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SHELF OFF ALAGOAS AND SERGIPE (NORTHEASTERN BRAZIL)

2. GEOLOGY

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RESUMO

A granulometria e a composição de quase 200 amostras da plataforma continental dos Estados de Alagoas e Sergipe foram estudadas. A área mostra cinco tipos de fácies sedimentares: (1) fácies terrígena, (2) fácies de lama, (3) fácies de material orgânico, (4) fácies de algas, (5) fácies do rio São Francisco.

A fácies terrígena encontra-se numa zona estreita ao longo da costa. Na parte alagoana, os depósitos são arenosos, na parte sergipana mais síltico-argilosos. A fração fina foi fornecida pelos rios que desembocam nesta área. A maior parte da fração areia é constituída de matérias terrígena, sendo raros os restos de organismos.

A fácies de lama acha-se em alguns lugares isolados da plataforma e na parte superior do talude continental. A sua origem ficou duvidosa. Da fração areia destaca-se a abundância de Miliolidae.

A fáceis de material orgânico é composta de sedimentos arenosos com uma certa percentagem de lama. Sua ocorrencia é principal-

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mente na parte sul da área. A matéria terrígena constitui apenas uma pequena percentagem das frações grosseiras e finas. A fração areia mostra principalmente foraminíferos, brizoários, ostrácodas, moluscos e fragmentos diversos. Dos foraminíferos o gênero *Amphistegina* é o mais importante. A parte calcária da fração fina é constituida de uma vasa fina calcária com pequenas gulhas de aragonita. Esta fácies é uma das mais comuns nas plotaformas continentais tropicais.

A fácies de algas é destacada pela abundância de algas do gênero *Halimeda*, cujos fragmentos são do tamanho de cascalho e de areia grosseira. A ocorrência é principalmente na parte da área. Ali formam-se em alguns lugares verdadeiras crostas. Nas frações arenosas mais fina destaca-se entre os foraminíferos o gênero *Archaias*, além de raros brizoários, ostrácodas, moluscos e fragmentos diversos. Uma tal extensão dêste tipo de fácies numa plataforma continental aberta não é comum, ocorrendo as algas normalmente dentro dos recifes orgânicos nas lagoas e numa zona tranquila fora do recife.

A facies do rio São Francisco ocupa o lugar em frente da foz dêste rio, tanto na zona costeira, como no profundo canyon que corta a plataforma numa direção NW-SE. Os sedimentos perto da foz são sílticos devido à baixa salinidade. Onde a salinidade é normal os depósitos são argilosos. Também os foraminíferos mostram a influência fluvial. Perto da beira da plataforma, os sedimentos são argilo-arenosos, com muito organismos, pertencendo à fácies de material orgânico. Uma constante corrente de turbidez carregada de lama mistura todo material nesta área até grandes profundidades. A influência do rio dirigiu-se para o sul devido à direção da corrente costeira.

INTRODUCTION

In part 1 of this series of papers on the continental shelf off Alagoas and Sergipe the most important data on location of the area, sampling localities, and other necessary oceanographical information have already been given. For comparison, reference to that part may be made (Cavalcanti & others 1967).

The bottom samples taken with a dredge are because of that composite samples. They represent a part of the surface layer at that particular place.

The depth distribution of the samples is as follows:

0	— 10	meters	7,4	% of samples
10	— 20		17,4	
20	— 50		53,7	
50	— 100		12,6	
	100+		8,9	

At various sites the dredge did not bring up any sample. This means that the bottom there showed no soft deposit, although this may not be considered as hard ground. The reason for this supposition will be explained below.

Each sample was examined on board of the vessel, and given a general macroscopical description. In the laboratory were effectuated grain size analyses by sieving in seven main fractions (>2 mm, 2000-840 μ, 840-420 μ, 420-210 μ, 210--105 μ, 105-53 μ, and <53 μ). The latter fraction was obtained by wet-seiving, and, if constituting more than 10% of the total sample, subdivided into six more fractions (53-32 μ, 32-16 μ, 16-8 , 8-4 μ, 4-2 μ, and < 2 μ) by the pipette method. The six coarse fractions were studied by a binocular microscope and calculated by their content of terrigenous components, using the following scale: A — abundant, F — frequent, C — common, R — rare, I — one exemplar. After their composition one could distinguish various types of deposits, of which a distribution map was drawn (fig. 1).

CHARACTER OF THE BOTTOM SAMPLES

Generalities

The majority of the bottom sediments consists of material of organic origin, chiefly calcareous matter. In this way it is possible to distinguish five different types of facies: (1) terrigenous facies — material of terrigenous origin, which can be dominantly sandy or muddy; (2) mud facies — isolated patches of muddy deposits on the middle of the shelf and at the continental slope; (3) organic material facies — dominantly micro-organisms and molluscs; (4) algal facies — constituted of calcareous algae fragments; (5) São Francisco river facies — material provided by the São Francisco river.

Only with respect to the terrigenous facies deposits, the isolated muddy, and the São Francisco river sediments, it has some sense to determine their respective colours, which were estimated using the Rock-Color Charts devised by Goddard & others (1948), with the samples still wet. Three colour types could be determined: 5 YR 4/4 (moderate brown),

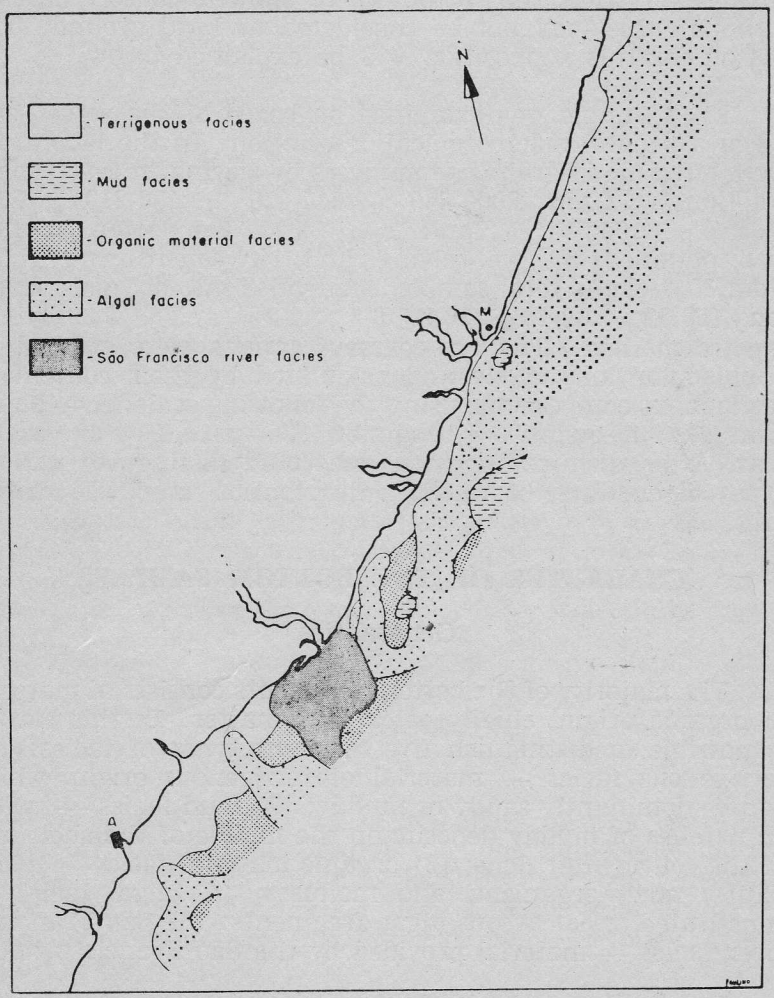

Fig. 1 — Areal distribution of the sedimentary facies.
Distribuição superficial das fácies sedimentares.

dominating in the coastal area of the State of Alagoas; 10 YR 5/4 (moderate yellowish brown), dominating off the coast of Sergipe; 5 B 5/1 (medium bluish gray), dominating in the isolated mud patches and at the mouth of the São Francisco river. In these latter deposits, however, the colour at the surface in the oxydation zone is also 10 YR 5/4, just as in the coastal sediments of Sergipe. The brown colours of these latter deposits are due to their percentage of mud. The organic material and algal facies sediments show 5 Y 7/2 (yellowish gray) — colours in their components, due to the predominantly calcareous matter.

