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PETROLOGICAL- STATISTICAL APPROACH FOR DIFFERENTIATION AND IDENTIFICATION OF FLUVIO-MARINE ENVIRONMENTS IN THE NILE DELTA, EGYPT

By

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Key Words: Petrology, Fluvio-marine environments, Nile Delta.

ABSTRACT

Textural and coarse fraction compositional components are evaluated to distinguish samples from modern environments of the Nile delta of Egypt. These environments include: river, coastal dune, accretion ridges, beach, nearshore, lagoon and prodelta. In this study petrologic variables (12 textural and 18 mineralogical, faunal and floral) were considered for each sample. Discrimination was achieved by using simple bar graph of the raw data for each environment and Q-mode factor analysis. The factor analysis yielded four compositional assemblages: Factor 1 is dominated by terrigenous fine sand, factor 2 consists of biogenic mud, factor 3 contains terrigenous coarse and medium sands and factor 4 comprises composite silty sand. Discrimination of the seven environments is generally good but less in beach, coastal dune and river sands.

Having discriminating the examined environments using Q-mode factor analysis, a graphical model was constructed to determine the origin of "unknown" samples. As a test, this model is satisfactory to identify and interpret the origin of sediments of Holocene age from two additional cores recovered off the delta coast.

INTRODUCTION

The sedimentary environment is an interaction of the physical, chemical and biological processes, under which a facies develops. Due to the fact that these processes differ from one environment to another, each facies has distinctive characteristics. The main sedimentary characteristics of a facies include: its lithology, composition, grain size, texture and structures, in addition to its biota and color. Therefore, the study of a single feature of a facies is the key to its environment. Hence a sedimentary environment would be best determined and evaluated by studying a combination of some of these features.

The primary goal of this study is to identify and discriminate between the major fluvio-marine modern environments of the Nile delta. The ultimate purpose is to develop a basis for identification of the specific Nile delta facies from small individual samples. Such interpretation of origins of "unknown" samples and identification of their depositional state would facilitate delineation of the former Nile distributary channels, pre-modern shorelines and associated ancient environments which can help in determining evolutionary changes of the northern part of the Nile delta.

Background

The classical Nile delta has began to form in Late Pliocene yet the modern one has developed since 6000-8000 years B.P (Stanley and Warne, 1994). During this long period, the Nile River contributed very large quantities of sediments to the Mediterranean Sea. In such manner, fluvial deposition built the delta gradually outward, whereas marine processes such as waves and currents transport some of these sediments in cross-shore and alongshore directions on the continental shelf as far as Israel (Ball, 1942; Hilmy, 1951; Inman and Jenkins, 1984). This represent a progradational and fluvially dominated phase in the recent history of the Nile delta. The most sedimentological aspect of this phase was the development of a series of fluvio-marine environments: channel-interchannel deposition in the upper delta plain; coastal lakes and lagoons in the lower plain; delta front with beach-dune complex; muddy lobes, prodelta and Late Holocene relict sediments on the continental shelf (Sestini, 1989). In addition, this phase is characterized by the formation and migration or abandonment of numerous distributary channels. Earlier historical documents and scientific evidences indicate the presence of at least seven branches crossed the delta during the Middle to Late Holocene time (pre-Dynastic to Roman time). Most of these branches silted up and no longer active due to the shift in the main flows of the Nile to the new Rossetta and Damietta (Fig. 1).

Recently, damming and complex channelization of the river cut off the revirine sediments to the Mediterranean coast. Such human interventions bring about the delta, indeed, in disequilibrium state as the hydrodynamic forces began to rework and assimilate the delta sediments. Hence, the delta became completely wave dominated and being suffering from series of responses such as coastline erosion, salinization and pollution (Stanley, 1996). Thus, one can note that the evolutionary stages of the Nile delta are controlled by natural and anthropogenic influences; sea level fluctuation, climate change, land subsidence, sediment influx, transport processes. The latter is the most important factor as it causes an eastward littoral transport as well as a seaward dissipation of the sediments and therefore affect greatly in the distribution and composition of the sediments on the Nile Delta coast and the adjacent environments.

MATERIAL AND METHODS

1. Sedimentological Procedures

A total of 210 samples were collected from seven modern deltaic environments: river (n=13), beach (n=52), coastal dunes (n=35), accretion sand ridges (n=15), coastal lagoons (n=38), nearshore (n=36), and prodelta (n=21). In addition, a series of 10 samples were selected from two shallow cores dredged from the nearshore zone off the Burullus-Baltim coast. Core V-6 was recovered in the inner shelf, 7.6 km northwest of Burullus inlet and core V-19 was collected 4.5 km north of Burullus inlet using vibrocorer. These subsurface samples were incorporated in this study to test the reliability of results. The two cores of maximum length of 4 m. Information about these samples are listed in Table 1 and locations are shown in Figure 1.

Each sample was first washed with fresh water and was oven dried. Then two subsamples were split from the bulk sample by using a sample-splitter. One of the two subsamples was desegregated to be used for textural analysis, while the other one was intended for the sand-size fraction (compositional) analysis.

Grain size determination was made by the conventional sieving method. Samples contained more than 5 % mud were subjected to pipette analysis according to the procedure of Folk (1974). Thus, grain size analysis resulted in 12 textural variables: -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and >10 Φ.

The analysis of sand-size fraction is carried out by a simple and rapid petrographic technique which depends on estimation of the sand size compositional constituents of the sample. This analysis was performed by splitting a cut from the sediment sample by using the microsplitter. This cut was then mounted over a girded tray to be examined under the binocular microscope. Grains were chosen by following a grid pattern on the tray as to avoid bias. For each sample, the relative percentages of 18 sand-size components were calculated from point counts of about 400 grains. These components include: light minerals, heavies, mica, "glauconite" (cf. Pimmel and Stanley, 1989), carbonate fragments, ooids, pyrite, gypsum, plant debris, echinoderms, sponge spicules, bryozoans, corals, molluscs, ostracods, foraminifera, shell fragments and "others" (these include any unidentified grains or biogenic shells).

Previous studies have proved that it is possible, by using this technique, to place unknown samples in their correct environments without knowing any prior knowledge about their origins or locations. Furthermore, it is very useful for extraction some valuable environmental information like, depositional areas, transport paths (cf. Pugliese and Stanley, 1991).

2. Statistical Procedure

Database induced from the above mentioned compositional and textural analyses was statistically treated by applying Q-mode factor analysis. Factor analysis is a multivariate statistical technique that results in considerable savings of efforts with negligible loss of information. It can be divided into two broad classes called R-mode and Q-mode techniques. The first is concerned with interrelations between variables. The latter describes the relationships among objects (samples) on basis of the variables. By employing Q-mode technique, a great number of data are collectively compared and reduced to few meaningful "factors" or "facies". Such new factors contain the same amount of information and facilitate the detection of any similarities or differences that may exist between samples. A detailed explanation of factor analysis and how it works is given by Imbrie and Van Andel (1964) and Klovan (1966).

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The database file is composed of all textural and compositional analyses data of the examined 210 surficial samples. This file is arranged in the form of N × n matrix, where N is the number of samples (210) and n is the vertical compositional-textural variables (30). This 210 × 30 matrix is subjected to Q-mode factor analysis using CABFAC program of Klovan and Imbrie (1971). From the output matrix, the first four eigenvalues which account for 82.73 % (Table 3) of the total information have been extracted. Therefore, the 30 variables are reduced to four factors (I, II, III, and IV) that would be managed for distinction between the study depositional environments.

3. Bivariate Plotting

In order to differentiate between the examined surficial environments, the varimax factor loadings of the four extracted factors were plotted on several bivariate diagrams. Each diagram shows two different factors plotted versus each other. Accordingly, six plots have been yielded: factor I vs. II (1), I vs. III (2), I vs. IV (3), II vs. III (4), II vs. IV (5), and III vs. IV (6). Based on these six factorial plots, each environment was compared with the other environments and attempted to be discriminated from them. Number of comparisons between environments is equal to (n2-n)/2, where n is the number of examined environments i.e. 21 comparisons were given (river vs. lagoon, river vs. dunes, lagoon vs. dunes,...etc.). As each comparison is based on the above mentioned 6 factorial plots, thus, a total of 126 (21 × 6) plots were generated. In each plot, the boundary line between the two compared environments is marked by a straight line. It is hand-drawn so that clear separation field, as can as possible, is obtained. All of these plots were visually categorized into 5 classes depending on the degree of distinction between samples of the two compared environments. These classes include: very good (wide separation field with no overlap), good (narrow separation field with no overlap), moderate (slight overlap), weak (partial overlap) and poor (considerable overlap).

