area of shoaling waves, the size properties of the sediment grains at any specific location are that of an equilibrium population, stable with respect to the supply of sediment and the forces (currents, gravity) that act upon it. In the case of the oolites however, it is probable that oolitization masks this effect to some extent since the potential nuclei that are stable within the zone of oolitization become coated in situ and thus exceed the size requirements of an equilibrium population for that location. Progressive shoreward changes in the size properties of the delta sediments undoubtedly reflect both hydraulic and growth conditions. The writer has attempted to provide an interpretation which recognizes both factors. Nonetheless, there is probably no unique solution to this problem.

Method

The sediments of the delta are ideally suited to grain size analysis by mechanical sieving. With the exception of irregularly shaped skeletal fragments practically all the grains present are either spheroidal or equidimensional. This fact eliminates the interpretive problems that arise when elongate grains (smallest "diameter" the same as diameter of a spherical grain but mass greater) are present in quantity. Furthermore, the delta sediments contain only neglible amounts of material finer than coarse silt (0.05 mm.), thus virtually all the grains present can be handled efficiently by the sieving process.

Subsequent to the sieving of the delta sediments it was discovered that certain of the samples contained up to 15% by weight of grains coarser than the coarsest sieve used (2.057 mm.). The presence of this material caused a mode to appear in the grain size distributions of these samples that was an artifact produced by not having any sieves coarser than 2.057 mm., which sieves, if present, would have separated the grains into a number of fractions. Fortunately, this deficiency in the range of sieve sizes used, affected only a few of the 76 samples sieved.

Preparation of Samples

Each sample was washed on a B.S.240 sieve (aperture size 0.066mm.) held over a 1 litre glass container. If the wash water was cloudy, a small portion was decanted into a test tube and a few drops of dilute hydrochloric acid added. The suspended material was found to consist of impalpable particles of calcium carbonate and in all cases the amount of material, both carbonate and non-carbonate, passed by the sieve insignificantly. The washed samples were dried at 80°C. for four hours, allowed to cool for about 12 hours, then split off into 30-35 gm. lots for sieving.

Sieving Procedure

The sample splits were sieved through a series of British Standard sieves covering the size range from -1.00 to +4.00 phi (aperture sizes from 2.057mm. to 0.066mm.), and spaced at 1/4 phi intervals. Because a new set of sieves was used, the writer did not check the calibration of the screens. Examination of the sieving results did not reveal any anomalies which could be attributed to errors in calibration. To accomodate the large number of sieves required to cover the selected size range, it was necessary to run the samples through three separate series arranged as follows:-

1st series			2nd series			3rd series		
sieve no.	aperture		sieve no.	aperture		sieve no.	aperture	
	phi	mm.		phi	mm.		phi	mm.
8	-1.04	2.057	25	+0.74	0.599	72	+2.24	0.211
10	-0.75	1.676	30	+1.00	0.500	85	+2.49	0.178
12	-0.49	1.405	36	+1.24	0.422	100	+2.72	0.152
14	-0.27	1.204	44	+1.50	0.353	120	+3.01	0.124
18	0.00	1.003	52	+1.76	0.295	150	+3.26	0.104
22	+0.23	0.853	60	+1.99	0.251	170	+3.49	0.089
pan			spacer			200	+3.71	0.076
			pan			240	+3.91	0.066
						pan		

Each sample was sieved for a total of 10 minutes in each series. Check runs, with sieving times of up to 30 minutes per series, showed that there was no particular advantage in extending the sieving time beyond 10 minutes. It was found however, that the last sieve in the second series could not drain effectively unless a spacer was placed between it and the underlying pan. This was due to the fact that the bulk of the sediments analyzed consisted of grains that would pass into the third series and as a result the pan of the preceeding sieve set was commonly overloaded.

The weight of sediment retained on each sieve was weighed to an accuracy of 0.001 gm. Sieving losses were found to amount to less than 1% in all cases. The weight percentages retained in each sieve fraction were calculated from the total weight retained (see Appendix 1 for the tabulation of results). In the discussions and illustrations that follow, the phi values of the British Standard sieves are rounded out to the nearest whole quarter phi value. For convenience, all grain size fractions are referred to the diameter of the aperture of the sieve on which the grains were collected. For example, grains stated to have a diameter of 1.50 phi, were caught on the 1.50 phi sieve and have true diameters less than 1.25 phi and greater than 1.50 phi.

Results of Sieve Analysis

The simplest means of classifying grain size distributions is in terms of the number of modal classes that they possess. This information can be obtained by an examination of the raw results once the weight percentages contained in each fraction have been calculated. Modal classes are usually defined as the size fractions that contain a larger percentage by weight than those on either side of it in the sequence. Modal classes in the grain size distributions of the delta sediments occur at almost every size fraction over the range of sizes sieved, however some of these are very minor and contain less than 1 weight percent of the total distribution. Modal classes such as these are clearly insignificant since they can be produced by errors inherent in the sieving process. In this study an arbitrary cut-off point of 2 weight percent was used to define the significant modal classes.

The grain size distributions of the samples analysed have been divided into three categories according to the number of modal classes they possess. These categories are: unimodal with one modal class, bimodal with two and polymodal with more than two modal classes. Of the samples sieved, about 65% were found to have unimodal distributions, 25% have bimodal distributions and 10% are polymodal. Figure 13 shows the location of the various sample stations on the delta and the number of modes possessed by the grain size distribution of each of the samples sieved.

The basic framework, within which we shall conduct our statistical analysis and interpretation, is readily apparent in the above

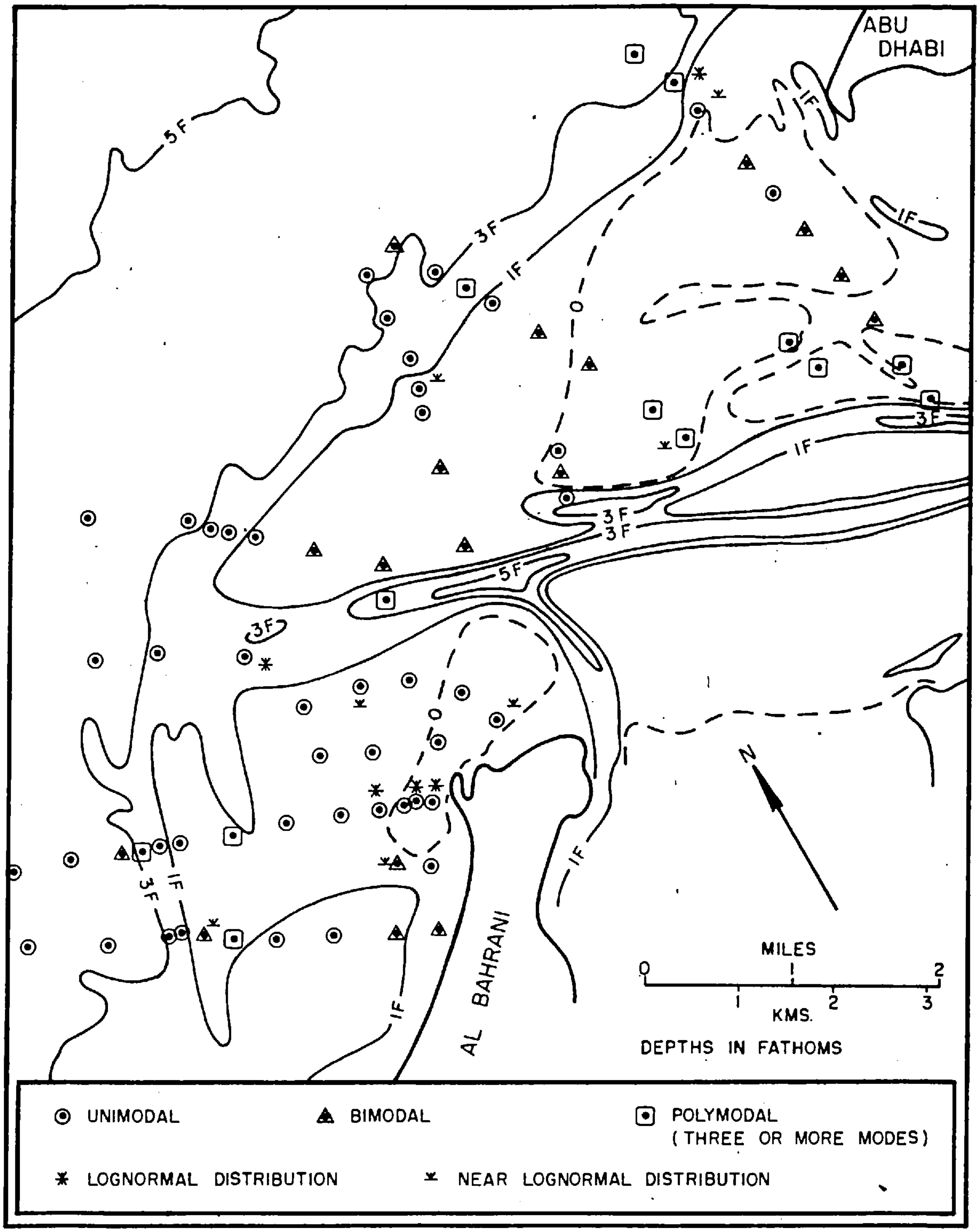


Fig. 13. MAP SHOWING LOCATION OF SEDIMENTS WITH UNIMODAL, BIMODAL AND POLYMODAL GRAIN SIZE DISTRIBUTIONS ON THE ABU DHABI - AL BAHRANI DELTA.

illustration. The delta slope and seawards is characterized by unimodal sediments except at the end nearest Abu Dhabi island where the grain size distributions are dominantly polymodal. It is worth noting that the increasing oolite content as one passes from the inner shelf, up the delta slope, to just inside the one fathom contour has no effect on the number of modes possessed by the grain size distributions of the various samples. The delta top in the Abu Dhabi section is characterized by oolite sediments with bimodal grain size distributions and in this respect shows a marked contrast to the sediments of a similar composition that lie to seawards. As might be expected, the coral rich sediments close to the reefs of the southeast corner of the Abu Dhabi section have polymodal grain size distributions. Note that the sample taken from the deep part of the axial channel where the sediment is a coarse lag deposit composed principally of coral debris, also has a polymodal grain size distribution.

The typical grain size distribution of the sediments on the Al Bahrani delta top is unimodal. Sediments with bimodal distributions are not nearly as widespread as was found to be the case on the Abu Dhabi delta top. Although the two sections of the delta are compositionally very similar, the grain size analysis results suggest that a sedimentological difference exists.

Statistical Analysis

In this study, four grain size parameters were determined for each of the samples sieved. These are mean size, which is a measure of overall average size; standard deviation which is a measure of sorting; skewness (or assymetry) and kurtosis (or peakedness) which serve to indicate whether the distribution is log normal viz. the results of the analysis when plotted on a logarithmic size scale would form a symmetrical Gaussian or normal probability curve.

It is evident from an examination of the raw sieving results that many of the delta sediments have non-normal grain size distributions since normality can only be possessed by those that are unimodal. McCammon (1962) in a study of the effeciency of percentile measures for describing the mean size and sorting of sedimentary particles considered that the graphic method of Folk & Ward (1957) was the best presently available for dealing with non-normal distributions. Friedman (1962) also stated that Folk and Wards sorting measure provides the best correlation with the standard deviation when the distribution departs from lognormality. Considering the above facts and allowing for the possibility that many if not all of the unimodal distributions encountered might also be non-normal, it was felt that Folk and Wards method was a logical choice.

Statistical Measures of Folk & Ward (1957)

The sieving results of each sample were plotted on arithmetic probability paper cumulative frequency curves using the phi scale (Krumbein, 1938) for size. The equations for calculating, mean size, sorting, skewness, and kurtosis require the 5,16,25,50,75,84,95 phi percentiles. These are taken from the cumulative frequency curves and are accurate to two decimal places. Tabulated results of the computations and the cumulative frequency curves are included in Appendix 1.

General Comments

Plotting sieving results as cumulative frequency curves allows one to make graphic comparisons of the grain size distribution character of sediments from various parts of the area being analysed. By applying mathematical or graphical tests to the results of analysis it is possible to determine whether the distributions obey any of the statistical laws that appear to obtain in natural environments. In 1938, Krumbein suggested that clastic sediments obey the logarithmic form of the normal (Gaussian) law. Although this has been found to be the case in many instances, a great deal of controversy has gone on regarding the interpretation of sediments whose grain size distributions deviate from normality. Since normally distributed sediments must firstly have only one mode and secondly be essentially unskewed, it is obvious that sediments with two or more modes or high degrees of skewness require either a new law or an interpretation that explains how non-normal sediments are created. The most popular method has been to show how non-normality evolves due to the mixing together of separate normal populations. This school of thought is well represented in the work of Folk (see Folk and Ward, 1957). A different approach was taken by Doeglas (1946) and Inman (1949) who maintained that normal populations, under certain hydraulic conditions are depleted in certain size grades and as a result become non-normal in character.

What makes the problem especially difficult is our comparative ignorance with regard to the actual creation of normality in sediment distributions. The writer can offer no solution to this particular problem. The results of this study show that normal or near normally distributed sediments are present in the environment, however, this finding is only used to support the theory that non-normality results from mixing together of separate populations.

As a matter of interest, a plot was prepared (Figure 14) that shows which of the delta samples have grain size distributions that approach lognormality. The standard that was used is that of Folk and Ward (1957) where lognormal distributions are those which have a skewness between -0.1 phi and +0.1 phi and a kurtosis of from 0.90 phi to 1.11 phi. If all samples analysed are included, then it appears that using Folk and Ward's method, a few bimodal and polymodal sediments fall within the field of normality as they define it. Allowing that these anomalies are due to operator error or a fault inherent in the method, then it is evident that of the remaining samples relatively few are lognormal. Note that all the truly lognormal samples are confined to the Al Bahrani section of the delta. On the Abu Dhabi section, the samples which are closest to lognormal are all near the one fathom bathymetric contour. At first, it seems strange that the sediments from the high energy environment at the front of the Abu Dhabi section are not lognormal, whereas those from the quieter waters of the Al Bahrani delta top have achieved lognormality. The solution may be that the sediments on the Al Bahrani section have achieved nearly normal status before deposition and thus require little additional sorting to achieve normality.

Mathematically Derived Measures

The measures calculated by the method of Folk and Ward (1957) are mean size (Mz), sorting (σ_I), skewness (Sk_I) and kurtosis (K_g). These four parameters serve to describe in numerical terms, the grain size characteristics of each sample analyzed. It should be recognized however,

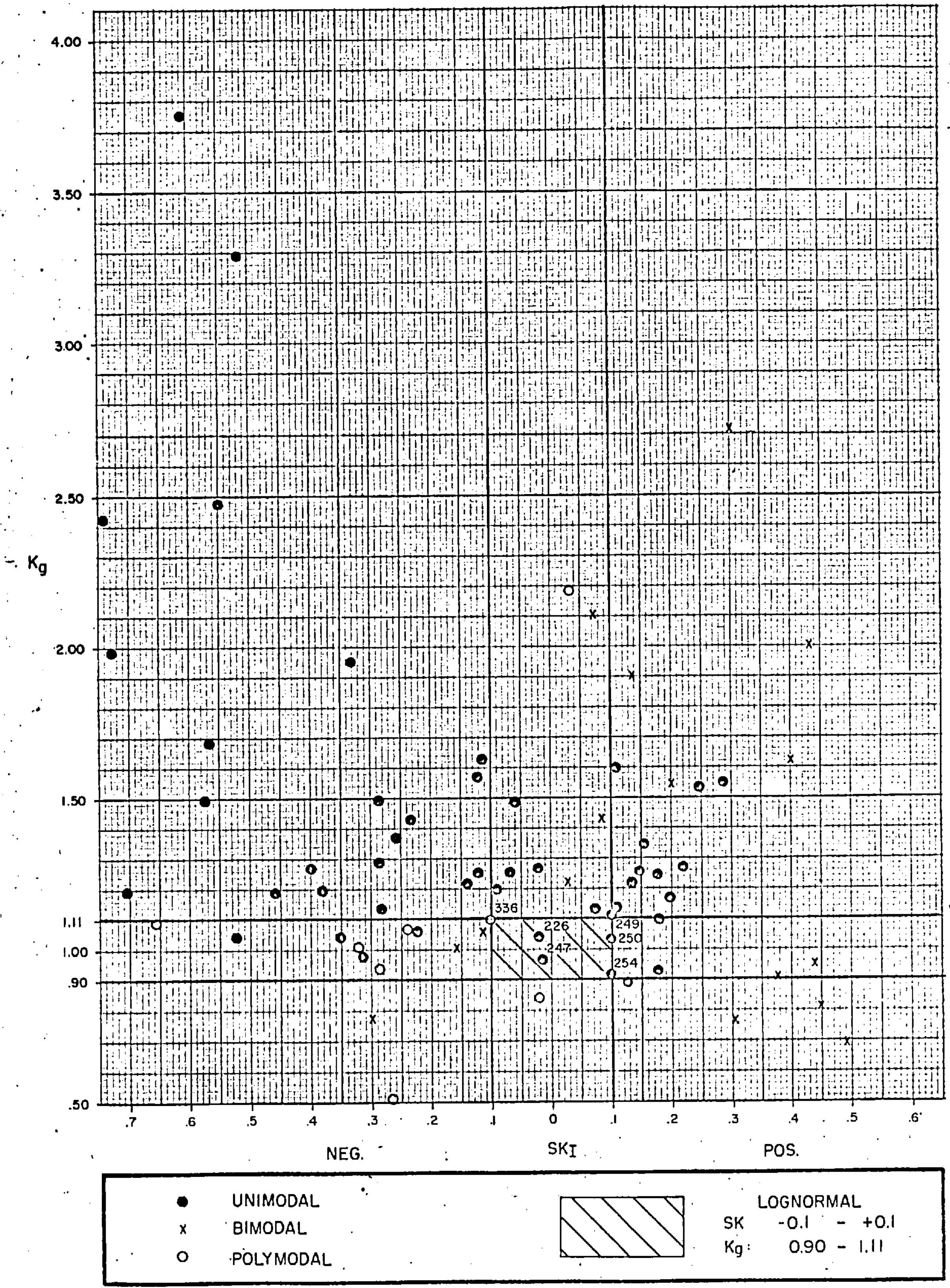


Fig. 14. CROSSPLOT OF SKEWNESS (SK_I) vs. KURTOSIS (K_g).

that to compare and contrast various samples they must all be unimodal. Sediments with bimodal or polymodal distributions cannot be so compared. In these sediments, mean size, sorting, skewness and kurtosis vary cyclically (Folk and Ward,1957) in such a way that sediments of entirely different character can have the same values. This is well illustrated by skewness, the measure of symmetry of the distribution. If one adds a new mode to a unimodal lognormal sediment then it's value of skewness will increase. However, when the new mode constitutes 50% of the sample the distribution will again be symmetrical (unskewed), Further addition of new material will cause the skewness to increase again up to the point where the new mode completely dominates and the distribution is again unskewed.