Grain size composition

Grain size composition of each sample was determined, and a descriptive classification of the sediments based hereupon was made. The classification used by Nota (1958) and Koldewijn (1958) was too detailed, especially for its mapping. On the other hand, the classification followed by Emery & Niino (1963) was too simple, because the deposits of the investigated area could not be characterized as only gravels, sands and muds. For that reason, the following classification was applied here, referring only to grain size and not to composition. More than 50% of one fraction determined the name of the sediment, in this case: gravel (> 2 mm), sand (2000-53 μ) and mud (< 53 μ). A component with less than 10% of the total sediment was not mentioned, between 10 and 40% with an adjective, and 40-50% with an adjective preceded by the adverb "very". If two components were present in quantities less than 40%, the first adjective represents that component which is present in less quantity than the other. For instance, a deposit with 23% gravel, 57% sand, 20% mud (sample 18), was termed as a "muddy-gravelly sand". Deposits with less than 50% of each class were named with nouns, for instance, 39% gravel, 36% sand, 25% mud (sample 21), was termed as a "mud-sand-gravel".

This fairly detailed subdivision, however, required a regrouping of the deposits in a few groups of sediments with similar characteristics. In this way could be distinguished:

group G_1 — gravels, very sandy gravels and sandy gravels, with 20% of the samples;

G_2 — muddy-sand gravels and sandy-muddy gravels, with 11%;

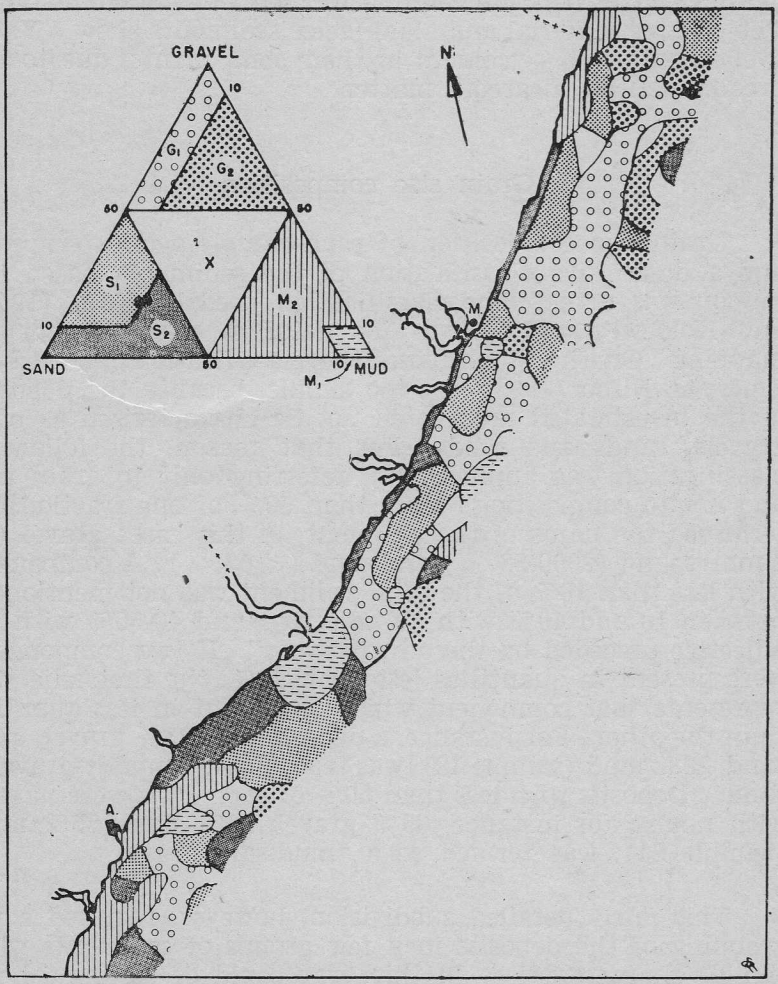

Fig. 2 — Sediment distribution based on grain size composition. Distribuição dos sedimentos segundo a composição granulométrica.

S_1 — gravelly, very gravelly and muddy-gravelly sands with 22%;

S_2 — sands, muddy, very muddy and gravelly-muddy sands, with 11%;

M_1 — muds with 22%;

M_2 — very sandy, sandy and gravelly-sandy muds, with 7%;

X — all mixed sediments, with 7% of the samples.

Other not mentioned types did not occur in the investigated shelf area.

Subdivided in these seven groups, a map was constructed, presenting the sediment distribution based on grain size only (fig. 2) The distribution pattern appears to be fairly irregular. When compared with the sediment facies map (fig. 1), one may conclude that only at two places some coincidence exists, namely (1) the algal facies off Alagoas is chielfly gravelly, and (2) the deposits near the mouth of the São Francisco river are muds.

Generally, muddy sediments are found in the N, near the frontier with the State of Pernambuco, frequently off Sergipe, and at various places near the shelf break. The gravels coincide often with the occurence of algae, being at those places calcirudites. The sandy deposits are found irregularly scattered over the entire area.

Although the grain size distributions of all available samples have been determined, not all of them could be used for interpretation. When constructing the cumulative frequency curves, especially of the samples belonging to the organic material and algal facies, these curves appear to be very irregular and plurimodal. This means that the sediment is composed partly of transported, partly of local material. However, a separation of these two chief genetic constituents was by no means possible. Therefore, only the area of the São Francisco river mouth and the coastal area with its predominantly terrigenous sediments can be taken into consideration.

For the interpretation the diagram of occurring sediment types in the shallow marine and littoral environment, propos-

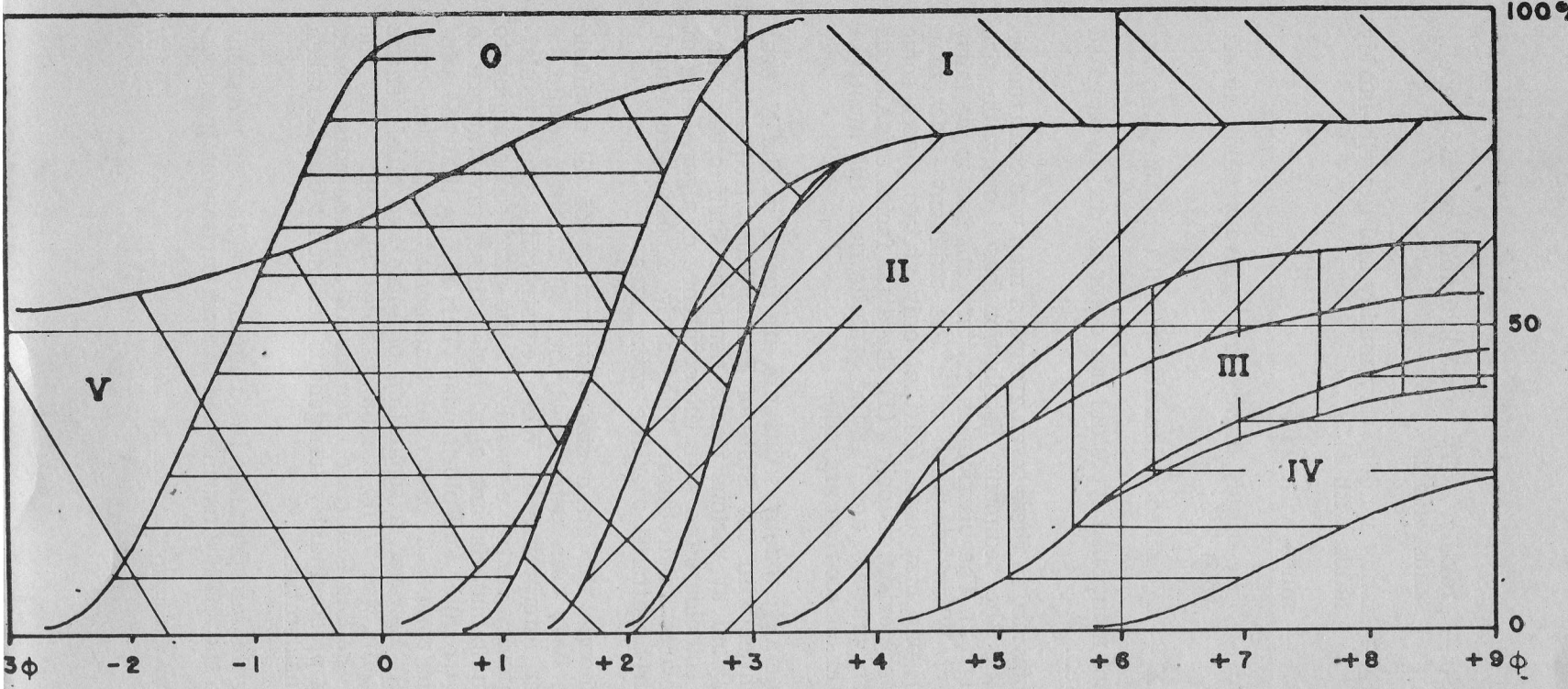

Fig. 3 — Zone diagrams of size distribution of sediments types from the litoral and shallow marine environment.
Diagramas de zona da distribuição granulométrica dos tipos de sedimentos nos ambientes litorâneos e de mar raso.

ed by Inman & Chamberlain (1953) and amplified by Bigarella, Salamuni & Pavão (1959), was used (fig. 3). As has been concluded by these authors, the deposits with curves belonging to group 0 are generally coarse littoral sediments, due to a fairly great slope angle and a supply of relatively coarse material. More often, beach sediments have their curves in groups I and II, being well to moderately sorted, with median diameters in the sand sizes. The less well sorted, silty and clayey deposits grouped in zones III and IV are generally calm water sediments. Group V joins the fairly coarse sediments composed of shell and coral fragments, where grain size distributions are poorly sorted and often bimodal.