RESULTS AND DISCUSSION

1. Main Characteristics of Modern Delta Facies

Figure 2 displays the sediment characteristics of each examined environment based on averaging relative percentages of the compositional and textural constituents. Assessment of these constituents would be very helpful for exploring the significant differences between each environment and the others. These differences can be generally ascribed to the variations in the environmental conditions and/or depositional processes, as represented in Table 3. On the other hand, these differences would be also very valuable for evaluating as well as discriminating each facies:

Sand Facies

These comprise the sand-rich environments: river, accretion ridges, beach, coastal dunes and nearshore facies.

River sand

The Nile River samples are moderately sorted ranging in size from fine- to medium-grained sands. These sands are enriched in light and heavy minerals. Common accessory components include mica and carbonate fragments. This fluvial facies is characterized, among other sand facies, by hosting the highest percentages of ooids, pyrite, sponge spicules and gypsum. Biogenic components and glauconite contents are the lowest of all other facies.

Coastal dune sand

The examined dune samples are very well sorted and very rich in fine- to medium-grained sands. Of the five Nile delta sand facies, the coastal dune sands are distinguished by the lowest proportions of carbonate fragments and also by abundance of heavy minerals (equals or second highest after beach sands). Proportion of light minerals is intermediate relative to other sand facies. Mica and glauconite pellets are common but their proportions are not diagnostic.

Accretion ridge sand

This facies is very poorly sorted varying in size from very fine to coarse sands. The most characteristic feature of this environment is its relative enrichment in light minerals, carbonate and shell fragments. It is very poor in heavy minerals and mica. Glauconite and gypsum are significant components.

Beach sand

The beach sands are well sorted fine to medium sands. This facies is characterized by its relative enrichment in heavy minerals as well as by the presence of some reworked marine biogenic components. Light minerals content is relatively lower than that of the river or dunes. With respect to mica proportion, it is very high; second largest after nearshore facies, whereas the glauconite proportion is intermediate relative to the other four sand facies.

Nearshore sand

This facies is composed of poorly sorted muddy sands. Comparing to the other sand facies. the nearshore sand has relatively high percentages of glauconite, mica, foraminiferas and plant remains. Light minerals record its lowest content, while heavies content is intermediate. Carbonate fragments, ooids and gypsum are relatively significant components.

1.b. Mud Facies

This facies comprises the samples which are composed of admixtures of silts and clays, or these which have a low sand content.

Lagoon mud

Among all other examined facies, the lagoonal deposits have the highest proportions of carbonate grains & nodules, plant remains, ostracods, molluscs, foraminifers and shell fragments. It is also distinguished by lowest light minerals and heavies proportions. Percentages of pyrite, gypsum and molluscs are generally higher than those of prodelta facies. They, therefore, serve as additional useful criteria for discriminating it from the prodelta.

Prodelta mud

Prodelta deposits, when compared with the other six facies, are found to be the richest in glauconite and mica. It is distinguished from the lagoonal mud by higher percentages of light minerals, heavies and also by the presence of some marine biogenic components such as echinoderm remains and bryozoans.

2. Application of Q-mode factor analysis for differentiation between modern environments

The resulting varimax score matrix is graphically depicted in Figure 3 to define the petrologic compositions of the extracted four factors. As shown in this figure, each factor score is represented by a series of bars of lengths proportional to the composition of this factor i.e. the longest bar contributes most heavily to the composition of that factor. From this figure, the composition of each factor has been interpreted as follows:

Factor I: **Terrigenous fine sand**

This factor represents samples that have a preponderance of fine sands and dominated by light and heavy minerals.

Factor II: **Biogenic mud**

Samples of this factor are composed of silts plus clays and rich in biogenic components (mainly ostracods, foraminifers and shell fragments).

Factor III: **Terrigenous coarse and medium sands**

It is associated with the coarse and medium sands that are dominated by light minerals.

Factor IV: **Composite silty sand**

Factor IV samples are silty sands enriched in some mineralogical components (light minerals, mica, gypsum and "glauconite") as well as some biogenic components like ostracods. foraminifers and shell fragments.

From results of the Q-mode factor analysis, some interrelations between compositional and textural constituents could be explored. These interrelations, as shown in Figure 3, include: concentration of terrigenous components in the sand fraction, association of biogenic components with silts and clays, and also association of mica together with glauconite pellets and their similarity in both abundance and behavior

From the bivariate plots in Figures 4 to 7, it is clear that the magnitude of discrimination between each two compared environments is directly related to the difference between factor loadings. An increase in the difference between factor loadings corresponds to an increase in this magnitude, so that best discrimination will be attained by maximum variation. On the other hand, the differences between factor loadings which, in turn, reflect variation in composition may be resulted from the difference in one or more of the following factors: modes of sediment transport, energy conditions, transport agent, medium of deposition and sediment supply.

Figures 4 (A to F), and 5 (A to D) show that the "factorial" plotting is quite effective for the differentiation of either prodelta or lagoon from each of the river, coastal dune, accretion sand ridges, beach and nearshore environments.

On almost all such combinations, samples from the two compared groups occupy different fields with no overlapping. They, therefore, provide a very good discriminations. This differentiation may be accounted for the contrasted energy conditions of the two groups. Both of the prodelta and lagoon sediments are deposited under low energy conditions with a least effect of waves or the other hydrodynamic factors, whereas sediments of the other group are accumulated under relatively active and high energy conditions. Differences in energy conditions are imprinted on sediments by adding or removing some constituents. Many authors have reported that the different energy conditions induce different textural responses (e.g. Inman,1949; Friedman, 1961; Visher, 1969 and Allen ***et al.***, 1971) as well as variable compositional components in the sediments (e.g. Krumbein and Sloss, 1963; Pettijohn, 1975, Inman and Jenkins, 1984; Frihy and Stanley, 1988 and Frihy and Gamai, 1991). Thus, contrasting of the energy conditions is expected to induce much different compositional-textural components in the sediments of the two groups and hence a clearest discrimination between them.

Figures 5 (E & F) display plots of good value for discrimination between coastal dune and both of the river and accretion ridge environments. This differentiation may be attributed to the difference in the medium of transportation. Dune sands are transported by wind while ridges or river sands are transported by water (waves and stream currents, respectively). Competency of wind to transport particles is generally weaker than that of waves or currents. The wind, therefore, selectively transport certain particles, usually the finer, rather do the former. In addition, wave action and water currents (with a less degree) are more likely to prevent deposition of fine particles than wind action (Friedman, 1961 & 1967; Shepard and Young, 1961). These differences in both type and nature of the transporting media are reflected in the factorial composition of each environment. Indeed, the wind blown sands were found to be rich in factor I (terrigenous fine sand). On the other hand, ridges are relatively poor in this factor but rich in factor III (terrigenous coarse & medium sands) and river sands are equally represented by both factors.

Factorial plots help also to discriminate satisfactorily between accretion ridges and both of the beach and river, coastal dunes and nearshore as well as between prodelta and lagoon (Figs. 6A to 6D). Despite some kind of overlap in these diagrams, they are able to discriminate, moderately, between each pair.

In case of sand ridges and beach (Fig. 6A), their discrimination is attributed to the difference in energy conditions. Sands of accretion ridges accumulate during storms and exceptionally high water (Psuty, 1966; Inman and Jenkins, 1984) much higher than that of the beach. Under these conditions, ongoing waves become strong enough to transport the coarsest sediments available on the beach to be heaped landward in the form of ridges (Reineck and Singh, 1980). Finer sediments require more time or lower energy to be settled with the coarse material, so they kept in suspension and transported seaward by the outgoing waves. Ultimately, accretion ridges would be composed mostly of coarse and medium sands whereas beach sands are normally finer in size.

Concerning ridges and river (Fig. 6B) the differentiation can be ascribed to the difference in transporting agent. The different actions of waves and stream currents under which ridges and river sands accumulate, respectively, release some textural and compositional variations. These include; concentration of coarse-grained particles and shell debris in ridges as waves are so vigorous that the fine particles are always kept moving and don't come to rest with the coarse particles. On the other hand, deposition on the river overbank comprises both fine and coarse terrigenous sands.

The discrimination between coastal dune and nearshore or between prodelta and lagoon (Figs. 6C & 6D) is most probably referred to the difference in the sediment supply. In the case of lagoon and prodelta, lagoonal sediments are derived from diverse sources (see Table 3) e.g. washover, tidal influx, river inflow, wind in addition to the bio-chemical in situ production (Nichols and Allen, 1978). Conversely, sources of prodelta sediments are limited. Most of these sediments are riverine in origin, where the sediment load (sand, silt and clay) of the Nile River accumulates at the mouths when it debauched to the sea. The sand-size components redistributed along the nearshore zone by the dominant east-trending longshore currents, whilst silt and clay are dispersed away toward the prodelta by rip and the other dispersion currents that induced from interaction between issuing and ambient waters.

