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Depositional patterns of modern Orinoco/Amazon muds on the northern Venezuelan shelf

by John D. Milliman[1], Jorge Butenko[2], Jean Paul Barbot[2] and Jan Hedberg[2]

ABSTRACT

Modern muds derived from the Orinoco and Amazon Rivers are gradually covering early-Holocene (shallow-water) reefs and sands on the continental shelf and upper slope north of the Paria peninsula. Throughout much of the area the muds are more or less continuous and locally as thick as 20 m. In other places the muds form an undulating topography (with lows consisting of underlying outcrops of relict sands/reefs) that appears to be migrating westward. Sediment accumulation apparently began after the opening of the Gulf of Paria about 10,000 years ago, and is continuing at present, due to the north and westward drift of the Equatorial Current. The undulating topography is attributed to nondeposition or erosion around locally exposed irregular hard grounds rather than to formation of a mud-wave type of bedform.

1. Introduction

Previous studies have shown that during the present high stand of sea level a significant amount of Amazon River sediment has been transported northwest along the shoreline and nearshore areas of the South American continent. Most of the sediment accumulating in the nearshore areas of the Guianas is Amazonian in origin (Allersma, 1968; Moquedet, 1973), and more than half the sediment in the Orinoco estuary and Gulf of Paria is derived from the Amazon (van Andel, 1967; Eisma *et al.*, 1978). In this paper we show that this mixture of Amazon and Orinoco sediment is transported through the Gulf of Paria (and around eastern Trinidad), and continues westward along the northern Venezuelan continental shelf and upper slope. van Andel (1967) reached similar conclusions based on sedimentological studies.

We are able to delineate these modern muds on the Venezuelan upper continental margin north of the Paria Peninsula through the results of extensive geophysical surveys (Fig. 1). A variety of geophysical techniques (low-frequency echo-sounding, high-resolution seismic profiling, side-scan sonar), numerous short (1-2 m) gravity cores and one boring (upon which both sedimentological and geotechnical analyses

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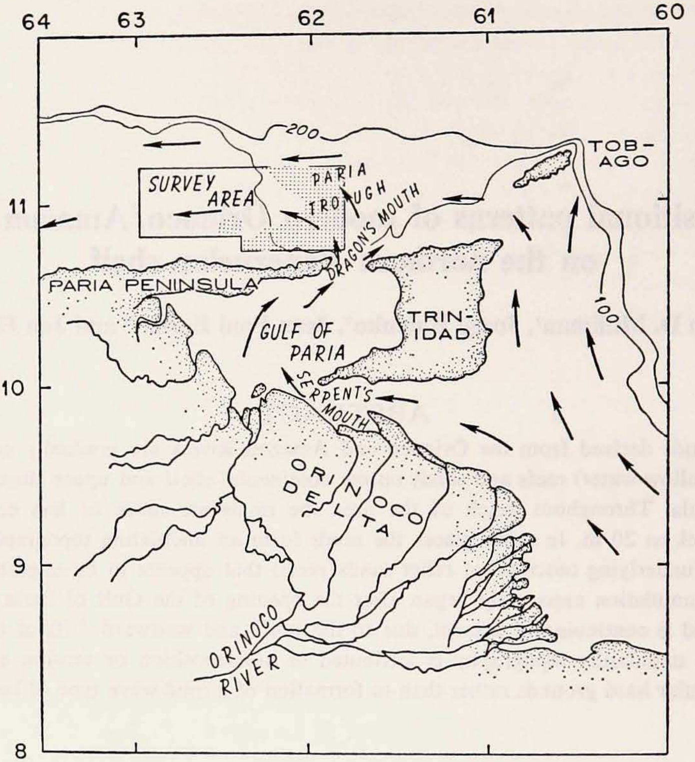

Figure 1. Location map of the survey area on the northern Paria continental shelf. The soft acoustically transparent mud bottom (without internal reflectors) is shaded. Arrows represent the dominant currents in the area. Depth contours are in m.

were made) were used to delineate the morphology and recent history of this area. Widely spaced (10-13 km apart) regional lines were supplemented by detailed studies of several smaller (9 km²) areas with close (150-250 m) line spacings; navigational fixes were made with a Motorola Miniranger 3, at a nominal spacing of 150 m (Fig. 2).

2. Morphology of the north of Paria shelf

The northern Paria shelf is characterized by a prominent embayment, here termed the Paria Trough, which swings the 100 m contour landward into the Dragons mouth (Fig. 1). As a result, isobaths in this area trend perpendicular to the shoreline rather than parallel to it. Shallowest depths (30-40 m) are in the far west, deepening to more than 150 m in the northeast (Fig. 2). Four geomorphic and sedimentary facies dominate the study area.