São Francisco area

Figure 4 presents the zone diagrams of the cumulative size frequency curves of the fine deposits in the São Francisco facies area. Two chief groups can be clearly distinguished: (1) the clayey sediments, and (2) the silty sediments. Their area of occurrence has been presented in figure 5.

The clayey deposits occur chiefly at some distance from the coast, at various depths, inside as well as outside the river canyon. They are very fine sediments, with 60-80% of their particles <2 μ evidently of terrigenous origin provided by the river. Their small sandy fractions (commonly less than 2%) show an abundance of quartz grains, being the organic fragments chiefly foraminifera, undeterminable fragments and plant fibers.

The silty sediments are restricted to the area near the river mouth, up to a distance of some 5 miles. Here the bottom surface occurs at a depth of at maximum 50 m, which means that these sediments are not formed in the canyon. Also in this case, the coarse fractions which constitute generally less than 2% of the total sample, are composed of terrigenous grains: quartz and mica. The very few organic grains are foraminifera and broken fragments not more recognizable. When compared with figure 7 of part 1 (Introduction), one can conclude that the occurence of the silty deposits coincides with the areas of low surface salinity.

Sample 162 does not belong neither to the first, nor to the second group of sediments. It is a fine sandy deposit from the river mouth, being thus of fluvial provenance.

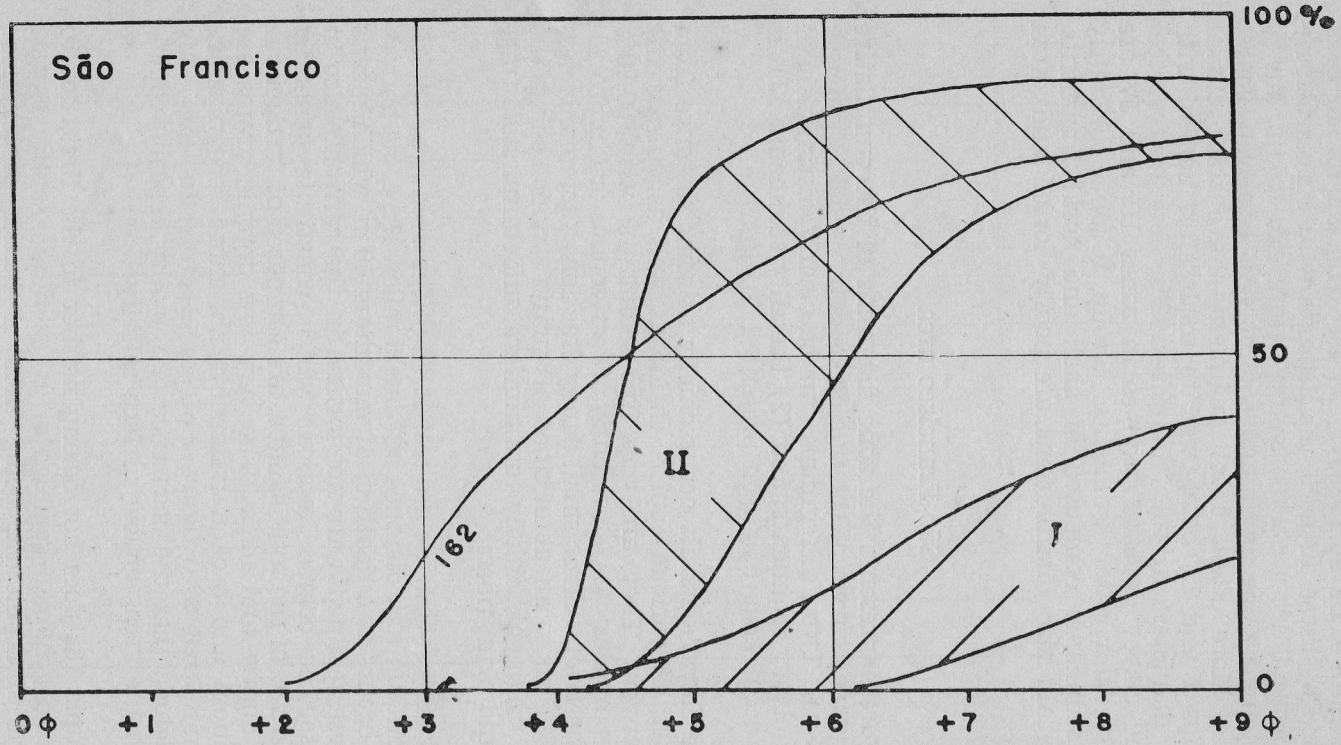

Fig. 4 — Grain size distribution of the sediments of the São Francisco river facies.
Distribuição granulométrica dos sedimentos da fácies do rio São Francisco.

Its coarse fractions consist of quartz grains and some rare plant fibers.

The statistical parameters of the medium samples which could be determined, are mentioned in table I. It appears

Table I. Grain size data of some representative sediments of the São Francisco area.

sample	$Md\phi$	$Qd\phi$	$Skq\phi$	q	gravel	sand	silt	clay	obs
162	4.84	1.77	+0.28	40.0	—	36.85	50.15	13.00	mouth
170	5.35	1.05	+0.10	29.1	—	0.09	90.11	9.80	II
174	—	—	—	77.6	—	0.05	29.18	70.77	I
180	3.38	—	—	82.1	1.32	57.77	11.58	29.33	coarse
181	—	—	—	74.8	1.15	15.06	23.16	60.63	
182	—1.32	2.10	—0.58	—	56.45	33.09	10.46		
183	2.95	—	—	69.4	7.62	48.73	14.80	28.84	
184	—0.40	1.96	—0.02	—	42.20	56.03	1.77		
185	3.17	1.26	+0.29	77.0	1.56	70.74	14.30	13.40	
186	1.56	1.45	+0.19	—	9.82	71.93	5.25	13.00	
190	2.10	—	—	72.7	28.84	30.95	13.21	27.00	

Tabela I. Dados granulométricos de alguns sedimentos representativos da área da foz do rio São Francisco

that the deposits are poorly sorted ($Qd\ \phi > 1$), and that the q-values of samples 162 and 170 are low. Generally these quotient-values (Hissink 1929) vary between 75 and 83 for the clayey samples and between 16 and 38 for the silty samples of the investigated area.

The principal grain size data and the statistical values of the coarse samples found at the end of the canyon of the São Francisco, are also mentioned in table I. One observes a fairly wide range of deposits, poorly sorted and very skewed. The bulk of the coarse fraction consists of organic material, so that these deposits are no longer considered as belonging to the São Francisco facies area. Bryozoans, foraminifera, ost-

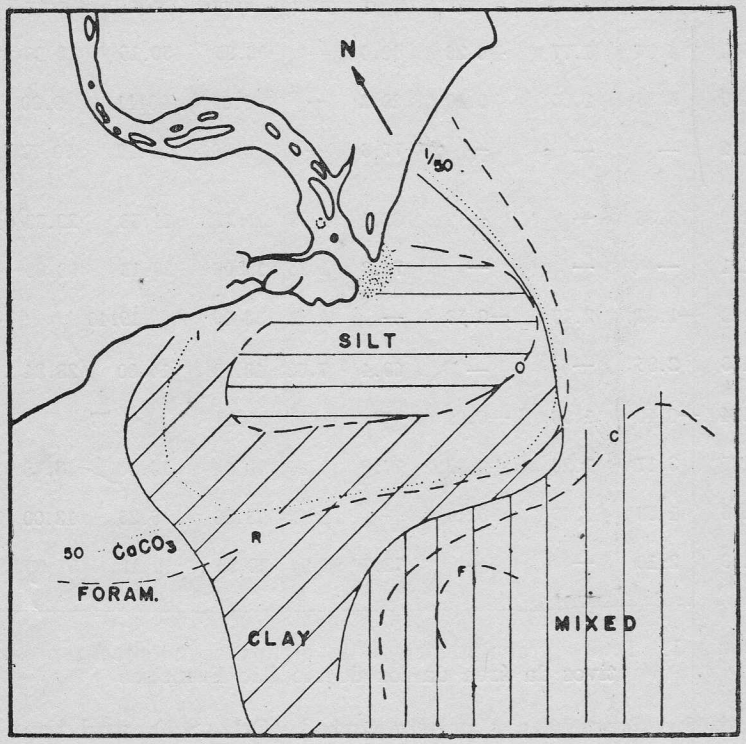

Fig. 5 — Sediment distribution, carbonate content and foraminiferal frequency in the São Francisco area.
Distribuição dos sedimentos, conteúdo de carbonatos e frequência dos foraminíferos na área do rio São Francisco.

racods, mollusks, and fragments dominate. The samples are excellent examples of the already made remark, that their irregular grain size distribution must be due to transported local material, thoroughly mixed. Furthermore it has to be mentioned that the samples came from considerable depths, varying between 75 (sample 184) and 400 m (sample 182). At the stations 187, 188, 189, no sample could be taken because of their depth being greater than the length of the cable.