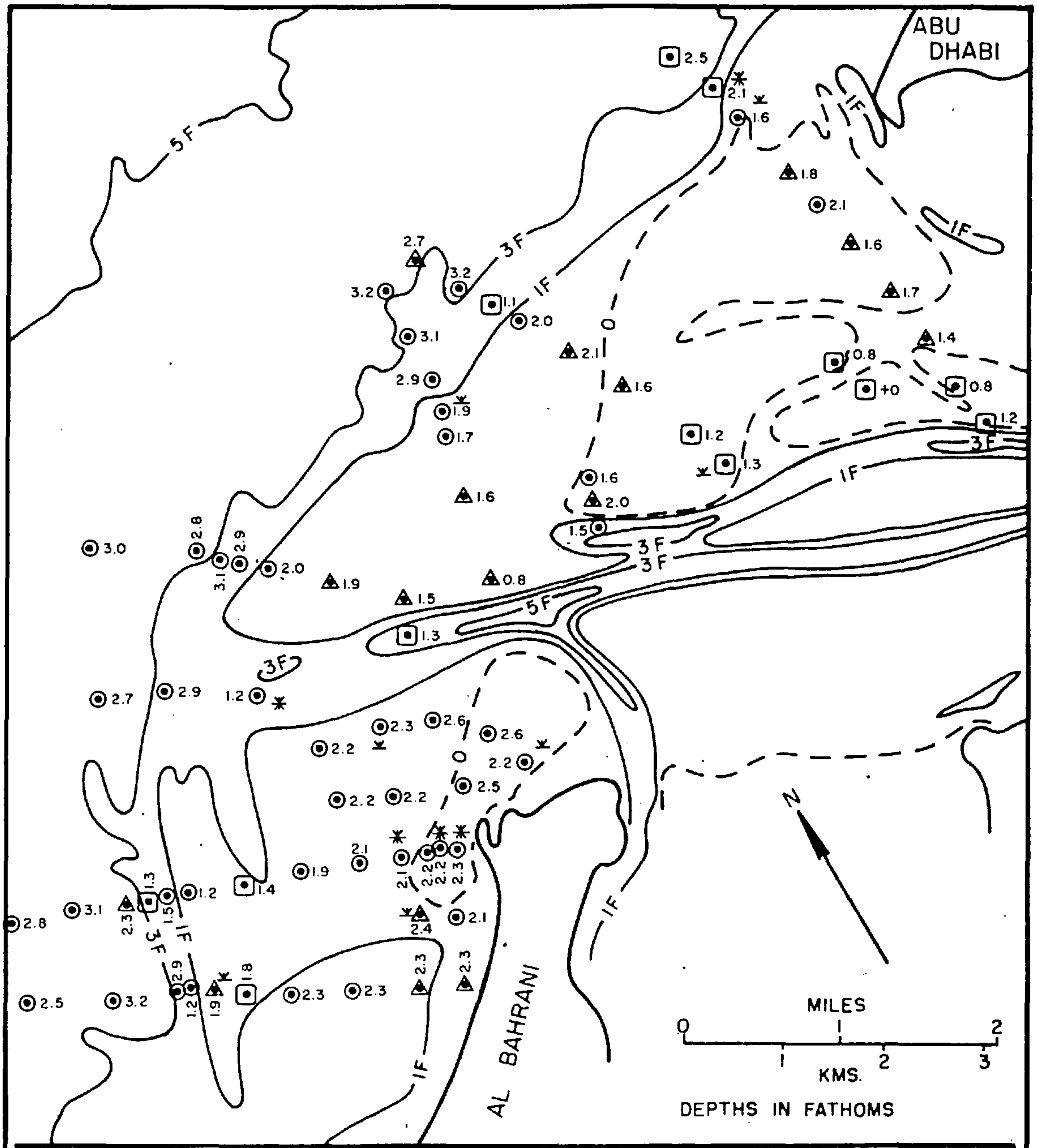
The grain size distribution characteristics of the samples with unimodal distribution is as follows. Sediments seawards of the 3 fathom contour and between the 3 and the 1 fathom lines are in general very negatively skewed (tail of coarse material) whereas those on the Abu Dhabi delta top are positively skewed (tail of fines). The unimodal sediments of the Al Bahrani section are essentially symmetrical. Sorting improves as one moves up the delta slope. Somewhat unexpectedly, the best sorting on the delta occurs on the delta top of the Al Bahrani section. In general, the sediments of the delta are considerably coarser than those of the inner shelf.

The above general description of grain size characteristics can be understood intuitively given certain facts about the makeup of the sediments and the bathymetry. We know that the faunal remains, though not dominant, are more abundant in the off-delta area. One would therefore anticipate that the sediments would be skewed to the coarser side of the scale. We also know that oolitization increases the size of the grains that are moved onto the delta slope. This, with increasing depletion of fines with shallowing depths will coarsen the sediment landwards. At some point, however, sorting will reach a maximum and then decrease as fines derived to seawards and indigenous faunal remains are added to the sediment. To test the validity of these intuitive conclusions, each of the grain size parameters will be examined in turn.

Mean Size (M_Z)

The mean size is a measure of the overall average size of a sediment. It tells us the "centre of gravity" of the distribution but nothing more. Because of this, it is only of very general usefulness when describing the areal variation in the distribution character of sediments. Unimodal, bimodal or polymodal sediments in an area can have precisely the same mean size, yet have no other common feature in terms of environment, constitution or sedimentological history.

The writer has used phi sizes in the discussion that follows. The more familiar Wentworth sizes and verbal scale are shown below. The reader will note (Figure 15) that all mean sizes fall within Wentworth's sand category (2mm. to 1/16mm., -1 to +4.00 phi). Gravel size (2-4mm.) occur only in the tails of the distributions and silt (less than 1/16 mm.) is virtually absent.



SAND SIZES (WENTWORTH)

VERY COARSE	COARSE	MEDIUM	FINE	VERY FINE
0 – 1 PHI	+1 – 0 PHI	+ 2.25 – +1.00 PHI	+3.00 – + 2.25	+ 4.00 – +3.00 PHI
1 – 2 MM	1/2 – 1 MM	1/4 – 1/2 MM	1/8 – 1/4 MM	1/8 – 1/16 MM

MAP VALUES ARE ALL PHI POSITIVE

Fig. 15. MAP SHOWING MEAN SIZE (M_Z) OF SEDIMENTS AT SAMPLE STATIONS IN THE ABU DHABI-AL BAHRANI DELTA AREA.

Wentworth Sands	phi Values
very coarse (v.c.) 1-2 mm.	0.00 to -1.00 phi
coarse (c.) 1/2 - 1 mm.	+1.00 to 0.00 phi
medium (m.) 1/4 - 1/2 mm.	+2.25 to +1.00 phi
fine (f.) 1/2 - 1/4 mm.	+3.00 to +2.25 phi
very fine (v.f.) 1/16 - 1/4 mm.	+4.00 to +3.00 phi

Figure 15 shows the areal distribution of mean size on the Abu Dhabi-Al Bahrani delta. The sediments seawards of the 3 fathom contour range in mean size from +2.3 phi (f.) to +3.8 phi (v.f.) but are most commonly close to the boundary between fine and very fine grained. The sediments coarsen somewhat up the delta slope to the one fathom contour however, values here are not in particularly sharp contrast to those beyond the delta slope to seaward. The similarity is more apparent than real, however, since the mean size of the inner shelf sediment is influenced by the presence of coarse shell debris and that on the delta slope due to increased oolite content. Just inside the 1 fathom contour the mean size is again slightly coarser due to increased oolite content but it is augmented by coarsening of a solely hydrodynamic origin. The sediments here are in the medium size class (1/4 to 1/2 mm.).

The delta top of the Abu Dhabi section is characterized by sediments whose mean size ranges as high as +0.8 phi (c.). Note the abundance of bimodal and polymodal distributions in contrast to the number found on the delta slope. The general trend on the delta top is one of coarsening towards the axial channel. The distribution of sediment size on the Al Bahrani delta top is quite different from that of the Abu Dhabi section.

The Al Bahrani delta top consists of two main elements; a frontal zone composed of unimodal, bimodal and polymodal sediments whose mean size coarsens from fine to medium grained landwards and an interior zone characterized by unimodal fine grained (+2.25-3.00 phi) sediment. In terms of areal extent, the unimodal and fine grained interior sediment comprises 3/4 of the Al Bahrani section. Between the two zones, there appears to be a zone of interference or transition that separates the coarse and complex sediments of the frontal area from the fine unimodal sediments of the interior. It is noteworthy and significant that whereas the two elements are in close juxtaposition, the zone of transition is extremely narrow. This suggests that opposing hydraulic forces have shaped this part of the delta and that neither dominates. In contrast, the Abu Dhabi section appears to be under the influence of a very dominant direction of water movement that moves sediment from the delta front to the axial channel.

Sorting (σ_I)

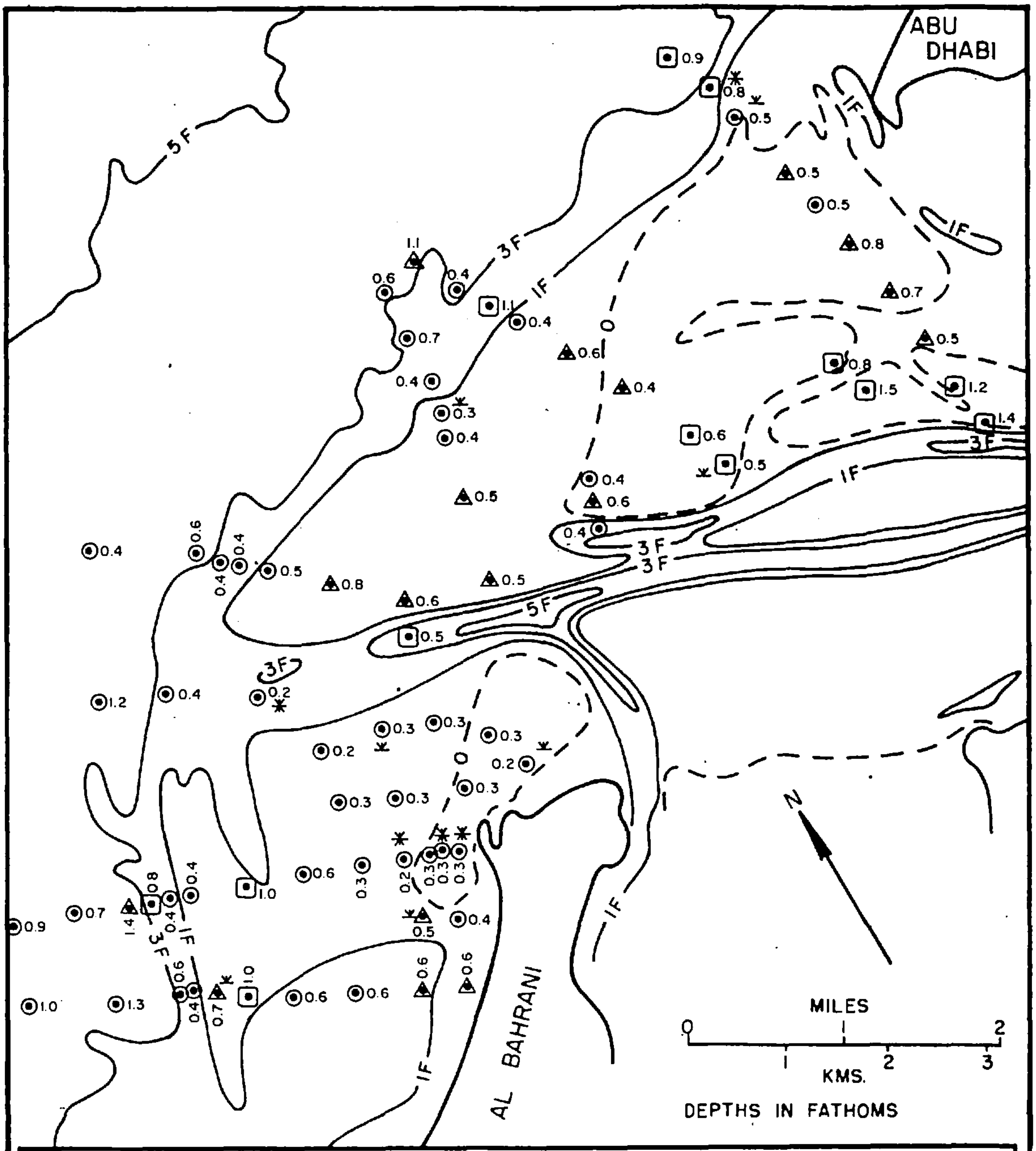
Sorting measures tell us to what degree the grains making up the sediment are concentrated about the mean size of the distribution. Obviously unimodal, unskewed sediments can have the best sorting since having more than one mode necessarily results in a greater dispersion of sizes. In the case of bimodal sediments, sorting varies in a cyclic way (Folk and Ward, 1957) depending upon the relative amounts in each mode. Sorting will decay as a second mode is added, improve when equal amounts of each mode are present and decay again when the new mode begins to dominate the distribution. With polymodally distributed sediments, sorting will largely depend upon the spacing of the modes. If the modes are widely spaced, the sorting will be poor, if they are close together (approaching unimodality) the sorting will be good. Similarly, if one mode is very dominant over all the others, then sorting will be better than will be the case if the modes are of equal importance.

The verbal scale for sorting suggested by Folk and Ward (1957) is as follows:

less than .35 phi-very well sorted (v.w.)
0.35 to 0.50 phi-well sorted (w.)
0.50 to 1.00 phi-moderately sorted (m.)
1.00 to 2.00 phi-poorly sorted (p.)
2.00 to 4.00 phi-very poorly sorted (v.p.)
greater than 4.00 phi-extremely poorly sorted (e.p.)

The sediments of the inner shelf (beyond the three fathom contour) are moderately to well sorted (see Figure 16). Between the three and one fathom contour (delta slope) sorting generally improves but not dramatically. In general, the sorting on the delta top is good, however, there is a definite decrease in quality where bimodal sediments are present and polymodal sediments have poor sorting.

The Al Bahrani section of the delta shows some distinctive sorting characteristics the origins of which have already been implied in the discussion of mean size. A large portion of the Al Bahrani delta top has very well sorted sediments, even though they are in a relatively sheltered area (compare the somewhat poorer sorting of the sediments of the frontal zone on the Abu Dhabi section). The suggestion is made that these well sorted sediments are derived from the Abu Dhabi section and receive additional sorting in the axial channel before being deposited on the Al Bahrani delta top. Sorting noticeably worsens as one proceeds



SORTING

<0.35	VERY WELL SORTED
0.35 – 0.50	WELL SORTED
0.50 – 1.00	MODERATELY SORTED
1.00 – 2.00	POORLY SORTED
2.00 – 4.00	VERY POORLY SORTED
>4.00	EXTREMELY POORLY SORTED

Fig. 16. MAP SHOWING SORTING (σ_I) AT SAMPLE STATIONS IN THE ABU DHABI – AL BAHRANI DELTA AREA.

south from the axial channel. The frontal zone of the Al Bahrani section has well to moderately well sorted sediments and sorting is more or less commensurate with the number of modes present. The frontal zone here has sorting properties similar to those sediments in the same position on the Abu Dhabi section.

Skewness and Kurtosis (SK_I & Kg)

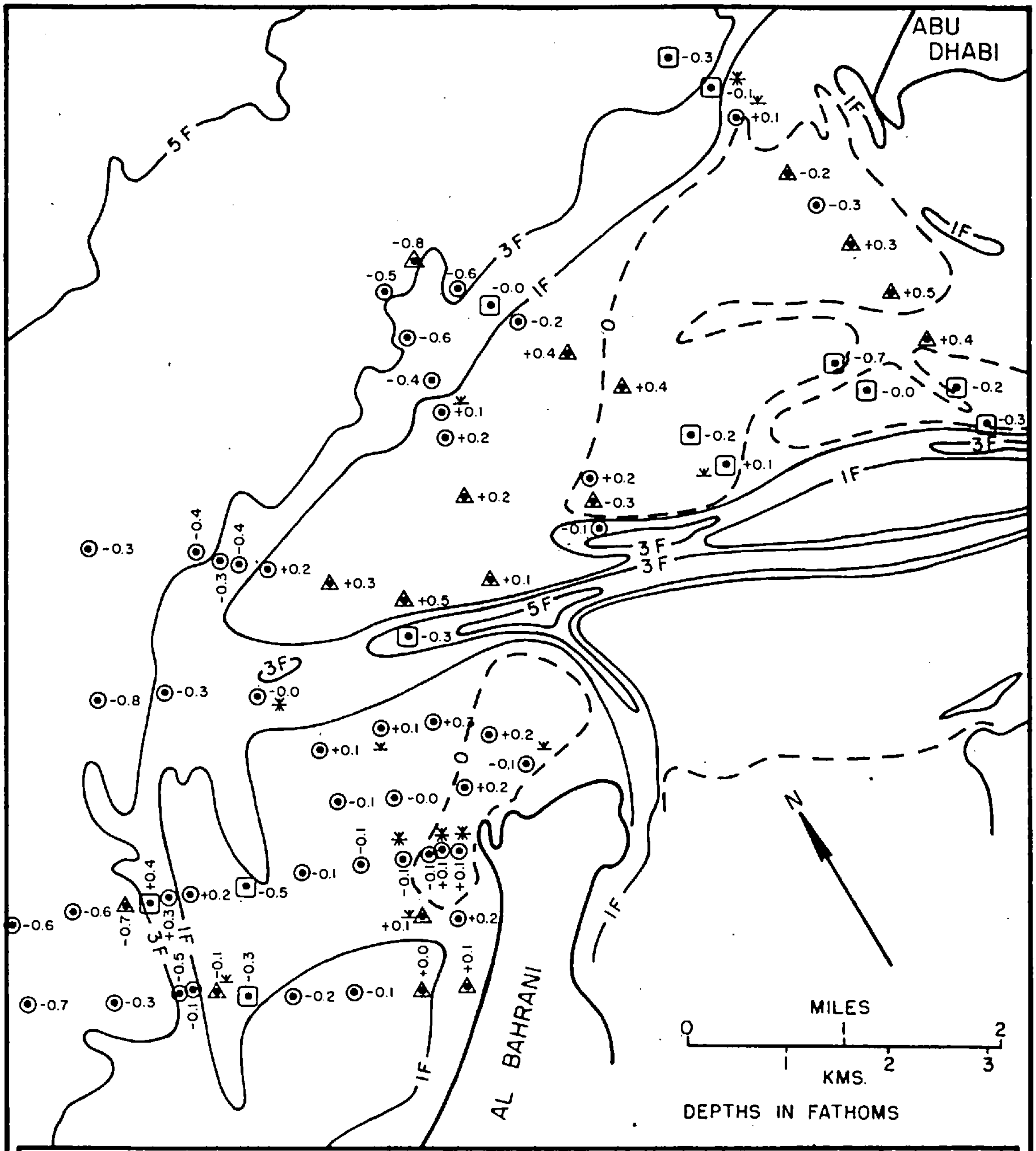
Skewness is a measure of the asymmetry of a grain size distribution. Using the method of Folk and Ward (1957), which employs phi values for size, a distribution that is positively skewed has a tail of fines, whereas one that is negatively skewed has a tail of coarse grains. It is to be noted that in a bimodal sediment, the position of the secondary mode will determine the sign of the skewness. The range of values is from +1.00 to -1.00 phi. Normally distributed sediments have skewnesses from +0.1 to -0.1. The verbal equivalents of skewness values are given below.