Regarding the discrimination between the nearshore and dunes, sediments of the nearshore are derived from many different sources. The Nile River has been known as a major source for sediments on the continental shelf off Egypt (Ball, 1942; Hilmy, 1951). Organisms and authigenic components represent additional significant sources for nearshore sediments. Relict sediments of the old Nile branches have also been known to be reworked and redistributed along most of the nearshore zone Coutellier and Stanley, 1987; Frihy and Gamai, 1991; Stanley ***et al.***, 1992). On the other hand, dune sands are derived by the selective sorting of the wind to beach sediments. The wind pick up fine-grained particles from the beach to be accumulated as dunes.

In all these cases, differences between the two discriminated groups are likely imprinted on their factor loadings so that these factors would be varied enough to give adequate discrimination on the bivariate plots.

Figures 6E, 6F, 7A & 7B show that the discrimination of the nearshore from the river, beach and accretion ridges as well as between river and beach is weak. This is, more or less, due to the same sediment inputs (the Nile) transported by the same depositional medium (water). Dispersion and other coastal currents redistribute these sediments all over this zone. By means of longshore and cross-shore currents, sediments in the nearshore zone are drifted toward the shoreline to be deposited on the beach. Under stormy conditions, high energy breaking waves heap large quantities of these sediments onshore in the form of ridges. However, the slight discrimination between the nearshore and those environments is most probably attributed to the biogenic and authigenic production within the nearshore zone. Addition of such components results in compositional and textural constituents slightly differ from those of river, beach or ridges. The slight difference between river and beach may be resulted from actions of longshore currents and breaking waves under which beach sands are deposited and differ particularly from action of the stream currents which dominate in river environment.

Discrimination between beach and dune sands is not clear and insignificant (Fig. 7C). They are often quite similar. Previous studies of Friedman (1961), Shepard and Young (1961) and Reineck and Singh (1980) reported that sands may be transported from the beach to the coastal dunes and back again. Each sand grain may has been deposited many times either by water or by winds with the result that distinguishing between beach and dune sands is not so obvious. However, action of currents, waves or winds are insignificant and may not be enough to create an effective variation or diagnostic component.

Summary of these results are presented in Figure 8 where the 21 comparisons have coded from 1 to 21 and denoted by bold number placed in the upper left corner of each cell. The 42 bivariate plots which displayed here are highlighted by bold numbers placed together with the other non-selected ones in the lower half of each cell.

Testing for identification of subsurface samples of unknown origin

In the context of developing a basis for identifying the specific Nile delta facies from samples in subsurface borings, a series of generalized factorial scatter diagrams have been prepared. The factorial scatters were constructed by plotting the transformed compositional-textural data (data treated by Q-mode factor analysis) of the seven environments on two axes at a time. The scatter plot which showed the clearest separations between the whole environments has been considered as a model. By means of this model, origins of unknown samples can be identified. Figure 9 shows that among all possible factoriasl plots, plot 3 (factor I vs. IV) is the only one which permits a satisfactorily discrimination between all environments collectively. Visually, it can be noted that each environmental facies occupies for somewhat a specific field. This field is delimited manually. Also it is noted that beach and dune are considerably overlapped and occupy the same field. This reflects the great similarity between these two environments. Thus, partial overlap of other fields should reflect a particular similarity between their corresponding environments. Plots 1 (factor I vs. II), 2 (I vs. III), 4 (II vs. III), 5 (II vs. IV) and 6 (III vs. IV) are less helpful due to considerable overlapping of many environments.

The stratigraphic positions of the 10 core samples were known but no information was available as to sedimentary structures, hardness, color, etc., so that identification of facies could not be determined from the visually obvious petrologic attributes. By using the previously established model, an attempt is made to interpret the depositional origins of these samples.

At first, the compositional and textural attributes of each unknown sample were determined and recalculated in the exact same manner as with the original 210 samples. Then, a preliminary definition for their depositional origins has been indicated on the basis of these compositional and textural raw data. This definition is accomplished by correlating the compositional and textural percentages of each sample with the averaged percentages of each environment which are graphically represented in Fig. 2. According to the abundance of these attributes and the interrelations between them, a preliminary origin has ascribed to each unknown sample. Figure 10 shows that unknown samples No. 1, 2, 6 and 7 are correlated well with the accretion ridges, whereas samples 3, 4, 8 , 9 and 10 are the nearest to prodelta environment. Core sample No. 5 is best correlated with the nearshore environment. The petrologic data from the ten unknown samples were merged with the 210 original ones. Q-mode analysis was employed on the new N x n matrix (N= 220 and n= 30) following the same manner as cited before. The first four factors account for 81.86 % of the initial information were extracted and rotated. They are comparable to those of the surficial 210 samples of known facies (Table 2). In order to determine origins of the 10 unknown samples, the factor loadings of each sample were plotted on the prepared model. Their origins, then, were induced from the field in which each unknown sample fallen, as shown in Figure 11. According to the plot pattern, the first two unknown samples in both cores (samples No. 1, 2, 6 and 7) were identified as accretion sand ridges. Samples No. 3, 4, 8, 9 and 10 were identified as prodelta, whereas sample No. 5 was referred to nearshore environment. These interpretations are generally consistent with the results of Khafagy ***et al.*** (1989) and also with the stratigraphic positions of the unknown samples within the two cores.

CONCLUSION

The present study serves to discriminate, on basis of compositional constituents and grain size measurements, the modern sediments recovered from fluvio-marine environments in the Nile delta region and to provide information about their characteristics. Using bivariate plots of the statistically treated data, it is possible to discriminate most of the major fluvio-marine environments within the Nile delta. The ability to discriminate environments is related to several diverse factors, including sediment sources, hydrodynamic action and selective grain sorting. Bivariate plotting of factors extracted from data matrix is successfully defined depositional paleo-environment of subsurface core samples recovered from the Nile delta. This definition is consistent with interpretations achieved by previous studies. It is anticipated that application of the same method to the other sedimentary environments, especially those affected by the same sediment input, would successfully discriminate them .

Table 1. Information on the collected samples.

Environment	Sample Type	Location	No. of Sample	Total No. of Samples	Symbol in Fig. 1
River	Overbank	River Nile	13	13	●
Lagoon	Bottom	Edku Lagoon	7	38	*
		Burullus Lagoon	20		
		Manzala Lagoon	11		
Coastal Dunes	Composite	Edku	12	35	+
		Burullus	8		
		Gamasa	15		
Accretion Ridges	Composite	Tel Farama	15	15	♦
Beach	Beach-face	Nile Delta coast	52	52	o
Nearshore	Bottom	Inner shelf	36	36	x
Prodelta	Bottom	Rosetta Promontory	10	21	▲
		Damietta Promontory	11		
Unknown	Subsurface (core)	Baltim coast	10	10	★

Table 3. Eigenvalues and cumulative variance % of the 210 surficial samples.

Factor	Eigenvalue	Cumulative Variance %
I	116.35	55.41
II	34.69	71.93
III	13.33	78.27
IV	9.35	82.73
V	7.99	86.53
VI	4.61	88.73
VII	3.93	90.61
VIII	3.56	92.29
IX	2.46	93.46
X	1.84	94.34

Table 2. Summary of the main sedimentary characteristics of the major Nile Delta environments.

Environment	Definition	Textural-Compositional Criteria	Transport Agent	Depositional Processes
River	Natural flume accommodates and directs sediments from the drainage basin to the receiving basin.	Moderately sorted fine- to medium-grained sands rich in terrigenous components. Biogenic components are scarce.	Stream currents	Settling during floods and high water levels.
Lagoon	Interdistributary bay which opens to the sea and connected to it by small tidal channels.	Mud very rich in biogenic components especially ostracods, foraminifers, mollusks and plants.	Waves, tides & winds.	Washover, tidal influx, wave drift, river inflow & *in situ* production.
Coastal Dunes	Hills of wind-blown sands occupy the landward zone of the coast, marginal to the deltaic plain.	Very well sorted fine- to medium-grained sands very rich in terrigenous constituents.	Wind	Saltation
Accretion Ridges	Continuous linear mounds heaped by stormy waves and lienear high water line.	Very poorly sorted, very fine-to coarse-grained sands rich in light minerals & shell debris.	High (stormy) energy breaking waves & tidal currents.	washover & shoal
Beach	It occupies the region of high tide to that of low tide and separates subaerial delta from the subaqueous part.	Well sorted fine-to medium-grained clean sands, very rich in terrigenous constituents.	Breaking waves, tides & longshore drift.	Saltation + Rolling
Nearshore	A region from the continental shelf fronting the deltaic plain and receives most sediments delivered by delta proper.	Poorly sorted muddy sands dominated by mica, glauconitized pellets and foraminifers.	Waves and longshore & cross-shore currents.	Longshore & cross-shore drift
Prodelta	The finest and most distal sediments in the deltaic complex.	Pure to sandy mud rich in glauconitized pellets, mica and echinoids.	Rip and dispersion currents*.	Suspension settling.

