Sedimentary Structures and Textures of Río Orinoco Channel Sands, Venezuela and Colombia

United States Geological Survey Water-Supply Paper 2326–B

Prepared in cooperation with the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables

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SEDIMENTARY STRUCTURES AND TEXTURES OF
RIO ORINOCO CHANNEL SANDS, VENEZUELA AND COLOMBIA

Eolian dune on the downstream end of a sand wave, Río Orinoco near the mouth of the Río Cuchivero.

Chapter B

Sedimentary Structures and Textures of Río Orinoco Channel Sands, Venezuela and Colombia

By EDWIN D. McKEE

Prepared in cooperation
with the Venezuelan
Ministerio del Ambiente y
de los Recursos
Naturales Renovables

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2326

THE WATERS AND SEDIMENTS OF THE RIO ORINOCO AND
ITS MAJOR TRIBUTARIES, VENEZUELA AND COLOMBIA

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1989

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

McKee, Edwin Dinwiddie, 1906–1984
Sedimentary structures and textures of Río Orinoco channel sands, Venezuela and Colombia

(U.S. Geological Survey water-supply paper ; 2326–B)
"Prepared in cooperation with the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables.
Bibliography: p.
Supt. of Docs. no.: I 19.13:2326–B
1. Sedimentation and deposition —Venezuela—Orinoco River.
I. Venezuela, Ministerio del Ambiente y de los Recursos Naturales Renovables. II. Title. III. Series.
QE571.M43 1989 551.3'55'-0987 88–600423

FOREWORD

The Río Orinoco is one of the great rivers of the world. It drains about 900,000 square kilometers and discharges to the ocean an average flow in excess of 36,000 cubic meters per second and an average sediment load of about 7,600 kilograms per second (240 million tonnes per year), ranking it third largest in the world in terms of flow to the oceans and sixth largest in terms of sediment loads. It is an international river, draining parts of Colombia and Venezuela, and forming the boundary between these two nations along some 300 kilometers of its course.

The basin is rich in natural resources, containing extensive fields of petroleum and natural gas, including the largest proven reserve of heavy crude oil in the world, and rich deposits of bauxite, iron ore, gold, diamonds, and other mineral wealth. Its renewable resources include its forests, fish and wildlife, agriculture and grazing lands, and most important, its waters. The basin is not developed to any great extent; large parts of the watershed still are undisturbed. Although it accounts for 70 percent of the nation's land, it supports only 5 percent of the population. This situation, though, is likely to change in the near future. The development of the Río Orinoco's natural resources is the key to Venezuela's future.

In 1981, Project Orinoco-Apure was organized under the auspices of the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables to serve as the focal point and coordinating body for scientific studies of the resources of the basin and for feasibility studies and preliminary planning of its development. An important part of the project effort was directed to investigations of the basin's water resources. In 1982, the United States Geological Survey and the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables agreed to collaborate in a series of scientific studies of the Río Orinoco and its major tributaries. A strong foundation already had been laid for the hydrology of the basin with the establishment of a gaging and sediment sampling program in 1965, but by 1980, the program had been substantially reduced. Data on the bed sediments of the rivers and on the sediment transport were especially sparse. The main emphasis of the collaboration therefore was directed toward sediment studies. The studies had three principal objectives: (1) to develop and test new technology for measuring the water and sediment discharge of large tropical rivers, (2) to determine the characteristics of the bed material and suspended sediment of the major rivers of the basin, and (3) to provide measurements and samples that along with the existing hydrologic information would provide a set of baseline scientific data against which future changes in the basin could be measured. Between March 1982, and June 1985, seven major campaigns to collect data along the river and in the major tributaries were completed, and the collaboration expanded considerably to include participation of engineers, scientists, and consultants from universities, private enterprises, and other government agencies of Venezuela, Colombia, and the United States.

At the beginning of the collaboration, it was agreed that the results of these studies would be made available to the scientific community. A few short papers have been published in symposium proceedings and in technical journals, but the main results and all the basic data are contained in this series of reports. Each chapter is self-contained; taken together, they provide comprehensive data and analyses of the waters and sediments of the Río Orinoco and its major tributaries in Venezuela and Colombia. The results of these studies should be of interest and a value to anyone who is concerned with large tropical rivers.

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Recursos Naturales Renovables
Republica de Venezuela

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Sedimentary Structures and Textures of Río Orinoco Channel Sands

By Edwin D. McKee

ABSTRACT

Most sedimentary structures represented in sand bodies of the Río Orinoco are tabular-planar cross-strata which, together with some wedge-planar cross-strata, are the products of sand-wave deposition. Locally, in areas of river meander where point bars characteristically form, trough structures forming festoon patterns are numerous. At a few localities, sets of nearly horizontal strata occur between tabular-planar sets and are interpreted to be the deposits of very fast currents of the upper flow regime; elsewhere, uncommon lenses and beds of silt, clay, or organic matter consisting of leaves and twigs, seem to be the result of quiet-water settling through gravity.

By far the most common grain size represented in the tabular-planar and wedge-planar cross-strata of the sand-wave deposits is medium sand (¼–½ millimeter) as determined by screen analyses. Many samples, however, also contain moderate quantities of coarse or very coarse sand. Eolian dunes on top of the sand-wave deposits are dominantly fine grained. The river channel sands were determined to be largely moderately well sorted, although in some places they were mostly well sorted, and in others, mostly moderately sorted.

INTRODUCTION

Sedimentary structures and textures of Río Orinoco channel sands in Venezuela were studied during March 1983, when the river was at low stage. The project was conducted as one of a series of studies on hydrology, water chemistry, and other aspects of the Río Orinoco, most of which are described and discussed in chapters of U.S. Geological Survey Water-Supply Paper 2326. Work was done largely during a trip on the barge *Duida* from Puerto Ayacucho downriver to Ciudad Guayana (fig. 1). Some preliminary work was done in small boats upstream as far as Santa Barbara, but mostly the studies were conducted along the banks and on emergent bars accessible from the *Duida*.

The sedimentary-structures work was conducted contemporaneously with other river studies wherever opportunity permitted. Carl Nordin, in general charge of the program, and Robert Meade and Clare Cranston, of the U.S. Geological Survey, contributed greatly to the sedimentary studies, in addition to their individual assignments. Two groups of Venezuelan geologists and hydrologists participated in the detailed program of trenching, sampling, and measuring. One group, consisting of David Pérez Hernández, Antonio Ahogado, and Ricardo Smith, helped on the upstream reach as far downstream as Cabruta; this group was then succeeded by Alfredo DeLeon and Alfred Viloria. Appreciative thanks for assistance is due to all of these men. For help in the work upstream from Puerto Ayacucho, thanks are extended to Lois and Omar Hernández. Finally, for assistance and encouragement involving the entire research project, thanks are given to Dr. Abel Mejía, Project Coordinator.

TERMINOLOGY USED FOR SEDIMENTARY STRUCTURES

Definitions of terms adopted for use in the accompanying report are largely those used in the

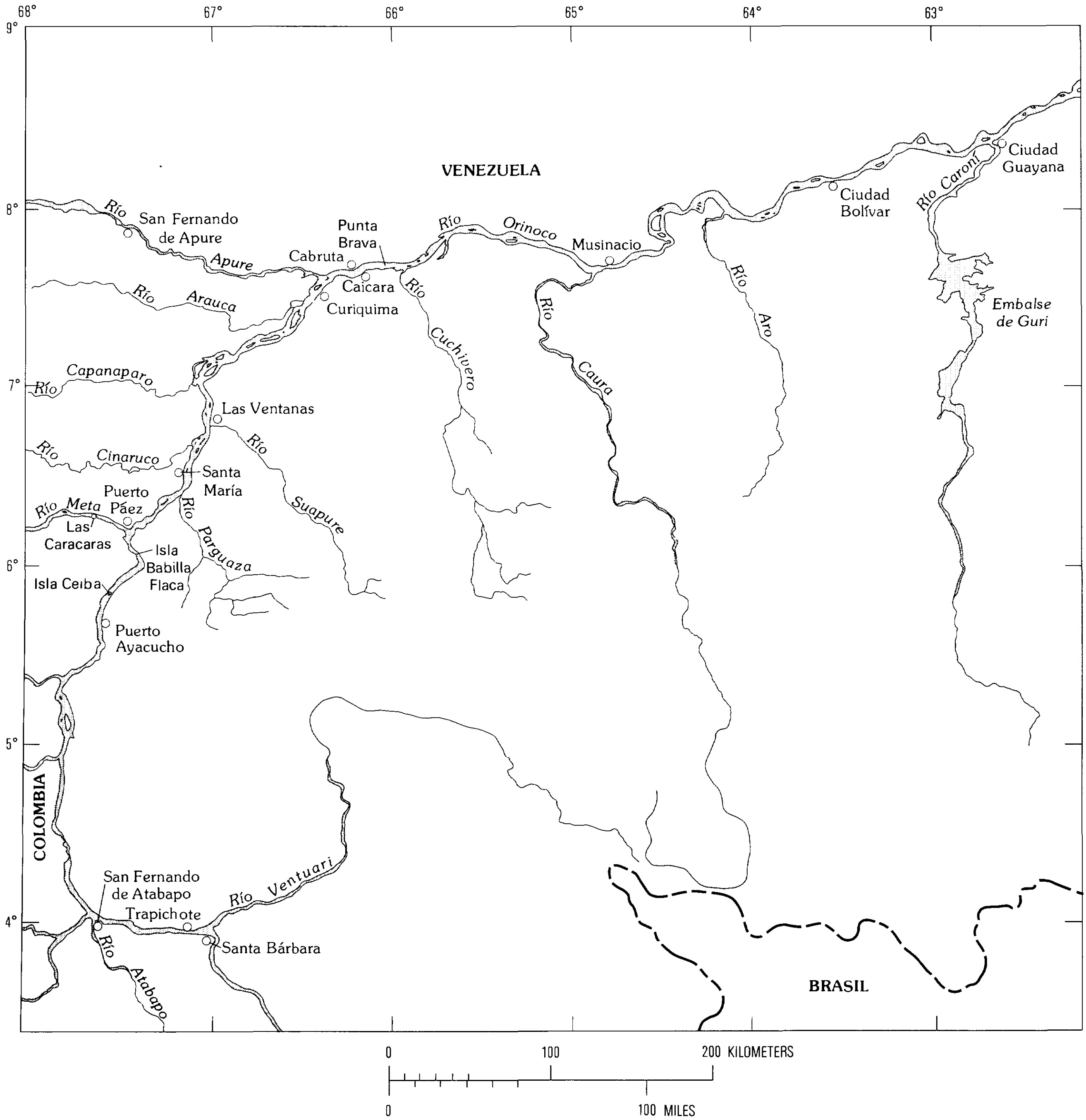


Figure 1. Location of study reach along Río Orinoco, Venezuela.

monograph of the Supai Group of Grand Canyon (McKee, 1982). For the convenience of the reader some of the more common terms, especially those involving quantitative designations, are presented here as a glossary. This list is not intended to be inclusive, but rather a list of selected terms that seem to be ambiguous and in a number of examples have been used in more than one way in recent literature.