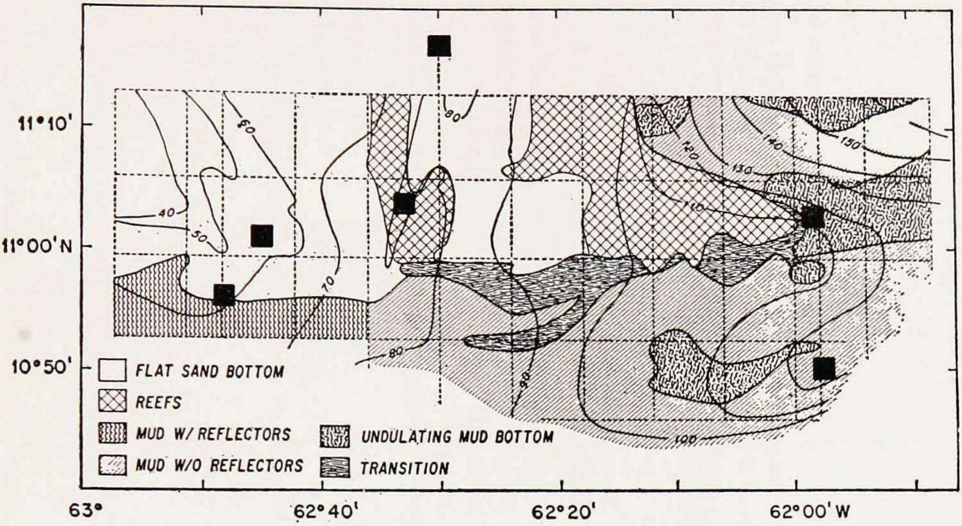

Figure 2. Generalized morphology/sedimentology of the survey area, based on regional data (dashed lines). The shaded boxes are site-surveys, in which adjacent lines were 150-200 m apart; more detailed bathymetry for three of these sites is shown in following illustrations. Bathymetric contours are in m.

(1) The northwestern and north central sections of the study area are characterized by a shallow flat sandy bottom, with little or no topographic relief or subbottom acoustic penetration; water depths mostly range from 40 to 75 m. The sediments display a wide range of compositions, but can be considered as gravelly/muddy biogenic sands (Table 1).

(2) A topographically uneven area, with local relief between 10 and 20 m, occurs in the central area; water depths vary between 90 and 120 m (Figs. 3, 4). Subbottom penetration by low-frequency echo-sounding and high-resolution seismic profiling (Acoustipulse) is minimal. The several topographic prominences within this geomorphic zone are composed of shallow-water algal/coral limestones, hence leading to the term "reefs." Carbon-14 dates indicate the limestones to be between 8 and 10 thousand years in age (Table 2). Between the reefs, the bottom is covered with low-carbonate mud (Table 1).

(3) In the southwest part of the study area depths range from 40 to 75 m. The seafloor is flat and generally acoustically transparent but with 2 to 5 reflectors within the upper 5 to 20 m of sediment. The upper 1 to 2 m of the sediment consists of very soft muds (silts and clays) underlain by stiff clays (Table 1), which presumably are old soil zones, overconsolidated by dessication (or from which overburden was eroded) at a lower stand of sea level.

(4) South and east of the reef zone, in water depths between 75 and 165 m, the

Table 1. Average sedimentologic/geotechnical values for surface sediment samples from various geomorphic zones on the northern Paria continental shelf. Number of samples from which averages are based are given in parentheses after zone designation. The ranges of values of the samples are placed in parentheses after the averages. Geotechnical values for the acoustically laminated and transparent muds include subsurface (1-2 m) sediments; note the significant difference between surface and subsurface shear strengths.

Geomorphic zones	Percent gravel (>2 mm)	Percent sand (.062-2 mm)	Percent silt (2-62 μm)	Percent clay <2 μm	Percent $CaCO_3$	Water content (percent) (relative to dry weight)	Shear strength (t/m^2)
Flat-sand bottom (16)	26 (6-79)	49 (10-74)	25 (10-47)		58 (0-95)	44 (22-62)	0.52 (0.26-0.78)
Reefs proper (13)	52 (12-68)	25 (20-48)	23 (12-40)		60 (51-71)	n.a.	n.a.
Inter-reef muds (4)	5 (0-15)	32 (3-75)	63 (11-97)		24 (12-39)	108	n.a.
Muds with reflectors (3)	tr	24 (tr-64)	25 (15-30)	51 (20-70)	7 (0-8)	56 (47-65)	0.51
						50 (29-97)	5.52
Muds without reflectors (11)	tr	1 (tr-3)	31 (20-45)	68 (54-70)	7 (0-36)	107 (73-117)	0.43 (0.27-0.90)
						95 (64-106)	0.46 (0.34-0.71)
Mud waves (1)	tr	1	33	66	2	109	0.47
Hard-bottom with (3)	27 (0-47)					105	0.48
mud piles		24	13 (7-18)	36 (12-81)	50 (4-78)		
Transition (3)	7 (0-22)	14	79 (38-100)		25 (0-63)	24	n.a.

