MISSÃO NO EXTERIOR

RELATÓRIO DE ATIVIDADES E

RELATÓRIO TÉCNICO.

PROJETO REMAC

Rio de Janeiro
Janeiro de 1974
PROJETO REMAC

PETROBRÁS - Petróleo Brasileiro S/A - MME
CPRM - Companhia de Pesquisa de Recursos Minerais - MME
DNPM - Departamento Nacional de Produção Mineral
DHN - Diretoria de Hidrografia e Navegação - MM
CNPq - Conselho Nacional de Pesquisas

MISSÃO NO EXTERIOR

RELATÓRIO DE ATIVIDADES

LEOPOLDO AMARAL BARRETO
CPRM
1 - INTRODUÇÃO

Visando o processamento e interpretação dos dados geológicos e geofísicos coletados durante o Cruzeiro Woods Hole–Águas Rasas, fomos designados a cumprir estágio junto à Woods Hole Oceanographic Institution, Massachusetts, USA., no período entre 16 de abril e 16 de novembro de 1973.

Os resultados obtidos permitiram a elaboração de dois relatórios técnicos que, após aprovação pela Gerência Técnico-Executiva do Projeto, serão publicados em revistas técnico-científicas de ampla circulação internacional.

O presente relatório visa apenas apresentar um sumário das atividades desenvolvidas junto aquela Instituição, já anteriormente reportadas nos relatórios mensais apresentados conjuntamente com os outros membros da equipe brasileira.

2 - EQUIPE E ÁREA DE TRABALHO

Trabalhamos em colaboração com o Geólogo Carlos Alfredo Becker do Amaral (DNPM), orientados pelo Dr. J.D. Milliman, da WHOI, chefe científico do Projeto.

A área de trabalho foi a Margem Continental Norte Brasileira, compreendida entre o meridiano 40º Oeste e o Cabo Orange, extremo Norte do Brasil.

3 - TRABALHOS EXECUTADOS

As tarefas executadas objetivaram como resultado final a elaboração de dois relatórios técnicos, abrangendo um deles os aspectos da Geomorfologia e Estrutura Rasa e o outro tratando da
caracterização e distribuição dos Sedimentos Superficiais na área.

No Quadro 1 acham-se discriminados os períodos dispendidos em cada tarefa.

3.a – Geomorfologia e Estrutura Rasa.

Inicialmente foi preparado um Mapa-base na escala 1:2.000.000, projeção Mercator. A linha de costa e a drenagem costeira foram retiradas das cartas 1:1.000.000 do IBGE, edição de 1972. Neste mapa foram lançadas as linhas executadas pelo N.Oc.Prof. Besnard na área, com os respectivos valores batimétricos corrigidos. Foram ainda utilizados os dados batimétricos das linhas sísmicas efetuadas pela Petrobrás e os valores das Cartas"Geodé" O mapa batimétrico resultante é apresentado em redução na Figura 1.

Todos os registros eco-batimétricos (PDR 3.5kHz) foram detalhadamente examinados, tendo-se confeccionado a partir dos mesmos um mapa com feições morfológicas mais notáveis e de reflexões obtidas em sub-superfície. Foram selecionados e montados para ilustração 10 registros PDR, representativos das feições morfológicas típicas.

Levando-se em conta a localização geográfica e a qualidade do registro, foram selecionadas 20 linhas de reflexão sísmica para interpretação. Após interpretadas, as mesmas foram reduzidas para uma escala conveniente à publicação (figura 2).

3.b – Sedimentos de Fundo

Das 242 amostras de sedimentos superficiais coletadas na área durante o Cruzeiro Besnard (WHOI – Águas Rasas), foram selecionadas para processamento 150, visando-se a cobertura de toda a região assim como detalhamento em algumas áreas críticas.
Estas amostras foram processadas de acordo com o fluxograma anexo (figura 3).

Os resultados obtidos foram integrados às informações obtidas no ano anterior (amostras das Operações Geomar I, II e III), o que permitiu uma cobertura bastante ampla. Os diversos parâmetros obtidos foram plotados em mapas base (escala 1:2.000.000) contornados, e posteriormente reduzidos.