Cross-Stratification (Modified from McKee and Weir, 1953)

Scale as applied to foreset length.
1. Small scale—less than 0.33 m.
2. Medium scale—about 0.33 to 6 m.
3. Large scale—greater than 6 m.

Classes of dip angles (foreset surfaces).
1. High-angle strata—dip 20° or more.
2. Low-angle strata—dip less than 20°.

Basic types of cross-strata.—Based primarily on the character of the lower bounding surface of each set of cross-strata, and, secondarily, on the shape of each set of cross-strata.
1. Tabular-planar—contain bounding surfaces that are virtually parallel (fig. 2).
2. Wedge-planar—contain planar bounding surfaces that converge.
3. Lenticular—contain one or more bounding surfaces that are curving and not planar.
4. Trough structure—the lower bounding surface is trough-shaped; laminae filling the trough may be symmetrical or asymmetrical.
5. Festoon troughs—group of troughs each having a partially dissected underlying trough or troughs with festoon pattern.

Bedforms

Classification.—Considerable confusion exists concerning terminology for rhythmic bedforms formed in cohesionless sediment by water currents as stated by Miall (1977, p. 33). The size, shape, and internal structure are features most commonly used to differentiate kinds of bedforms, and three or four principal classes generally are recognized: for example, three forms adopted for reversing tidal currents (Allen, 1979), and four forms for fluvial deposits (Coleman, 1969). Furthermore, many names are synonymous in part or in total.

Sand waves.—As defined by Friedman and Sanders (1978, p. 570), these are rhythmic bedforms larger than ripples, formed by water currents in cohesionless sediments. In the classification of Coleman (1969, table VI), they are shown as having greater wave height and wave length, in general, than either megaripples or aqueous dunes and are characterized by long-crested, parallel ridges that in plan view range from relatively straight or gently curved to moderately sinuous. Because they grade in size, shape, and ripple index from typical aqueous dunes and from the still smaller megaripples, they are used as synonymous with these features by many geologists (Collinson, 1970; Smith, 1971; Karcz, 1972; Singh and Kumar, 1974). Other probable synonyms of sand wave are large-scale ripples (Williams, 1971), linguoid bars (Allen, 1968), and currents (Allen, 1979), and four forms for fluvial deposits (Coleman, 1969). Furthermore, many names are synonymous in part or in total.

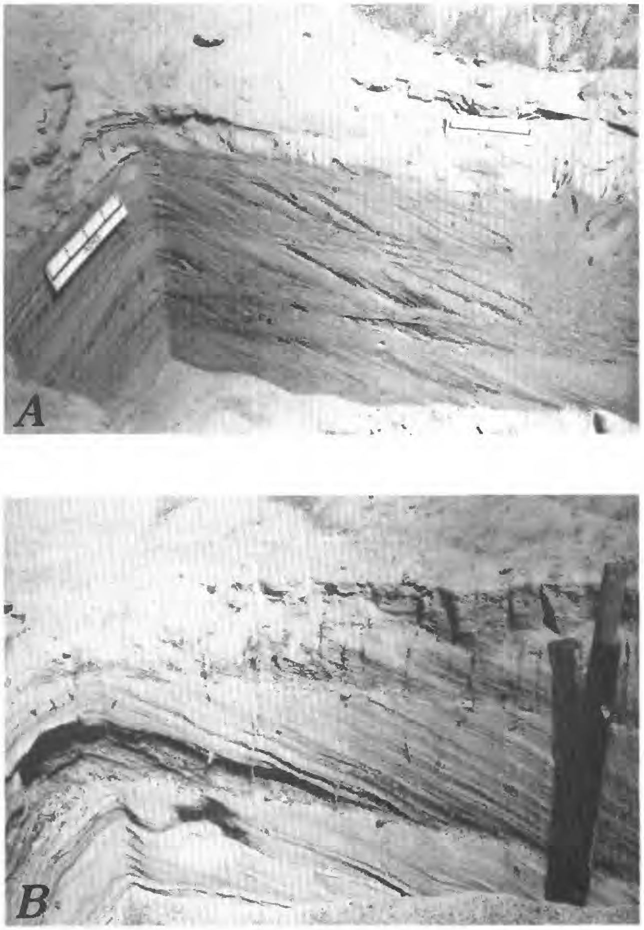


Figure 2. Tabular-planar structures (*A*, *B*) in trench; foresets dip downstream; left bank of Río Orinoco at Musinacio. Machete in *B* is about 60 centimeters long.

Dunes (aqueous, not eolian).—As defined by Collinson (1978), aqueous dunes contrast with sand waves in having smaller length-to-height ratios, crest lines that are sinuous and commonly discontinuous, and have deep scour troughs on the lee side in front of crest-line saddles. The lee-side scour troughs normally produce trough

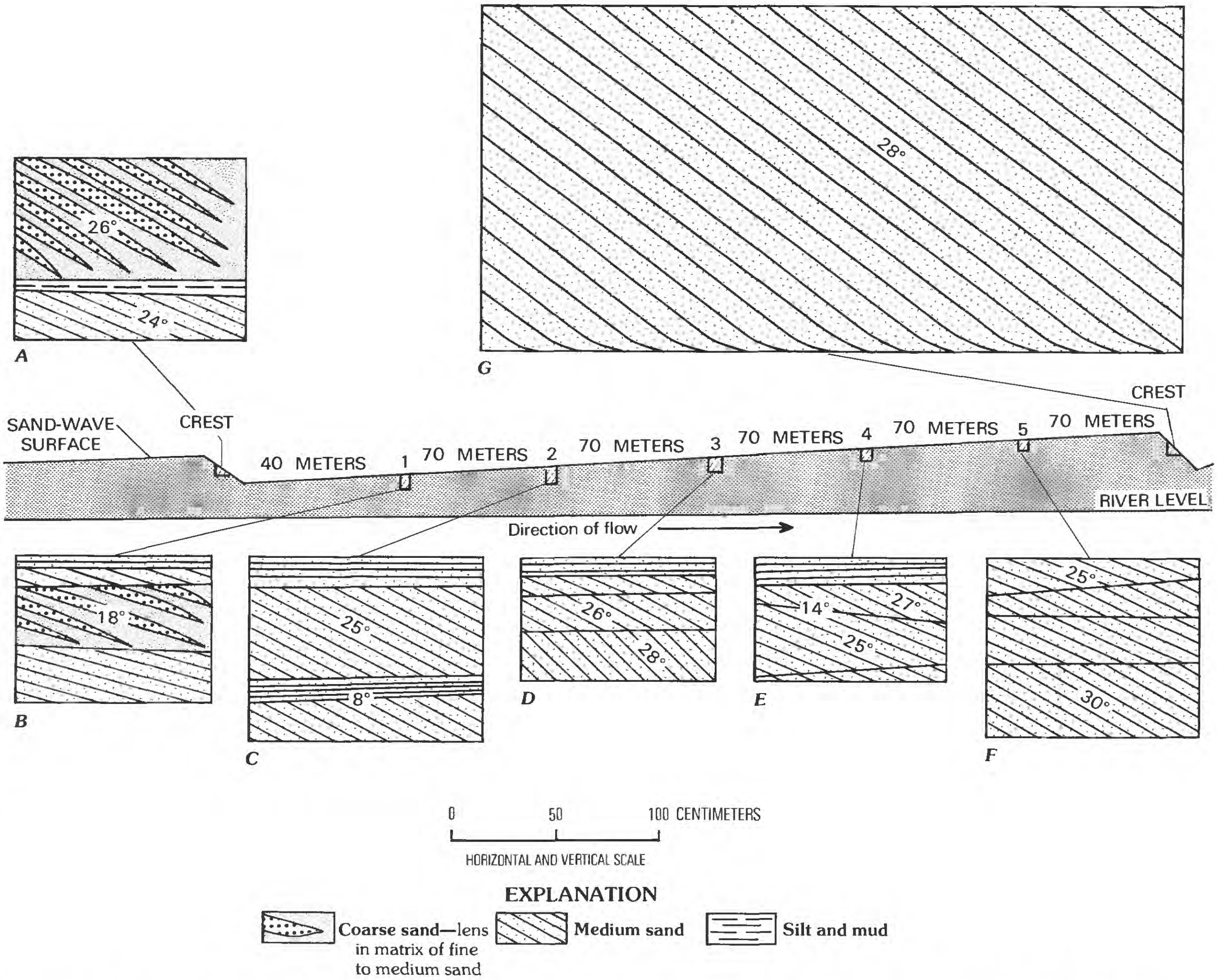


Figure 3. Profile of sand-wave deposits and tabular-planar structures (*A–F*) exposed in trenches on bar parallel to direction of river flow; Río Orinoco at Curiquima.

cross-bedding with festoon pattern. Both aqueous dunes and sand waves are variable in size, depending on depth of the water (Coleman, 1969, table VI). Ripple marks commonly are formed on their stoss surfaces. The term *megaripple*, as normally used, may be synonymous with aqueous dune, although Coleman (1969) considered it to represent a low-water and a rising stage, whereas the dune characterizes a flood stage.

Megaripple.—In the classification of Coleman (1969, table VI), megaripples are described as small bedforms that form "with increasing discharge and velocity. . ." and with relatively smooth water. They have linguoid or lunate crest lines in plan view and a ripple index much greater than in small-scale ripples. They commonly are considered a variety of aqueous dune.

Crest of fluvial sand wave.—The hinge line or junction of the stoss surface and the foreset beds. It forms a low ridge normal to current direction which, in plan view, generally is relatively straight or gently curved to moderately sinuous.

Point-bar deposits.—The sediments accumulated on the inside of bends in the wavelike loops of meandering rivers. They characteristically have trough structures.