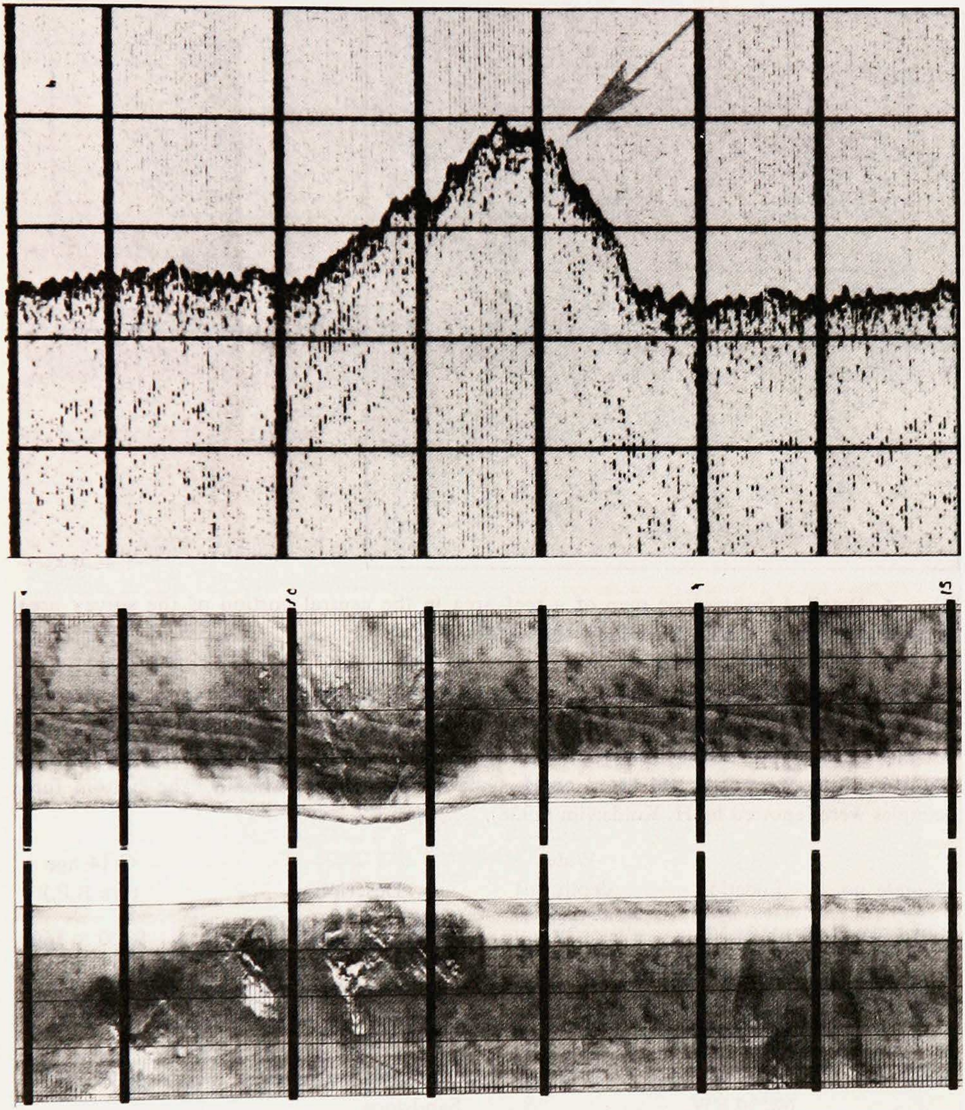

Figure 3. Echo-sounding and side-scan records of the reef zone. Note the generally smooth seafloor away from the reef. Vertical scales are 10 msec (approximately 7.6 m) on the echogram (above) and 25 m (approximate) on the side-scan sonar (below). Distances between fix points are approximately 150 to 200 m.

seafloor is covered with acoustically transparent muds. In contrast to the muds in the southwest, essentially no internal reflectors are seen. Echo-sounding and side-scan sonar records show a generally smooth bottom and simple topography (Figs. 5, 6). Where the transparent sediment thins or the acoustically reflective sub-bottom

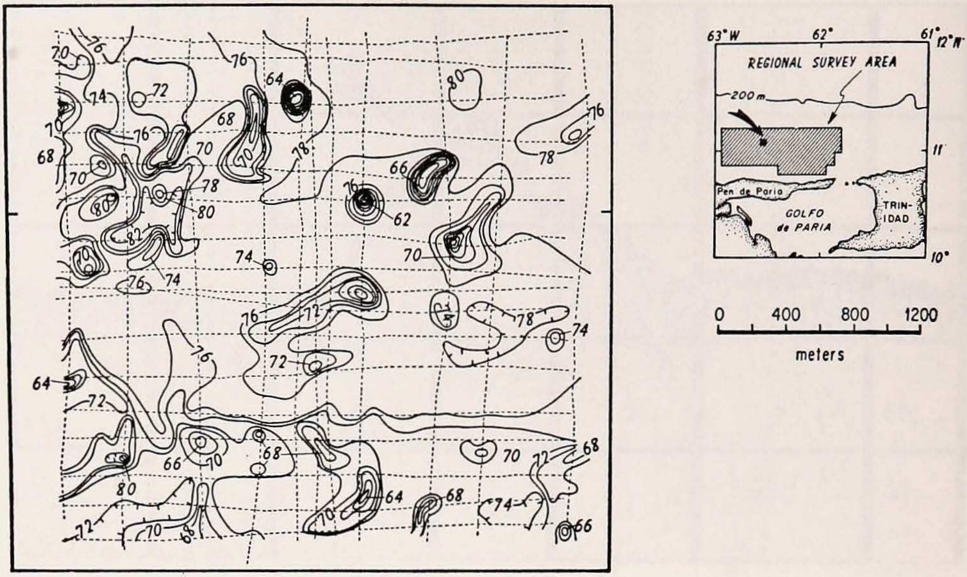

Figure 4. Detailed bathymetric map of a reef area in the central portion of the survey area. Contours are in m, dashed lines show ship tracks.

Table 2. Carbon-14 dates (and locations, descriptions) of limestones taken from the north of Paria continental shelf. The top two samples were from gravity cores taken by McClelland Engineers Inc., and were age dated at Isotopes Inc. The middle three were taken *in situ* by the submarine *Souscoupe* and dated by H. Gote Ostlund (Univ. Miami). The bottom three samples were reported by H. Koldewijn (1958).