4 - SEÇÕES E MAPAS PRODUZIDOS

Os resultados obtidos nas diversas fases do estágio foram plotados em mapas-bases (escala 1:2.000.000) e em diversas seções, que se encontram em fase final de desenho e redução na WHOI. Os mesmos serão utilizados como ilustrações dos relatórios técnicos produzidos. A seguir são relacionadas estas ilustrações:

a - Geomorfologia e Estrutura Rasa

1. mapa base com linha de costa e "track" percorrido no Cruzeiro "WH-AR" e locação dos dados batimétricos cedidos pela PETROBRAS;

2. Mapa batimétrico com topografia e drenagem costeira (figura 1);

3. mapa de detalhes batimétricos e reflexões 3.5 KHz em sub-superfície;

4. 10 montagens de registros PDR caracterizando os tipos de fundo;

5. 20 seções sísmicas de reflexão reduzidas (figura 2).
b. - Sedimentos Superficiais

1. mapa de estações de amostragem (todas as estações da área);
2. mapa de % de areia mais cascalho;
3. mapa de % de silte;
4. mapa de % de argila;
5. mapa de razão de % silte/argila;
6. mapa granulométrico (triângulo sedimentológico)
7. mapa do grau de arredondamento;
8. mapa de % de grãos com película de ferro;
9. mapa dos constituintes carbonáticos;
10. mapa dos constituintes minerais leves;
11. mapa dos constituintes minerais pesados;
12. mapa de % de montmorilonita;
13. mapa de % de caolinita;
14. mapa de % de illita;
15. mapa de razão de % illita/caolinita;
16. mapa de teor de fósforo;
17. mapa de teor de nitrogênio
18. mapa de teor de carbono orgânico.

5 - CONCLUSÕES

Considerando a finalidade básica do estágio-processamento e interpretação dos dados geológicos e geofísicos coletados pelo Cruzeiro Woods Hole-Águas Raras na Margem Continental Nor te Brasileira - concluímos que o mesmo cumpriu plenamente seu objetivo.

Quanto ao aspecto de treinamento, podemos afirmar que foi bastante proveitosa a vivência com os métodos adotados naque- la Instituição de pesquisa, de alta produtividade. Entretanto, o estágio ressentiu-se de um maior treinamento na parte inter pretativa, dado o grande volume de material a ser trabalhado.
6 - RECOMENDAÇÕES

Torna-se necessário ser propiciado aos geólogos e geofísicos engajados no Projeto REMAC cursos de pós-graduação no exterior, em instituições de ensino e pesquisa de renome internacional. Tal medida possibilitaria uma maior afirmação do conceito técnico-científico do nosso país no exterior no âmbito da Geologia e Geofísica Marinhos.

7 - ILUSTRACOES

Figura 1 - Mapa Batimétrico
Figura 2 - Linhas de Reflexão Sismica Reduzidas
Figura 3 - Fluxograma do Processamento das Amostras de Fundo
Quadro 1 - Resumo das Atividades em WHOI

8 - ANEXOS

Anexo I: Relatório técnico do estágio
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FIGURA 1

MAPA BATIMÉTRICO
FLUXO DE PROCEDIMENTO ANALÍTICO DAS AMOSTRAS

ANÁLISES MINERALÓGICAS E TEXTURAIS

AMOSTRA S/TREATAMENTO

ÁNALISES QUÍMICAS

NITROGRAVIÊ N
CARBONO ORGÂNICO
CO2

SECAGEM, PESAGEM E IMPREGNAÇÃO C/(NaPO3)6

PENEIRAMENTO ÚMIDO

SILTE
E ARSILA

ARDA

SECAGEM E PESAGEM

CENTRIFUGAÇÃO

COMPONENTES CARBORÂNICOS

REMOÇÃO CO2 C/HCL DILUIIDO

PENEIRAMENTO

FRAÇÃO
125–250 μm

BROMOFÓRMIO

MINERAI PESADOS

MINERAI LEVES

COLORAÇÃO

FELDSPATO SÓDICO

FELDSPATO POTÁSSICO

QUARTZO

FIG. 3
Anexo I - Relatório técnico do estágio
CONTINENTAL MARGIN SEDIMENTATION OFF BRAZIL. PART I. NORTHERN BRAZIL
Leopoldo A. Barreto², John D. Milliman³, Carlos A. B. Amaral⁴ and
Odimo Francisconi².

Abstract

The surface sediments of the northern Brazilian continental shelf
and upper slope are represented by three major and two minor sedi-
mentary provinces. Relatively immature (in terms of both surface
texture and composition) Amazon River sediments dominate the shelf
and upper slope north of Para State. In contrast, the sediments on
the inner and middle shelf south of Para State are characterized by
a high degree of textural and compositional maturity, indicating
derivation from neighboring coastal rivers. Carbonate-rich sediments,
composed primarily of reef and coralline algal debris, form the third
major sedimentary province, which dominates most of the outer shelf
and the entire shelf off Ceara State; os special interest is the
presence of oolitic sediments on the outer Amazon shelf, in which
the ooids are composed of magnesian calcite. Some shelf sediments
have been derived from local outcrops (particularly on the outer
Amazon shelf); much of the shelf sediment off Ceara State probably
was contributed by the Acaráu River.
Most of the sediments on the northern Brazilian shelf appear to be relict, although they are actively moving northward on the inner shelf south of the Para River. The primary site of modern terrigenous sedimentation is the wedge of Amazon muds which progrades across the inner shelf. Northward flow by the Guiana Current, however, has directed much of the Amazon sediment northwards along the South American coastline. Some Amazon sediment appears to be escaping across the shelf to the slope, but tidal, estuarine and other currents have winnowed out most mud from middle and outer shelf sediments.