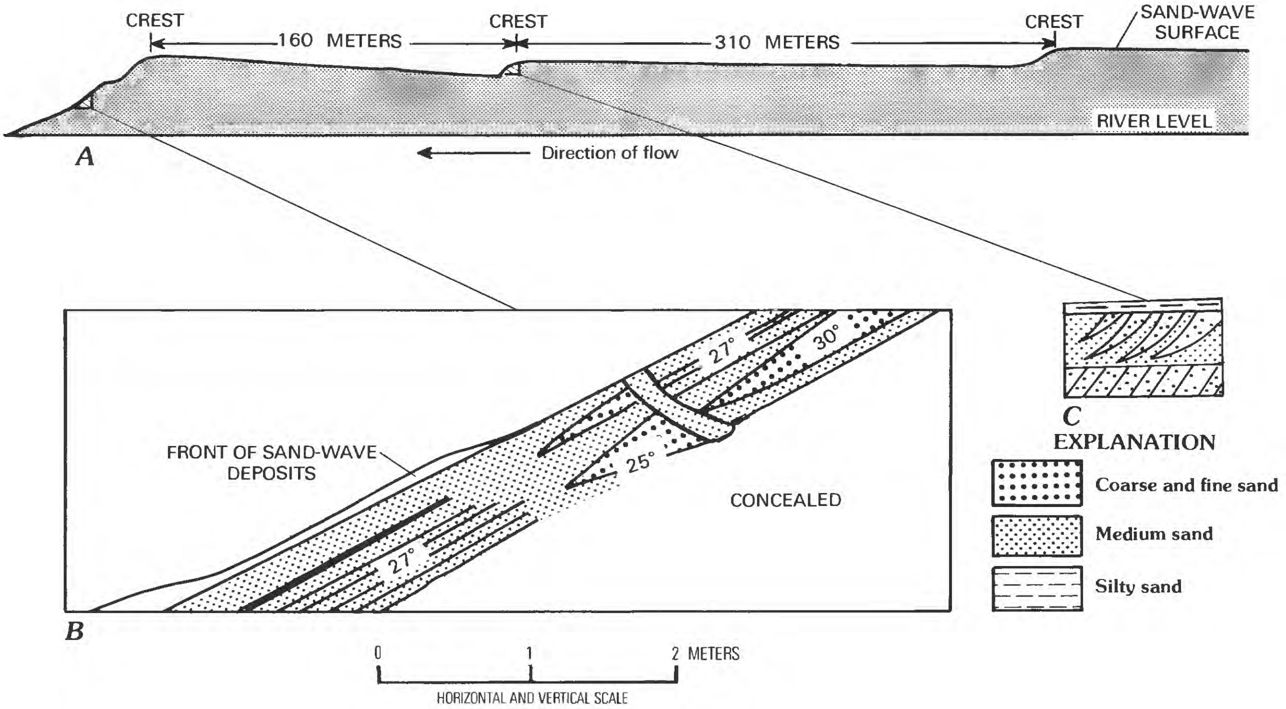


Figure 4. Profile of sand-wave deposits (*A*) and sedimentary structures (*B, C*) at crests of bar parallel to direction of river flow; Río Orinoco upstream from Las Ventanas, 2 river kilometers upstream from mouth of Río Suapure.

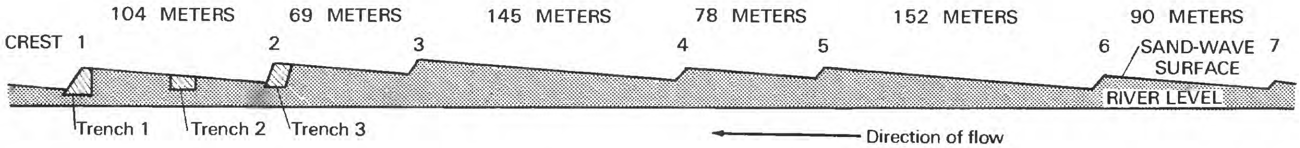


Figure 5. Profile of sand-wave deposits showing positions of crests and intercrest areas, and trench locations on bar parallel to direction of river flow; Río Orinoco near Isla Babilla Flaca.

Flow regimes.—Classified as *lower* and *upper* by Simons and others (1965, p. 36). Bedforms in the lower flow regime are listed as ripples, ripples on dunes, and dunes; the mode of sediment transport is in discrete steps and the relation between bed and water surface is "out of phase." In the upper flow regime, bedforms consist of plane beds, antidunes, and chutes and pools; the mode of sediment transport is continuous and the relation between bed and water surface is "in phase."

Sand-flow toes.—This term as applied by Ahlbrandt and Fryberger (1982, p. 26–27) refers to the leading edge of avalanche sand deposits where they taper to a point, commonly near the base of a flow. The name originally was applied to eolian foresets, but what seem to be typical flow-toes were recognized in sand-wave deposits of the Río Orinoco in many places.

SAND-WAVE DEPOSITS

Deposits of sand waves on the Río Orinoco were examined on islands and banks at 14 localities along the river between Puerto Ayacucho in the southwest and Musinacio to the northeast (fig. 1)—a distance of about 650 river km (kilometers). The morphology of these deposits, as seen at a low stage of the river, consists of relatively flat sheets of sand crossed by low, largely straight sand crests oriented at right angles to the direction of river flow. Each crest apparently was formed at the downstream end of a sequence of sand-wave deposits. In most areas, the approach surface was nearly horizontal, but sloped gently downriver with stream gradient. This crest was asymmetrical with its steep side facing downriver. Commonly its form was accentuated either by an accompanying trough or furrow in front, or it formed the lower end of a bar.

The size of individual sand-wave deposits differed greatly from one locality to another. The largest of those measured along Río Orinoco had terminal ridges or crests separated by distances greater than 300 m (meters). At Curiquima, one was 390 m long (fig. 3); upstream from Río Suapure, one was 310 m long (fig. 4). Minimum crest-to-crest distances were less than 100 m at several localities, such as near Isla Babilla Flaca, where three were 69 m, 78 m, and 90 m, respectively (fig. 5);

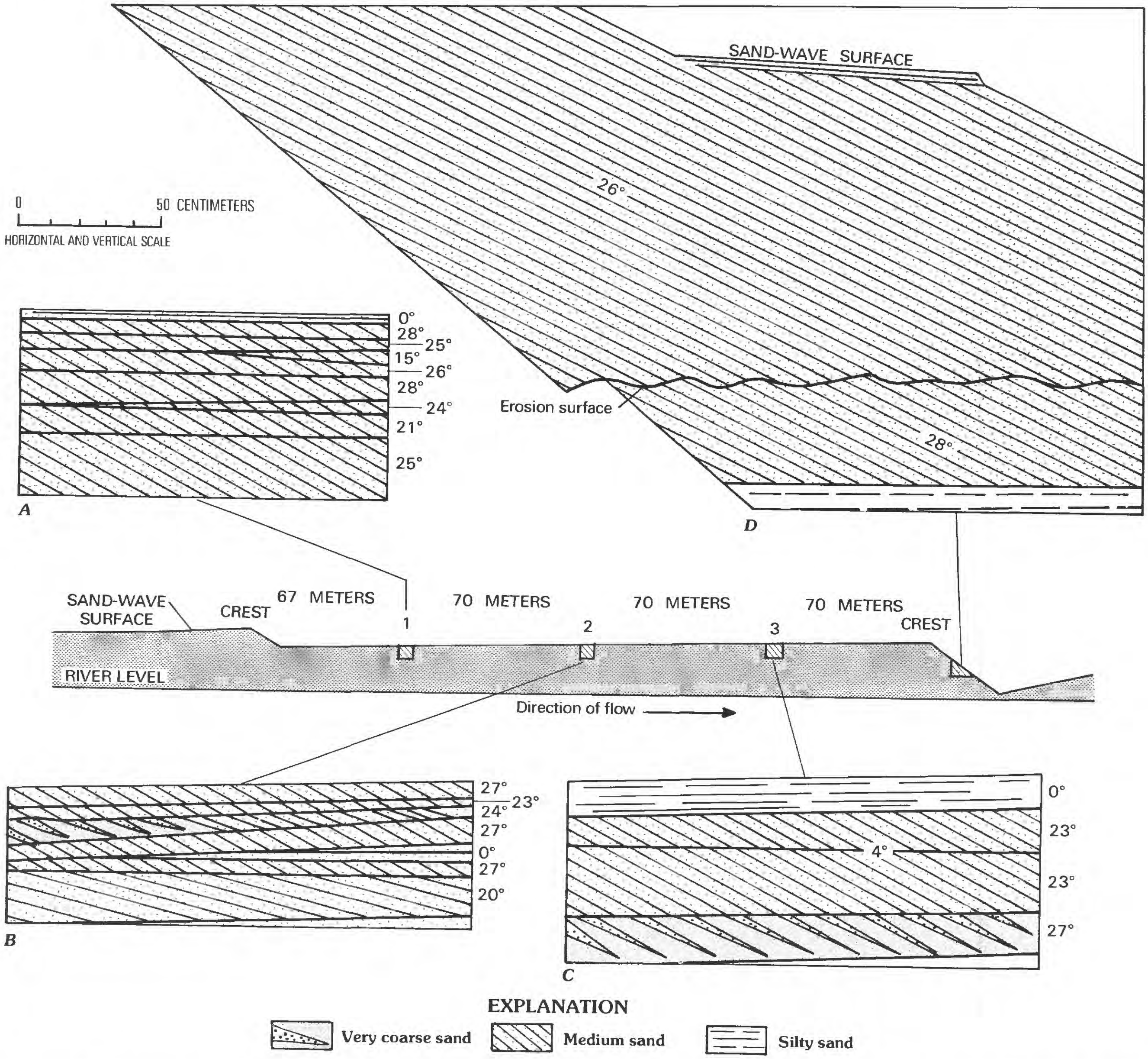


Figure 6. Profile of sand-wave deposits showing positions of crests and intercrest areas, and trench locations on bar parallel to direction of river flow with cross-stratification patterns in each (*A–D*); Río Orinoco at Musinacio.

and downstream from Puerto Ayacucho, 78 m and 90 m. The heights of individual ridges or crests, above the generally flat surface of inter-ridge spaces, likewise differed greatly from one locality to another but commonly was 2.4 m or more.

CROSS-STRATIFICATION

Characteristics of the cross-stratification in sand bodies of the Río Orinoco channel were determined largely by trenching at various selected localities on bars and banks of the main river channel. Trenches were dug in T- or L-shaped forms to expose the stratification in three dimensions. These trenches were of various sizes as much as 3 m long and 1 m or more deep, depending on features to be determined in each situation. At some localities, trenches were dug both on the crest of a sand-wave deposit or at three or more equally spaced intervals within the area between crests (figs. 3, 6).