-1.00 to-0.30	very negative
-0.30 to-0.10	negative
-0.10 to+0.10	symmetrical
+0.10 to+0.30	positive
+0.30 to+1.00	very positive

Kurtosis is a measure of the peakedness of a grain size distribution. This characteristic is determined by ratioing the spread in the tails of the distribution to the spread in its centre. Distribution curves that are "normal" are mesokurtic (0.90 to 1.11), those that are abnormally peaked are leptokurtic (1.11 to 3.00), abnormally flat are platykurtic (0.67 or less to 0.90).

Variations in Skewness (see Figure 17)

Most of the grain size distributions of the sediments that lie in



SKEWNESS

-1.0 TO -0.3		VERY NEGATIVE
-0.3	-0.1	NEGATIVE
-0.1	+0.1	SYMMETRICAL (UNSKEWED)
+0.1	+0.3	POSITIVE
+0.3	+1.0	VERY POSITIVE

Fig. 17. MAP SHOWING SKEWNESS (SK_I) AT SAMPLE STATIONS IN THE ABU DHABI - AL BAHRANI DELTA AREA.

waters deeper than one fathom along the front of the delta are negatively skewed. This tail of coarse material is best developed beyond the three fathom contour. Sample examination shows that it is clearly due to abundant organic detritus. Extreme skewness is best developed south of the axial channel. There is a decrease in organic content as one moves up the delta slope and this is reflected in decreasing negative skewness.

On the Abu Dhabi delta top, most of the sediments are positively skewed, whether they are unimodal or bimodal. As would be expected, the polymodal sediments near the coral reefs of the southeast corner of the delta top are skewed to the coarse side due to the presence of abundant organic detritus.

On the Al Bahrani delta top, those sediments that front on the open sea or are near the axial channel have tails of fine material, whereas those of the interior, whether simple or complex in grain size distribution, are negatively skewed. Close to Al Bahrani island however, where strong tidal flow to the north is suspected, the sediments are positively skewed.

The pattern of skewness on the delta suggests that positive skewness developes in areas of vigorous tidal or wave induced water flow. The areas with negative skewness (coarse tails) are characterized by a relative abundance of organic detritus. In a sense however, positive and negative skewness on the delta are both related to the amount of organic detritus which in turn is a function of a complex of factors. Where very vigorous flow occurs the shifting sediments provide a poor foothold for bottom dwelling forms. This appears to be the case on the

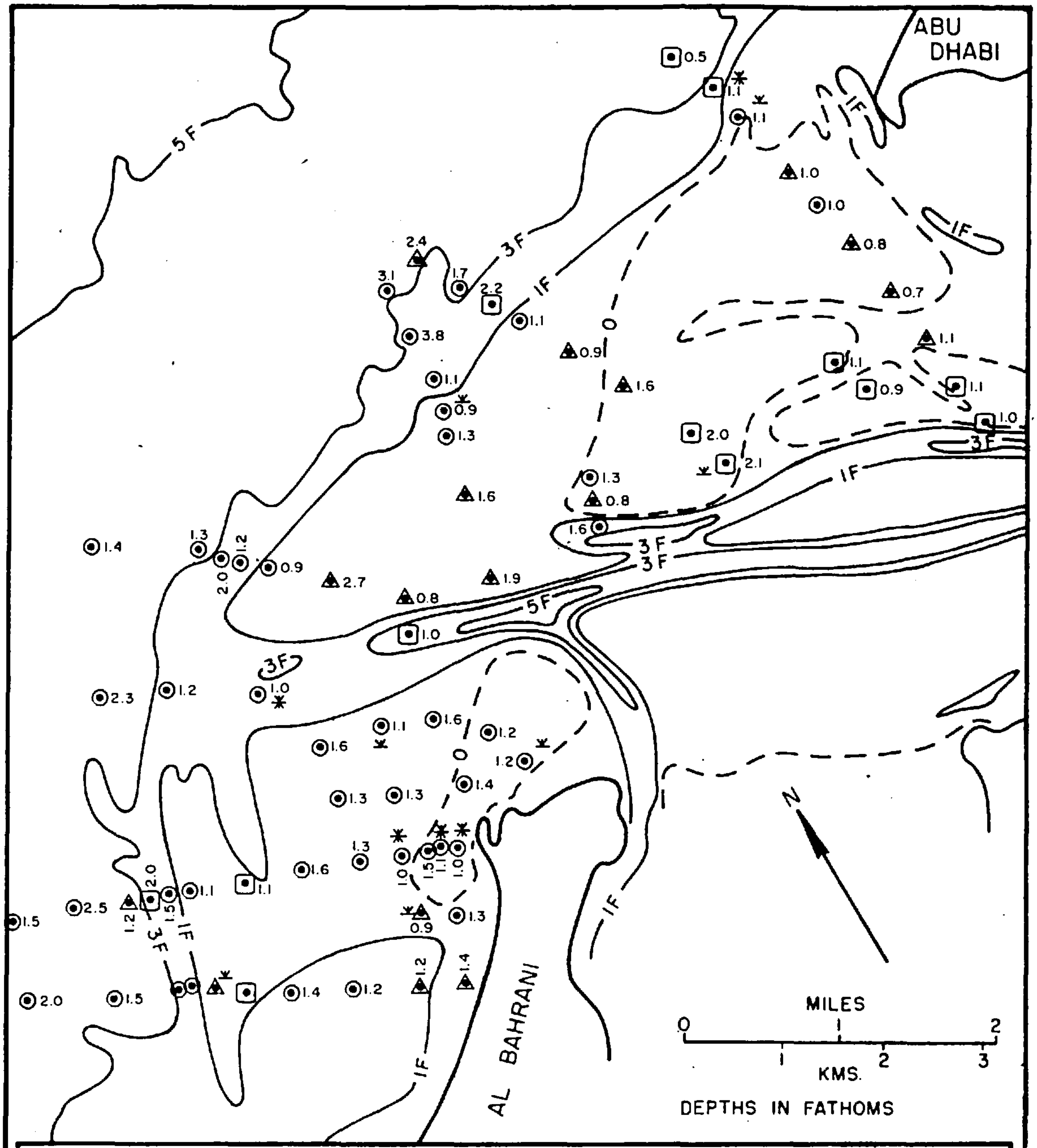
Abu Dhabi delta slope. On the other hand, the Al Bahrani delta slope and the adjacent part of the delta top, appear to receive considerable detritus carried there by the ebb tides surging out of the axial channel. In the deeper and quieter bottom conditions of the inner shelf, fauna flourish and although their detritus does not dominate in the sediments there is sufficient to skew the distribution in a negative sense.

Variations in Kurtosis (see Figure 18)

According to Folk and Ward (1957), whether a grain size distribution is flattened (platykurtic) or peaked (leptokurtic) depends upon the proportions in which the contributing populations are present. If two separate populations with different mean sizes are combined in subequal proportions, the distribution will be platykurtic, whereas if one is very dominant over the other, the distribution will be leptokurtic.

Low numerical values of kurtosis indicate a platykurtic distribution while high values show the distribution to be leptokurtic. This is so because kurtosis is a ratio of the sorting in the tails of the distribution over the sorting in the central portion of the distribution. As material is added in the tails of the distribution, the standard deviation value in the tails will increase (sorting becomes poorer) and therefore, the value of kurtosis increases.

In general, the grain size distributions of the delta sediments are leptokurtic, that is they have one dominant mode and other modes poorly developed. This is particularly true of the sediments seaward of the one fathom contour that are classed as unimodal due to the minor nature of their secondary or tertiary modes. The reader will recall that modes



KURTOSIS

< 0.67	VERY PLATYKURTIC
0.67 – 0.90	PLATYKURTIC (FLATTENED)
0.90 – 1.11	MESOKURTIC
1.11 – 1.50	LEPTOKURTIC (PEAKED)
1.50 – 3.00	VERY LEPTOKURTIC

Fig. 18. MAP SHOWING KURTOSIS (K_g) AT SAMPLE STATIONS IN THE ABU DHABI - AL BAHRANI DELTA AREA

containing less than two weight percent were not considered to be significant. Such modes do however, contribute to skewness and kurtosis. Between the leptokurtic sediments seawards of the one fathom contour and the leptokurtic sediments of the interior delta top, there is a relatively narrow zone of sediments with mesokurtic distributions. Distributions become mesokurtic when they approach true unimodality or when their modes are all very close together. Note, for example, the polymodal distributions in the southeast corner of the Abu Dhabi delta top. These compute to be mesokurtic because, even though they have up to five modes present, the modes are only 1/4 phi apart. The sediments with mesokurtic distribution are confined mainly to zones of high water agitation where sorting action would be strong and the probability of developing more than one mode slight. The five samples with platykurtic grain size distributions are with one exception, bimodal. All are near channelways. They probably owe their character to periodic influx of coral detritus onto the delta top from the channels. By this means a secondary mode of subequal size has developed.

Interpretation using Modal Populations

A mode or modal class within a grain size distribution has been defined as the size fraction that contains a larger percentage by weight than those on either side of it in the sequence. The sizes adjacent to the modal size are called the proximal classes. By comparing the abundance of grains, by weight, in the various modes of a complex distribution, one can class the modes as primary, secondary, tertiary and so on, to the limit required. As pointed out by Folk (1966), there is no simple way to find the mode accurately. Fortunately, for most purposes, great accuracy is not required. The writer has chosen to use the phi value of the 1/4 phi interval that contains the mode as the modal size. Note that all values given are phi positive unless otherwise indicated.

The Modal Population

The grains which make up a distinct entity within a sediment are often described as a population. The definition of a population may be based upon mineralogy, colour, shape, origin or any number of classifying characteristics. In grain size statistics, the population is sometimes a size assemblage that appears to obey a distribution law, such as the lognormal law that is common to many naturally occurring sediments (Krumbein, 1938). Within the sediments here being examined, such a rigorous definition of a population is generally not possible. On the delta, very few of the sediments possess the characteristics of lognormality either in terms of skewness and kurtosis or the most necessary requisite, unimodality. Considerable change in the characteristics of skewness and kurtosis takes place on the delta from sample station to sample station and it is equally profound between the unimodal sediments as it is between those of more complex character. What is most striking is that within this matrix of change the individual modal sizes are singularly persistent. This fact suggests that under the conditions prevailing on the delta it is relatively easy for skewness and kurtosis to be changed but difficult to change or obliterate a mode. The key to understanding grain size distribution character on the delta would seem to be in recognizing the existance and behaviour of modal populations and in not being too concerned about deviations from the laws of statistical distribution.

The Abu Dhabi-Al Bahrani Delta Modal Populations

Figure 19 shows the primary and secondary modes that occur in samples from the various stations on the delta and nearby shelf. It is quite clear that areas of the delta can be defined in terms of the modes. The delta slope and nearby shelf have modes of 3.25-3.50 phi (v.f.sand). All modes are phi positive unless otherwise indicated. The Abu Dhabi delta top has modes of 1.75 phi (med. sand) near the one fathom contour and 1.50 phi (med. sand) combined with 2.25-2.50 phi (fine sand) modes within the interior. The Al Bahrani delta top has chiefly unimodal assemblages whose modal sizes range from 2.25-2.75 phi (fine sand grades). Note that the modes of the Al Bahrani delta top are close in value to the finer modes of the bimodal sediments on the Abu Dhabi section. Figure 20 shows some histograms typical of sediments from various parts of the delta.

With the exception of those on the lower part of the delta slope and the nearby shelf, the sediments that form the main modal classes are composed of oolites. Evidence will be presented suggesting that the development of the various modes of oolites is due principally to hydrodynamic conditions on the delta and not to in situ generation of separate populations of oolites.

Modal Sizes

Figure 21 shows the distribution of modes according to whether they occur singly or in combination and whether they occur on the Abu Dhabi and Al Bahrani sections of the delta. The delta slope and deeper water sediments are lumped together in one category covering both sections. Figure 22 summarizes the data without indicating location.

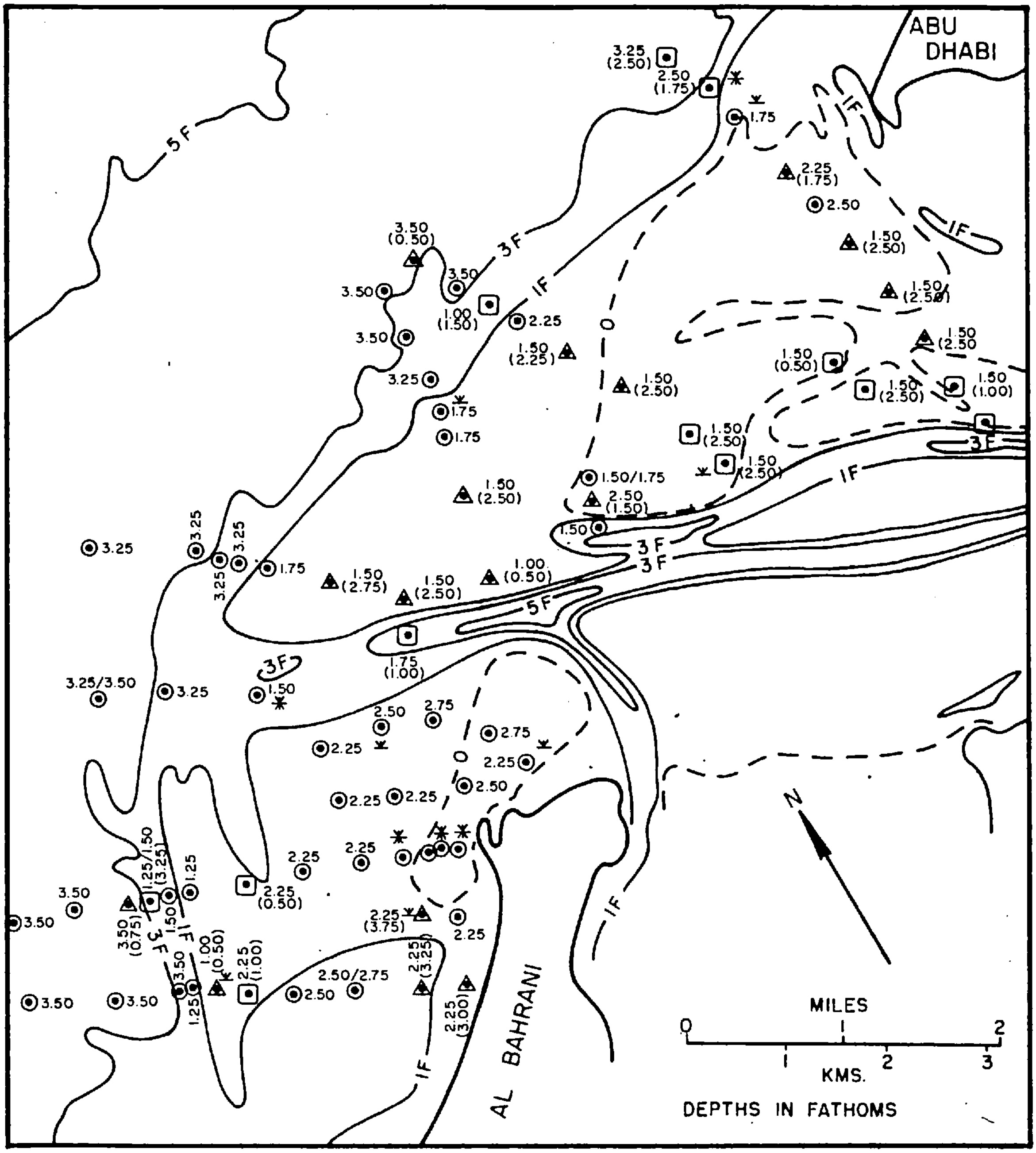


Fig. 19. MAP SHOWING PRIMARY AND SECONDARY (BRACKETED) MODES AT SAMPLE STATIONS IN THE ABU DHABI-AL BAHRANI DELTA AREA. ALL VALUES ARE PHI POSITIVE. APPROXIMATELY EQUAL MODES ARE SHOWN THUS: 1.50/2.75.

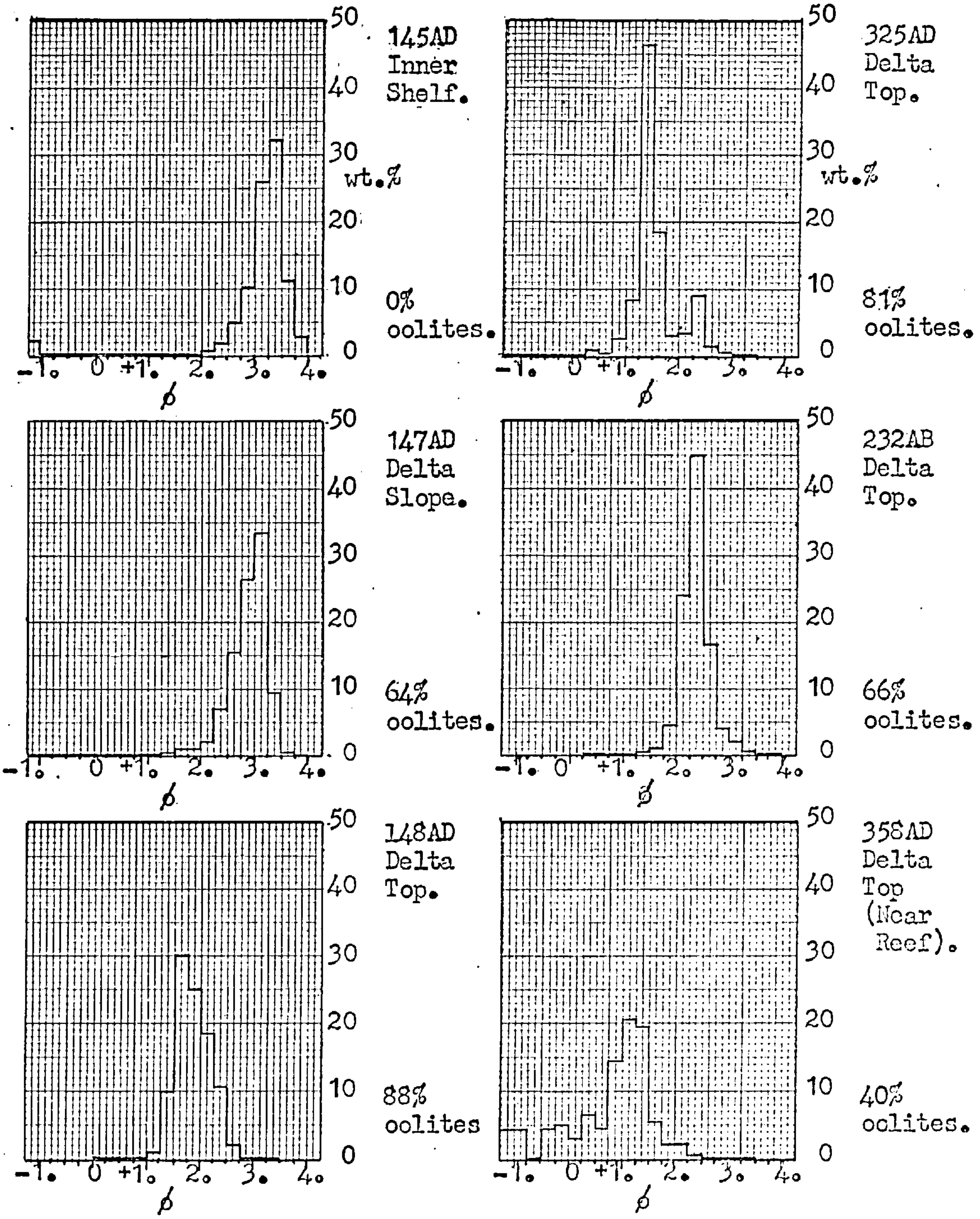


Figure 20:Histograms of typical grain size distributions on the Abu Dhabi-Al Bahrani delta and nearby inner shelf.Sample location according to section of the delta shown by AD(Abu Dhabi) or AB(Al Bahrani) following sample number.