*currents induced from the interaction between riverine and receiving basin waters.

To summarize up, quantitative assessment of both texture and composition of sand-size fraction is very helpful for distinguishing most of the modern Nile delta environments and also for interpreting the origin of unknown core sediments. However, this tool could be supportable to any other sedimentological criteria such as composition of the sand-size fraction, sedimentary structures, gross texture and position in sequence and would allow improved discrimination among the different studied environments.

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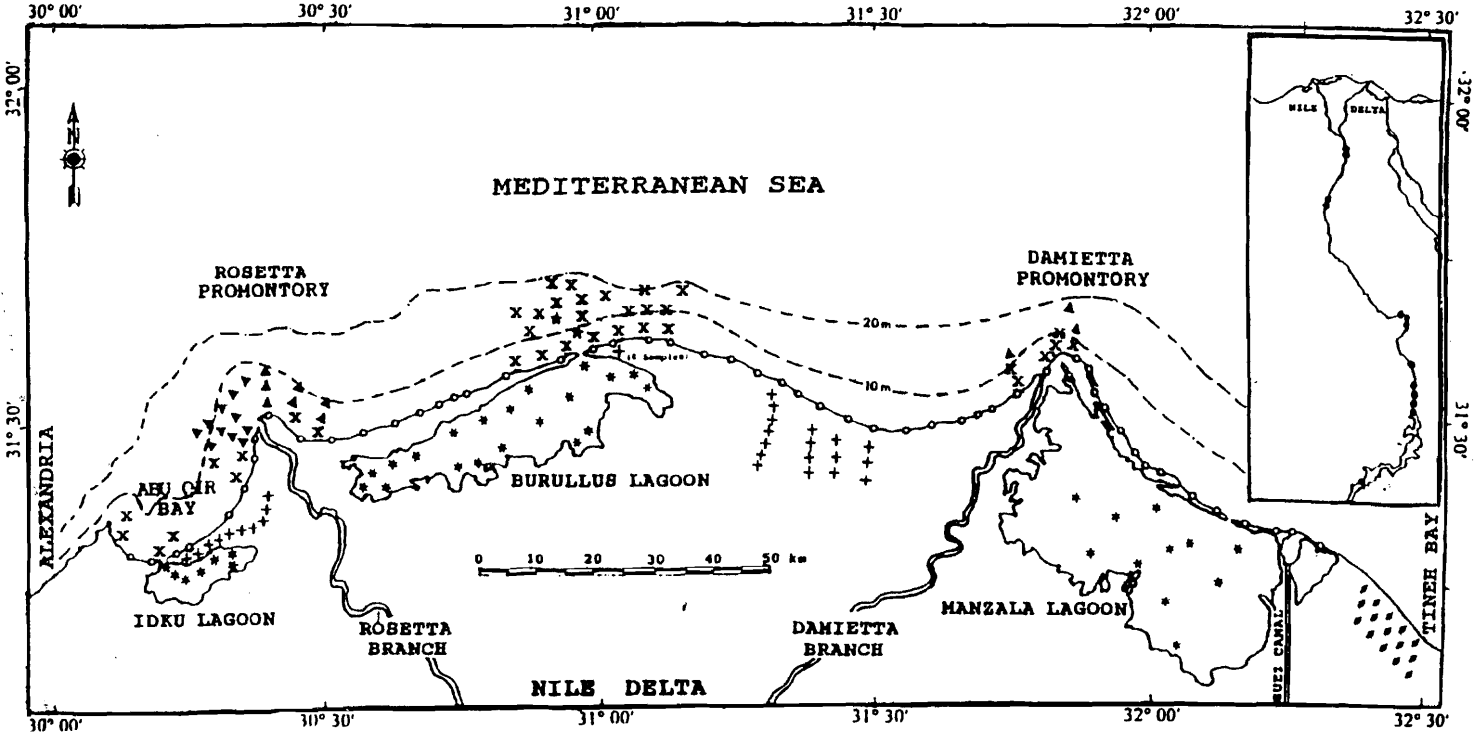

Fig. (1): Map of the study area showing locations of collected samples: • river; * lagoon; + coastal dunes; ♦ accretion ridges; O beach; x nearshore; ▲ prodelta and ★ examined core samples.

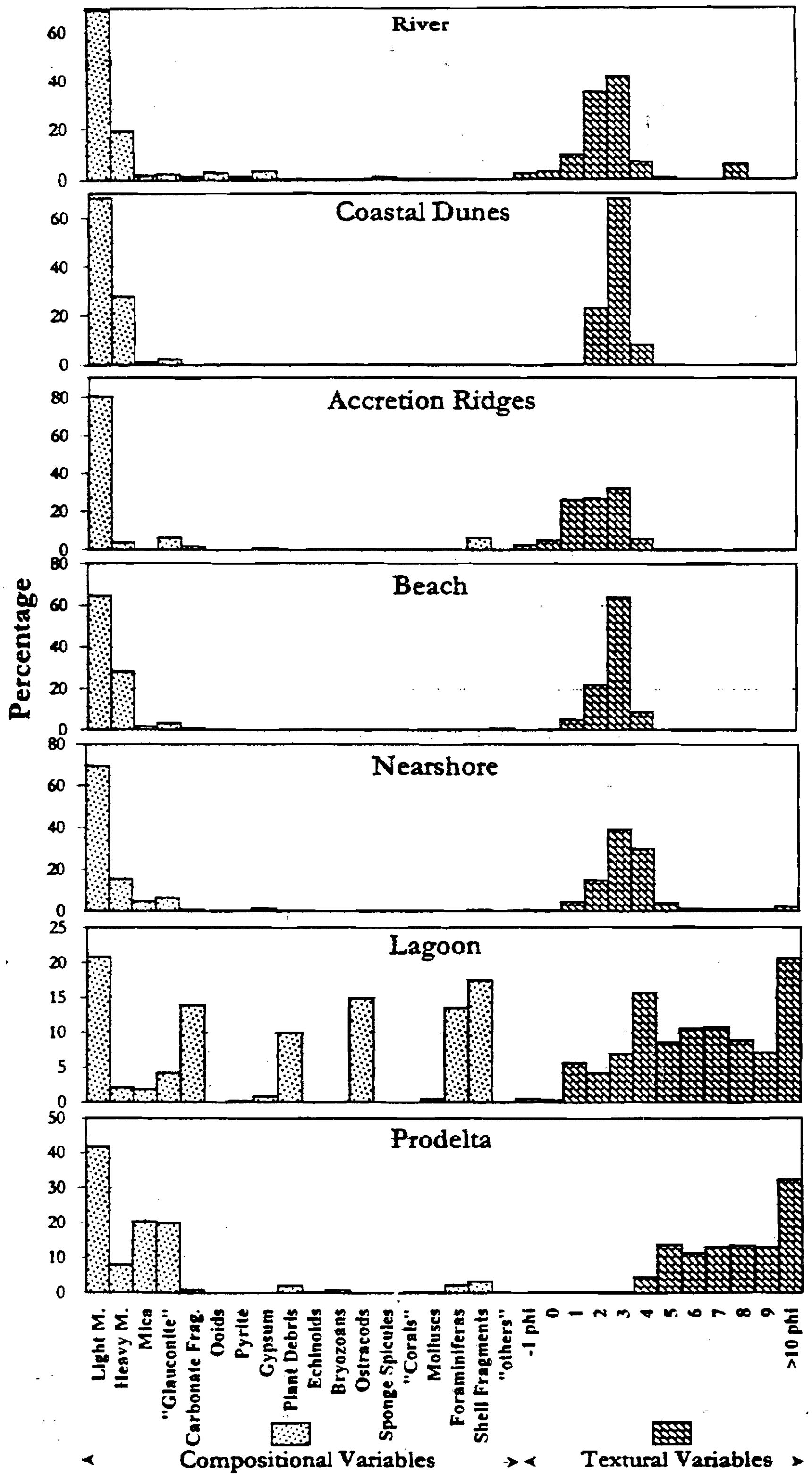

Fig. (2): Bar graphs represent the average percentages of the compositional and textural components of the study environments.