Of the three principal types of cross-stratification generally recognized, the tabular-planar type (fig. 2) is by far the most common in the Orinoco sand deposits, represented both in medium scale and rarely in large scale. Many trench sections show four or five tabular sets with foresets dipping downstream at angles between 18° and 30° and separated by near-horizontal bounding planes. In crests at the downstream ends of sand waves, many small sets of cross-strata commonly combine into one or two large sets as at Curiquima (fig. 3), near the mouth of Río Suapure (fig. 4), and especially at Musinacio (fig. 6). In such places, single sets attain thicknesses of almost 2 m—equal to the entire coset thickness in the adjoining intercrest areas upstream.

Trough-type cross-strata forming festoon patterns in sections normal to trough axes were present at several

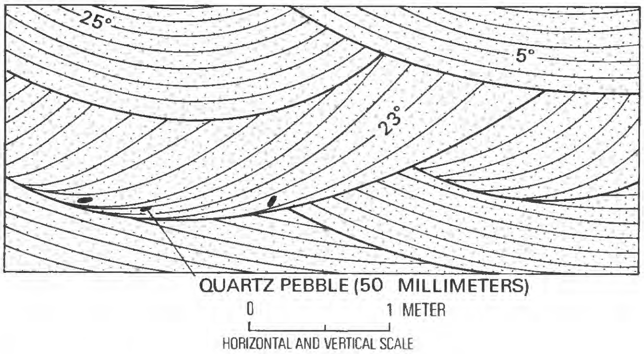
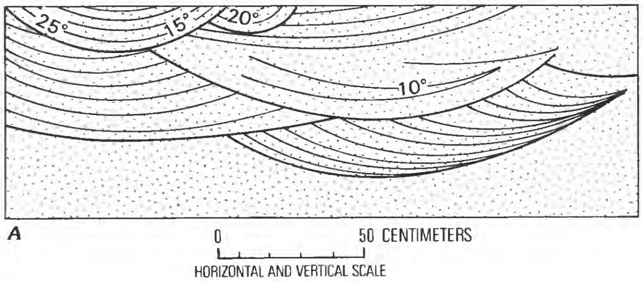


Figure 7. Trough structure with festoon pattern in sand; right bank of Río Meta at Las Caracaras gaging station.



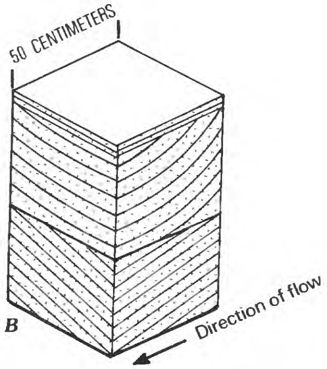


Figure 8. Festoon cross-stratification with trough structure (*A*, *B*) in pebbly sand; left bank of Río Orinoco, 1.9 river kilometers upstream from mouth of Río Apure. *A*, Section parallel to river; *B*, block showing trough plunging toward river.

localities. Two of these were at Puerto Páez near the mouth of the Río Meta (fig. 7) and on the Río Orinoco, 2 river km upstream from the mouth of Río Apure (fig. 8). In all places, the trough structures were relatively wide and shallow (fig. 9); some were filled symmetrically and others asymmetrically with sand laminae, indicating that the depositing currents were well above the trough rims at the time of sediment filling as has been shown experimentally (McKee, 1957, p. 132). A few scattered pebbles with diameters as much as 50 mm were in the low parts of some channel fills. The examples of trough bedding probably formed under point-bar conditions of sedimentation at low stages of the Río Orinoco. Such an environment is known to favor the development of this structure (Frazier and Osanik, 1961; Bernard and others, 1970).

A third type of cross-stratification—the wedge-planar (McKee, 1962, p. 63, 571, 585; 1982, p. 299)—was observed at some localities along the Río Orinoco, although it was much less common than tabular-planar cross-strata. Examples are illustrated from Isla Babilla Flaca, near river km 1134 (fig. 10) and at Puerto Páez at the mouth of Río Meta (figs. 11, 12). The explanation for

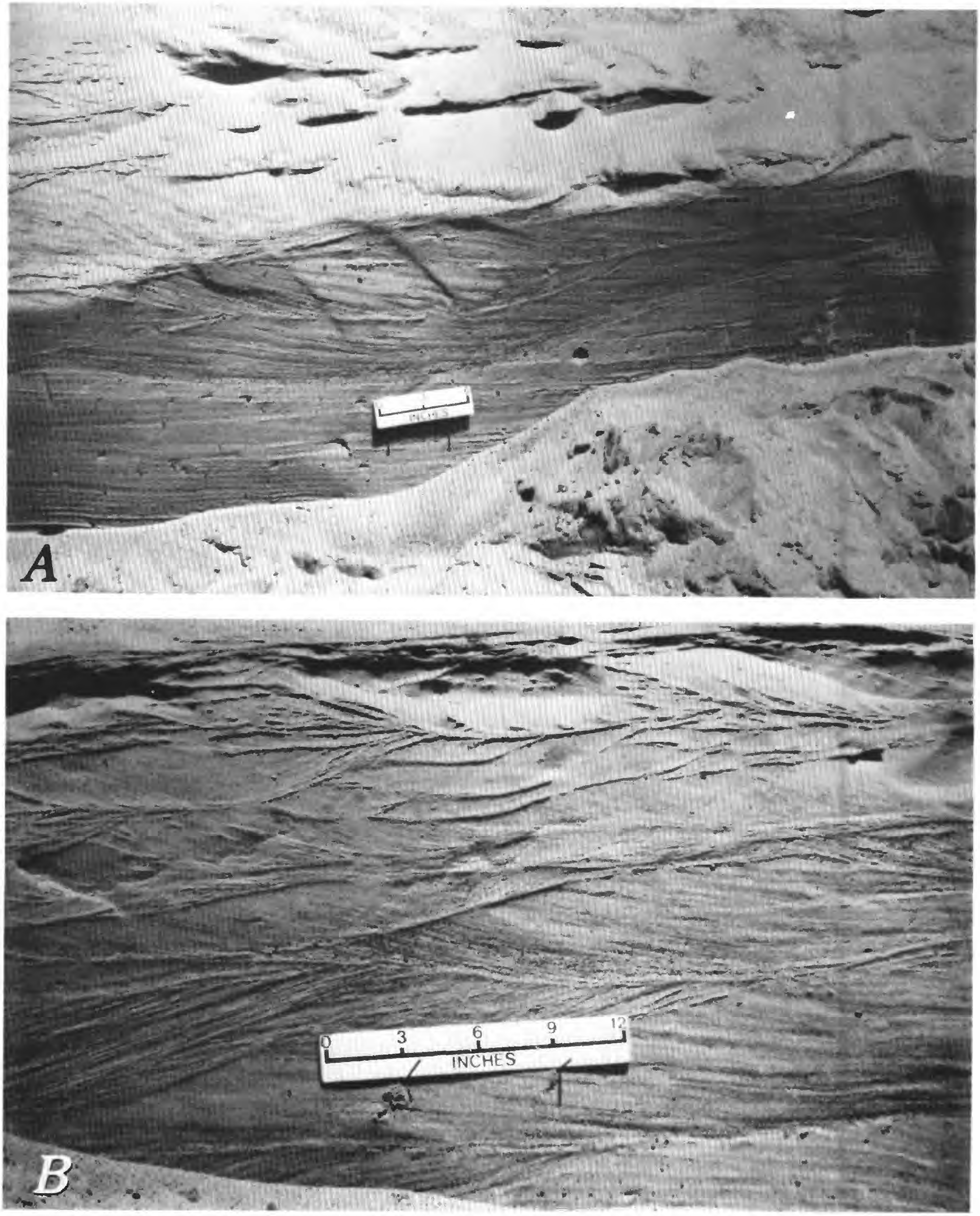


Figure 9. Trough structures with festoon pattern (*A*, *B*) in trench; right bank of Río Meta, 2 river kilometers downstream from Las Caracaras gaging station.

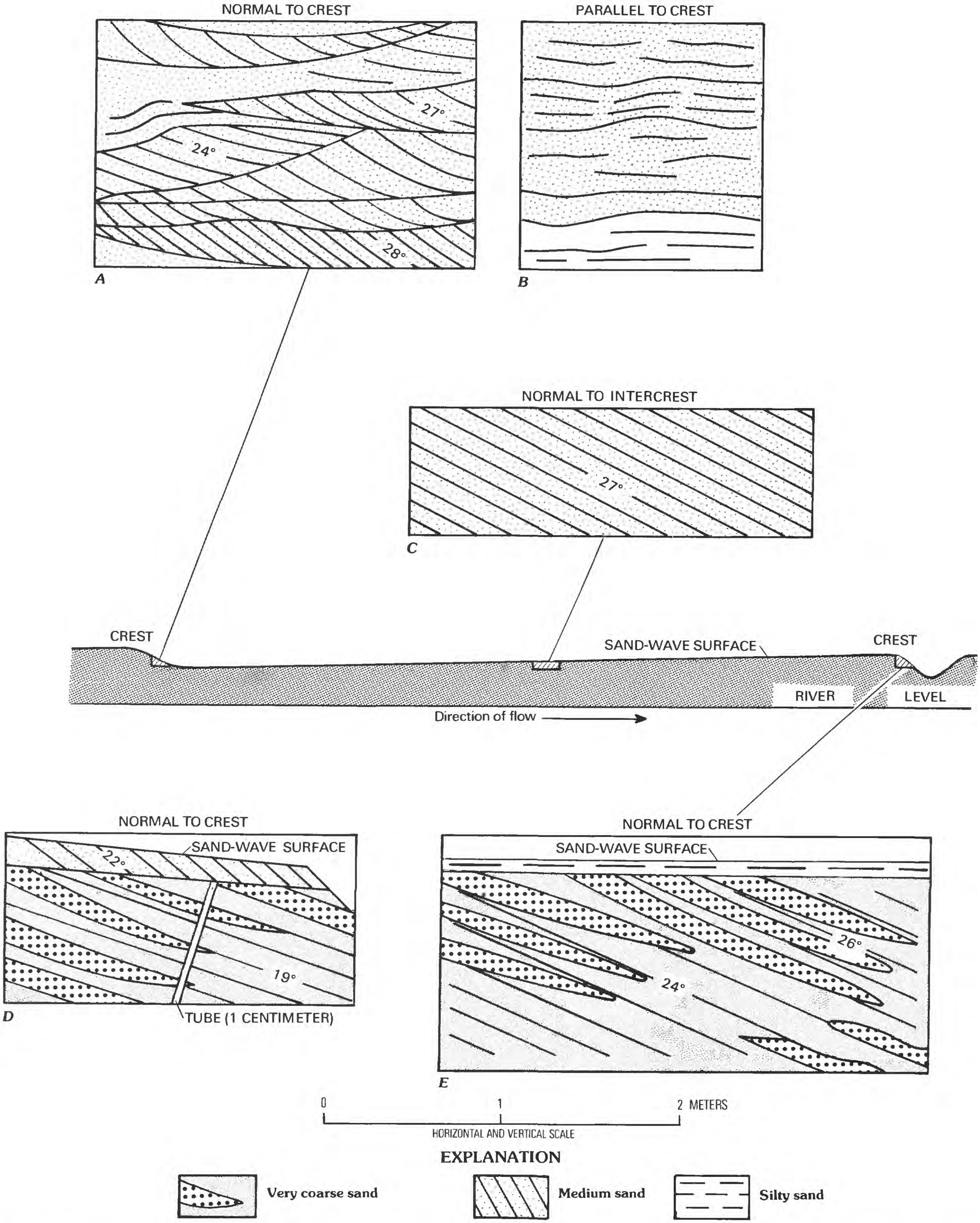


Figure 10. Profile of sand-wave deposits showing cross-strata patterns (*A–E*) exposed in trenches at crests and between crests on bar parallel to direction of river flow; right channel of Río Orinoco near Isla Babilla Flaca.