Coastal area

The grain size distribution of the coastal sediments has been presented for decalcified samples. It is obvious that the deposits of the coast off Alagoas are different from those of the coast off Sergipe (fig. 6). In the north, the sediments are much coarser than in the south. Only sample 116 is an exception, occurring in the south, and being identical to the samples of the northern group. The statistical values of the average samples of each group are mentined in table II.

Table II. Statistical values of medium samples of terrigenous sediments.

		$Md\phi$	$Qd\phi$	$Skq\phi$
group	A	0.90	0.60	+0.10
	S_1	3.92	0.15	0
	S_2	5.00	—	—
	S_3	>9	—	—
116		1.00	0.58	+0.03

Tabela II. Valores estatísticos das amostras médias dos sedimentos terrígenos.

When compared with the possible types as presented in figure 3, one can see that the sediments of the Alagoas coast belong to group 0, which means that they are fairly coarse. Almost all littoral deposits, at the beach as well as at the off-shore zone, are coarse, due more to supply of coarse material than to strong currents. This has also been found more northward in the area of Recife, State of Pernambuco, where the continental coastal deposits are of the same type,

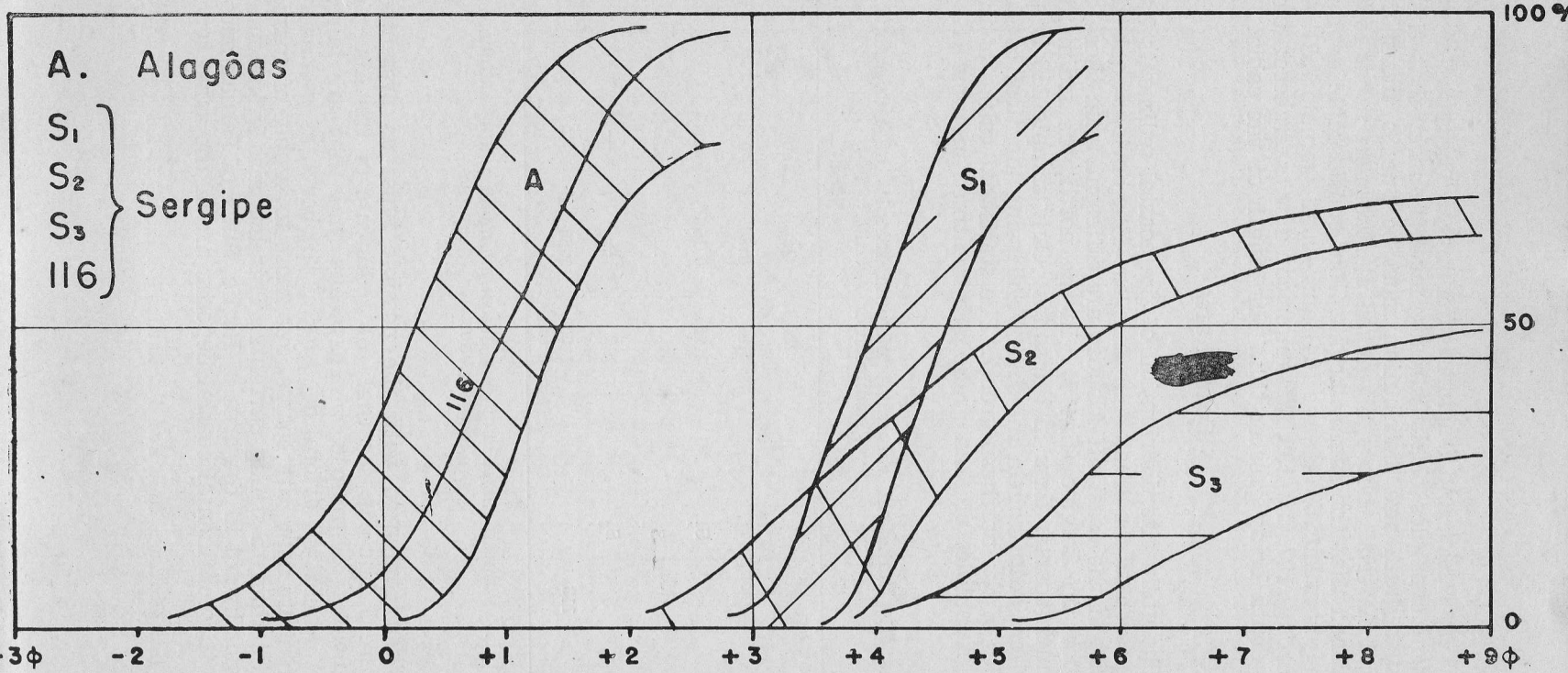

Fig. 6 — Grain size distribution of the sediments of the terrigenous facies.
Distribuição granulométrica dos sedimentos da fácies terrígena.

being generally sandy deposits of the Barreiras Group and at some places desintegrated crystalline rocks. The coast itself show a series of sandstone reefs with some coral growth at the seaward side. These reefs occur also more morthward, and have been described in the area of Recife (Mabesoone 1964).

In Sergipe, the coastal sediments are much finer. One may think, in the first place, about a mixing with fine sediment from the São Francisco river, which is transported southward. But also, the sediments on the continent are finer than in Alagoas. The littoral facies zone being wider in Sergipe, it can also be expected that sediments deposited in fairly calm water, as illustrated by the deposits belonging to group S_3, are present. This means that at normal shelf depths the agitation is not so strong as to inhibit the deposition of finer sediments. Futhermore, no sandstone reefs are found in this area, which could provide coarse material to the off-shore zone.

Other areas

The two isolated small patches with fine, muddy sediments, could not be sufficiently explained. The deposits are very clayey (sample 60 — 63,85% <2 μ, sample 96 — 75,52% <2 μ), with almost no organic material in their sand fractions.

Samples 80 and 81, from depths of 290 and 75 m respectivelly, came thus from the continental slope. Sample 81 shows ± 50% of clay size particles, sample 80 ± 75%, showing that downward the deposits become finer. Their sand fractions show an abundance of planktonic foraminifera.

The deposits of the algal facies, especially occurring in the N of the investigated shelf area, show generally 50-98% of fragmented algal material in the gravel size (>2 mm). The fine material found in these samples is composed of calcareous mud, when constituting less than 2% of the total, and of a mixture of calcareous mud and terrigenous clay, when constituting more than 2% of the total sediment.

The facies of organic material has generally less coarse deposits, the bulk being found between 1000 and 250 microns, the average size of foraminifera. Often they show some clastic quartz grains in the fraction $<$ 250 μ. The finer fractions, in this case, are composed of a mixture of calcareous and terrigenous muds, with dominance of the first type.

SUSPENDED MATTER

The São Francisco river has a run-off of about 3300 m3/sec, due to its dry drainage area. It supplies a large quantity of fine material to the sea. From the air, one can clearly see the muddy yellow-coloured water and its extension into the ocean. During the investigation of this area, also Secchi disc readings were effectuated; figure 7 shows the disc visibility distribution.

Because the quantity of suspended matter in the water near the river mouth is not known, the consideration has to be somewhat theoretical, compared with data published by Postma (1961). Secchi disc readings gave an impression of this quantity of suspended matter. It appears to be at the rivermouth abouth 60 mg/l, showing in front of it 8-15 mg/l; farther seaward the values are between 0,5 and 2 mg/l; These apparently low quantities are due to the finenes of the material, which gives the impression of a very loaded mass of water. Anyhow, the fairly great run-off transports a high quantity of fine suspended material into the sea, where it settles predominantly in the river canyon.