Sample no.	Location	Water depth (m)	Description	C-14 age (yrs B.P.)
NP-5-7A	11°04.3′N 62°32.4′W	79	Blackened algal Limestone	9720 ± 160
NP-5-1A	11°03.7′N 62°33.0′W	76	Fresh algal Limestone	9355 ± 290
CNP-2	11°02.6′N 62°30.5′W	73	Encrusted calcareous Sandstone	8035 ± 55
CNP-3	11°07.4′N 62°36.0′W	77	Encrusted coral-algal Limestone	8670 ± 55
CNP-4	11°07.4′N 62°36.0′W	60	Encrusted algal Limestone	9670 ± 60
1214	10°52′N 62°25′W	84	Hermatypic coral	9770 ± 220
1214	10°52′N 62°25′W	84	Algal/coral fragments	9930 ± 240
1019	11°06′N 62°27′W	119-128	Algal Limestone	13,720 ± 330

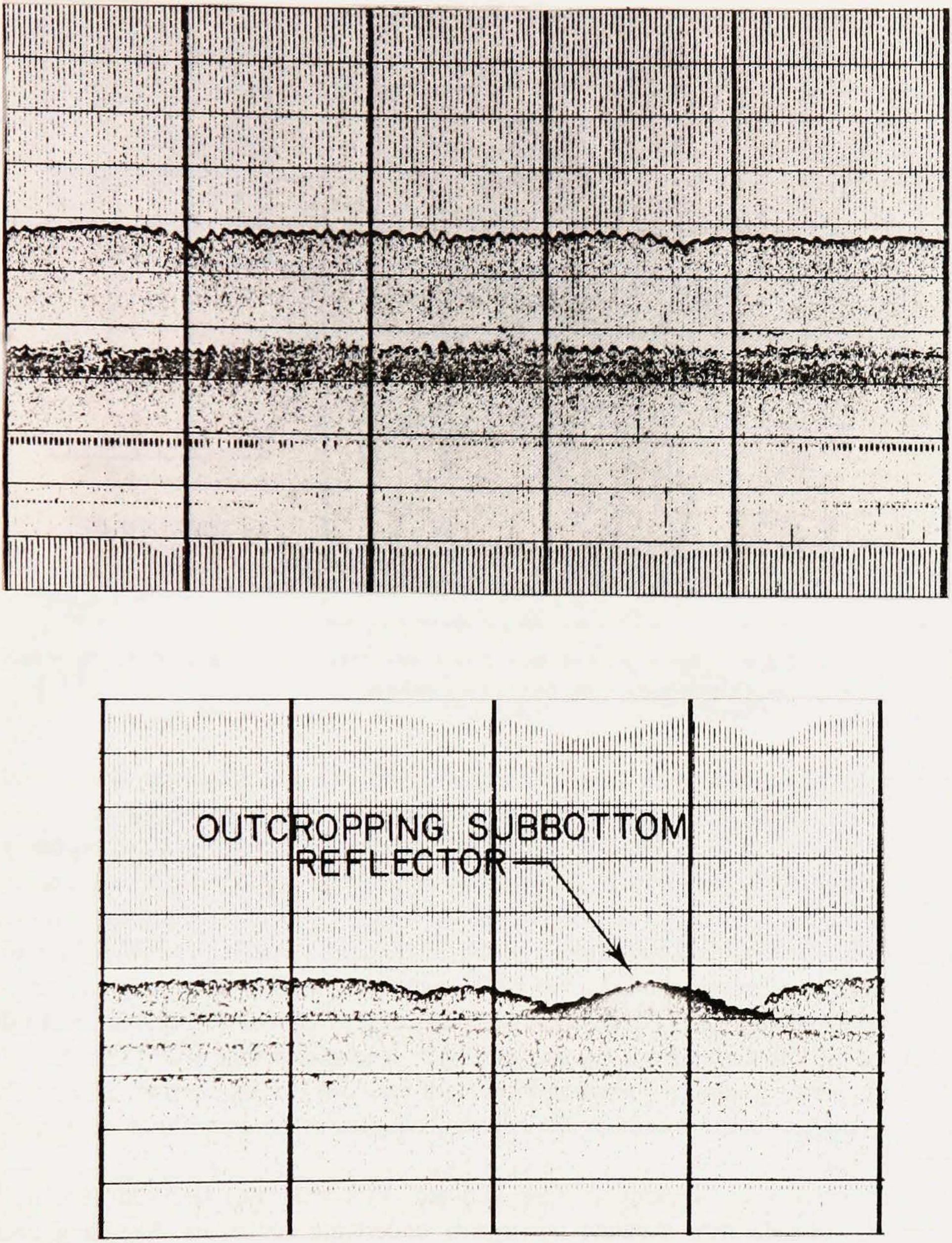

Figure 5. Low-frequency echo-grams of mud-without-reflectors. The upper record is typical of much of the eastern portion of the study area, where the acoustically transparent sediment lies 10-30 msec (7.6-23 m) above the sub-bottom reflector. Occasionally this deeper reflector outcrops (below); where observed or sampled, the outcropping material is early Holocene bioclastic sands or gravel. Vertical scale on both profiles is 10 msec.

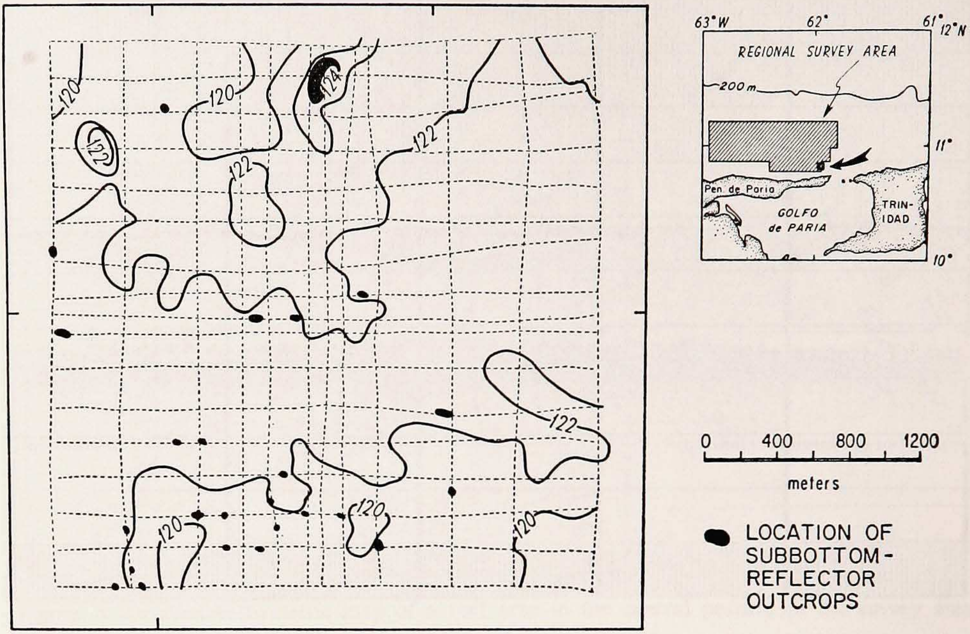

Figure 6. Detailed bathymetric map of mud-without-reflectors area in the southeastern corner of the study area. Contours are in m, dashed lines show ship tracks.