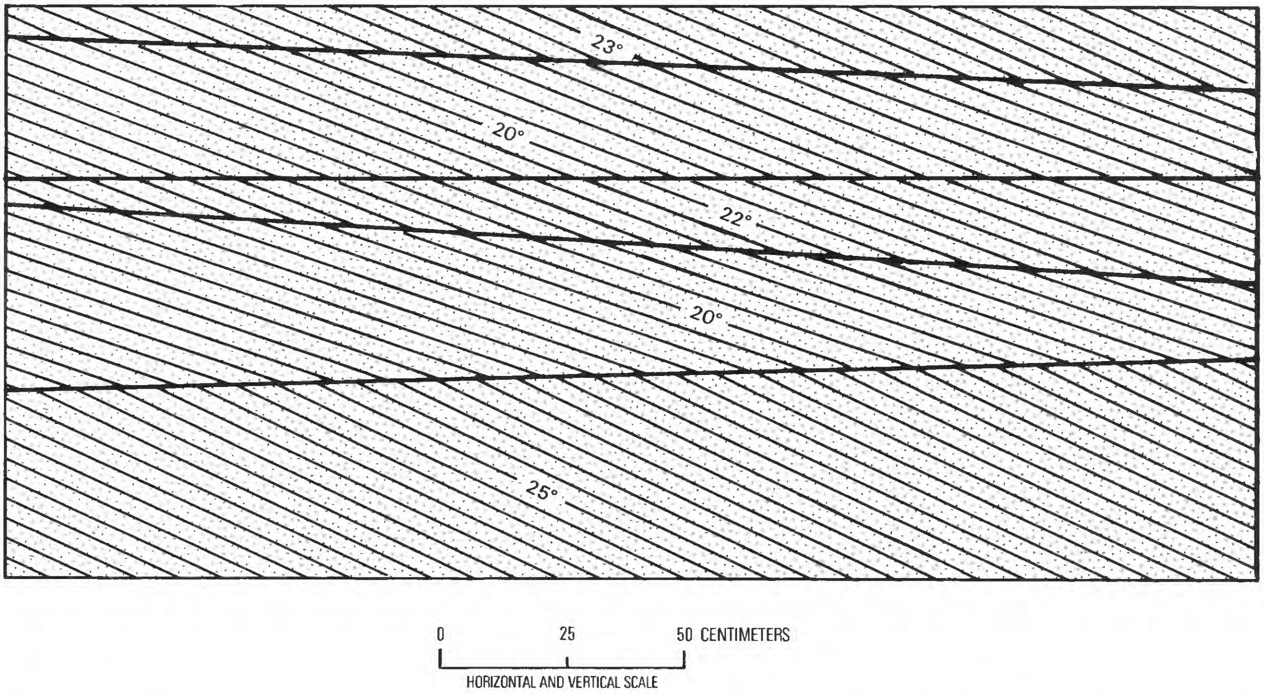


Figure 11. Tabular-planar and wedge-planar structure exposed in trench; left bank of Río Meta at junction with Río Orinoco.

why the planar-bounding planes are sloping in this type of cross stratification, rather than horizontal as in tabular-planar, is not known, but a likely explanation seems to be fluctuations or changes in water level that control the surface of sand-wave deposits during sedimentation.

MISCELLANEOUS SEDIMENTARY STRUCTURES

Depositional Features

A widespread and characteristic feature of stratification in most sand-wave deposits along the Río Orinoco is an alternation of coarse- and fine-grain sizes in the foreset bedding of tabular-planar sets. Because differences in the grain size of different strata are conspicuous by the light and dark shades of yellow and yellowish-brown sand, the lensing character of individual laminae or groups of laminae (figs. 13*B*, 14, 15) and the formation of flow toes in the sand (figs. 3*A*, 3*B*, 4*B*, 4*C*, 6*C*, 16) are readily apparent. Likewise, the characteristic structure of climbing ripples, considered evidence of an excess sand supply (McKee, 1965, p. 81), was noted at several localities along the banks.

Contorted Structures

In addition to those structures formed at the time of and during deposition, others of a penecontemporaneous variety result from local folding, faulting, and contortion on a small scale. These may be classified into three principal types according to genesis. They consist of (1) those structures, both tensional and compressional, resulting from avalanches; (2) structures caused by loading as from the accumulating weight of deposits settling from above; and (3) overturned folds that result from the drag or friction of large sand masses moving across a beveled surface at the top of a series of foreset beds.

Structures typical of each of the principal deformational processes were recorded in stratification of the Orinoco, though some structures probably were in deposits that did not consist of sand waves. In sections of

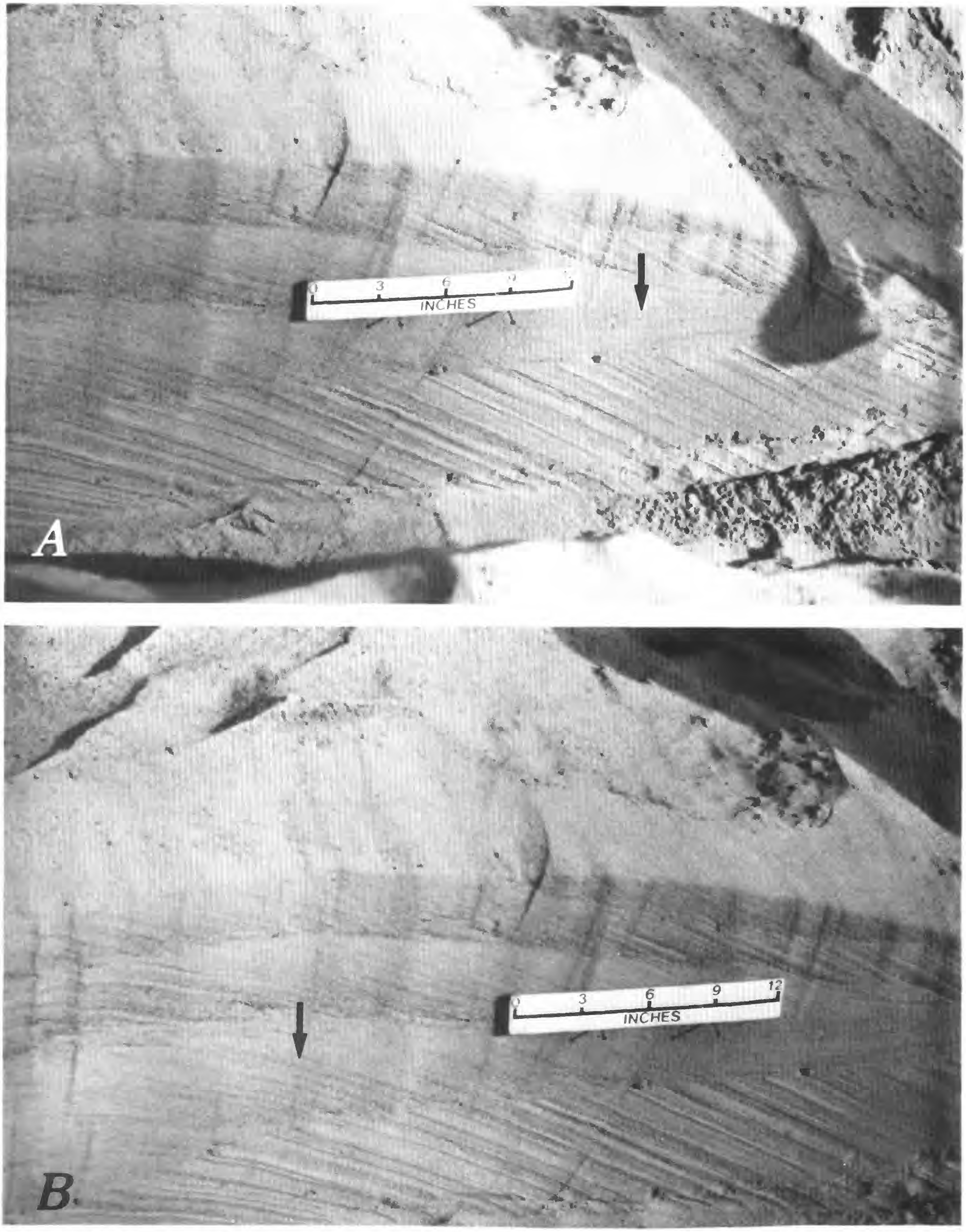


Figure 12. Wedge-planar cross-strata (*A*, *B*) exposed in trench; left bank of Río Orinoco near Puerto Páez.

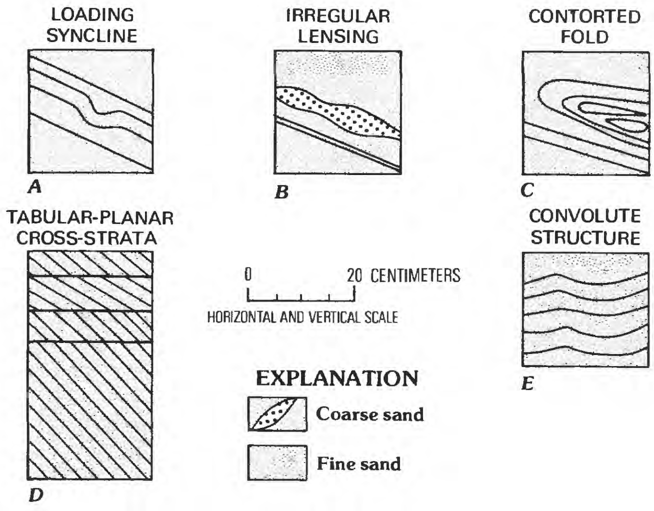


Figure 13. Minor sedimentary structures (*A–E*) exposed on face of bar; center of Río Orinoco, 2 river kilometers downstream from Puerto Ayacucho.

a sand bar about 2 km downstream from Puerto Ayacucho, small examples of sags from loading (figs. 13*A*, 17), of shattered and contorted folds (fig. 13*C*), and of irregular lensing (fig. 13*B*) were noted in laminae of coarse sand among the fine sand laminae. These were formed on foresets, probably the result of avalanches. Small convolute structures such as commonly form in the upper layers of loose sand as a result of sediment loading (McKee and others, 1967, p. 840) also were observed at this locality (fig. 13E).