COMPOSITION

Terrigenous fraction

This fraction is most frequent in the coastal area and in that of the infuence fo the São Francisco river. However, in the other areas with predominantly organic material, clastic grains are also met with, although in a small quantity.

The majority of the grains consist of quartz. In the coarser fractions ($> \frac{1}{2}$mm), the grains are generally rounded with a frosted, sometimes pitted, surface character. As to be expected, brilliant grains occur almost only in the coastal area. As frosting and pitting of quartz grains is generally considered as a consequence of chemical action either by dew in a dry climate, or by diagenetical attack of a carbonate component in an indurated rock it is well possibe that the grains actually found in the shelf environment got their surface character before being deposited in the ocean. In the finer fractions ($< \frac{1}{2}$ mm), the quartz grains are angular and not-worn, indicating evidently that they were fairly recently supplied from the continent.

Mica, a not very stable mineral in the warm and humid

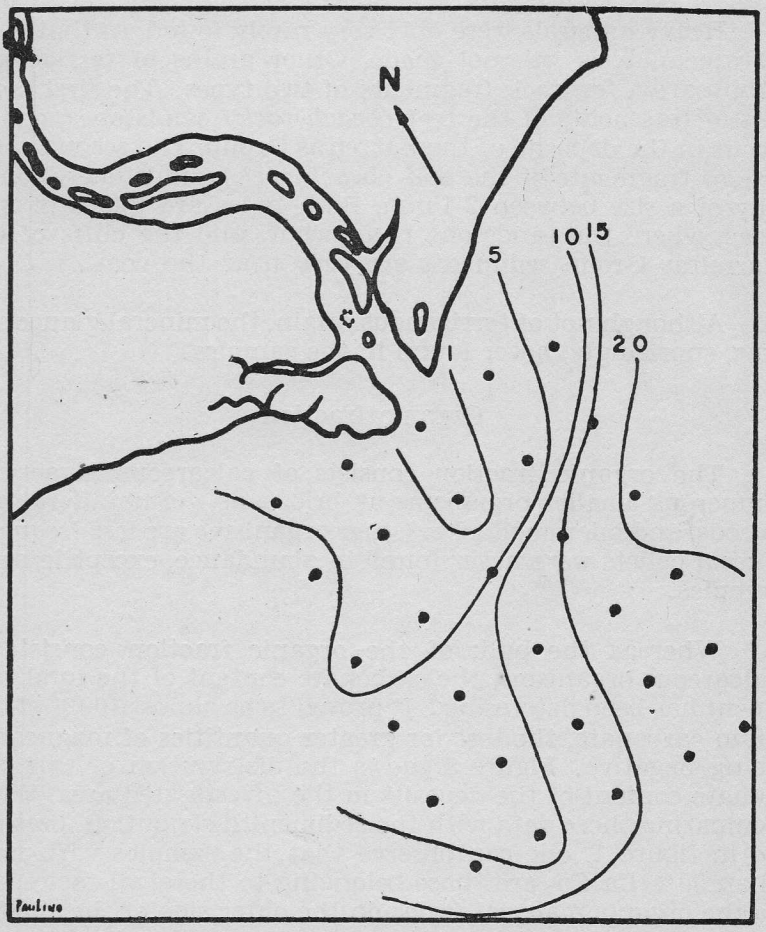

Fig. 7 — Secchi disc visibility (m) in the São Francisco area.
Visibilidade do disco de Secchi (m) na área do São Francisco.

tropical environment, was determined in most of the samples near the mouth of the São Francisco river. Evidently, they have been supplied by this stream from the dry interior. The same occurred, although in a much smaller degree, in front of the Vaza-Barris river, S of Aracaju in the State of Sergipe. This river comes also from the semi-arid interior, where a BSh climate reigns.

Heavy minerals were only very rarely found, so that a separate analysis was not made. Other grains of terrigenous origin are a few rock fragments of two types. The first consists of fragments of the reef *(beach rock)* sandstones, generoccur in the deposits of the Barreiras Group. The second consists of fragments of the reef *(beach rock)* sandstones, generally of a size between 2-1 mm. Both types are found of Alagoas, where the sandstone reefs occur, and the cliffs of the Barreiras Group sediments are very near the coast.

Although not of terrigenous origin, the mineral glauconite was, suprizingly, never found in the samples.

Organic fraction

The organic fraction consists of calcareous algae and numerous smaller organisms as briozoans, foraminifera, ostracods, and micromollusks. Other organisms are less frequent. Faecal pellets were never found in abundance, except in some samples.

Whereas the bulk of the organic fraction consists of calcareous organisms, the carbonate content of the total sediment has been determined. It proved to be almost 100% of calcium carbonate, the test for greater quantities of magnesium being negative. Figure 8 shows the distribution of this carbonate content of the deposits in the investigated area. When comparing these data with the sediment distribution, presented in figure 1, one can observe that the samples with more than 50% $Ca\,Co_3$ are those belonging to the algal facies and to the organic material facies on the outer side of the shelf in Sergipe. The lowest percentages occur near the river mouths, at the isolated mud patches (stations 60 and 96), and at the few analyzed fine samples of the slope (stations 65, 80, 81).

Thus, in the greater part of the samples, the calcareous algae constitute the bulk of the organic fraction. These algae occur generally in the intertidal and sublittoral environ-

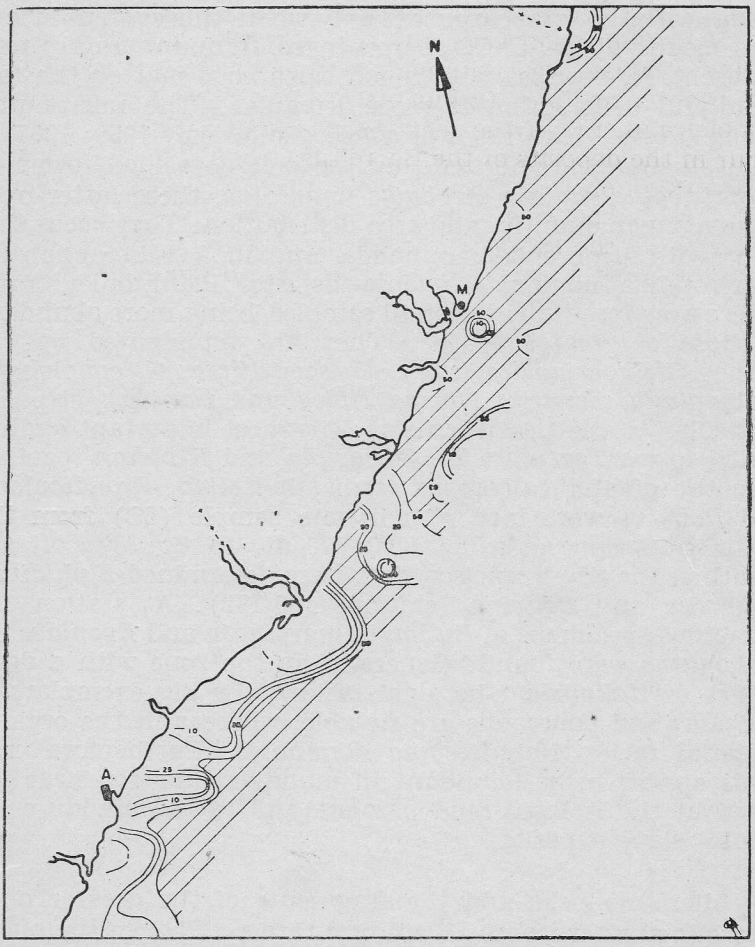

Fig. 8 — Carbonate content (%) of the bottom sediments. Hatched area shows high percentages.
Conteúdo de carbonatos (%) dos sedimentos do fundo. Área hachurado representa percentagem elevadas.

ments, up to depths of about 100 m, often covering extensive surfaces. The fragments are either masses of coralligenous algae associations *(Lithothamnion, Ginolithon, Prolithon,* etc.) or cylindrical or flakshaped parts of the stems of the algal genus *Halimeda*.