shoals, however, underlying strata are exposed (Fig. 6). The thickness of the mud layer generally varies between 3 and 20 m. Sediments appear to be normally consolidated soft muds, composed predominantly of clay; water contents are normally greater than 100% (Table 1), twice those noted in the clays of the western mud zone.

North of the mud zone and directly east of the reefs are acoustically transparent sediments with undulating topography (Fig. 7). These "waves" consist of prisms of acoustically transparent mud, 10's to 100's (sometimes 1000's) of m long and commonly 3 to 10 m in height overlying the acoustically reflective sub-bottom. Detailed study of the undulating muds shows topography so complex that even "smoothing" the bathymetric profiles (eliminating local highs and lows) yields a topography much more complex than that seen in the adjacent continuous "mud without reflectors" zone (Fig. 8).

Close inspection of many profiles indicates that the lows between the mud "waves" coincide with shoaling (emergent) underlying sediments. Sampling and *in situ* inspection (by the submersible *Soucoupe*) show the outcropping sediments to be reef limestone or, occasionally, coarse biogenic sand. Several small areas of seafloor within the study area are distinguished by acoustically hard (often with multiple echoes) bottom, covered with scattered "piles" of acoustically transparent mud (Fig. 9). The hard bottom sampled in these areas contains appreciable quan-

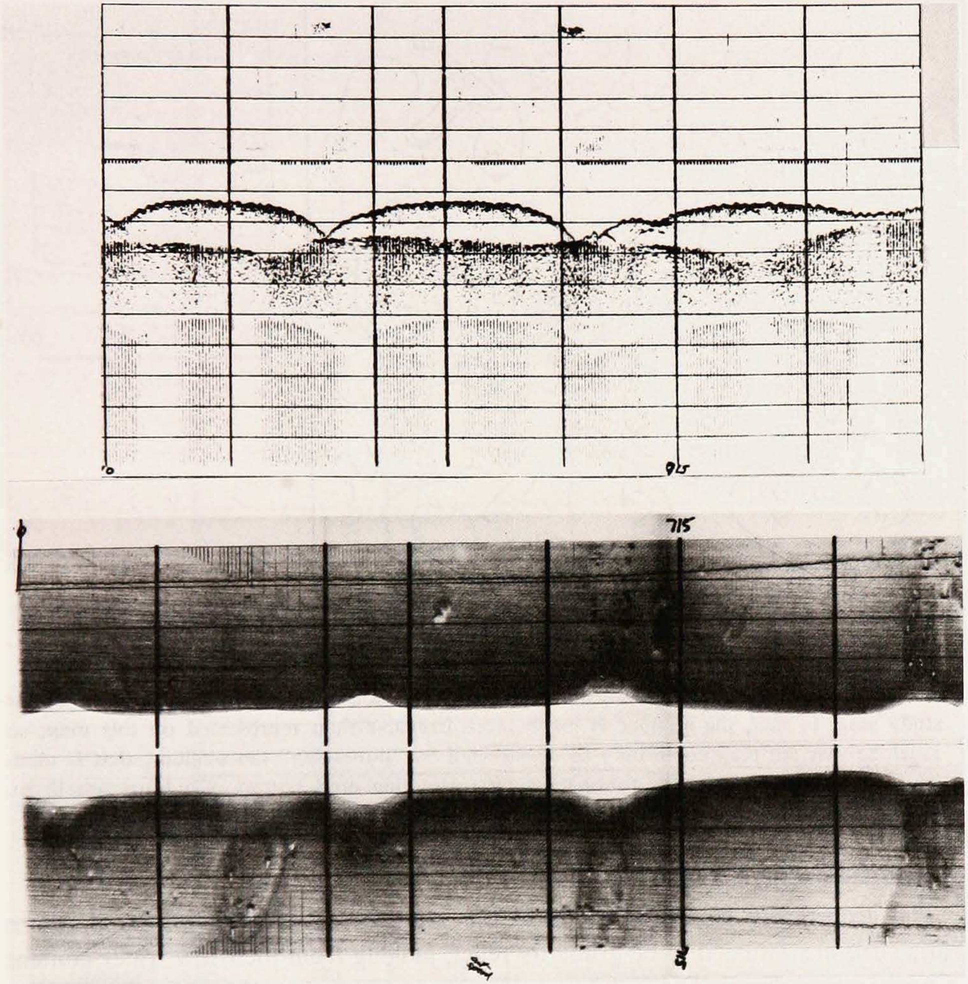

Figure 7. Low-frequency echo-gram and side-scan sonar records of undulating mud bottom. Scales the same as in Figure 3.

tities of biogenic sand and gravel (Table 1). Presumably the continuous transparent muds, undulating mud bottom and hard bottom with mud piles represent a continuum of decreasing mud cover and increasing exposure of underlying relict sands and reefs.