ø + Size Classes

0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	Type	Location
						●	●		●	●							Unimodal	Abu Dhabi Section.
						●					●						Bimodal	
						●				●								
						●			●									
							●		●									
		●		●														
		●			●												Polymodal	
		●		●		●				●								
		●		●		●												
●		●		●			●			●								
					●				●	●	●						Unimodal	Al Bahrani Section.
									●		●						Bimodal	
									●			●						
									●				●					
●		●							●								Polymodal	
●		●		●					●									
						●							●	●			Unimodal	Delta Slope &Inner Shelf.
						●							●				Bimodal	
							●			●			●				Polymodal	
					●	●							●					
				●			●			●			●					
●				●		●							●					

● = Mode

Figure 21: Modes and modal combinations in the grain size distributions of the sediments, according to location on the Abu Dhabi-Al Bahrani delta and nearby inner shelf.

φ + Size Classes

0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	Type of Dist.
					•	•	•		•	•	•		•	•			Unimodal
		X		X		•	•		•	•	•	X	•				Bimodal
X		X		X	•	•	•		•	•	•		•	•			Polymodal
☒		☒		☒	☒	☒	☒		☒	☒	☒	☒	☒	☒			☒

Legend

• = Modes that occur both singly (unimodal) and in combination.

X = Modes that only occur in combinations.

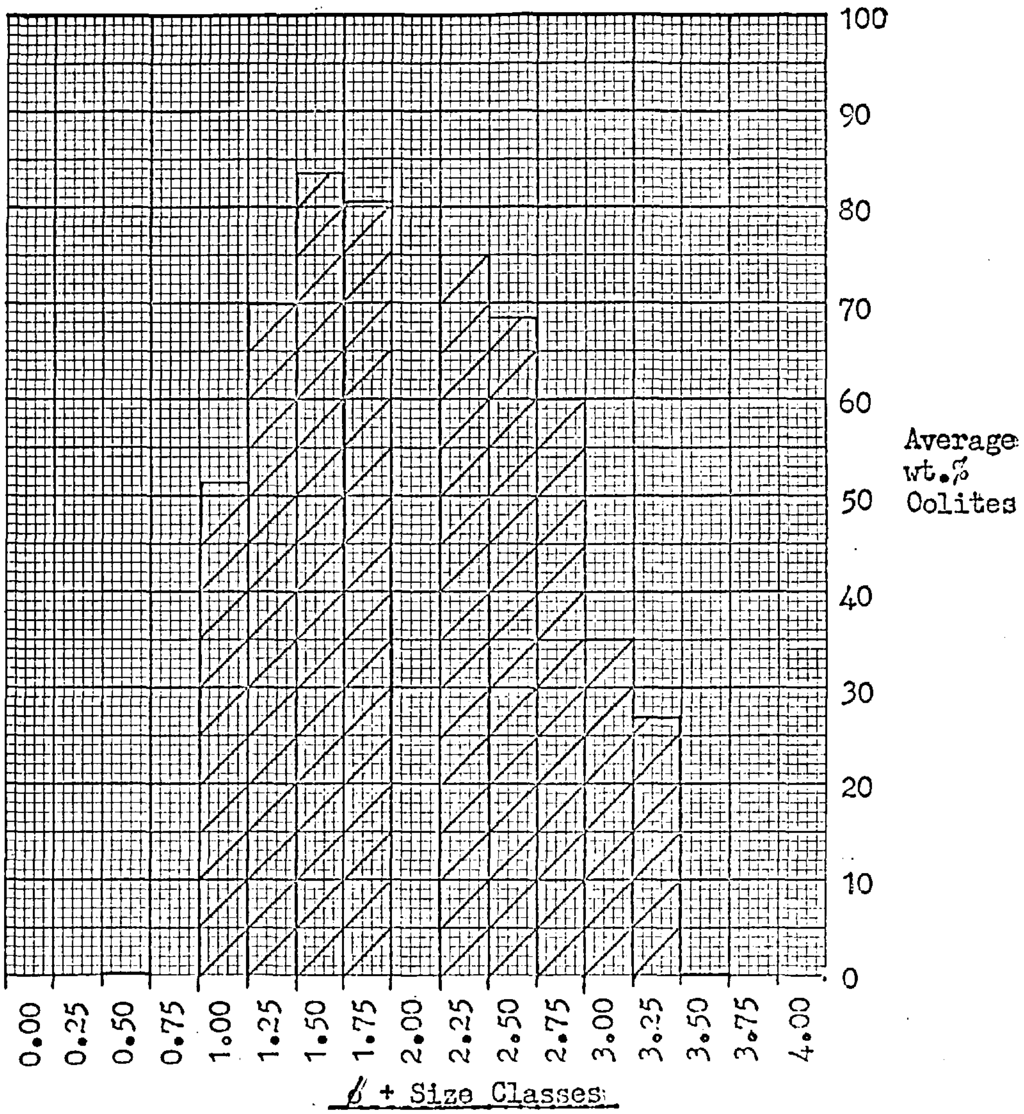
Note: No significant modes occur in size classes coarser than 0 phi or finer than 3.50 phi.

Figure 22: Summary of modes with respect to size class and to type of distribution in which they occur.

In the sediments analyzed, modes occur at most of the size classes within the range of from 0.00 phi to 3.50 phi (coarse to very fine sand grades). There are no modes at 0.25, 0.75 or 2.00 phi. All the modes that occur in the unimodal distributions (a range of 1.25-3.50 phi) also occur in bimodal or polymodal mixtures. This suggests that modal populations, once generated, tend to retain their individual identity. Modes of 1.00 phi and coarser do not occur alone but are always in combination, most commonly as part of a polymodal assemblage. The finer modes in these polymodal sediments are almost always those that characterize the unimodal sediments nearby. On the Abu Dhabi section, the fine mode is either 1.50 or 1.75 phi, with 2.25 or 2.50 phi on the Al Bahrani section and the 3.25 phi mode on the delta slope and inner shelf. Examination of the content of the coarse modes shows them to be high in organic detritus which strongly suggests that their enhancement in the distribution is probably a function of local abundance, and/or local current conditions that tend to deplete the finer grades.

Percentage Oolites in the Various Modes.

The percentage oolites in the different size splits was estimated for all samples sieved (see page.69.). Figure 23 shows the compiled data for the modal classes using bar graphs to illustrate the average percentage oolite in each class. The results show that the highest average, 83.4% occurs in the 1.50 phi class and nearly the same amount in the 1.75 phi class. The percentage oolite drops off rather gradually towards the finer end of the scale and sharply towards the coarser fractions. Note that the size range of 74% of the oolite nuclei (see below) is from 2.75-3.25 phi inclusive. In form, the histogram of the average



		0		51.4	70.0	83.4	80.7		75.0	68.5	60.0	35.0	27.1	0			Average wt.% Oolites.
0	0	5	0	7	4	16	7	0	15	17	4	2	10	12	0	0	No. of occurrences of mode.

Figure 23: Average weight percent oolites in primary and secondary modes in the grain size distributions of the sediments on the Abu Dhabi-Al Bahrani delta and nearby inner shelf.

percentage oolite appears to be a unimodal distribution, strongly skewed towards the fine end of the scale.

This data is interpreted as indicating the presence on the delta of a single "mother" population of oolites. The modal populations would therefore necessarily be solely the result of separation due to hydrodynamic forces. The following section provides what the writer believes to be supporting evidence for this conclusion.

Oolites, Nuclei and Insoluble Residues

One of the problems of grain size analysis performed on non-skeletal grains, such as oolites, is to determine what effect the process of grain growth has on the character of the sediment's grain size distribution. We know that on the delta, increasing oolite content up the delta slope is paralleled by increasing mean size and improved sorting. The critical question is whether the effective mechanism in the changes is oolitization or simply increased dynamic forces that accompany shallowing depths.

The first and most obvious effect of oolitization is that it increases the size of the sediments that are nuclei for the process. In the Abu Dhabi-Al Bahrani area, it is probable that without grain enlargment, a delta of the present dimensions would not be developed. The fine grained sediments of the inner shelf form a relatively thin skin over the underlying bedrock. The character of their grain size distribution is one where the main mass of the sediment are fines concentrated around a single mode and the remainder is skewed out over many grades towards the coarse end of the scale. These facts, suggest to the writer that the inner shelf sediments are in equilibrium with the supply and with the prevailing hydrodynamic conditions at the depths where they occur. Grain size enlargement due to oolitization allows these sediments to accumulate faster than they are depleted and to eventually become a deposit whose surface sediments are size graded according to the water depths at which they occur.

The process of oolitization is going on along the front of the delta and probably most vigourously on the delta slope. From analysis and examination of the sieving splits we know that the sediments of the inner shelf are composed of a mixture of fine carbonate and fine insolubles plus coarse organic detritus in the proportions of about 90% fines to 10% coarse. Of the fines, only 30% are insolubles, while the remainder are carbonate particles of indeterminate origin. Grain size analysis of the insolubles when compared to analysis of the total sediment, less it's coarse tail, are so close in character that it is safe to assume that grain size variations in one are a direct reflection of variations in the other. In short, the insolubles can be used as tracer populations with which to investigate the changes that take place at the onset of oolitization of the inner shelf potential nuclei and to what extent the grain size character of the nuclei affect that of the oolites that are produced. Furthermore, by comparing the grain size distributions of the tracer nuclei to those of sediments from all over the delta, we can draw some conclusions as to where the bulk of the oolites are generated.

Preparation

Four samples from the same traverse onto the Abu Dhabi section of the delta were processed to determine their insoluble residue content and to provide material for sieve analysis. The samples were #145 from just seawards of the 3 fathom bathymetric contour, #146 and 147 from the delta slope, and 148 from just inside the 1 fathom contour at the front of the delta top (see Figure 7). Each sample was treated with 10% HCl. After solution of the carbonate, the liquid portion was filtered off and the residue was washed into a beaker. The sample was then treated with hydrogen peroxide to remove any organic matter, washed and dried. After weighing, the sample was sieved through a series of sieves 1/4 phi apart, covering the range from 1.75 phi to 4.00 phi. The values computed were, percentage insoluble by weight, mean size (Mz), sorting ($_I$), skewness (Sk$_I$0 and kurtosis (Kg).

Results

The results of the insoluble determinations and sieving analysis are tabulated below. Also included are the results of grain size analysis performed on 518 oolite nuclei measured in thin sections of samples from all over the delta (see Appendix 1).

Sample	%Insolubles	Mz	$_I$	Sk$_I$	Kg	Mode
145	34%	3.22	.26	-.07	1.11	3.25 (lognormal)
146	37%	3.18	.28	-.13	1.05	3.25 (nearly lognormal)
147	24%	3.01	.23	-.03	1.07	3.01 (lognormal)
148	3.2%	2.63	.44	+.04	1.05	2.75 (lognormal)
Nuclei		2.68	.38	-.18	1.04	3.00 (nearly lognormal)

As might be anticipated, the oolite poor sediments from the base of the delta slope have the highest percentage of insolubles by weight. The sample with the highest oolite content, #148 (88%) has the lowest percentage of insolubles by weight.

Cumulative frequency curves for the insoluble residues and their sediments are shown in Figure 24 . Note how the lognormal or nearly lognormal curves of the insolubles closely parallel and/or coincide with that of the parent through the range of insoluble sizes. It would appear that in the samples #147 and #148 where oolites are the dominant constituent, the oolite population is probably close to lognormal in its distribution. The precise relationship between the grain size character of the oolites and that of their nuclei is somewhat difficult to determine. Perhaps all that can be suggested is that if a uniform coating is given to a population of nuclei that has a lognormal grain size distribution then the probability is that the resultant oolite population will also be lognormally distributed.

The validity of using the grain size distribution of the insolubles as representative of the potential nuclei population is supported by the similarity between the insoluble distributions and that of the nuclei measured in thin section. In terms of grain size parameters, a strong similarity exists between the insolubles in sample #148 (88% oolites) and the measured nuclei. By observation it is known that the nuclei in the oolites of sample #148 are about evenly distributed between carbonate and insoluble grains. The same holds true for the nuclei measured in thin section. These facts suggest that the carbonate nuclei have about the same grain size distribution character as the insolubles since there is so little disparity between the insoluble parameters and those of the measured nuclei.

In sample #145 where there is a very close coincidence between the cumulative frequency curves of the total sample and its insoluble from the 15 percentile on, it is possible to calculate the percentage of

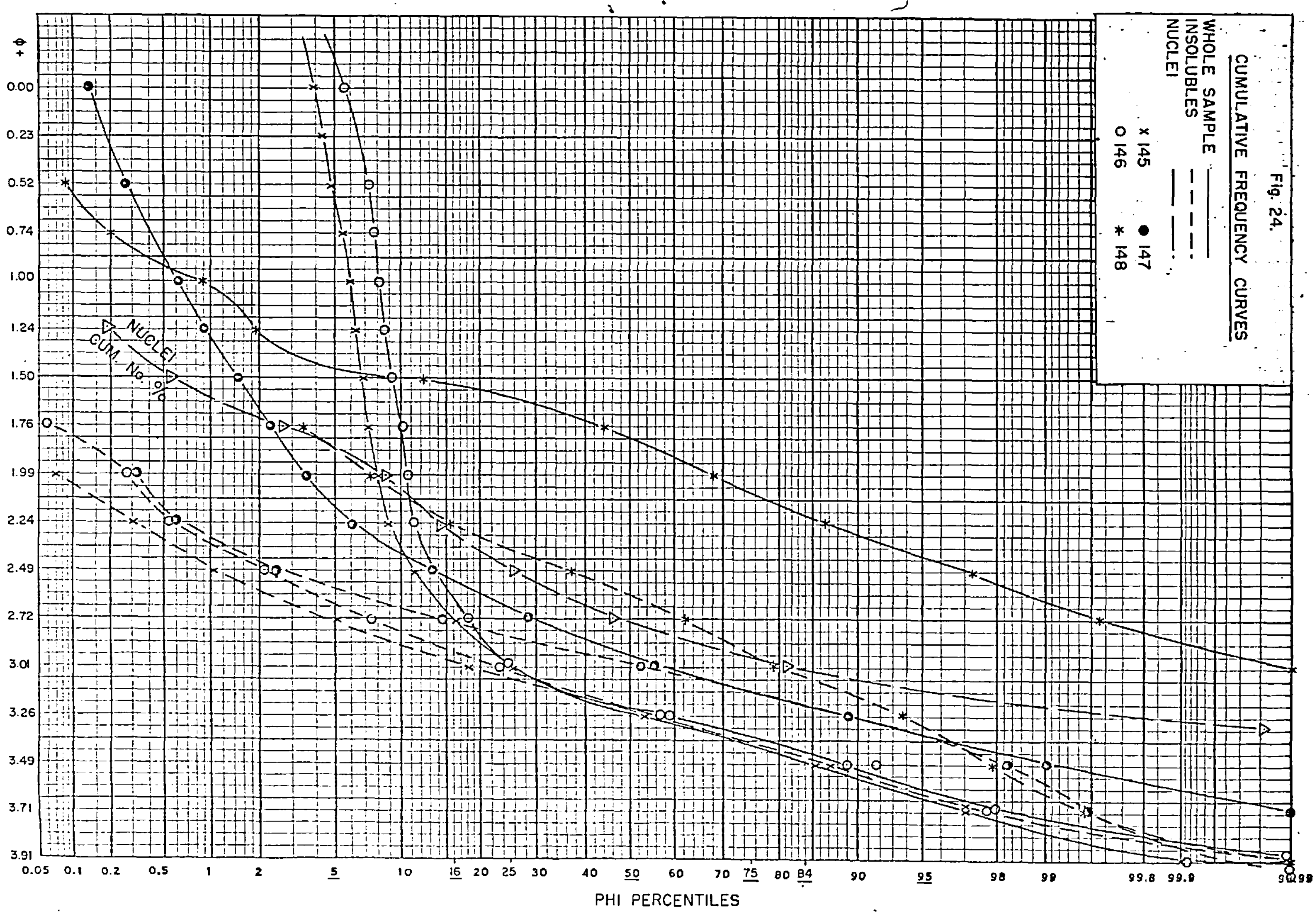


Fig. 24.
CUMULATIVE FREQUENCY CURVES

carbonate present that has approximately the same size characteristics as the insolubles. The insolubles from this sample have a size range of from 2.25 to 4.00 phi inclusive. In the total sample approximately 90% of the grains are concentrated in those weight classes. The whole sample contains 34% insolubles represent 34/90 of the sediment present. This calculates out to 37%. In rough figures, the population, which we judge to be the potential nuclei at this location, is composed of around 40% insolubles and 60% carbonate.

There is a progressive coarsening of the insoluble modes as one moves up the delta slope to the edge of the delta top. In the samples containing a high oolite content, the mode of the insolubles is close to that of the oolite nuclei measured in thin section. It would appear that the process of oolitization in effect freezes the grain size character of the insolubles. While this is undoubtedly true, the grain size similarity between measured nuclei and insolubles is related to the paucity of fines in the shallow and more turbulent water near the top of the delta slope. An additional conclusion that one can draw from the above facts is that few if any oolites begin their growth in waters where the 3.00 phi mode nuclei are unable to achieve some sort of equilibrium with respect to the forces that might move them out of the oolitizing environment. Once oolitization has begun on the potential nuclei they are more apt to remain and accumulate.