The areal distribution of foraminiferal tests (fig. 9) coincides with the total carbonate only where this content is low. That means, at low $CaCO_3$ percentages, foraminifera are rare to absent. In the area with much calcareous matter, the foraminiferal distribution is more irregular. The microfauna belongs to the West-Indies province (Boltovskoy 1959; 1965, p. 101), chiefly characterizede by the well-developed forms of *Amphistegina radiata, Archaias angulatus,* these latter ones dominating in quantity and area distribution. They occur together with peneroplids, miliolids, and in a lesser quantity with rotalids, nonionids, nodosarids, etc. Planktonic foraminifera are present in almost all samples, being more abundant in those of greater depths. They are represented by the species *Globigerinoides rubra, G. sacculifera, G. conglobata, Globorotalia menardii (forma típica* and *tumida),* etc., all particular to the Brazil current. The most important agglutinated forms *Textulariella, Guadryna* and *Reophax* together with the greater calcareous forms *Dentalina, Frondicularia* and *Robulus* were met with in one sample (5C) from the continental slope at a depth of 370 m. In the area off the mouth of the São Francisco river were determined *Elphidium, Ammonia* and *Bolivina* (stations 169-172). At station 176 numerous specimens of *Bulimina marginata* and *Eponides* cf. *umbonatus* were found. Generally, in the zone with a dominance of *Halimeda* (the algal facies), the big exemplars of *Archaias* and peneroplis are notable, whereas in the organic material facies *Amphistegina* dominates. Furthemore, miliolids appear to be abundant in muddy sediments, near the coast, at the isolated mud patches, and in the muddy continental slope deposits.

Micro-mollusks and the fragments of the greater ones, determined after Nobre (1940), are rare ($< 5\%$) in the major part of the area. They are absent near the mouth of the São Francisco and Vaza-Barris rivers, and occur commonly (5--25%) at some places in front of the State of Sergipe and just N of the São Francisco (fig. 10). This distribution coincides with the organic material facies (compare with fig. 1). Pelagic gastropods are present in almost all samples, as are small shells of *Caecum, Bulla, Atlanta, Aphisia, Piramidella, Creseis, Clio, Epiratella,* and *Peracle*. Many micro-shells of

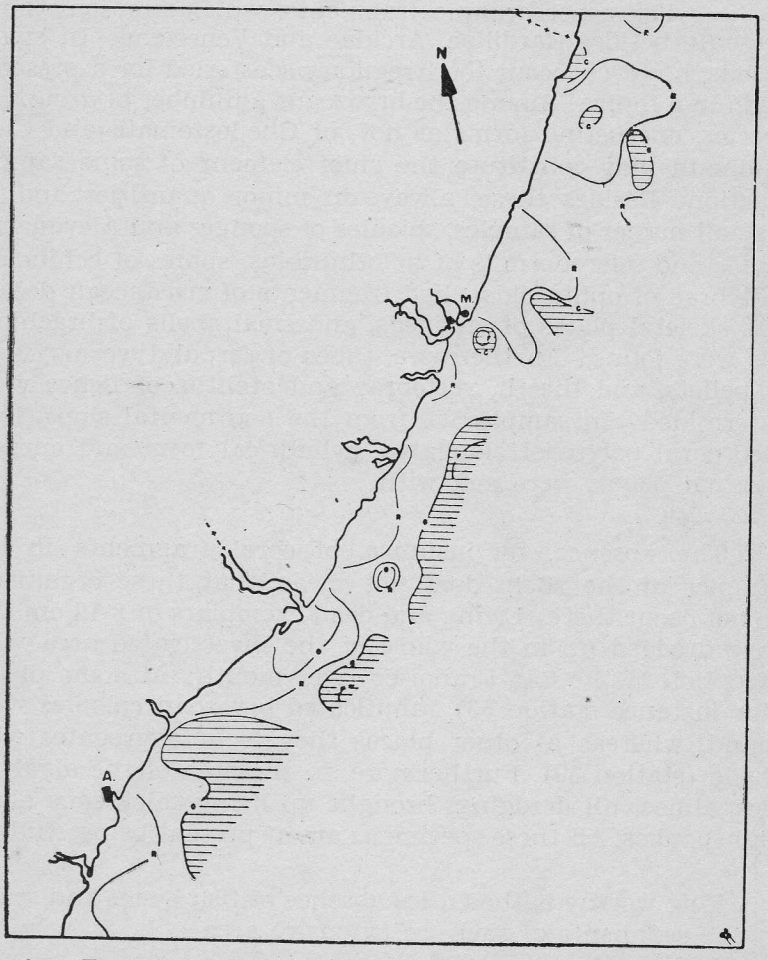

Fig. 9 — Foraminiferal frequency in the investigated shelf area. For explanation of sybols see text; hatched area shows hegh percentages.

small bentonic species and immature shells of other gastropods were commonly determined. Among the lamellibranchs, the Pectinacea (*Pecten*) and Nuculacea (*Leda*) are present besides Cardiilae, Arcidae and Veneridae. In small quantities occur also the shells of *Dentalium*.

The other organic fragments, which are sometimes presente besides Cardiilae, Arcldae and Veneridae. In small racods, however, occur too irregulary scatterled for a presentation in a figure. Among the bryozoans a number of groups of species, encrusting forms or not, of Che'lostomata and Ciclostomata may constitute the chief element of some sample fraction. Besides these, always in minor quantities and in a small numer of samples, spicules of sponges and Alcyonaria, plates and sclerodermits of holothurioids, spines of echinoids, vertebrae of ophiuroids, shell fragments of crustacean decapods, skeletal plates of cirripeds, and smal shells of brachiopods were found. Furthermore, tubes of serpulid worms, faecal pellets, and theeth, vertebrae and otoliths of fishes were determined. In sample 5C, from the continental slope, isolated coral polyps of elongated, cylindrical form and curved, ceratoid polyps were met with.

The absence, foi instance, of coral fragments in the samples of the shelf, does not mean that these organisms do not occur there. Living and dead exemplars of 8-12 cm size were dredged up in the whole of the investigated area with exception of the São Francisco river mouth. At some places (for instance station 53) ramificated bryozoan colonies were found, whereas at other places they from aggregates with shells (station 69). Furthermore, in the area of the algal facies, almost all dredgings brought up living calcareous algae and sponges. All these specimens are at present being studied.

Note worthy is the entire absence of fish bones and scales in the sediments of such an extensive area.

Organic carbon content was determined with Walkley and B'ack's rapid titration method (Piper 1950). The percentages found in the bottom sampes varied between 0 and 3%. However, the results will be neither figured, nor discussed here, being the subject of a separate paper on the geochemistry of the sediments.

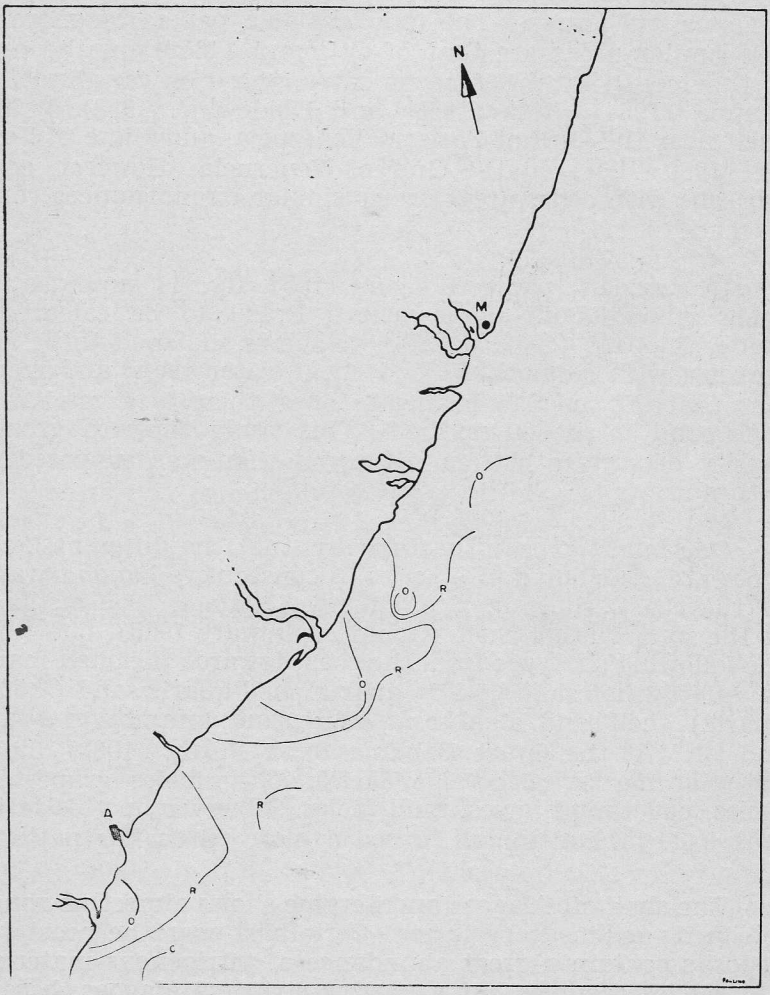

Fig. 10 — Mollusc frequency in the investigated area. For explanation of symbols see text.
Frequência dos moluscos na área estudada. Explicação símbolos no texto.