1 Contribution Number ______ of the Woods Hole Oceanographic Institution
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Introduction

The continental shelf and slope off northern Brazil (Amapa, Para, Maranhão, Piaui and Ceara States) (Fig. 1) represent one of the most interesting sedimentary environments in the world. The Amazon River, the world's largest in terms of drainage area and total runoff and the largest in the Atlantic Ocean in terms of dissolved and suspended load (Oltman, 1965; Gibbs, 1967; Lisitzin, 1972) obviously is of major sedimentary importance in the western part of this area.

Equally important, as will be discussed in this paper, is the influence of the equatorial Guiana Current, which flows NW over much of the shelf and upper slope with average current speeds exceeding 50 cm/sec. Nevertheless, the northern Brazilian shelf has remained relatively poorly studied. Other than the scattered samples collected by the HMS CHALLENGER and the METEOR, the basic sediment distributions were delineated first by ship-board analysis of small samples collected by bathymetric lead soundings during the late 19th and early 20th centuries. Using this information, Shepard (1932) concluded that the inner shelf northwest of the Amazon River is covered with mud, while the outer Amazon shelf and the entire shelf to the southeast is sand.
On the basis of 80 samples collected during GEOMAR I, Zembruscki and others (1971) indicated the presence of six sedimentological facies on the north Brazilian shelf, generally following the patterns described by Shepard. Perhaps most noteworthy is the presence of biodetritic and authigenic sediments on the outer shelf south of Amazon Canyon. Heavy mineral distributions in the Amazon area were described by Pomerancblum and Costa (1973), based on samples collected by GEOMAR I and II. With the data taken during Brazilian fishery studies, Coutinho and Onofrede (1971) discussed the broad aspects of carbonate sedimentation on the north Brazilian shelf. Milliman and others (1973) delineated sedimentary facies as derived from petrographic parameters of samples collected by various Brazilian and U. S. institutions. A brief paper by Gibbs (1973) touched on some of the sedimentologic parameters immediately seaward and north of the Amazon. This paper represents the synthesis of results from more than 500 sediment samples, collected mostly by Brazilian agencies prior to 1973 and by the N/O PROFESSOR W. BESNARD in early 1973 (Fig. 2). Analytical methods have been discussed in the preceding paper. This study is a part of the cooperative study of the Brazilian continental margin by Brazil (Project REMAC) and the Woods Hole Oceanographic Institution, funded by Brazil and by the International Decade of Ocean Exploration.
Some sediment samples were supplied by the Rosenstiel School of Marine and Atmospheric Science, University of Miami and the Lamont-Doherty Geological Observatory (through the Office of Naval Research Contract No. N))14-67-A-0108-0004). Although the authors performed most of the analyses, supplementary data were provided by Marcio P. A. Costa, Lois Toner, Catherine Offinger and Jeffrey Ellis. We thank C. P. Summerhayes, R. H. Meade and E. Uchupi for their critical comments on this manuscript.

**Study Area**

Northern Brazil is a low-lying land mass, with relief generally less than 100 meters. The Serra de Ibiapaba in Ceará State, with elevations exceeding 500 m is the only high-standing area near the coast. The coastal geology consists of two dominant sedimentary basins, the Amazon and Maranhão (Parnaíba) basins, both of which were filled in Paleozoic times and later reactivated in response to continental rifting in the Jurassic and Cretaceous. The Maranhão contains two smaller and apparently younger coastal basins, the São Luís basin in the north and the Barreirinhas basin in the south. Landward of these basins is an extensive Precambrian and early Paleozoic craton, which is primarily granitic in composition. A more complete treatment of the geology in this area can be found in DNPM (1971), Andrade and da Cunha (1971), Aguir (1971), Miura and Barbosa (1972), and Bigarella (1973).
The climate along the northern Brazilian coast is tropical. Temperatures generally range from 26 to 30 °C throughout the year, but rainfall varies greatly with location. While precipitation exceeds 2000 mm in the Amazon River Basin, it is less than 500 mm per year in Ceará State (and in recent years has averaged less than 100 mm). These differences in rainfall help determine the coastal morphology: Being arid, the coast south of Baia de São Marcos is characterized by many sand dunes and beaches, resulting in a relatively smooth coastline (Fig. 1). In contrast, the rainy coast north of Baia de São Marcos is covered with extensive mangrove swamps which help accentuate the irregular coastline.