Near the mouth of Río Cuchivero, the beveled lower part of a typical recumbent fold, of the type that forms from drag by a mass of sand moving across foreset tops (McKee, 1962, p. 553), was recorded (fig. 18). This feature is considered good evidence of flood conditions during which water transports a heavy load of sediment across the sand surface.

Climbing Megaripples

On a large sand bar along the right bank of the Orinoco, near the mouth of Río Cuchivero, an exceptionally fine example of climbing megaripple structure on a large scale was exposed by erosion (fig. 19). Two sets of 27°-dipping foresets were measured in the bank above river level and the corresponding low-angle beds (topsets) of the upcurrent side of each megaripple formed nearly horizontal planes. This structure clearly illustrates the rapid rate of sedimentation and the large quantity of sand transported by the stream at the time of deposition.

Additional Sedimentary Features

Relatively few features affecting the remarkably uniform, primary stratification and cross-stratification of the Orinoco channel deposits have been noted in the many trenches dug at various localities. Other than the penecontemporaneous structures already described, most exceptions to the uniformity consist of (1) incorporated organic matter; (2) partial destruction of laminae by boring or burrowing animals, or from plant growth; and (3) reworking of water-deposited sediments by subsequent current action or by the wind.

Organic matter, largely in the form of leaves, twigs, and other debris trapped in pockets or trough-like depressions adjacent to sand-wave deposits have accumulated as lenses or irregular beds. Such deposits were observed at various localities along the Orinoco, but apparently are not common in the channel sands. On the left bank of the Río Parguaza near its mouth, small lenses and thin flat beds of black carbonaceous matter (partially decomposed leaves) were noted between sets of tabular-planar sand in which foresets dipped uniformly between 15° and 25° (fig. 20). At Río Meta near Puerto Páez, some relatively thick black beds, consisting largely of twigs and plant debris, likewise were conspicuous between sand-wave deposits consisting of tabular-planar cross-beds of yellowish sand (fig. 21). Dips of foresets in these sands ranged from 20° to 28° downstream.

Partial destruction through bioturbation of stratification patterns among sand-wave deposits of the Río Orinoco seems to be a relatively uncommon feature, especially when compared with many other environments of sand deposition. The general scarcity of burrowing and boring organisms probably results from impermanence of river sand bars. Constant changes in river discharge and in velocity and direction of current flow make habitats for many organisms unstable. At Isla Babilla Flaca, near river km 1134, however, many vertical and high-angle tubes, about 1 cm in diameter, were noted penetrating foresets that dipped at 19° and 20° (fig. 10*D*) throughout a limited area. Elsewhere along the river, little evidence of laminae disruption by organisms was noted.

The reworking of sand-wave deposits by wind was a conspicuous feature on many of the large bars and some of the small ones. Eolian dunes of barchanoid type formed on top of the otherwise flat surfaces of sand-wave deposits. Examples were near Cabruta; at Punta Brava, 11 river km upstream from Río Cuchivero (fig. 22); and at the mouth of Río Cuchivero where they were 3.4 m

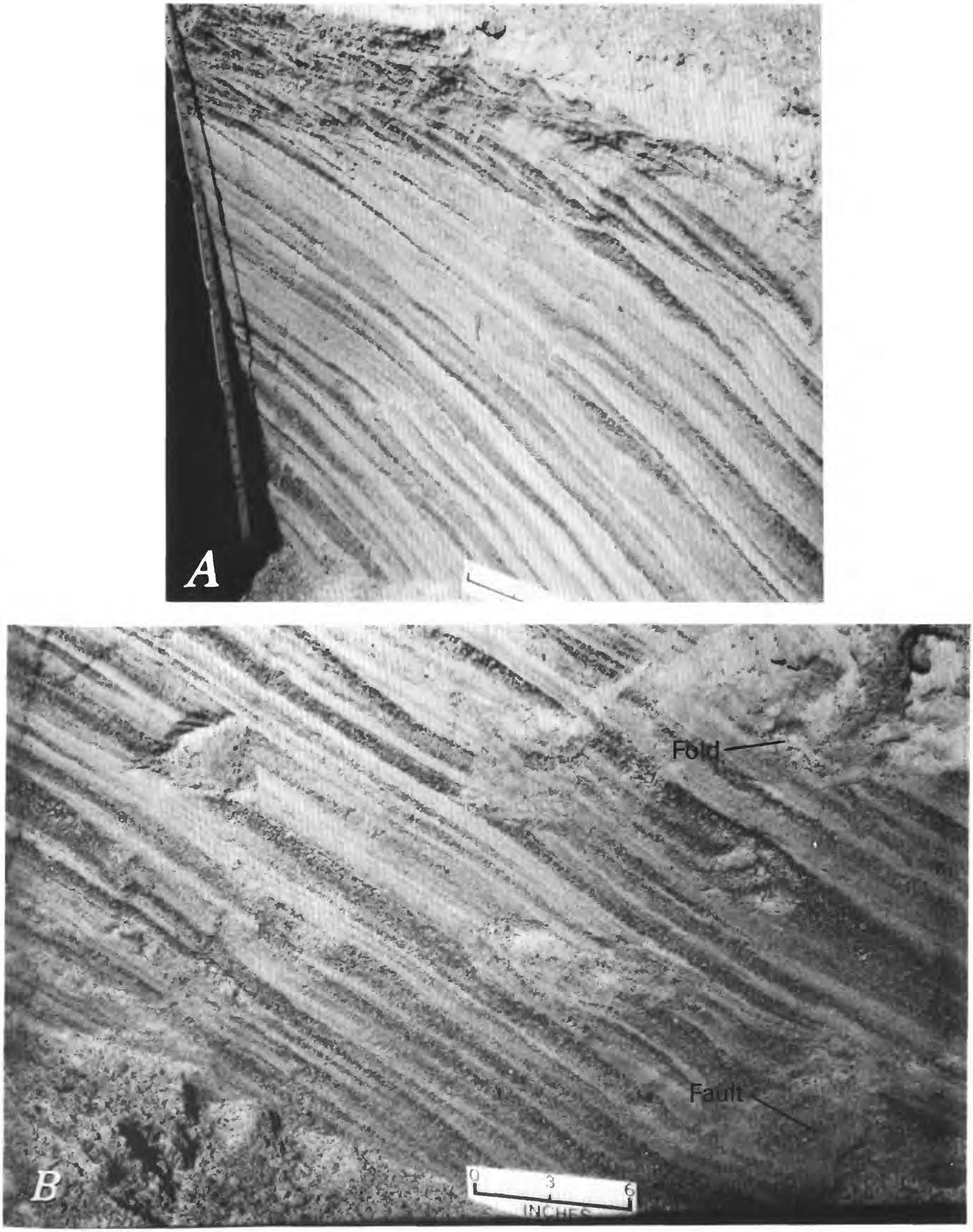


Figure 14. *A*, Lenticular laminae and lenses or flow toes of coarse sand (dark) in foresets of sand-wave deposits, and *B*, folds and low-angle faults in the same deposits. Center bar of Río Orinoco, 2 river kilometers downstream from Puerto Ayacucho.

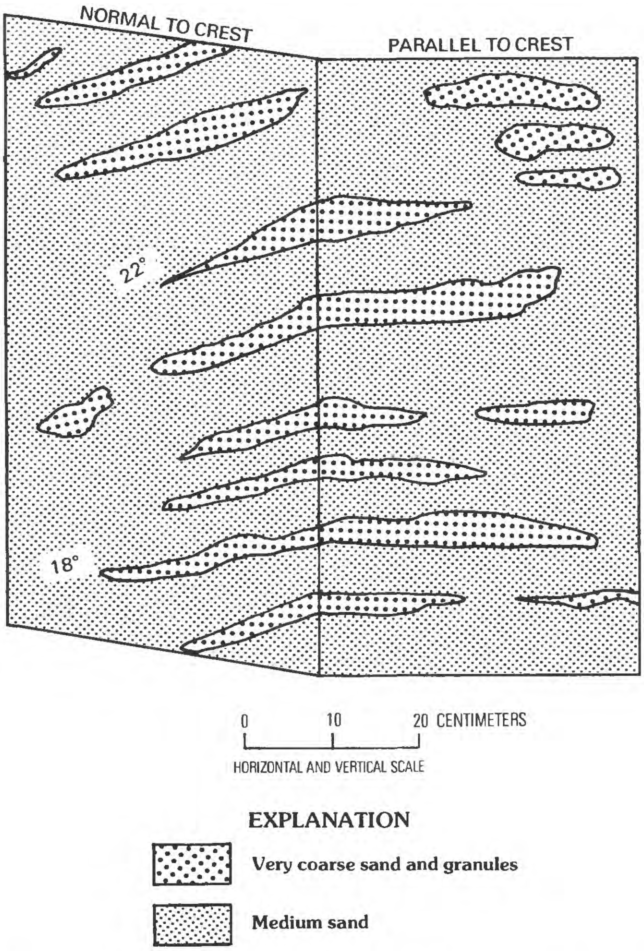


Figure 15. Alternating coarse- and fine-grained sand laminae and lenses in sand-wave deposits; Río Orinoco at Isla Ceiba.

high (fig. 23). In general, the foresets of eolian dunes were considerably longer than those of sand waves, and, therefore, formed thicker sets of tabular-planar type, and they commonly had large curving tangents with their flat basal bounding surfaces. Furthermore, the direction of dip in most eolian foresets was opposite to that of underlying sand-wave deposits, as wind commonly blew upriver, whereas water-formed foresets dipped downriver (fig. 24).

TEXTURE

The downstream part of the Río Orinoco drainage system, like that of most other large rivers, can be divided into two principal parts on the basis of depositional processes involved and types of sediment accumulated. One of these parts, the active channel, ranges from about 1 to 4 km in width, depending largely on the outcropping rock that confines its course in any particular area. The other part is the overbank part commonly known as the flood plain, which in places is as much as 25 km wide including the channel.