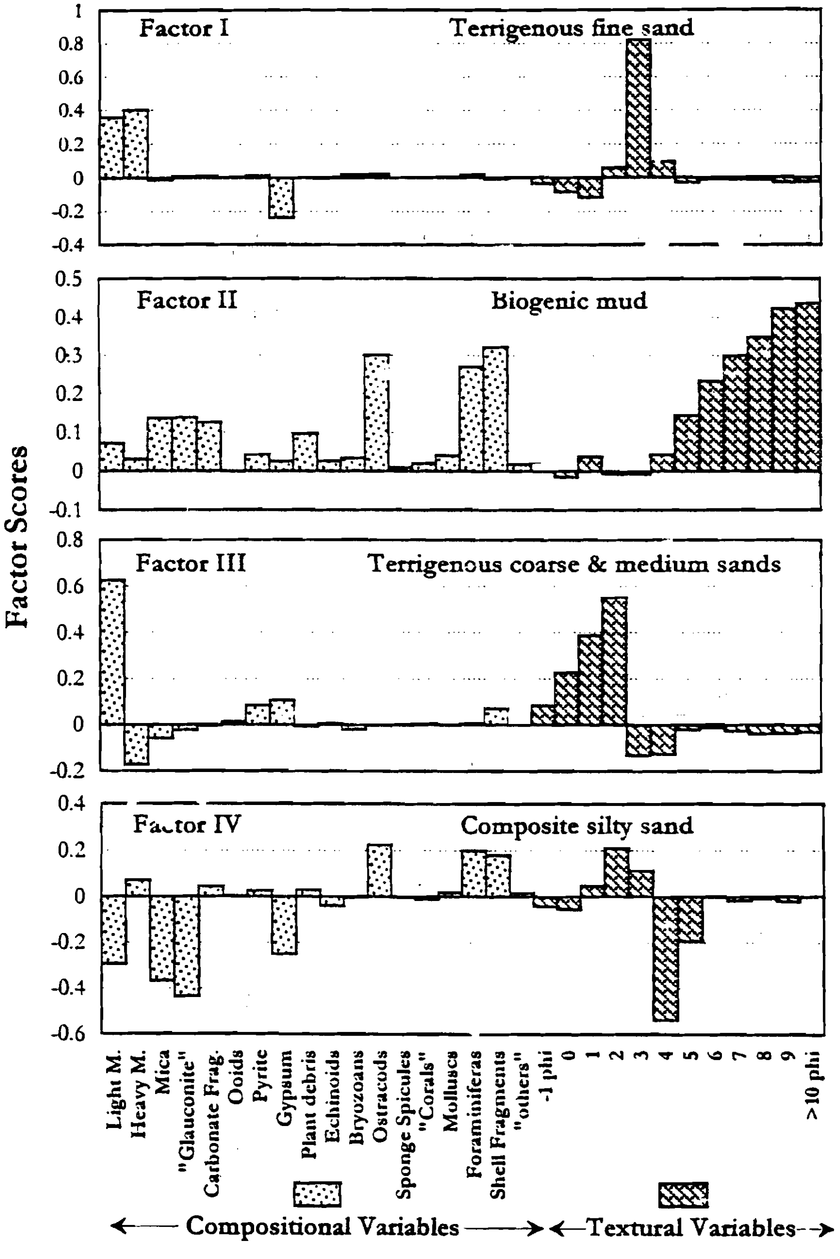

Fig. (3): Compositions of the four factors extracted from the application of Q-mode analysis to the compositional-textural raw data of the 210 surficial samples.

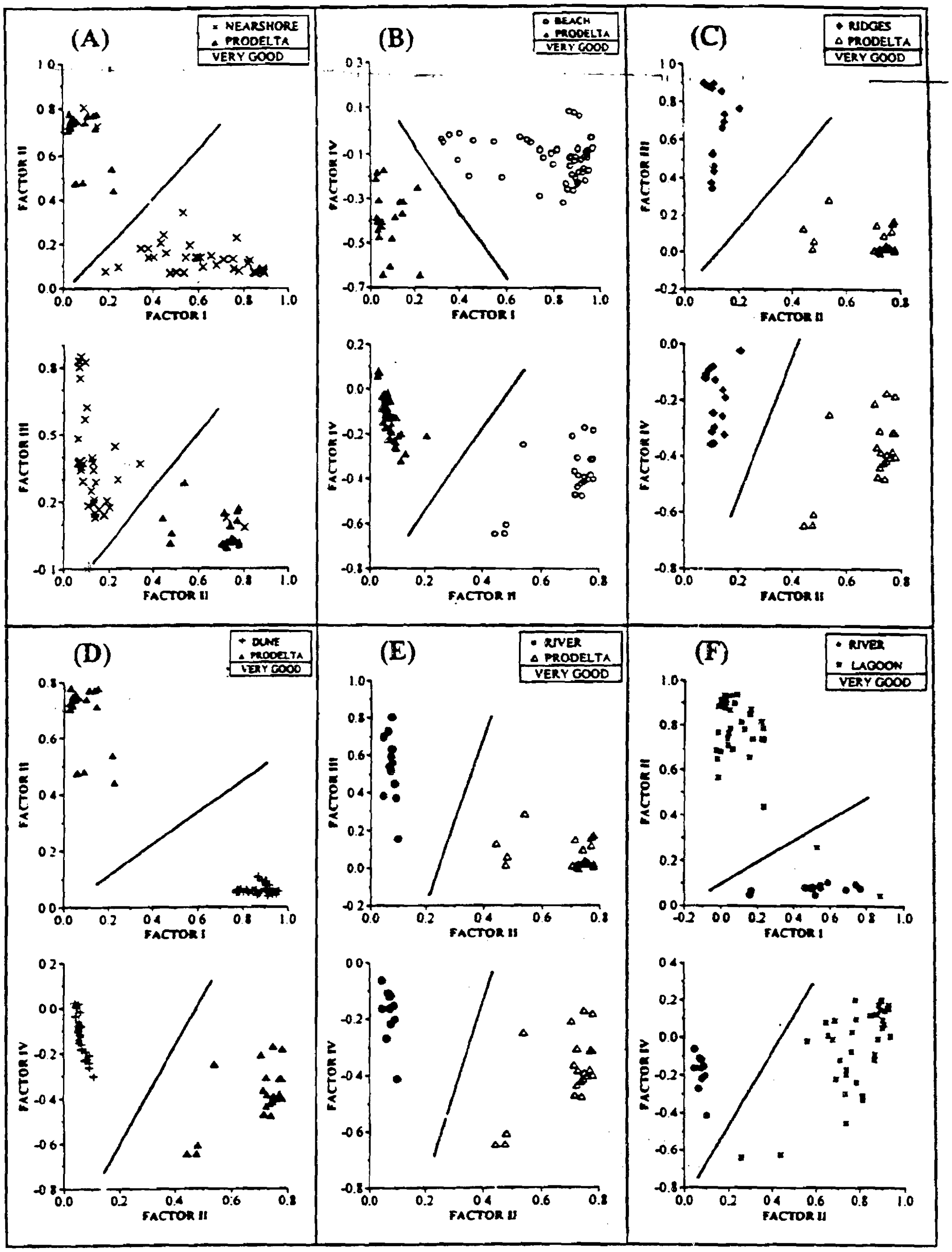

Fig. (4): Bivariate "factorial" diagrams showing very good discriminations between prodelta and each of the nearshore (A), beach (B), accretion ridge (C) dune (D) and river (E), as well as between river and lagoon (F).