The Amazon River system, which is the dominant fluvial influence in northern Brazil, is actually composed of two major systems: 1) The Amazon River proper, which flows from the Andes Mountains to the Atlantic Ocean, drains a total area in excess of 6 x 10^6 km^2 (Keller, 1962). Despite the fact that the Amazon flows mostly through a rain forest for more than 3000 km, most of the sediment carried in suspension is derived from the Andes Mountains (Gibbs, 1967); as a result, Amazon River sediment tends to be rich in feldspar and montmorillonite. 2) The Para River system is actually an estuary for the confluence of a distributary of the Amazon and the Tocantins River.
Because this latter river drains exclusively low-standing tropical rain forest, suspended sediment in the Para is rich in quartz and kaolinite compared to the Amazon River.

A large number of rivers drain the coastal area southeast of the Amazon-Para complex. Foremost amongst these rivers are the Gurupi, Itapecuru, Parnaiba and Acaráu. All these rivers flow throughout the year, except the Acaráu, which drains the Serra de Ibiapuãba only during rainy months. Although no stream gage data are available for these rivers, their rate of flow (and probably also suspended load) is probably at least an order of magnitude less than that of the Amazon-Para.

Morphology of the North Brazilian Continental Margin

The morphology and shallow structure of the north Brazilian continental margin have been described elsewhere (Milliman and others, 1974b) and will only be briefly discussed in this section. Shelf width varies from about 200 km seaward of the Amazon River to about 100 km off Ceará State. The depth of the shelf-slope break lies between 120 meters (off the Amazon) and 90 meters (off Ceará State) (Fig. 1).

Much of the shelf can be characterized as broad, flat and featureless; gradients average 1-2/1000. However, a significant part of the inner and middle shelf south of the Para River contains
symmetrical and asymmetrical sand waves, 5 to 10 meters in amplitude (Fig. 3). The waves are limited to the north by the occurrence of the Amazon mud wedge (see below); the seaward extent is defined by the depth of effective wave base. The symmetrical ripples probably form in response to oscillatory influences, such as waves and tidal currents, while the asymmetrical features indicate northward transport of sand by the Guiana Current (Milliman and others, 1974a).

The outer shelf and upper slope are bisected by numerous gullies and canyons, the largest being the Amazon Canyon (Fig. 1). The channels and ridges which cut across the middle and outer shelf off the Amazon River are particularly interesting. Undoubtedly these features represent Pleistocene fluvial systems which have not been buried by subsequent Holocene sedimentation (Milliman and others, 1974b).

**Sediment Texture**

**Size:** Surficial sediments on most of the middle shelf and on the inner shelf south of the Para River are composed of sand; average sand content in these areas is greater than 90 percent (Fig. 4). Sand is also a major constituent on the outer shelf, although locally gravel is dominant, especially south of the Amazon Canyon.
Gravel-rich sediments (containing more than 50 percent gravel) also occur on the inner shelf off the Para River and the middle shelf east of the Paranaiba River (Fig. 4). Most of the shelf gravel is biogenic, primarily reef and algal detritus (see below).

Mud-rich sediments dominate the inner shelf seaward and north of the Amazon-Para system. Sand contents in these sediments are generally less than one percent. One exception is the band of sand-rich sediment which extends seaward from the Amazon River (Fig. 4); the significance of this band is discussed in a later section. The transition from inner shelf muds to middle and outer shelf sand and gravel is relatively sharp. Sediments with under 5 percent sand lie less than 25 km landward of sediments containing more than 75 percent sand. Bathymetric charts show that the seaward edge of this mud belt has a steep gradient (Fig. 1) and low-frequency (3.5 kHz) echo-sounding profiles in this area indicate that the nearshore Amazon muds are prograding over an older (Pleistocene to early Holocene) sand surface (Fig. 3).

The muds on the inner shelf immediately seaward of the Amazon River are primarily silt, with the innermost shelf containing up to 9 times more silt than clay (Fig. 5). In contrast, areas north
of the Amazon are rich in clay, with the clay (silt + clay) ratio generally greater than 0.6. This distribution probably reflects winnowing by estuarine and tidal circulation near the Amazon mouth and the northward transport of clay by the Guiana Current.

Silt-rich mud is present on the Maranhao outer shelf, although mud constitutes less than 15 percent of most sediments. Only traces of mud occur over the rest of the inner and middle shelf, but 3.5 kHz echo-sounding records indicate a possible mud patch immediately off the Paranaiba River (Milliman and others, 1974b). Mud-rich sediments dominate the slope and rise, although the sparse sample coverage does not allow us to speculate on the distribution of size grades.

**Roundness:** Another aspect of sediment texture is the roundness of the sand grains. The non-carbonate 125-250 fraction on the shelf south of the Para River is composed largely of subrounded, subangular and rounded grains (Fig. 6). Grains off Maranhao State are particularly well rounded. Sediments on the middle and outer shelf off Piaui and Ceara states, however contain large amounts of subangular and angular grains.