Summary and Discussion

The potential nuclei population arrives at the foot of the delta slope already very well sorted and in fact nearly lognormal in distribution. Where or how it achieves this character is not known. Wave generated flow moves the potential nuclei onto and up the delta slope. As the sediment moves into shallower water, it's mean size coarsens, due presumably to a progressive extraction of fines. Distribution character is otherwise little affected and it is probable that at any specific location, the potential nuclei population is in some sort of equilibrium. With the onset of oolitization, some of the grains become trapped and the character of their grain size distribution frozen. Thus in a sediment composed mainly of oolites, the insoluble residue is composed of grains released from oolites and those that form the indigenous equilibrium population. The result is a loss in sorting quality.

The excellent sorting and near lognormal character of the potential nuclei population would appear to provide the pattern for the oolites that evolve from it. Continued oolitization under static conditions would move the mode of the population to progressively coarser sizes with little change in distribution character. Under the conditions existing on the delta slope, onshore water movement causes continuous differentiation of the deposit in such a way that the coarser oolite populations characterize only the shallower depths. It is noteable that fine oolite populations are found in the bimodal sediments of the delta top. This suggests to the writer that either the process on the delta slope creates a new modal population out of the extracted fines or under some conditions passes a fine population up the delta slope from deeper water. The striking similarity between the character of grain size distribution of oolite nuclei from all over the delta and that of the insoluble residue of the potential nuclei population strongly suggests that fine grained oolite populations have moved as units from somewhere near the base of the delta slope onto the delta top. Another implication of the above evidence is that the area of oolite generation is the delta slope since otherwise one would encounter a greater diversity in the grain size characteristics of the nuclei.

Conclusions derived from Grain Size Analysis of the Delta Sediments

Grain size analysis of the delta sediments has provided us with a reasonably precise picture of the size characteristics of the oolites at various locations. More importantly we are now able to reach some general conclusions with respect to oolite generation and the probable pattern of sediment movement on the delta surface. In this regard, the evidence presented in the foregoing pages appears to support the following:

1. The oolite sediments that have been examined on the Abu Dhabi-Al Bahrani delta were all formed on the delta slope of the Abu Dhabi section.
2. The Abu Dhabi delta slope has served as the sorting field where various modal populations of oolites were created.
3. The finer modal populations of oolites were abstracted from the delta slope and moved onto and across the coarser and more stable populations of the delta top.
4. The finer oolite modes ultimately reach the axial channel where they are carried seawards and deposited on the delta top of the Al Bahrani section.

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APPENDIX 1

Grain Size Analysis Data

1. Equations (Folk and Ward, 1957).

The equations for computing mean size, sorting, skewness and kurtosis require the 5,16,25,50,75,84 and 95 phi (ϕ) percentiles.

Mean Size (M_Z)

$$M_z = \frac{(\phi 16+\phi 50+\phi 84)}{3}$$

Sorting ($_I$, Inclusive Graphic Standard Deviation)

$$_I = \frac{(\phi 84-\phi 16)}{4} + \frac{(\phi 95-\phi 5)}{6.6}$$

Skewness (Sk_I, Inclusive Graphic Skewness)

$$Sk_I = \frac{\phi 84-\phi 16+2\phi 50}{2(\phi 84-\phi 16)} + \frac{\phi 95-\phi 5-2\phi 50}{2(\phi 95-\phi 5)}$$

Kurtosis (K_G, Graphic Kurtosis)

$$K_g = \frac{\phi 95-\phi 5}{2.44(\phi 75-\phi 25)}$$

2. Tabulated results of computations.

Abu Dhabi Section

Sample	M_z	σ_I	Sk_I	K_g
145	3.15	.63	-.52	3.05
146	3.08	.71	-.61	3.77
147	2.92	.35	-.35	1.06
148	1.87	.33	+.13	0.89
149	1.67	.36	+.22	1.27
150	1.57	.51	+.20	1.56
152	0.79	.50	+.13	1.90
210	3.04	.44	-.26	1.39
211				
213	2.75	.64	-.40	1.28
214	3.07	.42	-.33	1.96
215	2.87	.40	-.38	1.21
216	2.02	.45	+.18	0.94
217	1.89	.79	+.30	2.72
218	1.49	.59	+.45	0.82
313	1.57	.38	+.15	1.27
314	2.01	.62	-.30	0.78
315	1.47	.42	-.12	1.57
320	2.73	1.14	-.75	2.44
321	3.17	.39	-.57	1.69
322	1.06	1.08	+.03	2.20
323	2.00	.39	-.22	1.07
324	2.08	.57	+.38	0.92
325	1.55	.40	+.40	1.61
326	1.24	.62	-.21	1.97
327	1.34	.50	+.07	2.10
358	0.78	.81	-.66	1.09
357	0.95	1.47	-.02	0.85
334				
335	2.49	.85	-.27	0.51
336	2.10	.80	-.10	1.11
337	1.64	.53	+.11	1.14
338	1.84	.53	-.16	1.04
339	2.07	.51	-.31	1.00
340	1.63	.75	+.30	0.77
341	1.70	.71	+.49	0.69
342	1.40	.50	+.43	1.05
343	0.80	1.17	-.24	1.08
344	1.22	1.43	-.29	0.96

Al Bahrani Section

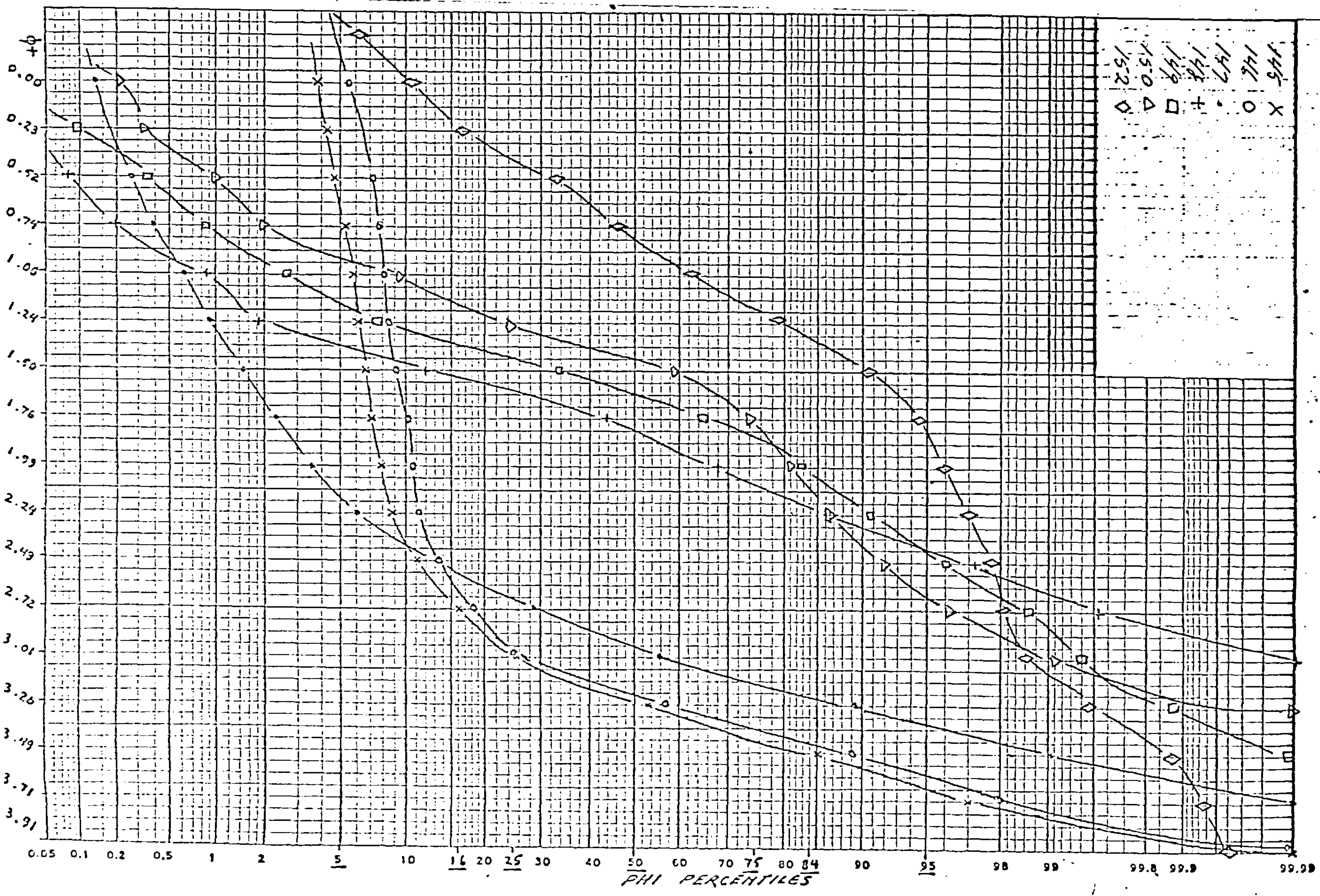
Sample	M_z	σ_I	Sk_I	K_g
166	2.23	.21	-.09	1.19
231	2.57	.26	+.29	1.55
232	2.34	.25	+.08	1.14
233	2.20	.18	+.11	1.59
234	2.22	.26	-.07	1.27
235	2.24	.21	-.02	1.28
236	2.41	.26	+.16	1.35
237	2.58	.25	+.20	1.18
238	2.84	.85	-.58	1.50
239	3.11	.67	-.55	2.48
240	2.27	1.39	-.71	1.21
241	1.49	.44	+.25	1.54
242	1.30	.75	+.43	2.00
243	1.23	.39	+.18	1.10
244	1.43	.98	-.53	1.06
245	1.88	.60	-.11	1.63
246	2.10	.25	-.12	1.26
247	2.18	.18	-.01	0.97
248	2.24	.32	-.06	1.48
249	2.23	.28	+.10	1.11
250	2.28	.26	+.10	1.04
253	2.13	.41	+.18	1.25
254	2.41	.50	+.11	0.93
295	2.50	1.04	-.73	2.01
296	3.24	.32	-.29	1.51
297	2.94	.59	-.46	1.21
298	1.18	.39	+.14	1.23
299	0.89	.66	-.12	1.08
300	1.83	.97	-.29	1.30
301	2.30	.60	-.24	1.44
302	2.33	.59	-.14	1.23
303	2.26	.56	+.02	1.23
304	2.31	.60	+.08	1.43

Insolubles

Sample	M_z	σ_I	Sk_I	K_g
145	3.22	.26	-.07	1.11
146	3.18	.28	-.13	1.05
147	3.01	.23	-.03	1.07
148	2.63	.44	+.04	1.05
Nuclei	2.68	.38	-.18	1.04
Channel				
224	2.65	1.16	-.82	2.26
225	2.85	.43	-.28	1.16
226	1.23	.23	-.02	1.04
230	1.30	.51	-.32	1.02

3. Cumulative frequency curves

The following cumulative frequency curves are plotted on arithmetic probability paper. In order to keep the illustrations to page size, the range of size classes shown was limited to the interval from zero to+4.00 phi inclusive. Where the 5 percentile occurs at sizes coarser than 0 phi, it's value is shown at the left hand side of the sheet.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PHI PERCENTILES
145 X
146 O
147 •
148 +
149 □
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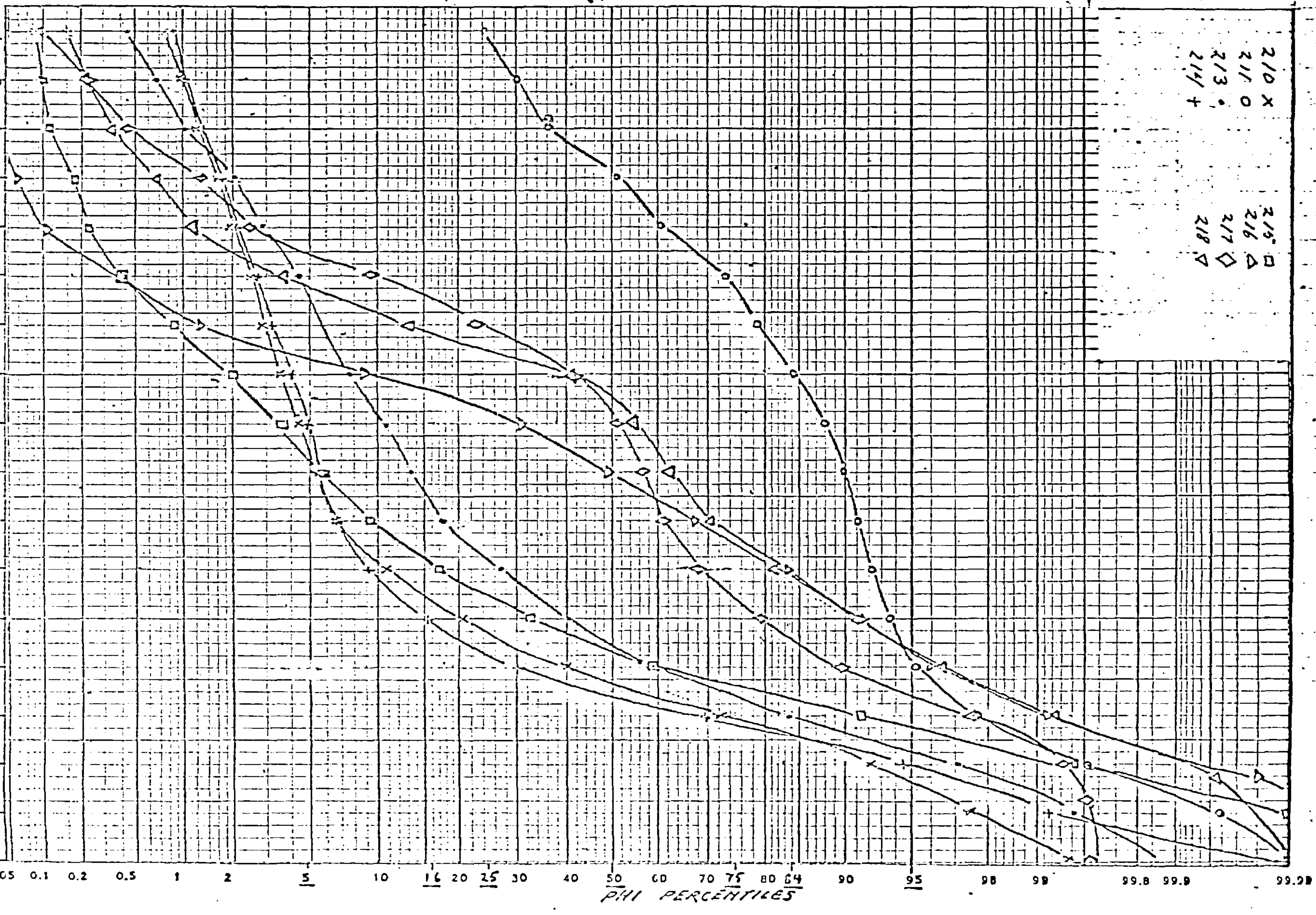
152 ◇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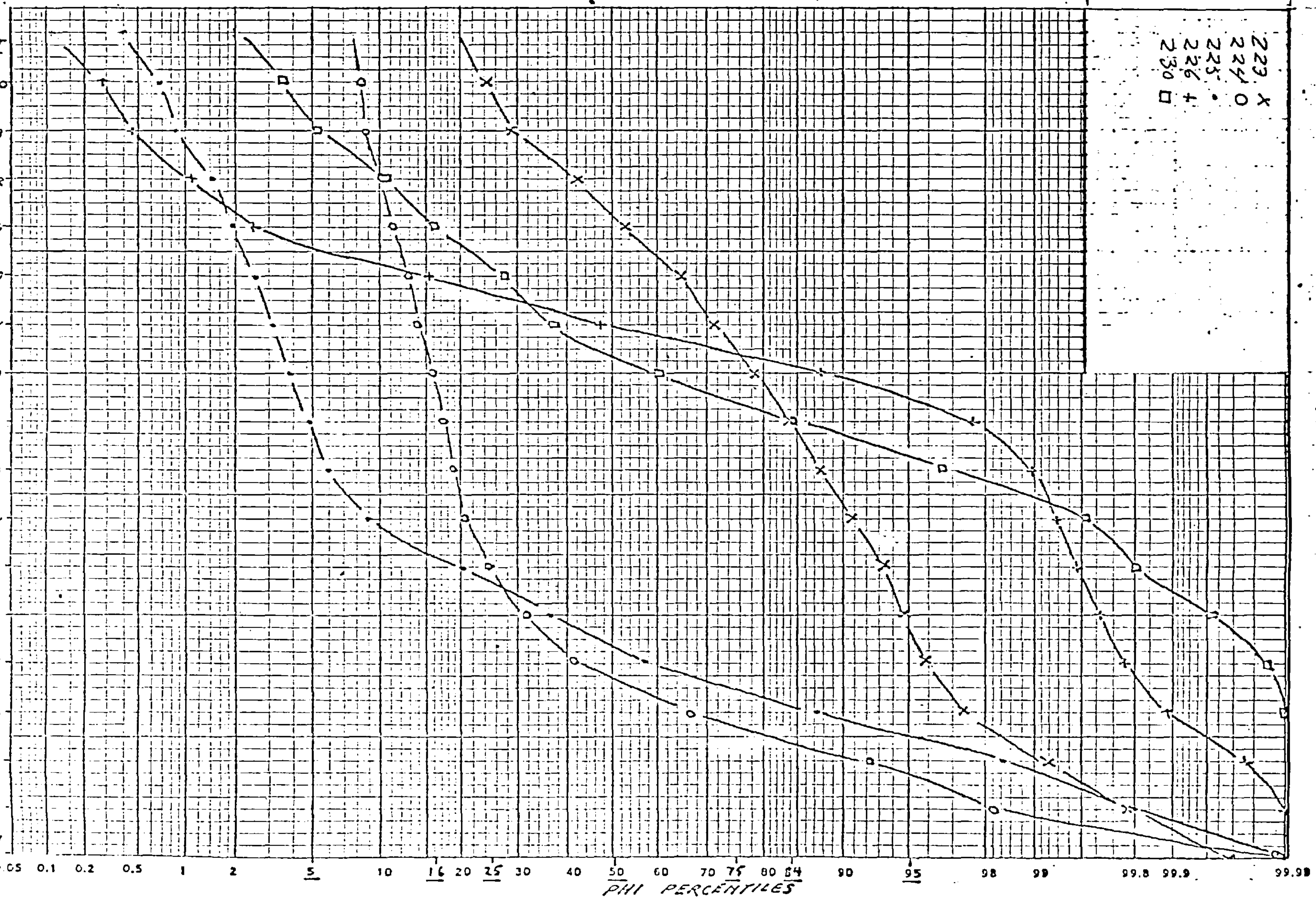
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PHI PERCENTILES
223 X
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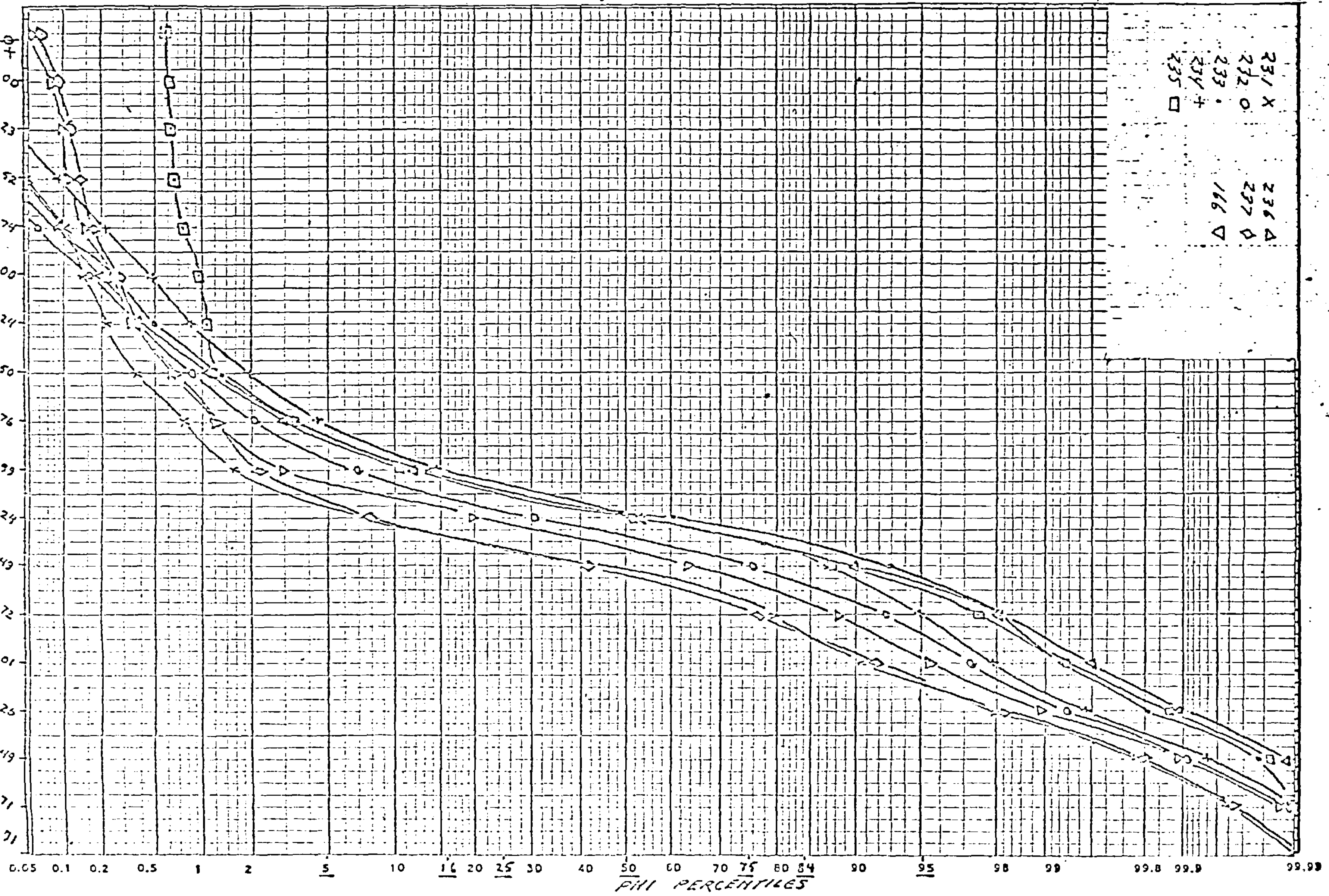