A transition zone buffers reefs in the west from the various mud zones in the east. Transparent muds are intermixed with local areas of acoustically reflective and rugged topography. The mud can occur either as "waves" or as continuously thick deposits. Echo-sounding and side-scan sonar records suggest that this transition zone reflects the gradual burial of the reefs by the westward movement of the mud.

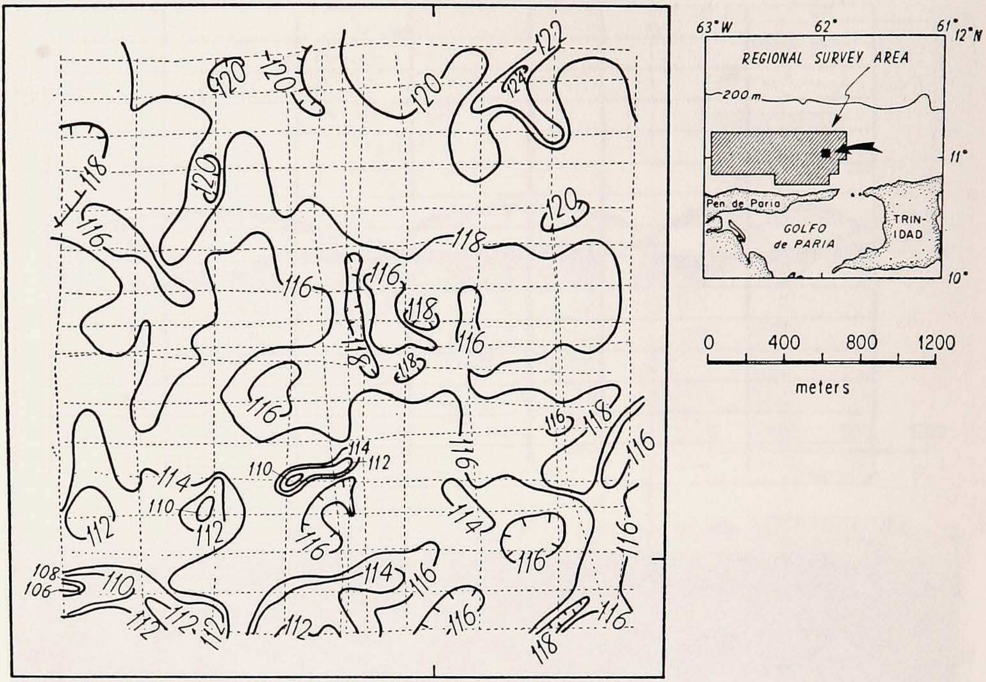

Figure 8. Detailed bathymetric map of undulating mud bottom in the eastern portion of the study area. In fact, the seafloor is much more irregular than represented on this map; so much so that the map could only be constructed by "smoothing" the seafloor, that is eliminating local highs and lows formed by the undulating mud bottom. Contours are in m, dashed lines show ship tracks.

3. Age and origin of the mud

The acoustically laminated muds in the southwestern section of the northern Paria shelf are assumed to be primarily relict, judging from their low water content and overconsolidation. Certainly the very stiff nature of the subsurface clays (shear strengths as high as 13 t/m^2) indicates relict soil zones. In contrast, the soft acoustically transparent muds in the east are presumably modern. These muds are partly underlain by reefs and biogenic sands, which seismic data indicate to be continuous with the emergent reefs in the west (Fig. 10). Carbon-14 dates of limestone samples from the reef show they were deposited mostly between 9300 and 9900 years ago (Table 1), during the last transgression of sea level. Presumably this carbonate environment became dormant when the transgressing sea became too deep for effective reef growth and/or increasing influx of terrigenous muds killed the reef organisms (see below).[3]

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[3] A shallow boring in the mud zone (10°56.8′N, 61°51.9′W) penetrated 18.6 m of soft mud before reaching stiff clay containing coral fragments. Coral fragments 3.4 m below the top of the mud/stiff clay contact were dated at greater than 40,000 years, but the actual age of the mud/stiff clay contact is not known.