Detrital sediment that is being deposited in the active channel of the Orinoco consists preponderantly of sand-size particles and generally includes extremely little silt or clay (table 1). Very fine grained sediment is largely transported to the delta at the river's mouth, or is accumulated within the flood plain on each side of the river where it settles in quiet water.

The extensive sand deposits of the Orinoco channel, although including all size grades, are dominantly within the range of medium sand (¼–½ mm) on the Wentworth scale. A common feature, however, in places where coarse and very coarse sand (½–2 mm) is also present, is a sorting into alternating laminae of the two grade sizes on the foresets of tabular-planar units. This alternation seems to be characteristic in many localities and probably should be considered a diagnostic feature of sand-wave strata on the Río Orinoco, although its cause is not clear.

Grain-Size Distribution

Grain-size determinations were made from mechanical analyses of 55 sand samples from 17 localities. The samples were considered representative of tabular- and wedge-planar structures, trough- or festoon-type structures, surface lag deposits, eolian dune deposits, and tongues or sand-flow toes of relatively coarse sand. Size classification is according to the Wentworth scale as given in table 2.

Because most sand deposits in the downstream reaches of the Río Orinoco are the product of sand waves and mostly have either a tabular- or a wedge-planar structure, samples from them are considered separately from those of other types in this discussion of grain size. The 31 samples and 10 localities represented in table 1 illustrate that more than one-half the sediment deposited as sand waves is in the medium-size class. In contrast, only 3 samples are in the fine and very fine classes, and only 7 and 4 samples, respectively, are in the coarse and very coarse classes (table 1).

A second structure that occurs locally along the Río Orinoco is the trough type that forms a distinctive festoon pattern. As illustrated in table 3, this structure,

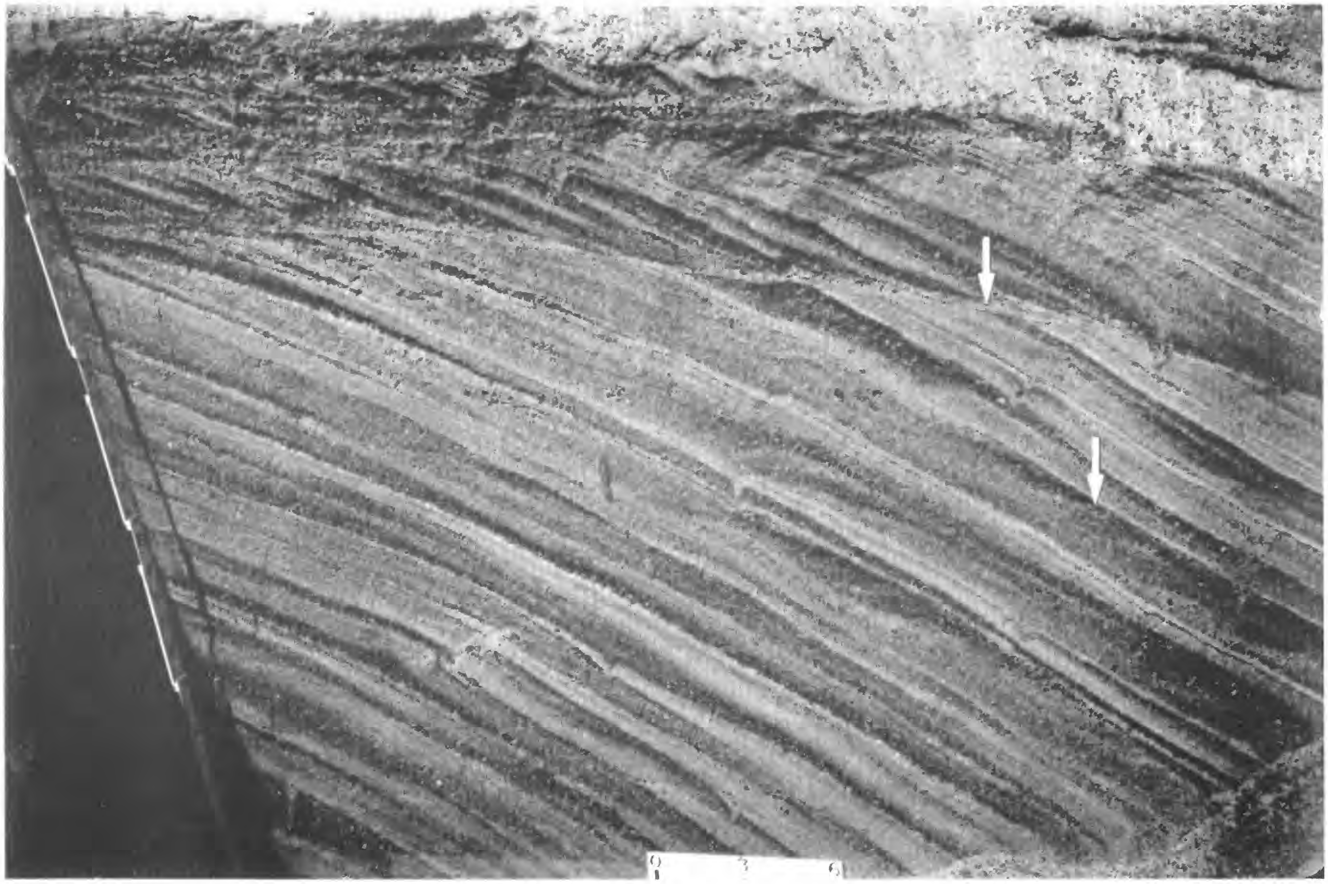


Figure 16. Sand-flow toes at base of foresets in sand-wave deposits; right bank of Río Orinoco, 2 river kilometers downstream from Puerto Ayacucho. Scale is in inches. Photograph by Lois Hernández.

which generally is considered the result of point-bar formation in areas where a stream meanders, is inconsistent in its grain size and commonly includes scattered granules and pebbles, especially near the trough bottoms. No one grain size seems to be dominant among the sands of these festoons.

Particles of very coarse sand and of granule- and pebble-size constitute a conspicuous though relatively minor part of many sand-wave deposits along Río Orinoco. They occur mostly as scattered grains, interpreted as lags, on bar surfaces, although in some vertical faces they form lenses (fig. 15) or concentrations filling irregular depressions. The percentages of size grades in lag samples from three representative localities along the river are shown in table 4 and illustrate typical coarse fractions.

At the opposite extreme in grain size are the sands of eolian dunes that commonly form on the surfaces of sand bars (figs. 22, 23). These wind-blown sands apparently were derived largely from the underlying sand-wave deposits and are composed mostly of fine grains (⅛–¼ mm) and to a lesser extent of medium grains (¼–½ mm). Relatively few of either coarser or finer sizes are present as shown in table 4. Thus, sorting (table 5) is very good—even better than in the sand-wave deposits.

In many sand-flow deposits that form bars and banks along the Río Orinoco, the presence of thin tongues of relatively coarse sand in the foresets of tabular-planar units is a prominent feature. These strata commonly dip at 20° to 28° and terminate near their bases as pointed sand-flow toes (figs. 3*A*, 3*B*, 4*B*, 4*C*, 10*D* 10*E*, 16). Mechanical analyses of 7 samples of these tongues and flow toes from 7 localities show that in 5 of

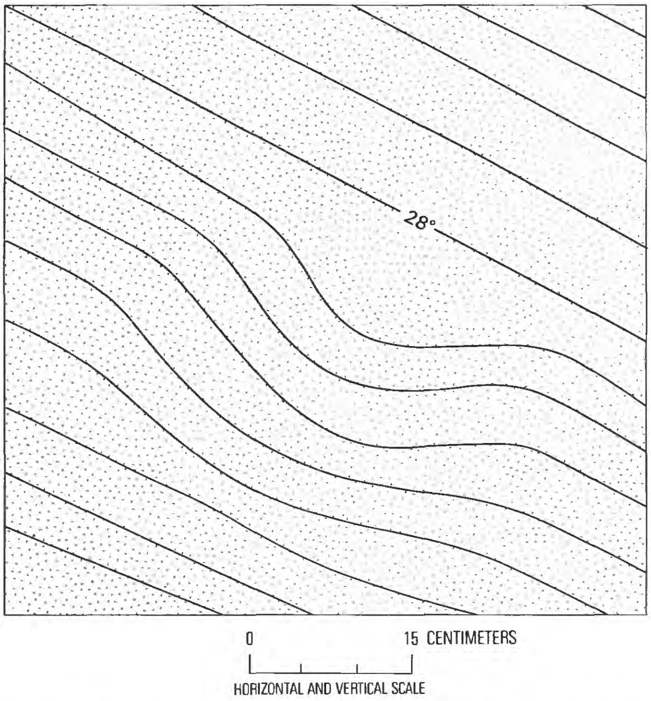


Figure 17. Penecontemporaneous sag or fold, probably caused by loading during deposition; right bank of Río Orinoco near Curiquima.

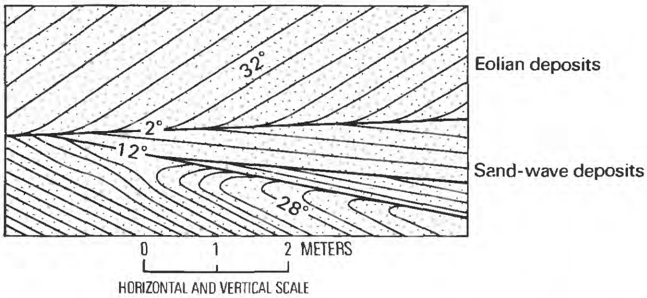


Figure 18. Recumbent fold, probably result of drag by sand load during deposition of overlying foresets, with upriver-dipping eolian foresets above sand-wave deposits dipping downriver; Río Cuchivero near mouth.

the samples, the dominant grade size of sand was very coarse (1–2 mm). In all samples of associated matrix, the sand size was less, mostly medium grade. This common textural feature in the tabular-planar structures seems to be distinctive in sand-flow deposits of the Río Orinoco but the cause has not been determined.

Sorting of Sand

The degree of uniformity in channel sands of the Río Orinoco was determined on the basis of 47 samples, collected from Trapichote above Puerto Ayacucho, downriver as far as Musinacio (fig. 1). Using the graphic standard-deviation method recommended by Folk (1968, p. 46), sand samples were assigned to classes of sorting as follows:

$<0.35\phi$—very well sorted	0.7ϕ–1.0ϕ—moderately sorted
0.35ϕ–0.50ϕ—well sorted	1.0–2.0ϕ—poorly sorted
0.50ϕ–0.70ϕ—moderately well sorted	2.0–4.0ϕ—very poorly sorted

A tabulation of samples representing the principal structure types in the Orinoco sands illustrates several features (table 5). First, tabular-planar cross-strata, which dominate the sand-wave deposits, are more than 50 percent in the moderately well sorted class and about 25 percent in the well sorted class. Second, sands with wedge-planar structures, which are much less common, range from poorly sorted to well sorted with nearly equal amounts in each class. Finally, the trough or festoon type, although variable, is mostly in the well sorted class.