ORIGIN AND GENESIS OF THE SEDIMENTS

Generalities

As Guilcher (1964) already pointed out, almost no data on the continental shelf deposits off th eastern coast of South America are known. The only avaiable papers on more or less similar areas are that of Ottmann (1959) on the area of the mouth of the Amazon river, those of van Andel & Postma (1954), Nota (1958) and Koldewijn (1958) on the shelf near the Gulf of Paria in Venezuela, and those of Zeigler (1959, 1964) on the Gulf of Venezuela. However, comparisons with other areas under similar circumstances could be made.

In a review paper, Rodgers (1957, fig. 1) supposes the shelf sediments off north-eastern Brazil to be calcareous muds. Shepard (1963, p. 223) presumes the shelf to be calcoreous, with coral banks and shoal water reefs, and mentions that off the São Francisco river there is a mud zone with sand at the outer shelf. This study shows a greater variety of surface bottom sediments than was supposed by both authors.

One might expect, theoretically, that the different facies types are distributed in a series of consecutive bands parallel to the coast, showing a progressive change. For instance, at the west Florida shelf (Gould & Stewart 1955), one finds the following six types from the coast towards the shelf margin: quartz-shell sand (>50% quartz, shell-quartz sand (<50% quartz), shell sand, algal sand, oolite sand, foraminiferal sand and silt. At the Great Bahama Bank Purdy (1963) found the following series: coralgal facies, oolitic facies, grapestone facies, pellet-mud facies, mud facies. However, in this latter area local circumstances caused a more patch like pattern.

The shelf off Alagoas and Sergipe shows almost no zonation in its sedimentary facies. Certainly, near the coast the deposits contain a great abundance of terrigenous material. This facies occupies but a narrow strip off Alagoas, becoming larger and more irregular off Sergipe. The organic material facies is not found at the outer shelf side of the algal facies in Alagoas, where this latter, save at a few places, reaches up to the margin. Off Sergipe a certain influence of the muddy São Francisco deposits is more evident. However, at the outer shelf edge, most deposits show a higher quantity of mud than more landward (see fig. 2). Also the few

samples of the continental slope are not all muds (for instance station 5). But generally, a certain zonation tendency cannot be denied, only the algal facies being exceptional.

Terrigenous facies

As its name already suggests, the deposits of the facies are chiefly of terrigenous provenance. In the N they are muddy (stations 1,10), possibly due to the supply of clayey material from weathered crystalline rocks which crop out in that area near the coast. Station 1 is furthermore characterized, besides the abundant quartz grains, by a great quantity of peneroplids. From there up to the mouth of the São Francisco, the sediments are sandy with an abundance of quartz grains, frosted in the coarser fractions, brilliant in the medium, and not-worn in the finer sizes. The coarse, frosted grains must have been derived from the sandstone reefs near the coast. As was already found (Mabesoone 1964), the majority of the quartz grains in these beach rocks becomes rapidly frosted by attack of the carbonate cement. The brilliant, medium size grains did come from the beach, where the quartz has commonly a glossy surface character. The finer grains are generally not-worn, independent of their environment. The lack of fine material in this region is due to the absence of rivers with a considerable drainage area. The small existing streams deposit their fine material in the coastal lagoons of Alagoas, and because of that do not transpart it into the ocean. One of these lagons, the Lagoa Mundaú near Maceió is being studied.

S of the São Francisco, the terrigenous facies deposits are muddy. This is due, in the first place, to the big supply of fine material by this river, which is not entirely deposited near its mouth or in its canyon. Furthermore, the rivers Japaratuba and Vaza-Barris also supply fine material to the shelf. These rivers drain partly the Sergipe basin with its Cretaceous calcareous sediments producing clayey weathering products. Because of this supply, the possibilities for the formation of calcareous sediments are less favorable, so that the terrigenous facies sediments have a wider extension hare. The surface characters of the quartz sand grains are the same as in the are N of the São Francisco river. Near the mouth of the Vaza-Barris river the foraminifera are rare, represented chiefly by miliolids.

Mud facies

The isolated patches with a mud sediment in the area off Alagoas (stations 60 and 96) remain unexplained. The accumulation of mud must be due to some peculiar circumstances with respect to the local currents, which has still to be investigated.

Station 60 has a somewhat greater depth (42 m) than its surrounding stations (20-30 m), which may be a cause for the accumulation of fine material. Station 96, however, does not show this phenomenon at all, so that in this case other environmental circumstances must determine the mud accumulation. In all samples occur relatively abundant miliolids.

The fine deposits of stations 80 and 81 are due to the fact that these sampling localities were made already at the continental slope (depths of 290 and 75 m, respectively). The small sand fractions consist almost entirely of planktonic foraminifera and some pteropod fragments. Generally in this area, the slope deposits are fine-grained.

Organic material facies

This facies occurs scattered over the southern part of the investigated shelf, beginning already N of the São Francisco river mouth. Its sediments are muddy to sandy, showing only a few algal fragments. In the foraminiferal fractions *Amphistegina* dominates. Furthermore, bryozoans occur sometimes frequently and ostracods and mollusks rarely. Other not more recognizable fragments are frequent to abundant, especially in the finer sizes. Quartz grains are rare, but the quantity of silt and clay may attain $\pm 40\%$. These fine fractions are chiefly of terrigenous origin, but a certain quantity of white calcareous mud is always discernible. This type of mud is supposed to have the following origin: (1) as biochemical disaggregation of skeletal material, especially that of calcareous algae; (2) by the action of boring organisms; (3) by a limited physical attrition of delicate skeletal material in turbulent water (Neumann 1965). In the investigated area, the first possibility seems to be the most probable. However, a certain chemical precipitation of fine calcareous matter may not be excluded because the salinity ($35\text{-}36^{0}/_{00}$) of the water favors its supersaturation with calcium carbonate (Trask 1937). In the fine fractions of some samples aragonite needles could be distinguished.

Algal facies

Calcareous algae are reported to be one of the chief constituentes of organic reefs and to be abundant in shallow water sediments in tropical areas. The shelf off Alagoas shows such an abundance of calcareous algae fragments that a special facies zone could be distinguished. *Halimeda* appears to be much more frequent than the lithothamnioids.

The genus *Halimeda* is represented in the present-day warm seas with some more than ten species distributed between 0 and 80 m in calm waters, because of its delicacy. Therefore, after its death, it desintegrates rapidly and disappears generally in the finer fractions. However, under favorable circunstances it may remain as flakes and segments, constituting pure Halimeda-sands, occurring often in the quiet lagoons between the organic reefs and the beach. Already in 1888, Agassiz (cited by Chapman & Mawson 1906) mentioned the fact that they constitute great calcareous masses of the Florida (USA) coast. Also other authors provide examples of similar phenomena, around a number of Pacific coral islands. In the lagoon of the Funafuti Atoll (New Hebrides) they are present in such a density that they have been compared with "green seaweed" or even "peat bog".

However, recent studies of open tropical shelves do not report such extended *Halimeda* areas as were found off the coast of Alagoas. These algae have been reported chiefly from outer zones of shelves, for intance in the Florida-Bahama region (Thorp 1939), the west Florida shelf (Gould & Stewart 1955), and chiefly from the lagoons and some other parts of the organic reef environment, especialy in the Pacific and the Great Barrier Reef. In that latter area, an extensive study was made by Maxwell, Jell & McKellar (1964) on the Heron Island Reef. In this environment *Halimeda* dominates in the lagoons, and *Lithothamnion* on the reef flats. These authors found that *Lithothamnion* and foraminiferal detritus were coarser than *Halimeda* and aragonitic coral. This is the reverse of what Chave (1962) reported on the relative durabilities of these organisms. Maxwell and his collaborators suggested that the size relationships depend not only on durability but also on relative abundance of source material.

In the investigated area, especially off Alagoas, it can be concluded that the *Halimeda* detritus is really coarser than

that of the other organisms (table III). This may here well be due to relative abundance, but it confirms the opinion of Chave (1962) too, that the *Halimeda* fragments did not disappear into the smaller fractions, being thus fairly durable. Furthermore, the shelf area off Alagoas apparently represents one big organic reef environment with rather calm waters, abundant algae *(Halimeda)* and few corals (chiefly *Millenora),* and without a supply of river material. In the foraminiferal fractions stand out in this algal facies *Archaias* and peneroplids.

The algal detritus covers extensive surfaces, often as fragments (gravels and sands), but at a number of places as a real crust. Here the dredge generally could not break it, coming up without sediment and so suggesting the presence of hard ground. It would be very interesting to have some sample of these crusts, in order to study its cementation. Real rock bottom was nowhere found, the whole area showing sediments of recent age.