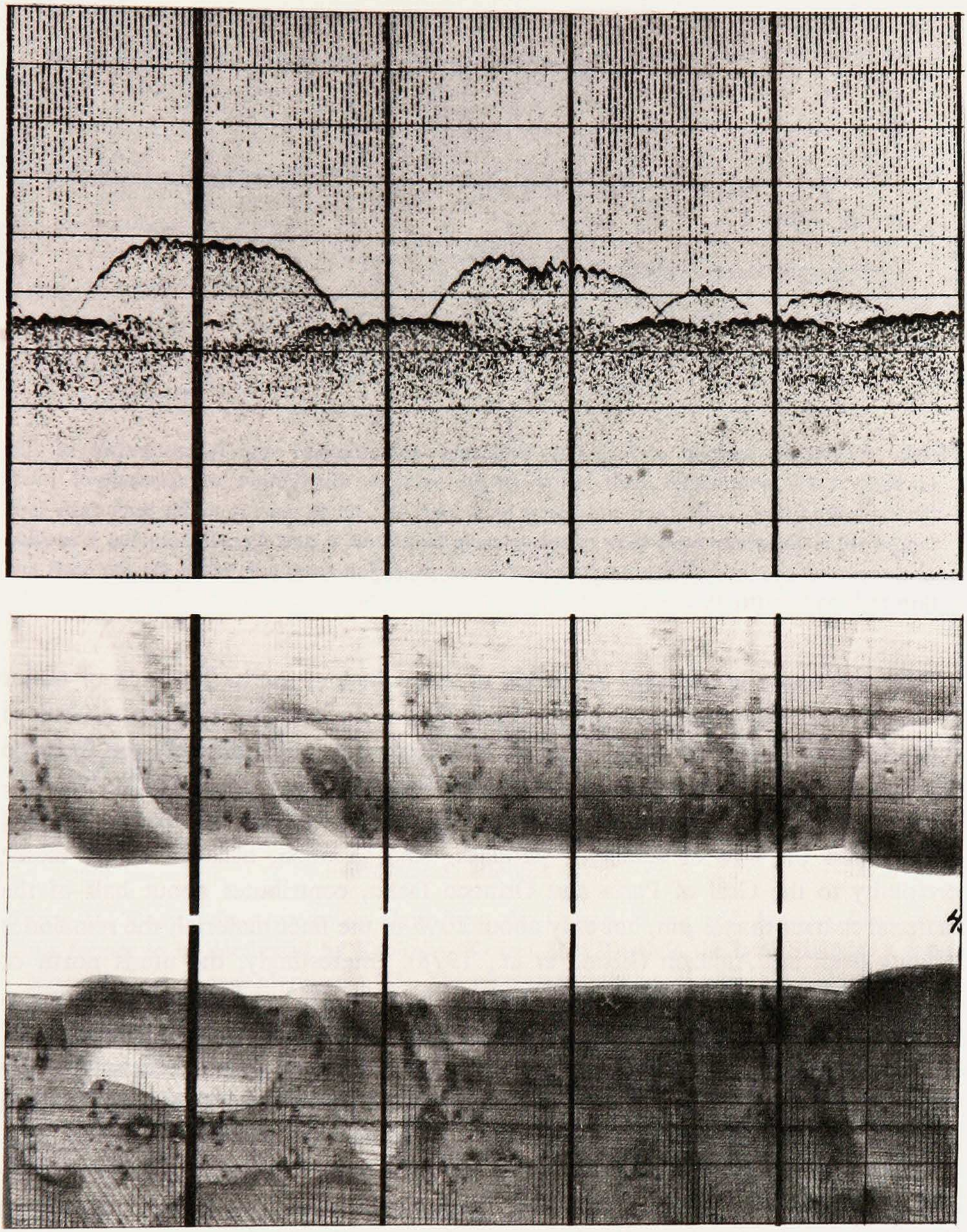

Figure 9. Low-frequency echo-gram and side-scan sonar records of hard bottom with mud piles. Scales are the same as in Figure 3.

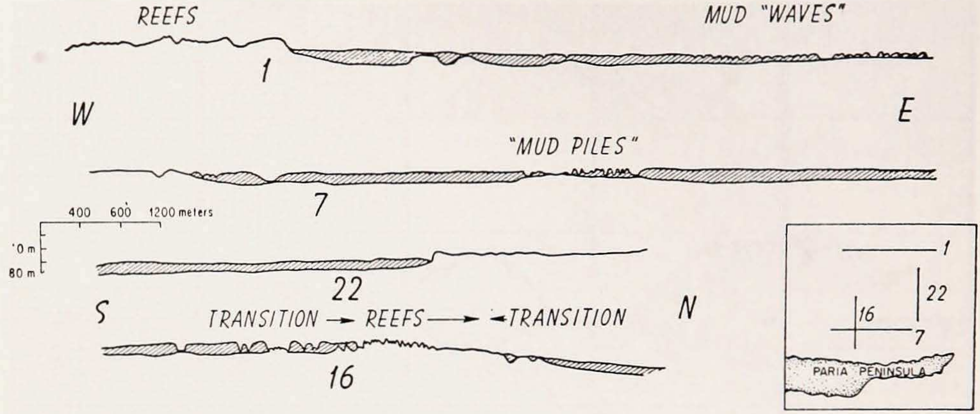

Figure 10. Shallow seismic profiles (low-frequency echo-sounder and Acoustipulse) on the northern Paria continental shelf, showing the relative distribution of transparent muds (shaded), transition zones, and the reefs. Note that the muds appear to be underlain (and lap on to) reefs, which have been dated as early Holocene in age. Presumably the transition zones represent exactly that, a gradual (and local) transition from soft muds (to the east) and firm reef seafloor (to the west).

The next question concerns the origin of these modern muds. The lack of major rivers draining either Trinidad or the Paria Peninsula, and the current patterns in this area suggest that the muds were derived from the south, possibly the Orinoco and the Amazon rivers (e.g., van Andel and Postma, 1954; Hirst, 1962). The relative contribution of sediment to the Gulf of Paria from the two rivers depends partly upon the size of sediment particles. The Orinoco, because of its closer proximity to the Gulf of Paria and Orinoco Delta, contributes about half of the material coarser than 2 μm, but only about 20% of the finer material, the remainder coming from the Amazon (Eisma *et al.*, 1978). Interestingly, the muds north of Paria contain practically no sand (average is less than 1%) and more than twice as much clay (68%) as silt. It is such finer material that one would expect it to be most easily transported from the south. An x-ray analysis of clay minerals from the northern Paria sediments shows a very close similarity to the Orinoco Delta clays (Fig. 11), which are largely Amazon-derived (Eisma *et al.*, 1978). Thus, we conclude that the transparent clay-rich muds are a mixture of Amazon and (to a lesser extent) Orinoco sediment. The muds presumably were transported northward through the Gulf of Paria and perhaps around eastern Trinidad (van Andel, 1967).