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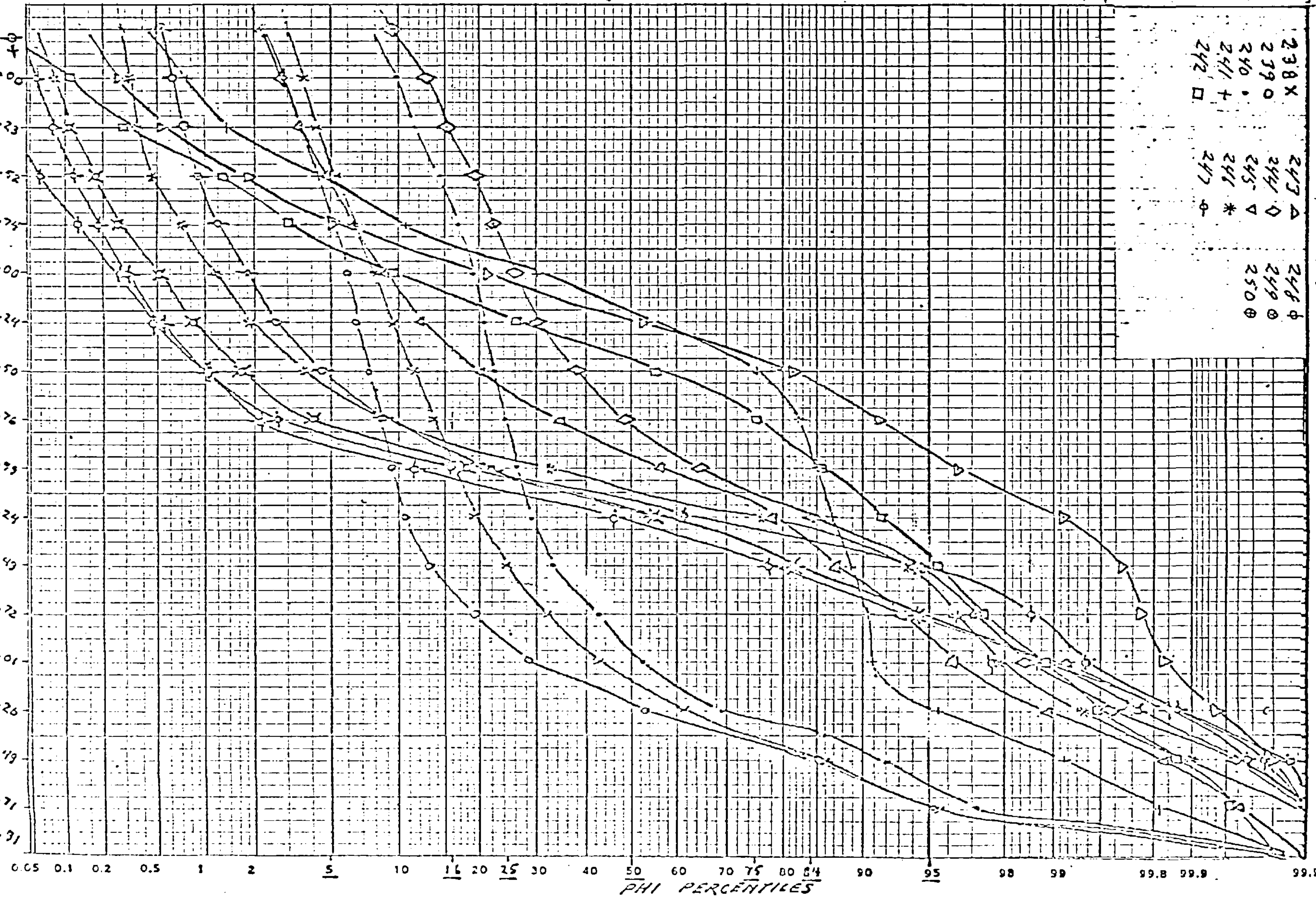
166 ▽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PHI PERCENTILES
238 X
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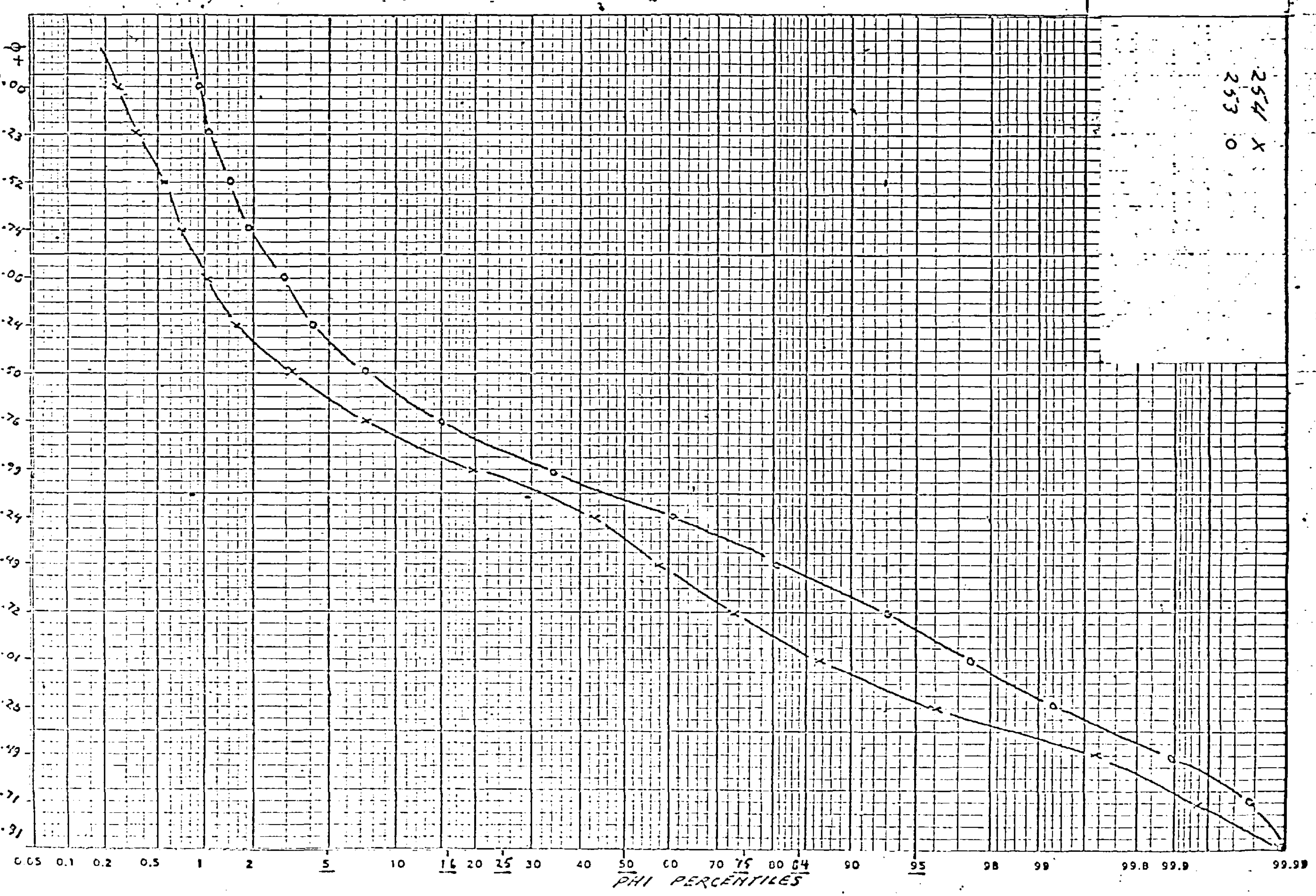
247 ϕ
248 ϕ
249 ⊗
250 ⊕