Table III. Size distribution and composition of sample 26 algal facies

>2 mm	56.66%	—	only *Halimeda*
2000 — 840 μ	9.64	—	*Halimeda* (A), shell fragments (R)
840 — 420 μ	1.63	—	*Halimeda* (A), foraminifera (C), bryozoans, ostracods, molluscs (R)
420 — 210 μ	0.51	—	algae (A), foraminifera (C) bryozoans ostracods, molluscs (R)
210 — 105 μ	0.65	—	algae (A), foraminifera (C) ostracods, fragments (R)
105 — 53 μ	2.91	—	indeterminable fragments (A) quartz (R) aragonite needles (R)
< 53 μ	28.00	—	chiefly calcareous mud aragonite needles (R)

Tabela III. Distribuição granulométrica e composição da amostra 26 — fácies de algas.

A — abundant, (F — frequent), C — common, R — rare, (I — one exemplar)

São Francisco river facies

Perhaps one of the most interesting parts of the investigated area is that occupied by the São Francisco river deposits. Off its mouth a canyon has developed in a SE direction, which at about 12 miles from the coast has already depths of more than 750 m. Althoug not studied, it is known that at the canyon end a delta exists.

The river brings to the sea a great quantity of fine sediment which as a steady turbidity current flows into the canyon and over its S border, into a southerly direction due to the main longshore current. The sandy part of the supplied material settles directly in front of the mouth (station 162), which means that the currents are not very strong. Only material <53 μ is transported farther.

The fresh river water causes a decrease in salinity in this area. This has a strong influence on the sedimentation, settling only the silt size fractions (q-values 16-38). As is well explained by Hissink (1929) and Wiggers (1955), a brackish environment causes the partial peptization of the flocculated material. The finest fraction (<2 μ) flocculates better with increasing salinity (van Andel & Postma 1954). Figure 5 shows the extension of the area with silty deposits, coinciding with the area of low salinity (compare fig. 7 of part 1 — Introduction), and with the absence of foraminifera and other organic remains in the small sand fraction. The area of <1% carbonate matter, however, extends farther from the mouth.

Outside the silty deposit area occurs an area with clayey sediments (q-values 75-83), coinciding with the area with a higher to normal salinity. As can be seen in figure 5, the clays extend south-westward, where at some distance they become mixed with the coarser shelf sediments. The sand fractions of these clays show already the presence of organic remains, principally foraminifera, ostracods and not more recognizable fragments. Furthermore, a certain quantity of plant fibers is still found in this area. Remarkable is the almost entire absence of faecal pellets. The sand franctions near the limit with the silty sediments area show a relative dominance of the foraminifera *Elphidium, Ammonia* and *Bolivina,* clearly representing the influence of the river. In sample 176, from 360 m, that is the canyon, the great number of exemplars of the foraminifera *Bulimina marginata* and *Eponides* cf. *umbonatus* is notable, a fact thus far unexplained.

Near the continuation of the shelf edge, but in the canyon at depths between 75 and over 400 m, the sediments consist of sandy clays. The fine fractions come still from the São Francisco river. The sand fractions, however, are chiefly of organic origin with foraminifera, bryozoans, ostracods, besides some rare other types and fragments. Only in the finer sizes (210-53 μ) some not-worn quartz grains were found. The whole sediment appears to be a mixture of material of different proceedings, slid into the canyon. Such mixtures can be very recent, as was pointed out by Egorov & Galanov (1966) who studied a number of canyons at the Colchis coast of the Black Sea. They found, by luminescent tracers, that after 18 days the coloured grains occurred up to depths of 1½ m below the surface. Also the leaves of trees and other plant remains in their samples showed a very recent accumulation, caused, after the opinion of these authors, only by submarine slides, because other mechanisms seemed to be fairly impossible. This means that such canyons are subject to rapid changes, chiefly determined by the river run-off. Also the foraminifera associations show this thorough mixture, with *Amphistegina,* agglutinated forms, and planktonic forms (for instance *Globigerinoides* and *Globorotalia*).

CONCLUSIONS

The investigated shelf off Alagoas and Sergipe is an interesting area with respect to its facies distribution, especially the abundance of *Halimeda* deposits. Comparisons made with the other investigated areas of South America, the Gulf of Venezuela (Zeigler 1964), the Paria-Trinidad shelf (Koldewijn 1958), the Gulf of Paria (van Andel & Postma 1954), the western Guiana shelf (Nota 1958), and the shelf off the mouth of the Amazon (Ottmann 1959), reveled that the calcirudites and calcarenites of these areas could be correlated with the organic material facies in northeastern Brazil. Algal facies are absent in all these other areas, apparently due to the supply of a great quantity of terrigenous material (Orinoco, Amazon). Algae are mentioned by Koldewijn (1958) as a common, but not dominant constituent at some parts of the Paria-Trinidad shelf, and in a greater quantity near the bioherms in that area. In the area of influences of the São Francisco river, off Sergipe, similar organic material and terrigenous facies occur, whereas the algal facies occupies only small patches.

Comparisons made with tropical shelf areas in other parts of the world, reveal that also there pure algal facies are not

frequent. Generally one finds organic material facies with the common organisms of tropical waters not only on open shelves, but also on shelves of mediterranean seas and in epicontinental seas, for instance the shallow parts of the Mediterranean Sea near the coast of North Africa (Leclaire, Gaulet & Bouysse 1965), and the shallow parts of the Red Sea (Rosenberg-Herman 1965) with bentonic foraminifera, as for instance Buliminidae, Miliolidae and Amphisteginidae, and only a few algae. The shelf off the south coast of Madagascar shows a thorough mixture of terrigenous and organic material, whereas algae are totally absent (Berthois, Battistini & Crosnier 1964).

Areas with more algal deposits are those related with the organic reef environment, of which are very well-known the Bahamas (Newell & Rigby, 1957 Purdy 1963a, b), Bermuda (Neumann 1965), the Great Barrier Reef — Heron Island (Maxwell, Day & Fleming 1961; Maxwell, Jell & McKellar 1964), the atolls of the Pacific Ocean — Funafuti (Hinde 1904), Bikini (Emery, Tracy jr & Ladd 1954), Kapingamaringi (McKee 1958), and the island Saipan (Johnson 1957). Almost all these sediments are found in the lagoons, and sometimes at quiet places on the outer shallow side. One may thus conclude that the abundance of *Halimeda* at the shelf off Alagoas is somewhat exceptional, due to a clear and quiet environment. It has to be studied, how far this area reaches up northward, and if more such areas exist.

The southern part of the investigated shelf, off Sergipe, within the area of river influence of the São Francisco, Japaratuba and Vaza-Barris, the algal facies is restricted to only some small patches. Also *Halimeda* is not the chief constituent here. The terrigenous facies with muddy deposits and many miliolids and *Amphistegina* dominates. This latter foraminifer is also the most important in the area of occurrence of the organic material facies. The shelf gives the impression to be normal, that is similar to other shelves where a certain river influence can be detected.

The canyon of the São Francisco river gets a constant supply of fine river material by turbidity currents of the steady type (Dunbar & Rodgers 1957). In the area of low salinity, chiefly silty sediments occur, whereas in the remainder the deposits are clayey. Only near the shelf edge, the deposits althoug with a high mud percentage, belong to the organic material facies. In the clayey sediment part, the foraminifera show obviously the river influence.

With respect to the continental slope, only a few observations can be made, being the number of stations in this area small (5C - 370 m, 73 - 90 m, 80 - 290 m, 81 - 75 m, 102 - 90 m, 103 - 110 m, 120 - 200 m, 131 - 86 m, 138 - 106 m, 147-96 m), representing only the upper part, and sometimes the break itself. Of these only sample 5C gives a real slope fauna, as has already been mentioned. All other samples are muds, with a few planktnic foraminifera in their sand fractions. Noteworthy is here, the abnormal high slope angle (4-20°, Shepard 1963, p. 216). This author claims the exceptionality of this feature, because the coast did not show indications of recent diastrophism. However, very recent studies, as yet to be published, discovered a certain tectonic action as recent as Late-Pleistocene on the adjacent continent. Even at some places the coast line is due to faulting. These movements might have caused the high angles of the continental slope in this area.

Finally, the bottom sediment, with exception of the muddy parts, appears to be a real "desert" for abundant fish life. Generally, calcareous algae, foraminifera and bryozoans are not suitable as food for the fish larves, which depend on the bottom throughout their development (Allee & Schimidt 1951), so that an economic fishery here seems to be almost impossible.

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