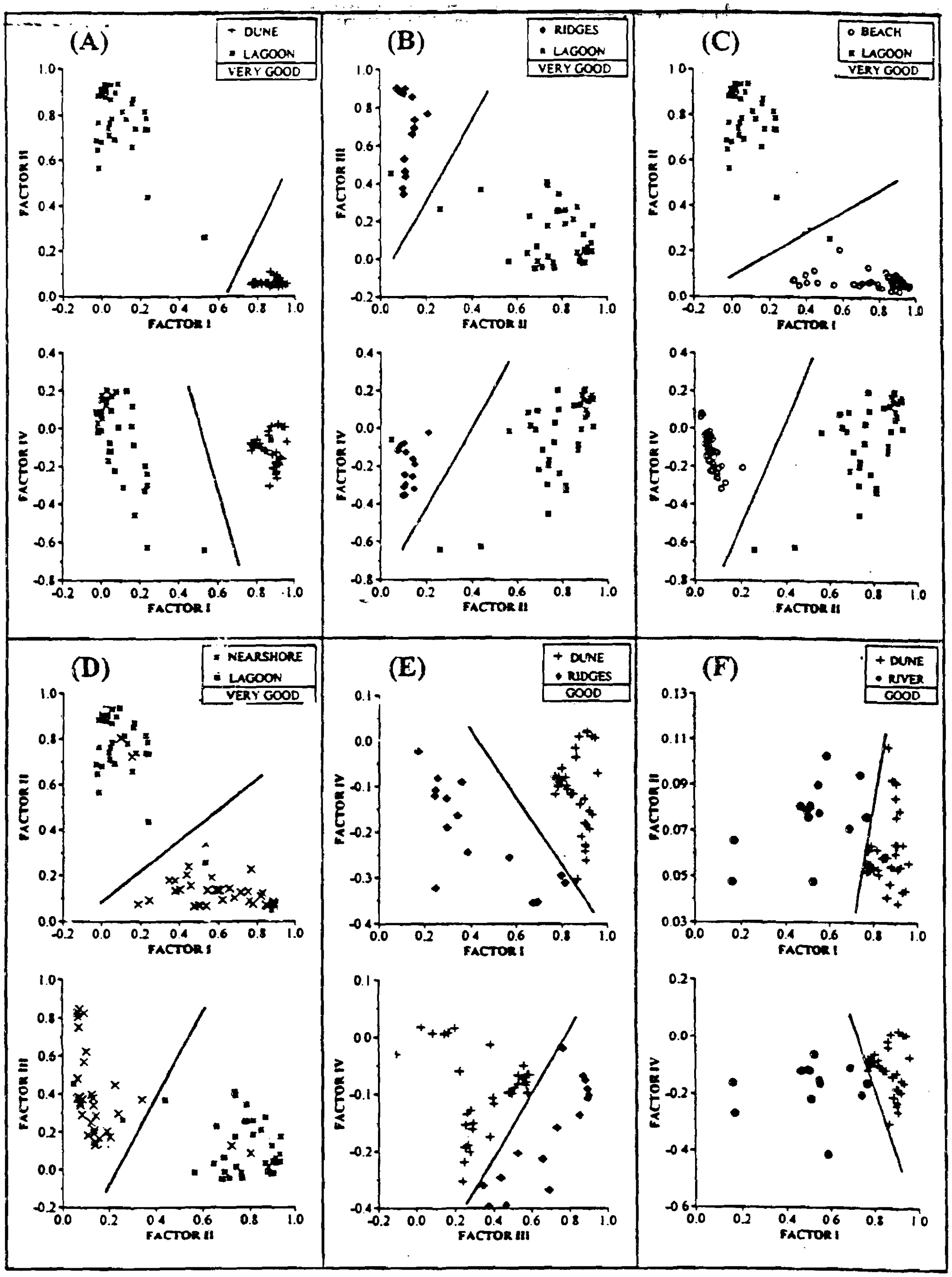

Fig. (5): Factorial plots showing very good discriminations between lagoon and each of dune (A), ridge (B), beach (C) and nearshore (D). E & F showing good discrimination between the dune and both of the ridge and river environments, respectively.

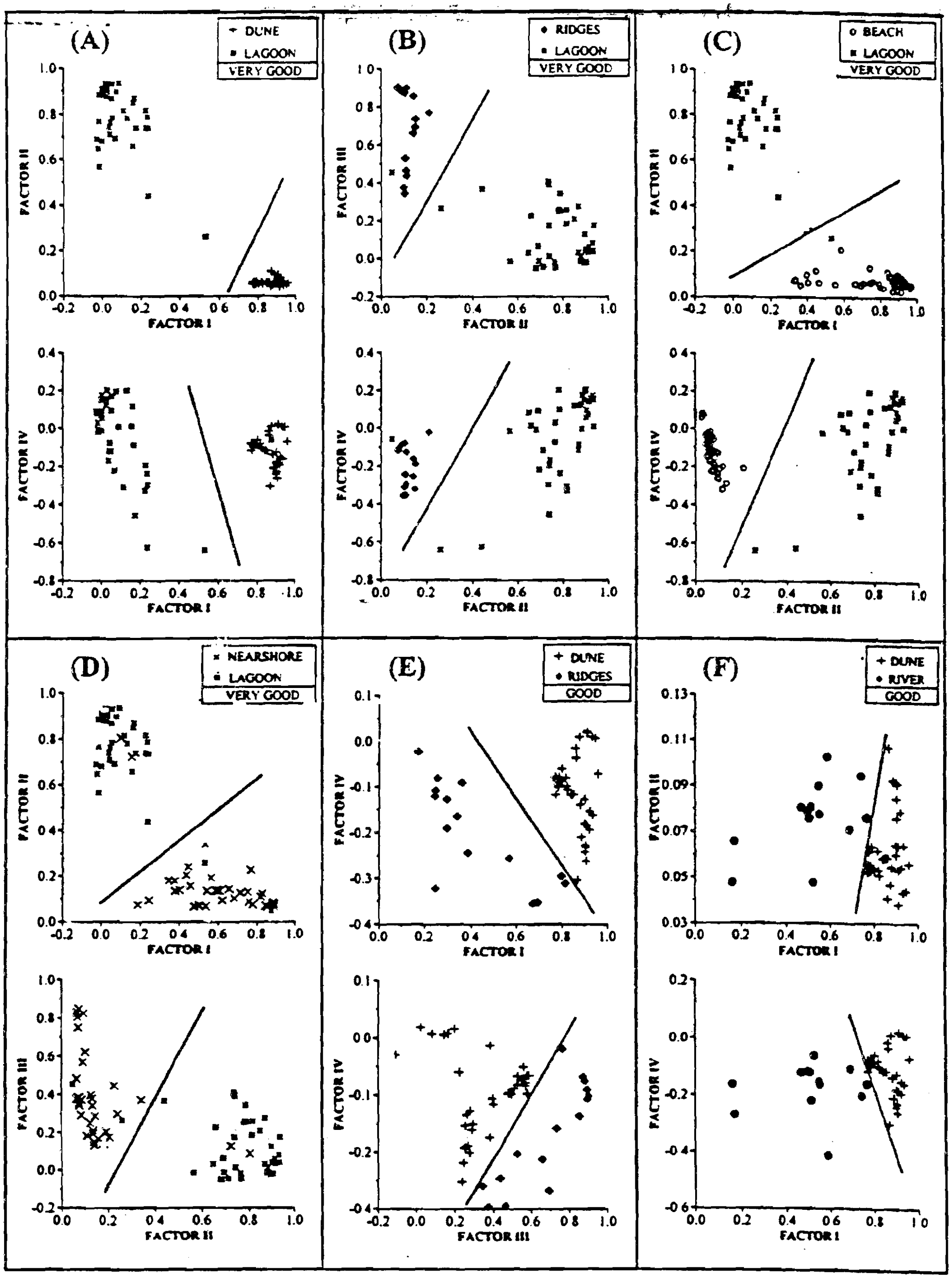

Fig. (5): Factorial plots showing very good discriminations between lagoon and each of dune (A), ridge (B), beach (C) and nearshore (D). E & F showing good discrimination between the dune and both of the ridge and river environments, respectively.