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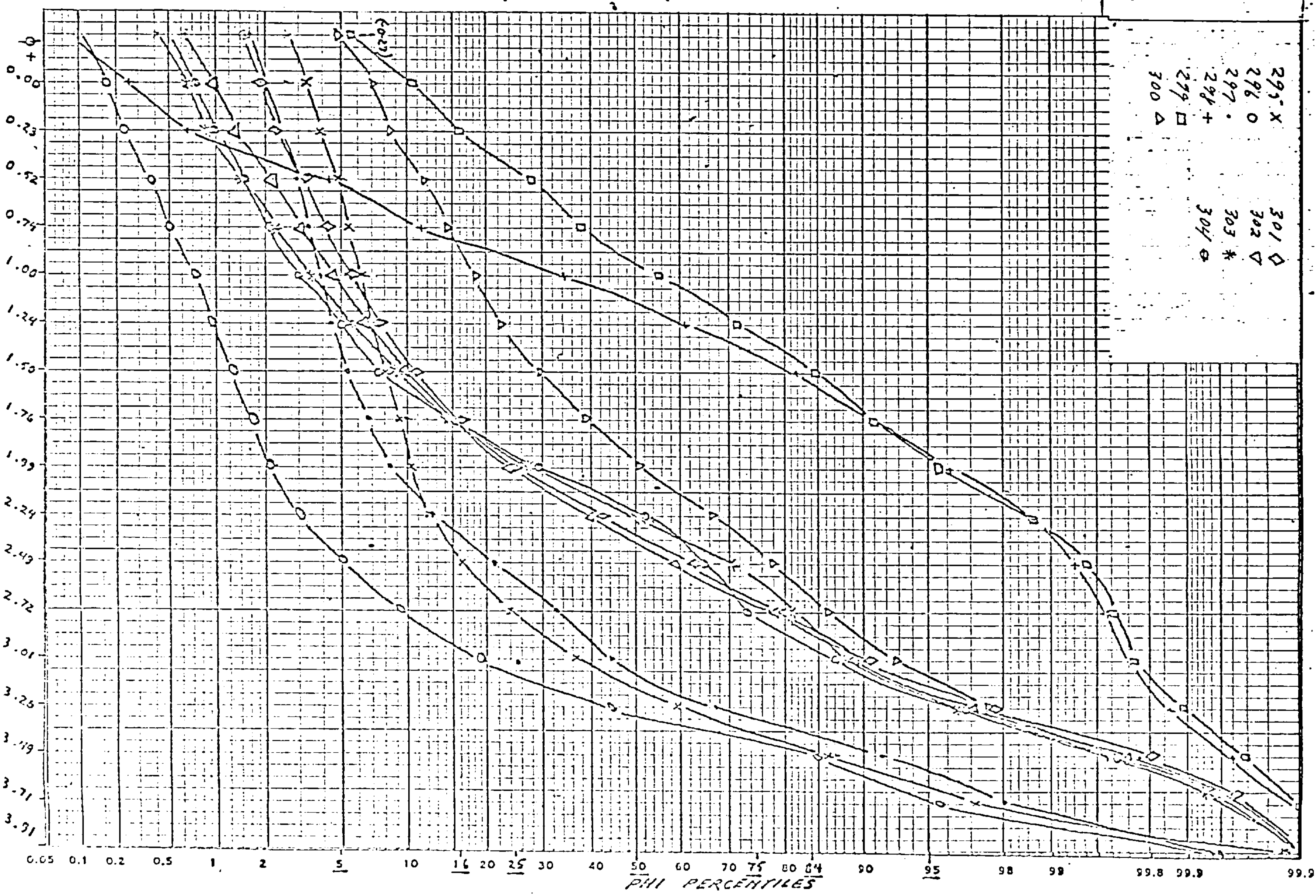
PHI PERCENTILES
254 X
253 O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PHI PERCENTILES
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298 +
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301 ◇
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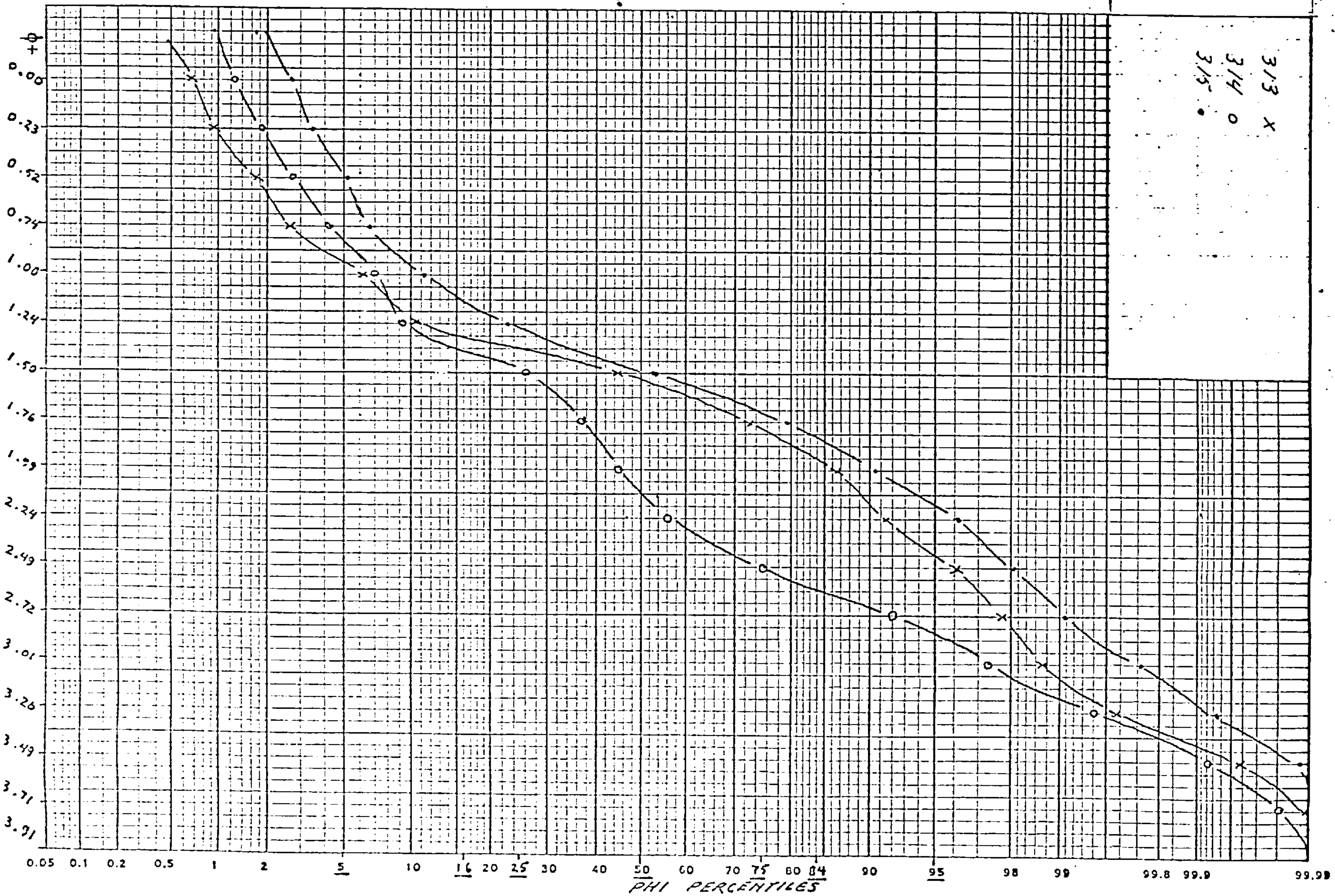
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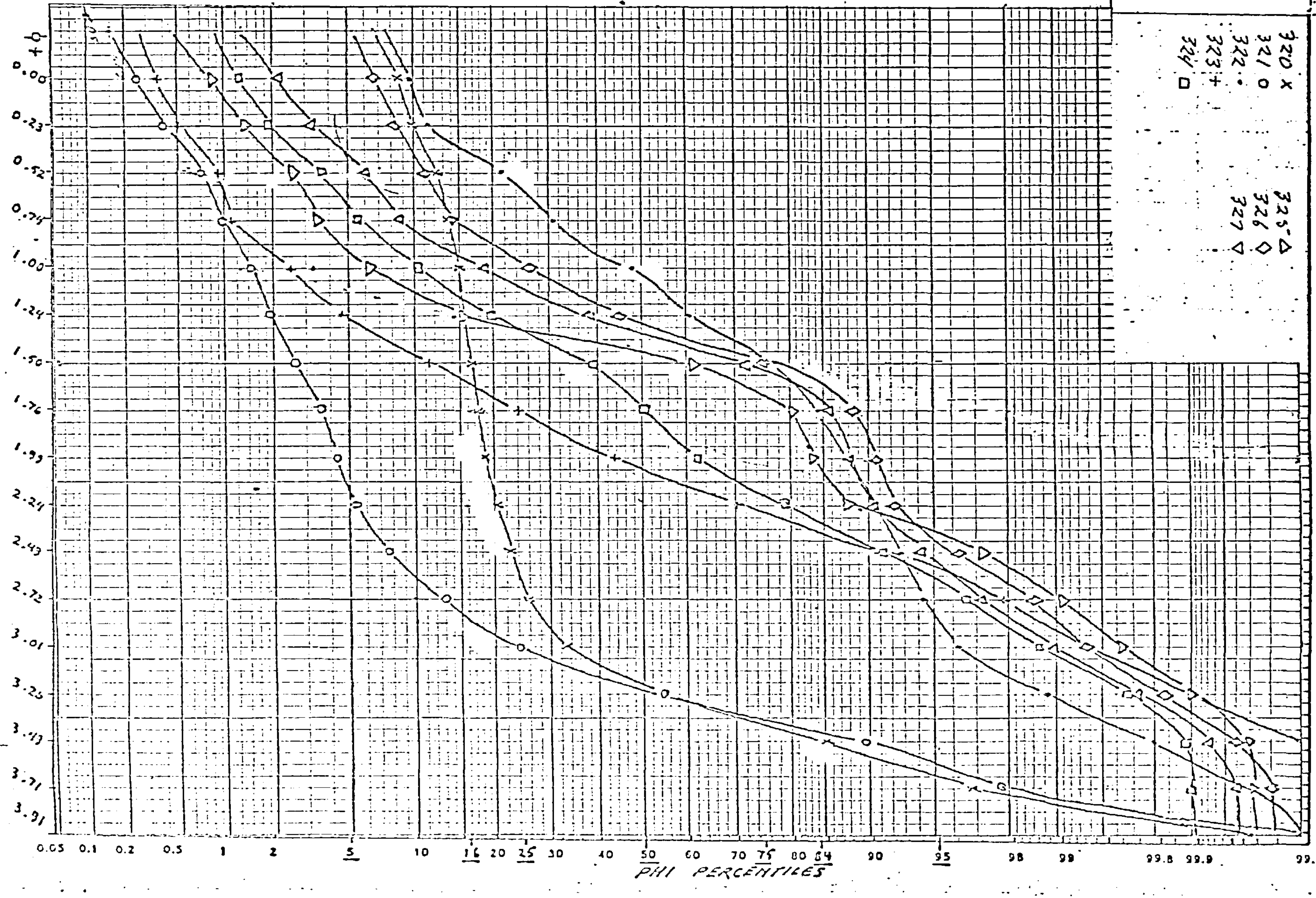
PHI PERCENTILES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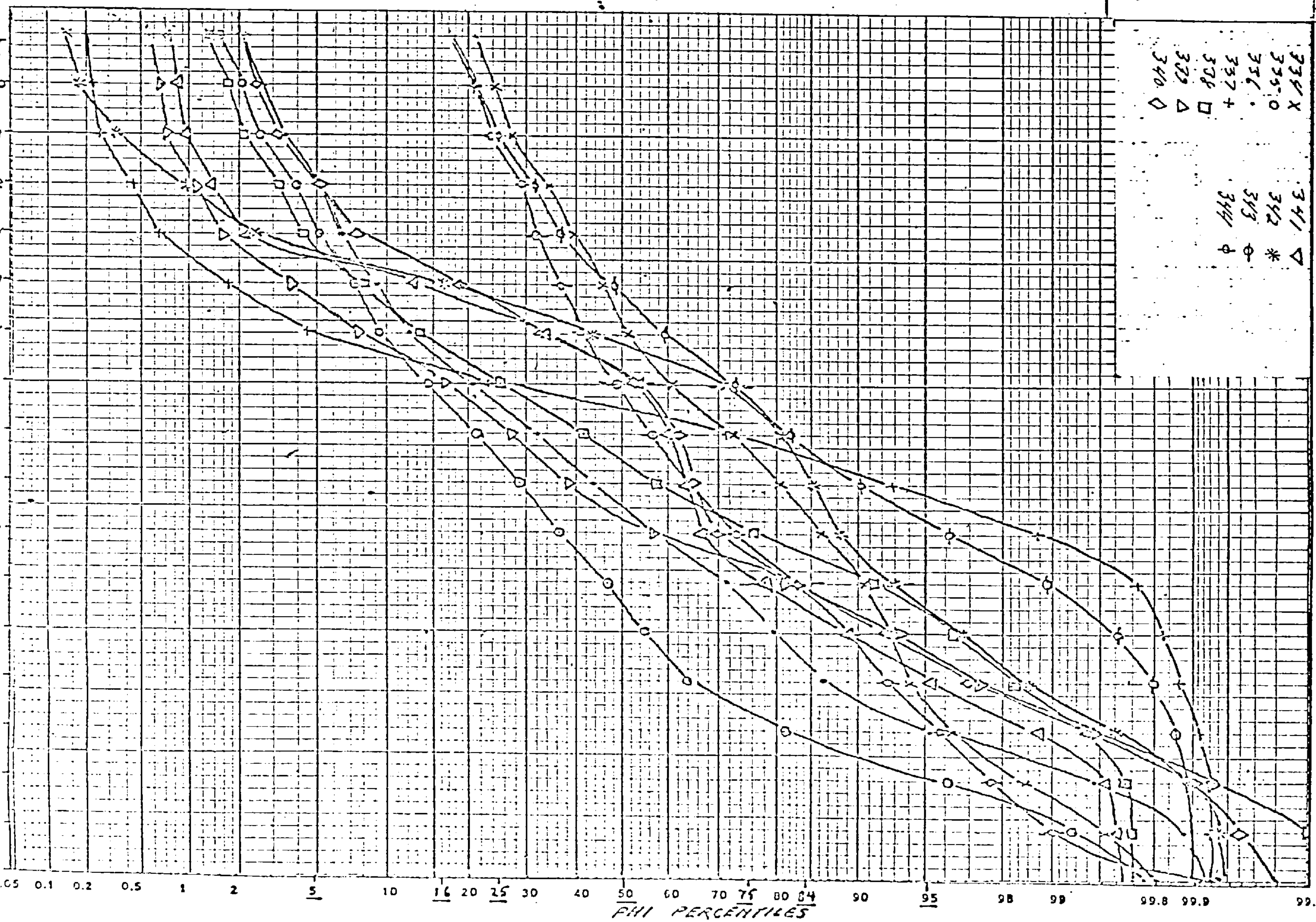
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PHI PERCENTILES
334 X
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337 +
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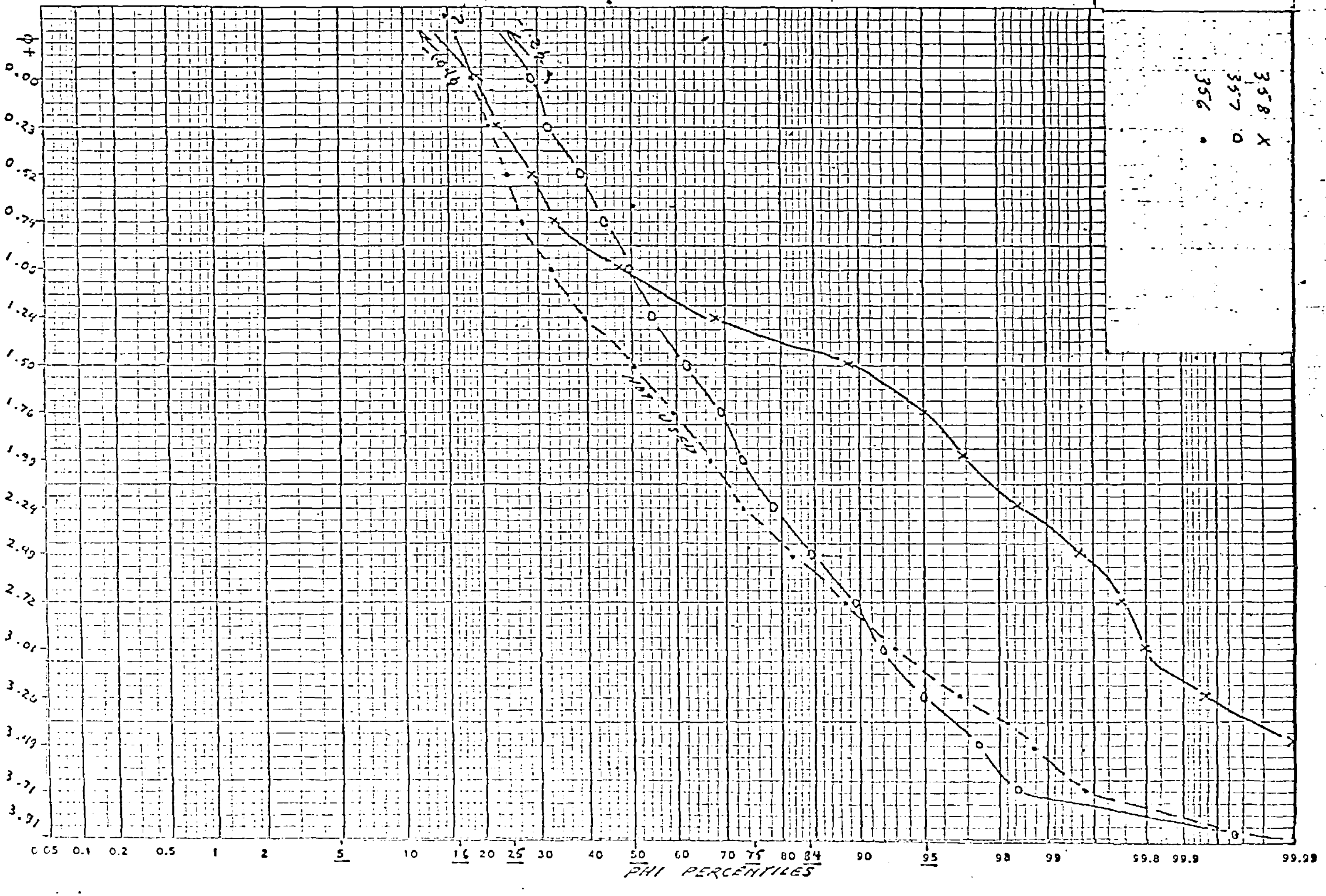
340 ◇
341 △
342 *
343 φ
344 φ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PHI PERCENTILES
358 X
357 O
356 •

4. Data derived from sieve analysis

The following tables give the weight percentages of sample caught on the 21 sieves used to analyse the delta sediments. Modal classes are indicated by brackets. Sieve sizes are given in phi units.

Sample	145	146	147	148	149	150	152
-1.0	2.86	3.20	0.03				0.94
- .75	0.22	0.63				0.02	0.82
- .50	0.22	0.56	0.03		0.02	0.05	1.60
- .25	0.38	0.63	0.03		0.00	0.05	2.83
0	0.29	0.74	0.03		0.02	0.09	4.68
+ .25	0.25	0.63	0.03	0.03	0.05	0.11	5.53
+..50	0.54	1.06	0.12	0.05	0.27	0.69	(14.00)
+ .75	0.64	0.50	0.12	0.10	0.50	1.08	10.17
+1.00	0.51	0.65	0.24	0.40	2.02	6.73	(22.67)
+1.25	0.38	0.36	0.24	1.22	4.51	15.30	16.14
+1.50	0.54	0.56	0.54	10.17	25.26	(34.01)	11.56
+1.75	0.60	0.63	1.01	(30.63)	(32.59)	14.86	3.55
+2.00	0.60	0.61	1.37	25.15	17.24	7.19	1.54
+2.25	0.95	0.61	2.26	18.87	8.22	5.29	1.04
+2.50	2.13	2.34	7.03	10.66	5.31	(5.50)	0.63
+2.75	4.96	4.50	15.73	2.26	2.77	4.31	0.41
+3.00	10.30	9.61	26.88	0.45	0.57	2.82	0.53
+3.25	26.39	29.41	(33.67)	0.17	0.53	1.69	0.85
+3.50	(32.40)	(32.18)	9.74	0.03	0.11	0.37	0.38
+3.75	11.77	8.57	0.89	--	0.02	0.05	0.06
+4.00	3.15	1.98	0.18	--	--	--	0.03
Total	100.08	100.06	100.17	100.19	100.01	101.21	99.96
Weight	31.480	44.42	33.62	40.38	43.68	43.75	31.83

Sample	166	210	213	214	215	216	217
-1.0	--	0.72	0.14	0.49	0.02	--	--
- .75	--	0.02	0.07	0.11	0.02	0.02	--
- .50	--	0.02	0.12	0.11	0.02	0.00	0.02
- .25	.007	0.02	0.12	0.16	0.02	0.00	0.09
0	.005	0.21	0.24	0.20	0.02	0.00	0.12
+ .25	.007	0.23	0.36	0.22	0.02	0.02	0.23
+ .50	.027	0.47	0.96	0.45	0.06	0.02	0.93
+ .75	.047	0.30	0.81	0.36	0.06	0.06	1.17
+1.0	.108	0.51	1.67	0.65	0.19	0.30	6.94
+1.25	.169	0.36	1.27	0.47	0.45	0.82	13.54
+1.50	.735	0.68	2.17	0.80	0.14	7.74	(18.90)
+1.75	1.762	0.89	2.68	0.83	1.63	(22.04)	9.51
+2.00	8.928	0.94	2.75	0.74	2.11	18.68	5.06
+2.25	(40.756)	1.38	4.30	0.93	3.46	17.88	4.68
+2.50	37.225	3.37	8.91	2.48	7.89	15.94	7.48
+2.75	8.359	10.99	13.60	6.22	15.93	8.0	10.18
+3.00	1.350	18.98	16.61	14.74	26.04	4.38	(10.39)
+3.25	3.99	(32.78)	(27.10)	39.83	(32.36)	3.24	8.46
+3.50	.103	19.51	13.26	24.62	7.98	0.84	1.68
+3.75	.010	5.28	2.27	4.71	0.67	0.08	0.14
+4.00	--	1.70	0.45	0.98	0.09	0.02	0.02
Total	99.997	99.36	99.86	100.15	100.18	100.08	99.54
Weight	40.815	46.89	41.79	44.90	46.60	50.04	42.85

Sample	218	224	225	226	230	231
-1.0	.019	2.842	.052	--	.409	--
- .75	.043	3.368	.105	0.039	.427	--
- .50	.049	0.450	.143	0.025	.411	--
- .25	.040	0.554	.095	0.045	.757	0.008
0	.062	0.939	.295	0.163	1.661	0.008
+ .25	.127	0.607	.176	0.166	1.564	0.015
+ .50	.359	1.467	.613	0.720	(5.659)	0.017
+ .75	.479	1.068	.501	1.479	5.306	0.052
+1.00	2.468	1.420	.677	12.494	(11.212)	0.042
+1.25	9.839	1.020	.542	32.407	10.060	0.077
+1.50	(28.162)	1.774	.767	(40.444)	22.942	0.158
+1.75	13.315	1.807	.893	9.730	(33.936)	0.379
+2.00	7.454	1.611	1.081	1.260	12.307	0.834
+2.25	7.751	1.987	3.000	0.298	2.880	6.963
+2.50	(11.249)	3.576	11.485	0.191	0.285	32.602
+2.75	9.823	6.921	15.919	0.152	0.140	(37.671)
+3.00	5.168	10.283	20.725	0.138	0.029	11.705
+3.25	2.864	25.195	(30.111)	0.143	0.016	7.495
+3.50	.684	(25.541)	11.221	0.082	--	1.766
+3.75	0.053	5.796	1.240	0.022	--	0.169
+4.00	--	1.760	0.373	--	--	0.031
Total	100.008	99.986	100.014	99.998	100.001	99.992
Weight	32.334	35.569	42.108	35.560	37.922	52.046

Sample	232	233	234	235	236	237	238
-1.00	--	--	--	0.543	--	--	1.886
- .75	--	--	--	0.006	--	--	0.383
- .50	--	--	--	0.027	0.030	0.031	0.261
- .25	--	--	--	0.009	0.024	0.033	0.485
0	--	--	0.012	0.021	0.018	0.017	0.572
+ .25	--	0.008	0.025	0.021	0.018	0.033	0.507
+ .50	0.011	0.023	0.055	0.051	0.018	0.028	1.363
+ .75	0.048	0.052	0.109	0.054	0.039	0.033	1,079
+1.00	0.098	0.158	0.291	0.185	0.098	0.080	1.632
+1.25	0.166	0.253	0.350	0.221	0.095	0.100	1.326
+1.50	0.523	0.811	1.096	0.639	0.284	0.283	2.121
+1.75	1.173	2.211	2.423	1.621	0.628	0.579	2.325
+2.00	4.783	10.029	9.829	6.620	1.650	1.152	2.325
+2.25	24.003	(46.585)	(39.124)	(41.809)	16.338	5.488	3.450
+2.50	(45.414)	32.811	33.756	35.637	(43.947)	33.527	5.018
+2.75	16.635	5.158	7.836	9.943	24.913	(35.431)	8.033
+3.00	4.339	1.108	2.937	1.872	7.188	14.564	11.005
+3.25	2.117	0.599	1.600	0.591	3.677	6.693	18.273
+3.50	0.600	0.173	0.495	0.113	0.933	1.718	(24.196)
+3.75	0.077	0.021	0.062	0.018	0.089	0.177	9.369
+4.00	0.013	--	--	--	0.015	0.033	4.389
Total	100.000	100.000	100.000	100.001	100.002	100.000	99.998
Weight	37.841	38.716	40.239	33.502	33.750	36.096	26.405