North of the Para River, sand grains are significantly more angular than to the south; subangular grains predominate. Sediments
adjacent and contiguous with the Amazon and Para system are particularly angular. The only two areas with subrounded grains occur on either side of the Amazon channel (Fig. 6).

**Sediment Composition**

**Carbonate Fraction:** The concentration of calcium carbonate within the sediments on the north Brazilian continental shelf is related to both the grain size of the sediment and the distance from shore. In addition, carbonate content is also controlled by bottom morphology. The importance of these various factors will be discussed in the following paragraphs.

Amazon shelf muds contain only small quantities of calcium carbonate, generally less than 3 percent (Fig. 7). Rapid terrigenous deposition masks carbonate grains and also buries possible substrates for epibenthic communities. Nearshore sands along the rest of the shelf are also low in carbonate, although several shallow banks seaward and south of the Para River have higher concentrations. Dominant organisms throughout most of the low-carbonate sediments are mollusks (mainly infaunal pelecypods); local populations of echinoids and benthonic foraminifera can be important. Components in the higher
carbonate sediments include bryozoans, coralline algae and barnacles (Fig. 8). Apparently these organisms grow on the available substrate (outcrops?) present on these shallow banks.

Carbonate content increases on the outer Amazon shelf but the absolute concentration depends greatly upon topography. Although sample control is relatively poor, it appears that high carbonate concentrations are restricted to topographic highs, whereas low concentrations (less than 5 percent CaCO₃) occur in topographic lows (valleys) (compare Figs. 1 and 7). The high carbonate sands and gravel are composed chiefly of coralline algae, bryozoans, benthonic foraminifera, mollusks and locally large concentrations of Halimeda plates and serpulid tubes (Fig. 8). The benthonic foraminifera are dominated by typical reef populations, such as peneroplids, amphisteginids, and various species of miliolids and textulariids. The presence of these various reef-related organisms and the generally coarse sediment texture suggest that these outer shelf sediments are derived from a series of shelf-edge "reefs", probably very similar to features found elsewhere in the world (Macintyre and Milliman, 1970; Milliman, 1974a). The fact that many of the
foraminifera tests are iron-stained indicate that at least some of the carbonate in this reef assemblage is relict in age.

The low-carbonate sands that lie in the valleys between the high-carbonate sediments are composed primarily of mollusks, thus bearing a close similarity to the inner shelf sediments. Possibly these terrigenous-rich sediments are relict Amazon-derived sediments that were deposited in river channels during the last low stand of sea level. In contrast, the high-carbonate "reef" sediments may have been deposited on high-standing banks which were not affected by the terrigenous influx.

One particularly interesting sedimentary assemblage on the outer Amazon shelf is scattered occurrences of magnesian calcite ooids. Stable isotope and petrographic data indicate that these ooids are unaltered, and carbon 14 dates suggest deposition during the last low stand of sea level (Milliman and Barretto, 1974). Although relict ooid-rich sediments have been described from many other continental shelves (Milliman, 1974a), we know of no other oolite deposit, either relict or modern which is composed exclusively of magnesian calcite.
Some sediments on the outer Amazon shelf and on the inner shelf seaward of the Para River contain appreciable amounts of lithoclasts, irregular fragments of quartzose limestone (Fig. 8). The presence of these fragments suggests close proximity to a subaqueous outcrop; other bathymetric and sedimentological data presented in this paper would support such an assumption.

The middle and outer shelf sands off southern Maranhão, Piauí and Ceara States are relatively rich in calcium carbonate, with some areas containing more than 95 percent CaCO₃ (Fig. 7). South of the Parnaíba River, inner and middle shelf sediments contain more than 75 percent carbonate, locally more than 95 percent, mostly in the form of branching coralline algae and Halimeda plates (Fig. 8). The general texture and composition of these sands and gravels resemble the maerl deposits reported in the Mediterranean (Joquette, 196_; Caulet, 1971, 1972). Mollusk-rich low-carbonate sands which occur to the east and west of this algal maerl probably reflect the terrigenous influence of the Parnaíba and particularly the Acarau River.
Non-carbonate Fraction

Heavy Minerals: Heavy mineral (specific gravity greater than 2.87) distribution in the carbonate-free 125-250 micron fraction differs greatly north and south of the Amazon-Para system. Sediments on the outer shelf immediately north of the Para and the entire shelf to the south contain less than 0.5 percent heavy minerals. One exception is the outer shelf east of Baia de Sao Marcos, where local concentrations can exceed 5 percent (Fig. 9). Sediments north of the Para generally contain between 1 and 3 percent heavy minerals, but a band of sediments directly seaward of the Amazon River mouth locally contains more than 25 percent. On the upper Amazon slope, heavy mineral content can exceed 50 percent of the insoluble fraction.