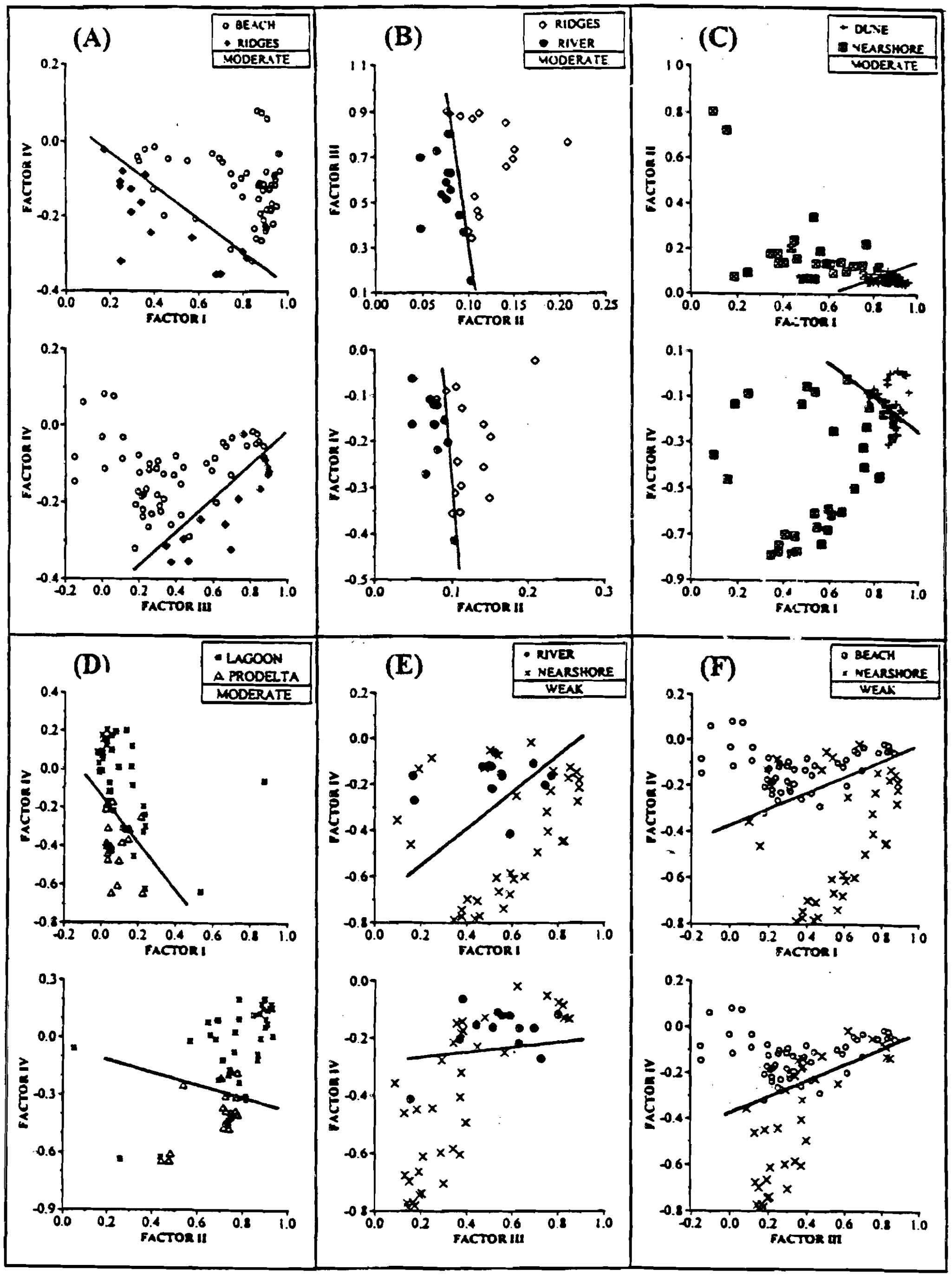

Fig. (6): Factorial plots from A to D have a moderate degree of discrimination, whereas E and F show a weak discrimination.

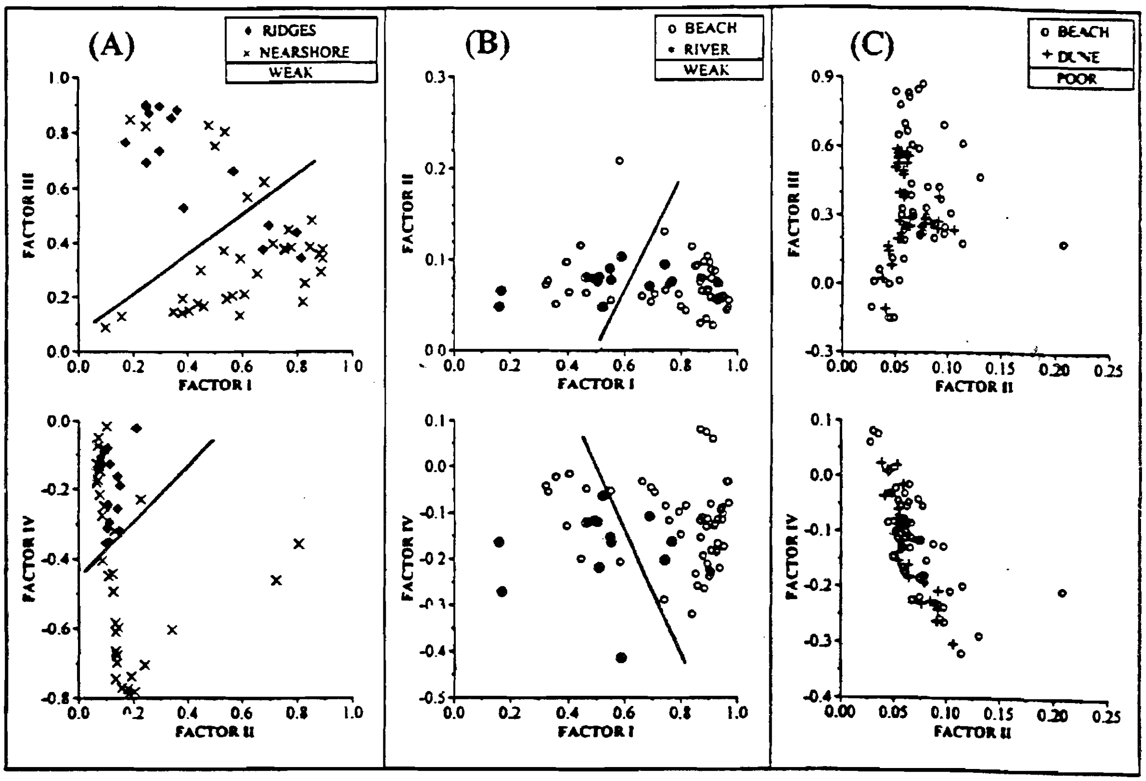

Fig. (7): Factorial plots in A and B show weak discriminations whereas these in C are poor.

	Prodelta	**Nearshore**	**Beach**	**Ridges**	**Dunes**	**Lagoon**	**River**
River	1 $1^V,2^G,3^M,$ $4^V, 5^V,6^G$	2 $1^{*},2^W,3^W,$ $4^{*}, 5^W,6^W$	3 $1^W,2^{*},3^W,$ $4^{*}, 5^{*},6^{*}$	4 $1^M,2^W,3^M,$ $4^M, 5^M,6^M$	5 $1^G,2^M,3^G,$ $4^W, 5^W,6^{*}$	6 $1^V,2^G,3^M,$ $4^V, 5^V,6^G$	
Lagoon	7 $1^M,2^{*},3^M,$ $4^M, 5^M,6^W$	8 $1^V,2^M,3^M,$ $4^V, 5^V,6^W$	9 $1^V,2^V,3^V,$ $4^V, 5^V,6^W$	10 $1^V,2^V,3^V,$ $4^V, 5^V,6^W$	11 $1^V,2^V,3^V,$ $4^V, 5^V,6^W$		
Dune	12 $1^V,2^V,3^V,$ $4^V, 5^V,6^V$	14 $1^M,2^W,3^M,$ $4^{*}, 5^W,6^W$	15	16 $1^M,2^M,3^G,$ $4^W, 5^M,6^G$			
Ridges	17 $1^V,2^V,3^V,$ $4^V, 5^V,6^V$	18 $1^{*},2^W,3^W,$ $4^{*}, 5^W,6^W$	19 $1^M,2^{*},3^M,$ $4^W, 5^W,6^M$				
Beach	20 $1^V,2^V,3^V,$ $4^V, 5^V,6^V$	21 $1^{*},2^{*},3^W,$ $4^{*}, 5^W,6^W$					
Nearshore	22 $1^V,2^V,3^V,$ $4^V, 5^V,6^W$						
Prodelta							

Fig. (8): Diagram displaying results of every combination of one environment against the others. Numbers in the lower half of each cell refer to plot code, while superscripts represent the degree of discrimination. Bold numbers indicate that these plots are presented in this study (Figs. 4-7).