Sample	239	240	241	242	243	244	245
-1.00	1.247	4.134	--	0.058	--	2.956	1.047
- .75	0.246	1.375	--	0.069	0.044	1.967	0.331
- .50	0.343	1.223	--	0.143	0.051	2.028	0.393
- .25	0.445	1.238	0.023	0.151	0,046	2.832	0.485
0	0.716	2.017	0.100	0.386	0.131	(3.168)	0.624
+ .25	0.462	1.393	0.170	0.534	0.236	2.113	0.564
+ .50	1.034	(3.354)	1.021	3.210	1.324	(4.084)	1.357
+ .75	0.636	2.249	1.786	6.394	3.300	3.002	1.405
+1.00	0.879	2.287	6.805	20.111	15.934	(4.316)	2.613
+1.25	0.570	1.358	16.849	(22.357)	(31.007)	4.080	3.190
+1.50	0.843	1.969	(28.513)	22.098	29.334	7.664	8.467
+1.75	0.973	1.910	20.580	7.310	10.020	11.566	14.511
+2.00	0.923	1.648	10.065	2.359	5.006	15.341	21.491
+2.25	1.371	2.687	5.590	1.744	2.699	(19.762)	(21.698)
+2.50	2.693	5.097	3.701	1.657	0.504	9.653	9.121
+2.75	5.734	8.410	2.201	(2.264)	0.118	2.612	5.984
+3.00	9.671	9.806	1.224	0.135	0.085	1.370	2.901
+3.25	24.592	16.772	0.865	(4.452)	0.098	1.072	2.702
+3.50	(31.684)	(23.094)	0.375	3.752	0.039	0.370	0.962
+3.75	10.246	5.043	0.084	0.650	0.023	0.046	0.114
+4.00	4.692	2.927	0.030	0.161	--	--	0.032
Total	100.000	99.991	99.982	99.995	99.999	100.002	99.992
Weight	36.170	39.258	42.875	37.847	38.910	41.035	40.222

Sample	246	247	248	249	250	253	254
-1.00	0.224	--	0.281	0.021	--	0.349	0.043
- .75	0.029	--	0.133	0.021	--	0.162	0.009
- .50	--	--	0.031	0.005	0.027	0.093	0.082
- .25	0.026	--	0.074	0.008	0.016	0.162	0.048
0	0.055	0.022	0.108	0.029	0.014	0.202	0.102
+ .25	0.032	0.014	0.094	0.021	0.022	0.142	0.077
+ .50	0.126	0.024	0.219	0.073	0.044	0.405	0.179
+ .75	0.229	0.072	0.281	0.104	0.052	0.396	0.156
+1.00	0.492	0.152	0.664	0.252	0.155	0.965	0.364
+1.25	0.642	0.193	0.761	0.306	0.199	1.250	0.545
+1.50	1.853	0.620	2.036	0.922	0.506	3.378	1.588
+1.75	4.767	1.615	3.822	2.326	1.344	7.573	4.179
+2.00	24.609	13.291	11.889	14.356	9.235	19.382	12.577
+2.25	(43.820)	(45.777)	(35.548)	(37.066)	(34.973)	(26.770)	(23.754)
+2.50	17.305	32.270	25.323	26.827	30.921	19.262	14.407
+2.75	2.182	4.579	15.007	12.019	15.559	13.115	(15.569)
+3.00	1.529	0.746	2.925	4.167	4.824	3.767	12.665
+3.25	1.448	0.485	0.676	1.202	1.793	1.764	9.759
+3.50	0.532	0.118	0.116	0.241	0.286	0.721	3.475
+3.75	0.097	0.019	0.011	0.031	0.024	0.120	0.366
+4.00	--	--	--	--	--	0.024	0.051
Total	99.997	99.997	99.999	99.997	99.984	100.002	99.995
Weight	37.973	41.425	35.217	38.519	36.749	44.966	35.197

Sample	295	296	297	298	299	300	301
-1.00	1.156	0.007	0.723	0.011	0.777	1.570	0.787
- .75	0.535	0.022	0.338	0.016	1.012	0.892	0.275
- .50	0.512	0.055	0.254	0.018	1.258	1.015	0.221
- .25	0.503	0.011	0.318	0.055	2.498	1.517	0.221
0	0.671	0.070	0.318	0.176	4.895	2.146	0.353
+ .25	0.544	0.059	0.272	0.397	5.193	1.452	0.402
+ .50	1.026	0.157	0.662	3.743	(12.350)	(3.187)	1.024
+ .75	0.594	0.127	0.407	7.062	9.536	2.421	0.906
+1.00	0.766	0.227	0.561	22.656	(17.553)	(4.028)	1.628
+1.25	0.639	0.192	0.512	(27.055)	16.558	3.940	1.707
+1.50	0.973	0.337	0.977	20.348	12.481	6.795	3.394
+1.75	1.177	0.402	1.410	9.482	6.863	9.712	5.616
+2.00	1.026	0.470	1.858	4.999	4.481	11.963	8.749
+2.25	2.082	0.929	3.916	2.638	3.225	(15.613)	17.333
+2.50	4.229	2.065	8.615	0.649	0.766	11.650	(20.748)
+2.75	7.931	4.391	11.635	0.261	0.164	8.237	16.766
+3.00	12.384	9.747	11.742	0.147	0.134	6.537	10.808
+3.25	21.675	24.864	22.854	0.156	0.160	5.066	6.821
+3.50	(28.343)	(40.436)	(24.522)	0.092	0.080	1.986	2.006
+3.75	10.426	11.059	6.150	0.041	0.028	0.225	0.202
+4.00	2.806	4.375	1.910	--	--	0.046	0.030
Total	99.998	100.002	99.954	100.002	100.002	99.998	99.997
Weight	33.817	45.757	34.586	43.632	46.352	43.048	37.091

Sample	302	303	304	313	314	315	320
-1.00	0.109	0.129	0.257	0.068	0.209	0.567	3.19
- .75	0.134	0.084	0.040	0.050	0.063	0.459	1.02
- .50	0.150	0.127	0.099	0.119	0.229	0.391	1.33
- .25	0.230	0.088	0.128	0.199	0.329	0.580	1.33
0	0.359	0.220	0.254	0.240	0.513	0.789	1.70
+ .25	0.318	0.194	0.193	0.285	0.455	0.741	1.41
+ .50	0.873	0.638	0.483	0.820	1.148	1.634	(2.40)
+ .75	0.844	0.707	0.559	1.009	1.116	1.630	1.10
+1.00	1.590	1.328	1.034	3.439	3.119	4.549	1.38
+1.25	1.758	1.677	0.999	9.691	6.081	11.020	0.81
+1.50	3.445	3.703	3.417	(28.946)	(12.560)	(31.201)	1.10
+1.75	5.192	6.268	6.893	28.762	11.690	26.105	1.12
+2.00	8.759	12.810	15.073	13.046	8.426	11.314	0.99
+2.25	15.534	(22.391)	(22.568)	6.401	9.532	5.131	1.31
+2.50	(19.584)	20.316	11.002	3.020	(19.797)	1.962	2.30
+2.75	19.168	9.476	9.178	1.569	16.749	1.050	3.21
+3.00	10.656	7.508	(14.507)	1.085	5.421	0.536	6.98
+3.25	8.489	(8.941)	10.289	0.898	1.973	0.268	22.60
+3.50	2.476	3.031	2.689	0.313	0.510	0.062	(30.13)
+3.75	0.275	0.306	0.290	0.040	0.068	0.009	11.42
+4.00	0.057	0.056	0.048	--	0.018	--	3.14
Total	100.000	99.998	100.000	100.000	100.006	99.998	99.97
Weight	43.975	46.392	42.056	39.636	39.795	45.508	38.26

Sample	321	322	323	324	325	326	327
-1.00	0.05	5.53	0.06	0.39	0.02	2.43	0.11
- .75	0.00	0.38	0.08	0.12	0.04	0.65	0.13
- .50	0.05	0.60	0.08	0.13	0.18	0.89	0.35
- .25	0.05	1.12	0.06	0.23	0.22	1.27	0.67
0	0.11	1.90	0.09	0.37	0.38	1.63	0.90
+ .25	0.13	2.72	0.15	0.59	0.49	1.39	1.09
+ .50	0.32	(9.90)	0.40	1.77	1.29	(3.12)	(2.79)
+ .75	0.26	8.50	0.36	1.66	0.96	2.62	2.58
+1.00	0.50	(16.93)	1.33	5.07	2.83	12.21	10.29
+1.25	0.47	13.18	2.09	9.19	8.74	19.10	19.26
+1.50	0.71	(15.94)	6.58	(20.37)	(46.57)	(30.74)	(33.97)
+1.75	0.95	7.76	12.80	10.65	18.90	12.41	13.59
+2.00	0.82	3.30	19.47	11.68	3.03	2.33	2.71
+2.25	1.05	2.52	(27.30)	(16.46)	4.48	1.48	1.94
+2.50	2.24	2.36	21.03	12.59	(9.14)	(4.13)	(3.64)
+2.75	5.32	1.72	6.03	5.47	1.85	2.26	3.14
+3.00	11.28	1.92	1.48	2.04	0.51	0.74	1.68
+3.25	30.62	(2.48)	0.51	0.94	0.27	0.44	0.88
+3.50	(33.52)	1.03	0.09	0.22	0.07	0.12	0.21
+3.75	9.43	0.18	0.02	0.02	--	0.02	0.03
+4.00	2.11	0.04	--	--	--	--	--
Total	99.99	100.01	100.01	99.90	99.97	99.98	99.96
Weight	37.95	44.84	52.74	59.71	55.12	59.61	37.58

Sample	334	335	336	337	338	339	340
-1.00	14.84	0.74	1.01	0.10	0.85	0.29	1.14
- .75	2.09	0.28	0.23	0.06	0.11	0.07	0.19
- .50	1.92	0.28	0.27	0.02	0.16	0.10	0.37
- .25	2.39	0.26	0.52	0.02	0.25	0.10	0.39
0	3.32	0.48	0.75	0.02	0.37	0.10	0.54
+ .25	3.10	0.57	0.66	0.04	0.37	0.07	0.65
+ .50	7.02	1.38	1.67	0.19	1.10	0.39	2.00
+ .75	4.53	1.09	1.31	0.21	0.99	0.42	2.17
+1.00	7.29	(2.24)	2.90	1.10	3.74	2.20	11.52
+1.25	5.10	1.89	3.03	2.74	5.38	4.11	14.41
+1.50	9.51	4.94	8.23	19.32	12.41	8.85	(20.19)
+1.75	11.73	(7.69)	(11.62)	(48.08)	(16.20)	10.68	8.54
+2.00	7.37	6.98	11.11	20.85	15.76	10.81	2.78
+2.25	5.91	7.86	13.73	6.01	(18.31)	17.82	5.11
+2.50	4.56	(10.04)	(14.68)	0.97	15.21	(25.40)	(12.78)
+2.75	1.97	8.17	8.06	0.10	5.13	11.74	9.49
+3.00	1.40	9.09	6.66	0.04	1.98	4.11	4.75
+3.25	2.19	(17.47)	(8.85)	0.04	1.08	2.22	2.38
+3.50	2.44	14.81	4.19	0.02	0.27	0.46	0.51
+3.75	0.86	3.01	0.40	---	0.02	0.05	0.05
+4.00	0.27	0.50	0.04	--	--	0.02	0.02
Total	99.88	99.90	99.92	99.93	99.69	100.01	99.98
Weight	40.55	45.50	46.52	47.04	43.25	40.89	57.10

Sample	341	342	343	344	356	357	358
-1.00	0.37	0.02	7.21	8.27	10.886	8.095	Orig. Data
- .75	0.13	0.02	3.01	(3.05)	2.039	5.448	Sheet lost
- .50	0.11	0.04	3.73	2.81	1.595	4.826	Polymodal
- .25	0.13	0.06	3.34	3.28	1.656	4.906	Dist.
0	0.13	0.04	(3.97)	(3.39)	(2.333	(5.820)	
+ .25	0.11	0.16	3.55	2.89	1.817	3.801	
+ .50	0.41	0.62	(7.16)	(5.27)	(3.703)	(6.886)	
+ .75	0.80	1.32	4.59	2.96	2.716	4.225	
+1.00	10.60	14.02	(12.07)	(5.29)	5.804	5.906	
+1.25	17.62	24.10	11.26	4.34	6.856	5.316	
+1.50	(22.75)	(31.44)	(13.68)	7.43	(10.799)	(7.067)	
+1.75	7.35	10.44	10.66	(8.16)	9.198	6.473	
+2.00	2.15	2.88	6.61	7.13	6.854	4.954	
+2.25	3.92	3.06	5.32	8.88	7.244	5.052	
+2.50	(11.46)	(4.80)	2.77	(10.52)	(8.437)	(5.882)	
+2.75	11.11	3.60	0.70	5.36	6.730	4.367	
+3.00	6.07	1.92	0.18	3.56	4.188	3.019	
+3.25	3.58	1.08	0.07	3.20	3.750	2.922	
+3.50	0.74	0.28	0.02	2.03	2.180	2.422	
+3.75	0.07	0.04	--	1.23	0.597	1.136	
+4.00	0.02	---	--	0.89	0.59	1.477	
Total	99.63	99.94	99.89	99.94	99.979	100.000	
Weight	50.88	49.97	38.52	46.27	48.252	28.782	

INSOLUBLES

Sample	145	146	147	148
+1.75	--	0.06	--	3.37
+2.00	0.07	0.23	0.30	3.86
+2.25	0.33	0.23	0.25	9.50
+2.50	0.71	1.61	1.89	19.52
+2.75	3.87	5.37	12.36	(25.96)
+3.00	12.71	15.81	(37.18)	16.61
+3.25	(36.19)	(36.17)	36.32	15.58
+3.50	33.86	32.44	9.94	4.10
+3.75	9.75	5.60	1.24	1.65
+4.00	2.52	2.38	0.51	.54
Total	100.01	99.91	99.98	100.70
Weight	7.466	12.919	7.522	1.661

5. Data derived from measurement of oolite nuclei.

A thin section projector was used to project thin sections of oolite sediments from all over the delta onto a screen. Measurements of the oolite nuclei were then taken from the projected image using a specially prepared scale. Approximately 20 nuclei per section were measured in the 30 sections used. The total number of nuclei measured was 528. Nuclei smaller than 0.1mm (3.26 phi) were included in the 0.1mm category. To check the apparent similarity of nuclei sizes on the Abu Dhabi and Al Bahrani sections of the delta, an additional 118 nuclei from all sizes of oolites on the Abu Dhabi section and 34 nuclei from 2.00 phi (.25 mm.) and 2.24 phi (.21 mm.) oolites on the Al Bahrani section were measured. Results are tabulated below, followed by number percent histograms.

Nuclei from both sections of the delta (528 Nuclei).

Size		No.	No.%	Cumulative No.%
mm.	Ø			
0.40	1.24	1	0.19	.
0.35	1.50	2	0.38	0.57
0.30	1.76	12	2.27	2.84
0.25	1.99	28	5.30	8.14
0.21	2.24	33	6.25	14.39
0.18	2.49	59	11.17	25.56
0.15	2.72	108	20.45	46.01
0.124	3.01	189	35.79	81.80
0.100	3.26	96	18.18	99.98

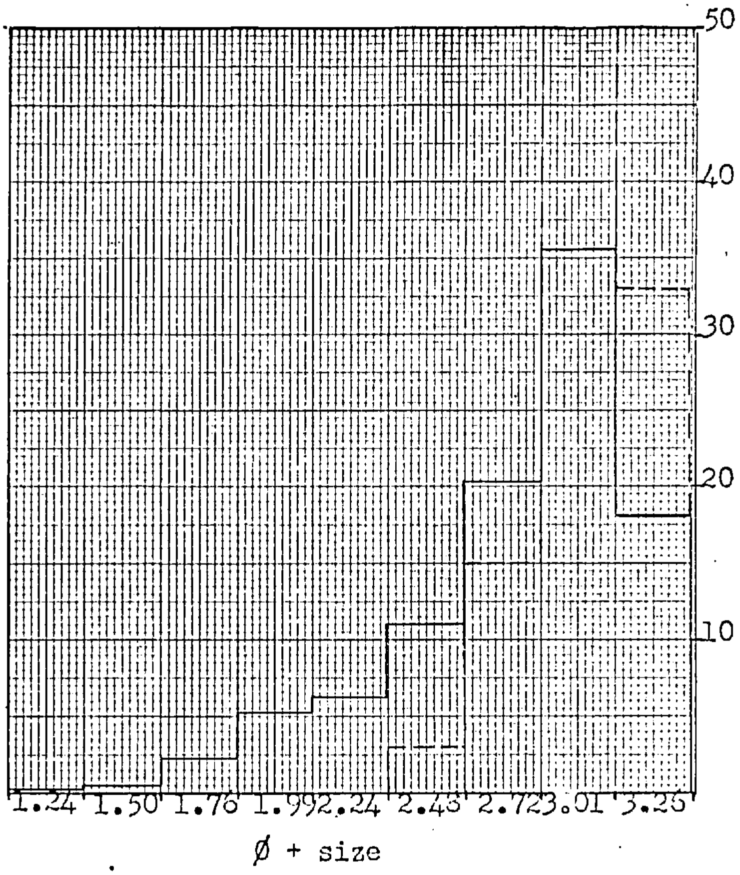
Abu Dhabi section (118 nuclei).

Size mm.	ø	No.	No.%	Cumulative No.%
0.35	1.50	1	1	
0.30	1.76	7	6	7
0.25	1.99	8	7	14
0.21	2.24	15	13	27
0.18	2.49	18	15	42
0.15	2.72	28	24	66
0.124	3.01	30	25	91
0.100	3.26	11	9	100

Al Bahrani section (34 nuclei).

In oolites of 2.00 phi (0.25 mm.) and 2.25 phi (0.21 mm.) diameter.

Size mm.	ø	No.	No.%	Cumulative No.%
0.18	2.49	1	2.94	
0.15	2.72	6	17.64	20.58
0.124	3.01	16	47.04	67.62
0.100	3.26	11	32.34	99.96



mm.

.40	.35	.30	.25	.21	.18	.15	.124	.10		Both sections (528 total)
1	2	12	28	33	59	108	189	96	No.	
.190	.38	2.3	5.3	6.2	11.2	20.4	35.7	18.1	No.%	All sizes of oolites

					1	6	16	11	No.	Al Bahrani section (34 total)
					3	15	50	33	No.%	2.00Ø-2.24Ø oolites

: Data and histograms for oolite nuclei measured in thin section. Solid line histogram for data from both sections of the Abu Dhabi-Al Bahrani Delta and dashed line histogram for data from the Al Bahrani Section. Note that nuclei smaller than 3.26Ø (0.10mm.) are included in the 3.26Ø class.