According to van Andel and Sachs (1964), the depth of the sill connecting the Gulf of Paria to the Caribbean at the Dragons Mouth is 95 m. While no Holocene sea level curve for this area is available, it would appear that this depth was reached by transgressive sea level about 10 to 12 thousand years ago (Curray, 1965; Milliman and Emery, 1968), suggesting a time when Gulf of Paria sediment may have

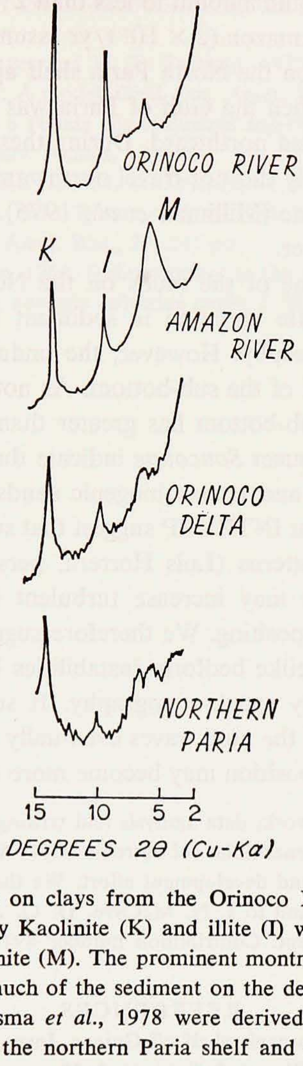

Figure 11. X-ray diffractograms on clays from the Orinoco River and Amazon River show the former to be dominated by Kaolinite (K) and illite (I) while the latter contains a much larger amount of montmorillonite (M). The prominent montmorillonite in the clays from the Orinoco Delta indicates that much of the sediment on the delta is derived from the Amazon (these diffractograms from Eisma *et al.*, 1978 were derived from Co-kα XRD). The close similarity between clays from the northern Paria shelf and the Orinoco Delta (bottom two diffractograms) strongly suggests a similar source for the acoustically transparent muds on the northern Paria shelf.

begun escaping northward into the Caribbean. Carbon-14 dates of limestones from the north of Paria shelf (Table 2), indicate that reef growth ceased subsequently, followed by burial by the muds. Assuming a total depositional area of 7000 km^2 (including the shelf off northern Trinidad), an average transparent mud thickness of 10 m, and a dry density of sediment of 0.75 g/cm^3, this deposit totals 5×10^{10}t of river-derived sediment. If formation of this deposit is assumed to have taken 9500 years, total sedimentation would amount to less than 2% of the combined load from the Orinoco (10^8 t/yr) and Amazon (2×10^8 t/yr assumed to reach the Orinoco).

Limestone accumulation on the North Paria shelf apparently has been restricted to low stands of sea level when the Gulf of Paria was closed, and terrigenous sediment could not be transported northward. During these lowered sea levels, in fact, Amazon sediment presumably did not travel northward, but was deposited directly offshore on the Amazon Cone (Milliman *et al.*, 1975). A similar conclusion might be made for the Orinoco River.

We are not sure why some of the muds on the Northern Paria shelf occur as featureless seafloor, with little variation in sediment thickness, while other areas display an undulating topography. However, the undulating bedforms may be related to the nature and relief of the sub-bottom. As noted previously, troughs often occur where the irregular sub-bottom has greater than normal positive relief. Observations from the diving saucer *Soucoupe* indicate that this outcropping bottom is characterized by both reefs and coarse biogenic sands. Preliminary data obtained by physical oceanographers at INTEVEP suggest that such outcroppings may locally alter nearbottom current patterns (Luis Herrera, personal communication). Also, increased bottom roughness may increase turbulent intensity thereby preventing suspended sediment from depositing. We therefore suggest that the undulating mud bottom does not reflect wavelike bedform instabilities but rather localized erosion/nondeposition around locally rough topography. If sufficient modern mud is deposited, the unstable sides of the mud waves eventually should slide down and cover the outcrops, after which deposition may become more evenly distributed.

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REFERENCES

Allersma, E. 1968. Mud on the oceanic shelf off Guiana. Inves. Res Carib. Sea and Adjac. Reg. (CICAR), FAO/UNESCO, Willemstad, Curacao, 1–20.

Curray, J. R. 1965. Late Quaternary history continental shelves of the United States, *in* The Quaternary of the United States, H. E. Wright, Jr. and D. G. Frey, eds., Princeton Univ. Press, Princeton, N.J., 723–735.

Eisma, D., S. J. van der Gaast, J. M. Martin and A. J. Thomas. 1978. Suspended matter and bottom deposits of the Orinoco Delta: Turbidity, mineralogy and elementary composition. Netherl. J. Sea Res., *12*, 224–251.

Hirst, D. M. 1962. The geochemistry of modern sediments from the Gulf of Paria. I. The relationship between the mineralogy and the distribution of major elements. Geochim. Cosmochim. Acta, *26*, 309–334.

Koldewijn, B. W. 1958. Sediments of the Paria-Trinidad shelf. Rept. Orinoco Shelf Exped. *3*, 109 pp.

Milliman, J. D. and K. O. Emery. 1968. Sea levels during the past 35,000 years. Science, *162*, 1121–1123.

Milliman, J. D., C. P. Summerhayes and H. T. Barretto. 1975. Quaternary sedimentation on the Amazon continental margin: A model. Geol. Soc. Amer. Bull., *86*, 610–614.

Moquedet, G. 1973. Contribution a l'etude des sediments superficiels du plateau continental de la Guyana Francaise. Thesis, Univ. Nantes, 141 pp.

van Andel, Tj. H. 1967. The Orinoco Delta. J. Sed. Petrol., *37*, 297–310.

van Andel, Tj. H. and H. Postma. 1954. Recent sediments of the Gulf of Paria. Versl. gewone Vergad. Afd. Natuurk. K. Ned. Akad. Wet., *20*, 245 pp.

van Andel, Tj. H. and P. L. Sachs. 1964. Sedimentation in the Gulf of Paria during the Holocene transgression: a subsurface acoustic reflection study. J. Mar Res., *22*, 30–50.

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