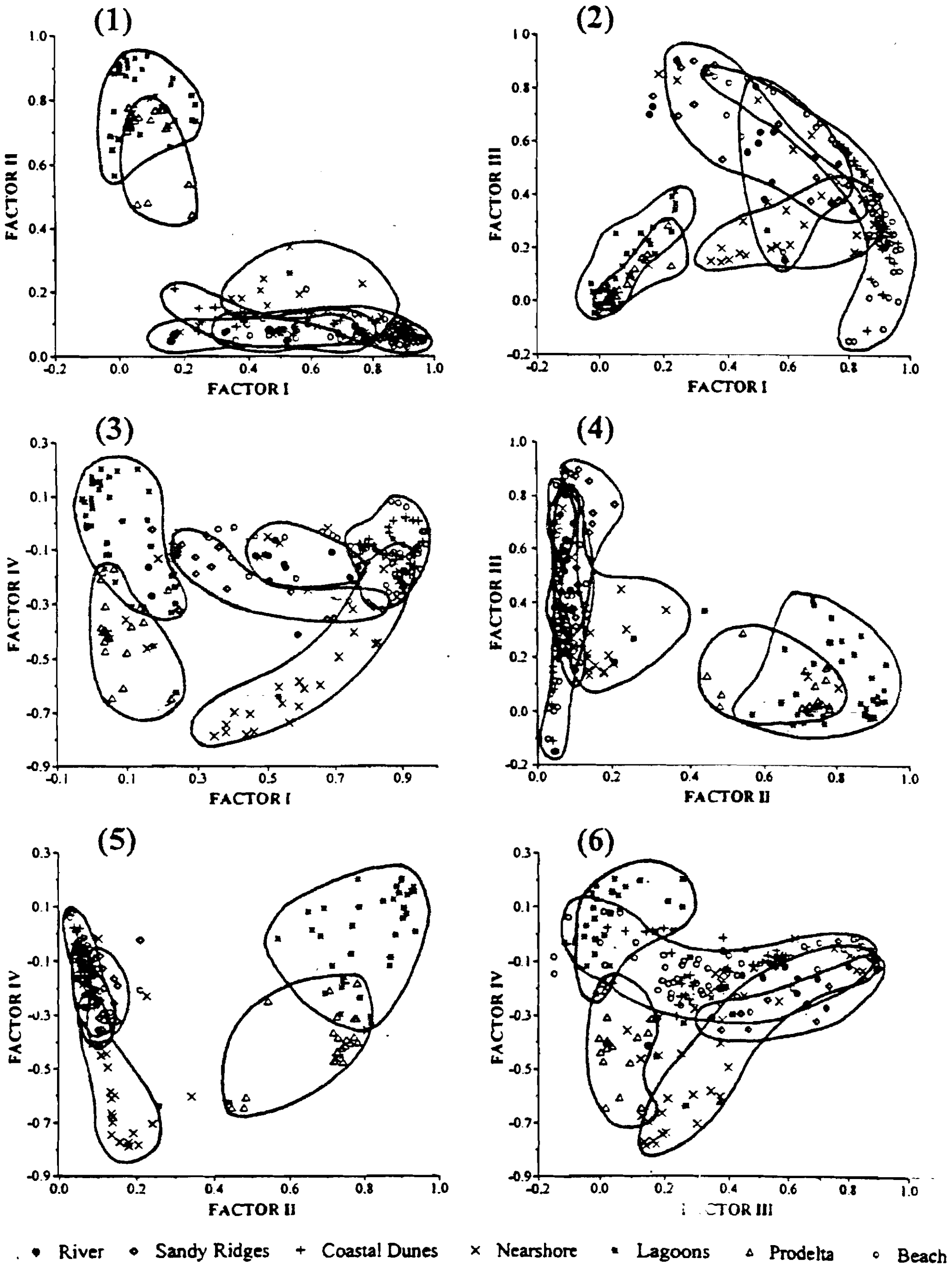

Fig. (9): Six scatter diagrams showing a collective factorial plotting of all study environments. Each diagram shows plots of two factors at a time. It is of note that plot 3 (factor I vs. IV) is the best one to discriminate between all environments. Other plots are ineffective due to considerable overlap.

Fig. (10)

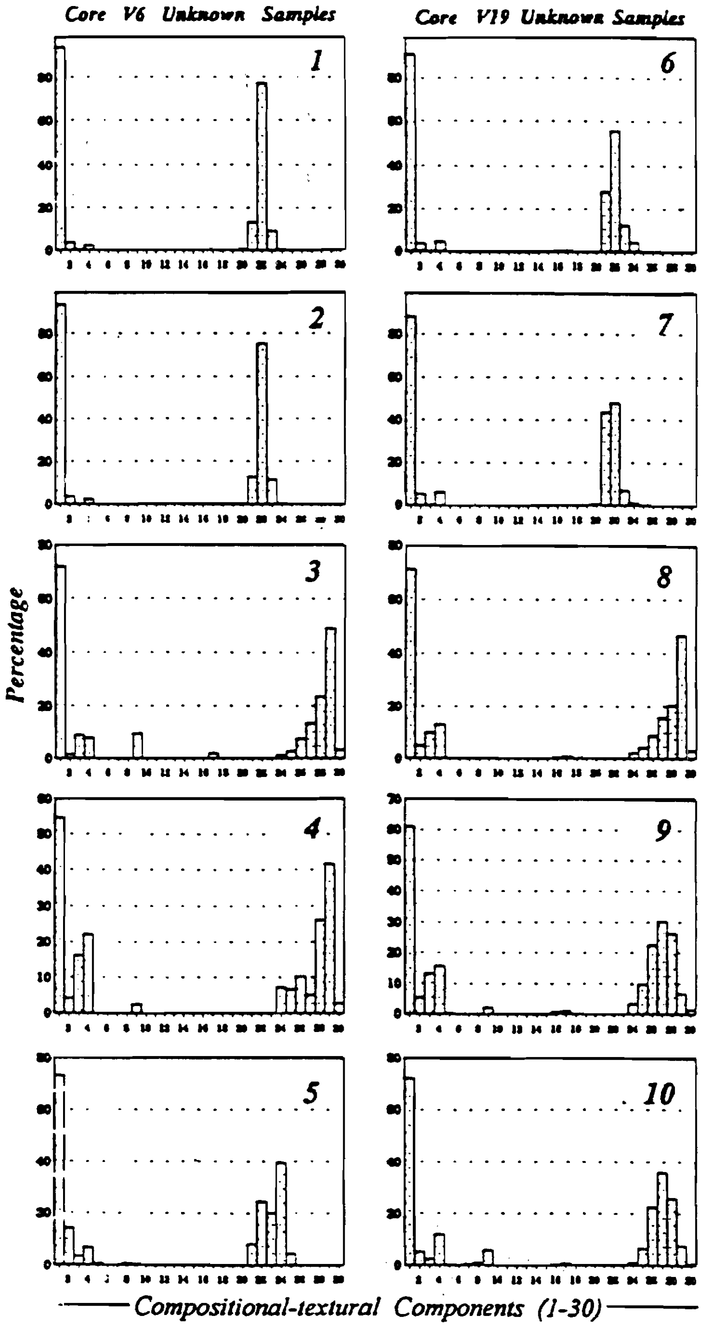

Fig.(10): Bar graphs depict relative percentages of the compositional and textural components for the 10 unknown core samples. Preliminary identification of origins of these samples attained by correlation of each bar graph with those of the study environments (Fig. 3). According to this correlation unknown samples No. 1, 2, 6 & 7 have been identified as accretion sand ridges; 3, 4, 8, 9 & 10 as prodelta and 5 as nearshore.

Fig. (11)

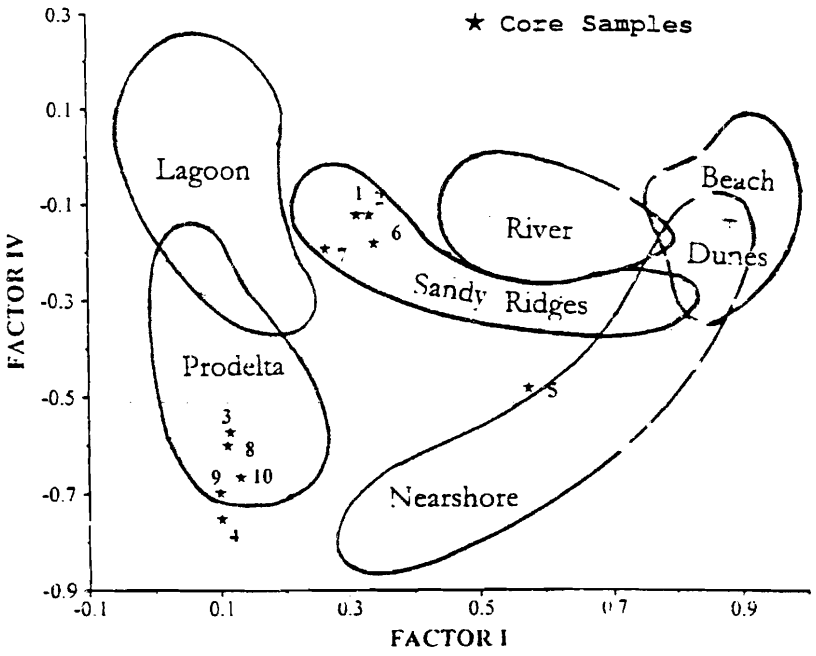

Fig.(11): Identifying origins of the unknown core samples based on the prepared factorial model (plot 3 in Fig. 9). A depositional environment has been ascribed to each unknown sample according to the field in which it lies.