Opaque and altered minerals dominate the heavy fraction. Opaques are highest on the inner shelf off Para and Maranhao states and decrease offshore and to the north (Fig. 10). Altered minerals show exactly the opposite distribution, with greatest concentrations on the shelf north of the Amazon River (Fig. 11). In most cases alteration has occurred by acquisition of limonite coatings. On the upper Amazon slope, however, some opaque grains are totally limonitic.
The character and distribution of heavy minerals within the non-opaque fraction can be characterized by three different minerals — hornblende, staurolite and kyanite. Hornblende is a dominant mineral in the shelf sediments north of the Para River, with local concentrations exceeding 40 percent of the non-opaque fraction. In contrast, hornblende is present in only minor amounts to the southeast; one exception is the area offshore from the Acarau River, where concentrations are greater than 20 percent (Fig. 12). Staurolite characterizes the shelf off Para, Maranhao and Piaui states; locally concentrations can exceed 45 percent. Kyanite occurs in the southeast portion of the study area, with concentrations as great as 40 percent, but generally between 10 and 30 percent (Fig. 12).

On the basis of the distribution of these three mineral species as well as the other prominent heavy minerals, the non-opaque fraction can be divided into 5 provinces (Fig. 13): 1) The shelf off Amapa State is characterized by a suite of relatively immature heavies, primarily hornblende, enstatite and hypersthene. Locally sillimanite is common to abundant, with lesser amounts of augite, epidote and diopside. 2) Sediments on the Para shelf contain a relatively stable heavy mineral suite, composed primarily of staurolite, tourmaline and zircon. 3) A somewhat similar province occurs off Maranhao state, except for the presence and local dominance of kyanite. The other two provinces occur off eastern
Piauí and western Ceará states, in the southeastern portion of the study area. 4) A relatively mature heavy mineral suite, composed mainly of kyanite, tourmaline and epidote occurs on the mid-shelf off Ceará State. 5) It is surrounded by a relatively unstable suite, dominated by garnet, hornblende, kyanite and tourmaline.

The distribution of these various heavy mineral suites obviously reflects different sediment sources and weathering and transport histories. The importance of these various factors will be discussed in a following section.

**Light Minerals:** The light fraction (specific gravity less than 2.87) on the north Brazilian shelf is dominated by quartz and feldspar, with lesser amounts of glauconite and rock fragments. Diatom frustules and phosphorite grains are rare.

Quartz and feldspar grains on the outer shelf off Amapá State are highly iron-stained. In the 125-250 micron interval, up to 85 percent of the light grains are iron-stained and most sediments have more than 40 percent iron-staining (Figure 14). In the nearshore area of Amapá State and along most of the rest of the shelf, however, sediments generally contain less than 10 percent iron staining. Two areas with 30 to 50 percent iron-staining are found seaward of the Para River, the same areas which other data suggest may contain outcrops of older strata (see above).
The sediments on the shelf south of the Para River generally are orthoquartzitic, with the average feldspar content being 1 to 2 percent of the insoluble 125-250 micron fraction (Figure 15). Sediments off Ceara State, on the other hand, are suborthoquartzitic on the inner and middle shelf and subarkosic on the outer shelf. North of Para State most of the shelf sands are subarkosic, with average feldspar contents of 15 to 20 percent.

Noteworthy is a band of arkosic sediment which stretches seaward from the Amazon; these sediments also are coarser and contain more heavy minerals than surrounding shelf sediments (see above).

Glaucosite distribution generally follows that of feldspar. Sediment south of the Para contains less than 5 percent glauconite, while off Amapa State contents can be as great as 25 percent. The rounded and worn nature of these grains indicate that the shelf glauconite is chiefly detrital. In contrast, glauconite on the slope, present in concentrations of 25 to 50 percent, is more lobate and fresher in appearance, suggesting either authigenic formation or the derivation from local outcrops.

Clay Minerals: Montmorillonite is the dominate layered silicate (in the finer than 2 micron fraction) north of the Para River. Values on the middle and outer shelf generally exceed 40 percent and locally are greater than 70 percent (Figure 16).
Nearshore values, on the other hand, are usually under 30 percent. Montmorillonite content decreases to the south and is less than 10 percent off Ceara State.

The other two prominent clay minerals on the north Brazilian shelf are kaolinite and illite. Off Para and Maranhao States, the clay fraction is primarily kaolinitic, while to the northwest and southeast, illite predominates over kaolinite (Figure 17). This pattern of stable (lateritic) kaolinite off Para and Maranhao closely matches heavy mineral and light mineral distributions (see above).

**Sediment Chemistry**

**Organic Matter:** The relative distribution of organic matter within sediments can be expressed in terms of nitrogen content. The highest kjeldahl nitrogen values in the north Brazilian continental margin occur in the fine-grained sediments seaward of the Amazon River and on the upper slope (Figures 18 and 19). Sands on the shelf south and seaward of the Para system, however, generally contain less than 0.020 percent nitrogen. The values of nitrogen relative to silt and clay content appear to be slightly lower than those observed off the eastern United States (Figure 19).
The ratio of organic carbon to nitrogen (C/N) can help in determining the composition (and thus source) of the organic matter. Off northern Brazil, the sediments adjacent to rivers (Amazon, Para, Parnaiba and Acarau) contain C/N ratios which exceed 10/1; these ratios decrease seaward but generally remain greater than 5/1 (Figure 20). In contrast, shelf sediments not directly affected by river runoff, such as the shelf off Para State, contain C/N ratios less than 5/1 and locally less than 2.5/1. Experience off the western and eastern United States indicates that sediments with high C/N ratios (greater than 15/1) reflect terrigenous or freshwater organic matter, while those with low ratios (5 to 6/1) indicate the dominance of planktonic organic debris (Emery, 1960; Milliman, 1974b). While a similar argument can be made for the north Brazilian shelf and slope sediments (Figure 20), the absolute ratios are markedly lower than those from North America. Perhaps terrigenous and planktonic sediments from such tropical areas actually contain less carbon relative to nitrogen. However, since fine-grained sediments contain relatively low amounts of nitrogen (Figure 19), we conclude that organic productivity (at least in terms of what remains trapped within the sediment) must be lower than for the eastern United States.
**Phosphorus**: The amount of phosphorus in surface sediments (expressed in ppm \( P_2O_5 \)) varies greatly throughout the north Brazilian shelf and slope. Much of the sediment south of the Amazon River contains less than 200 ppm \( P_2O_5 \). In contrast, values along much of the outer shelf and on the inner shelf off Ceara State exceed 1000 ppm \( P_2O_5 \) (Figure 21), probably in response to the abundance of bryozoans and coralline algae, both of which can contain more than 5000 ppm \( P_2O_5 \) (Milliman, 1974a). Another area with high phosphorus content is the shelf northwest of the Para River, although values are somewhat lower immediately seaward of the Amazon River (Figure 21). The source of this phosphorus-rich sediment is not known, but it may be related to organic matter (Milliman and others, 1974a).

The highest concentration of phosphorus on the upper margin is found on the upper slope off the Amazon Canyon. Local values can exceed 2000 ppm \( P_2O_5 \). These high values may reflect phosphorite-rich sediments derived from exposed outcrops on the upper slope, or perhaps the authigenic formation of phosphorite (see below).

**Sedimentary Provinces**

Based on the textural and compositional data presented in this paper, we can divide the sediments on the north Brazilian continental margin into 3 major and 2 minor provinces, each of which reflects different sedimentary sources and environments of deposition (Figure 22).
1) In terms of sediment supplied, the Amazon River is the most important source, not only for northern Brazil but for northeastern South America (see, for example, Eisma and van der Marel, 1971). By virtue of the fact that most of the sediment carried by the Amazon is derived from the Andes Mountains (Gibbs, 1967), this sediment can be characterized by relatively immature mineralogic and textural associations. The Amazon province on the north Brazilian shelf, therefore, is defined by the dominance of feldspar in the light fraction, hornblende, epidote and hypersthene in the heavy fraction, and montmorillonite and illite in the clays. Moreover, grains tend to angular and subangular, also indicative of a relatively immature sediment.

2) The coastal rivers that drain much of the area south of the Amazon River carry sediments derived from late Mesozoic and Tertiary sedimentary strata. Since these sediments have been exposed to the extensive lateritic chemical weathering typical of tropical rain forests, the component grains display a more mature character than those carried by the Amazon. The sands are strongly orthoquartzitic and have heavy minerals dominated by such stable components as staurolite, tourmaline and (to the south) kyanite; clays are primarily kaolinitic. The well-rounded nature of the grains suggests an extensive abrasional history, although
perhaps some of it was inherited from the parent sedimentary rocks. The particularly well-rounded grains off eastern Maranhao State, however, coincide closely with the occurrence of sand dunes which line the present-day coastline in this area; perhaps these shelf sands were deposited by aeolian processes during a lower stand of sea level.

3) A major sediment source on the outer shelf is biogenic carbonate debris. Carbonate-rich reef sediments line the outer shelf off Para and Maranhao States as well as forming on the topographic highs on the outer Amápa shelf. Coralline algal and Halimeda maerlss occupy much of the Ceará shelf. Presumably the dominance of carbonate in these sediments (average carbonate content often exceeds 75 percent) reflects both the availability of favorable substrate for attachment and the lack of terrigenous sedimentation.

4) The sediments off parts of Ceará State are characterized by their low carbonate content (particularly as compared with nearby maerl sands and gravels), relatively high feldspar content, unstable heavy minerals (garnet and hornblende), and high concentrations of illite and montmorillonite within the clay fraction. These angular and subangular sediments undoubtedly were derived from the Acarau River, which drains the Serra de Ibiapaba. The unstable nature of the grains partly reflects the arid mountain source and partly the fact that the river flows only seasonally, thus resulting in rapid transport and a minimal chemical weathering.
5) Some sediments on the shelf and upper slope appear to have been derived from nearby outcrops of older strata. As discussed previously, the carbonate-rich epibenthic assemblages on the inner shelf off the Para River indicate the presence of high-standing substrata, and the iron-stained nature of the terrigenous grains suggests the presence of one or more outcrops in this area. Some sediments on the outer Amapa shelf are not only highly iron-stained and contain lithoclasts, but also tend to be either more or less arkosic than surrounding Amazon sediments (Figure 15). Presumably these sediments have been eroded from underlying Pleistocene (presumably) strata which outcrop in this area (Figure 23).

The presence of glauconitic and phosphatic sediments on the upper Amazon slope may suggest derivation from underlying strata, and seismic profiles do indicate the presence of such outcrops (Figure 23). On the other hand, it is possible that the limonite, and possibly some of the glauconite and phosphorite, are authigenic rather than residual.

Sedimentary Processes

Comparisons with sediments from other shelves of the world and the available carbon-14 age dates from the shallow-water ooids (Milliman and Barretto, 1974) suggest that most of the coarse terrigenous grains on the middle and outer shelf are relict, and
were deposited during the last low stand of sea level and the subsequent Holocene transgression. The outer Amazon shelf sediments may have been iron-stained during subaerial exposure (see Milliman and others, 1972), although at least some of these grains may have been derived from local outcrops of older strata (see above).

The age of the carbonate-dominated sediments is more difficult to judge. In some instances, such as the maerl deposit off Ceará and Piauí States, the carbonate is obviously modern, as indicated by the pink color of living coralline algae. Other carbonates, such as the ooids, the iron-stained foraminifera and many of the biologically altered reef deposits on the outer shelf, are relict. In most instances, however, the carbonates probably represent a mixture of modern and relict forms.

The lack of modern terrigenous sedimentation (as shown by the paucity of mud) and the presence of carbonate-rich sediments along the outer shelf indicate that fluvially-derived sediments have not been transported offshore in the recent past. While echosounding profiles clearly show that the mud lense off the Amazon is modern and is prograding over relict middle shelf sands (Figures 1 and 3), most modern Amazon sediment appears to be transported northward by the Guiana Current. Judging from the ratio of clay
to silt (Figure 5), clay is preferentially transported northwards. Amazon muds have been detected in the Caribbean (Jacobs and Ewing, 1969) and similar muds are the prime contributor to nearshore and coastal sediments off Guiana (Eisma and van der Marel, 1971). The northward transport of sediments, however, is not restricted to Amazon muds. For example, the intrusion of Para-Maranhao sands north of the Para River system (Figures 13, 15 and 22) and the asymmetrical sand waves which characterize the inner and middle shelf off much of the coast south of the Para River (Figure 3) are indicative of transport by the Guiana Current.

Scattered data suggest that at least some Amazon sediment may be transported seaward, beyond the modern mud belt. One indication is the presence of low carbonate muds on the upper Amazon slope, although much of the non-carbonate fraction is either authigenic or residual. A stronger indication of offshore transport is the sand belt which extends seaward from the mouth of the Amazon to the Amazon Canyon (Figure 4). These sands are arkosic, extremely angular, low in calcium carbonate and contain high concentrations of unstable heavy minerals. While these sands are clearly Amazonian in origin, a relict age seems unlikely, since the belt crosses the modern mud belt. More probably the sands are modern, but winnowed, perhaps by tidal and estuarine currents in
the inner shelf and tidal and internal wave-induced currents on the outer shelf. Possibly these sediments are transported to the deep-sea via the Amazon Canyon and associated channels (Figure 1) in a manner similar to that observed in the Hudson Canyon (Keller and others, 1973; G. Keller, oral communication). At present, however, no observations of such offshore movement are available.
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23. Seismic profiles parallel to the Amazon outer shelf (Amazon Canyon is crossed in profile 139) and normal to the outer Amapa shelf and upper slope (profile 142), showing outcrops present on both the outer shelf and slope, probably uplifted and exposed during late Quaternary tectonism. Such outcrops may well contribute significant quantities of residual sediment. From Milliman, Amaral and Barreto (1974).