Deposits that accumulated as pockets or lenses of relatively coarse sand or that formed flow toes among foreset beds are largely moderately to poorly sorted. At the other extreme in size, the eolian dune sands, probably because they were derived mostly from sand-wave deposits, are well to very well sorted.

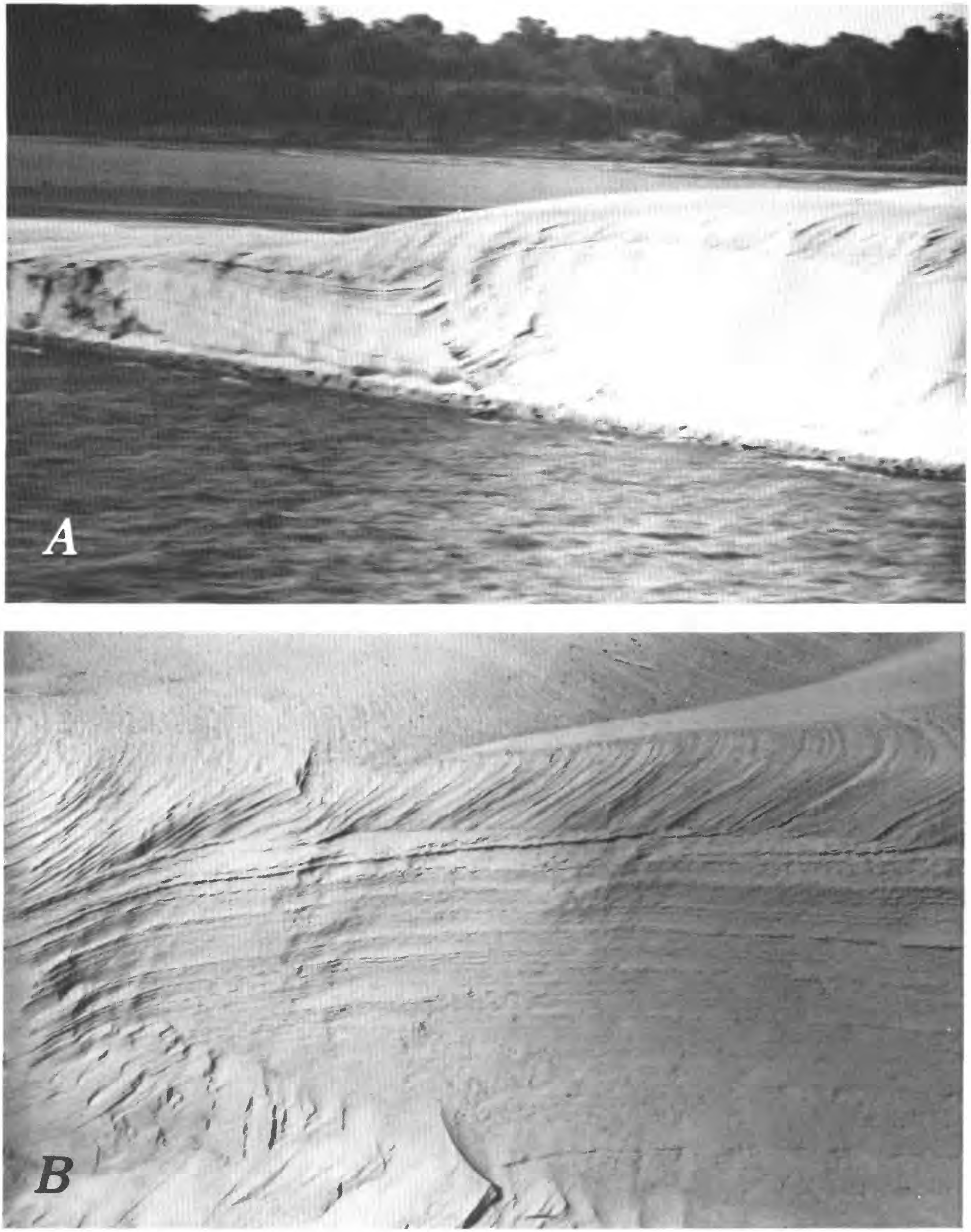


Figure 19. *A*, Large-scale climbing megaripple on face of sand bar; right bank of Río Orinoco upstream from Río Cuchivero. Foreset dips are downriver parallel to current movement. *B*, Close-up view of structure in center of *A*. Set is about 3 meters thick.

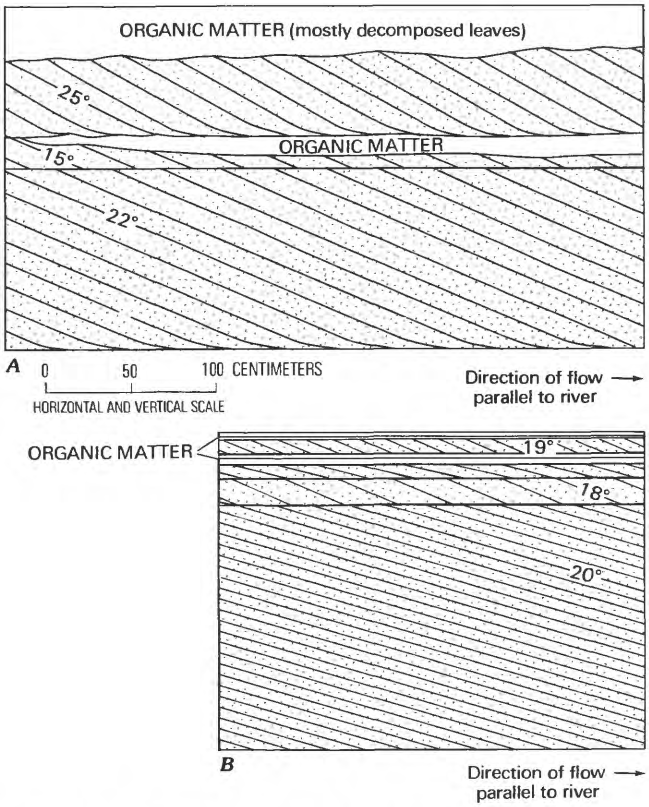


Figure 20. *A*, Lenses, and *B*, flat beds of organic matter among tabular-planar sets of sand-wave deposits; left bank of Río Parguaza near mouth.

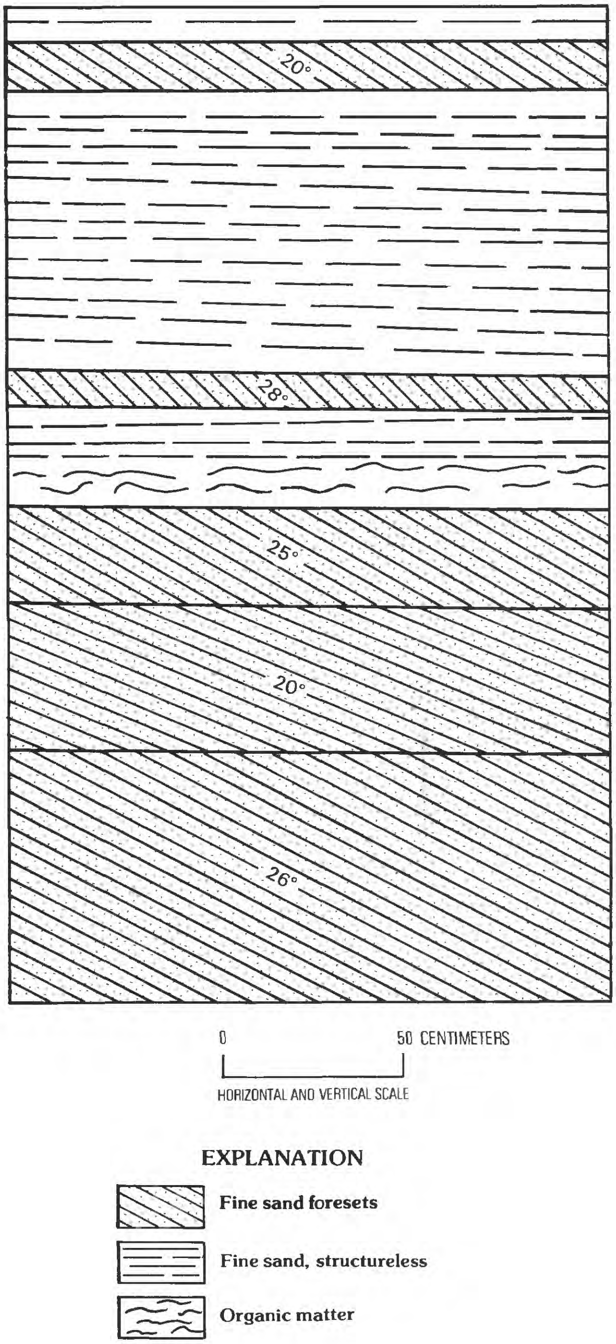


Figure 21. Organic matter (leaves and twigs) among tabular-planar sets of cross-stratified sand-wave deposits; left bank of Río Orinoco at mouth of Río Meta.

Figure 22. Eolian dune on surface of sand-wave deposits; Río Orinoco at Punta Brava, 11 river kilometers upstream from Río Cuchivero.

Figure 23. Barchan dune (3.4 meters high) on sand bar; Río Orinoco at mouth of Río Cuchivero.

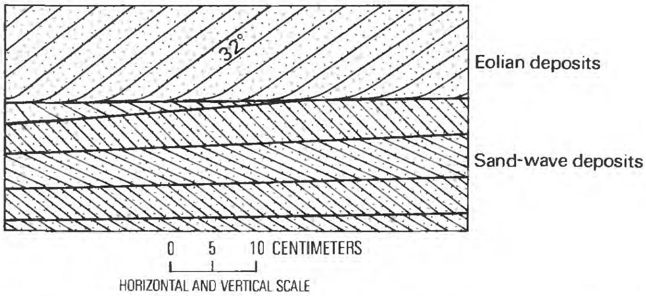


Figure 24. Cross-stratification of eolian deposits above sand-wave deposits exposed in trench; right bank of Río Orinoco at mouth of Río Cuchivero.

Table 1. Particle-size distribution of tabular-planar and wedge-planar sand-wave deposits
[Numbers underlined are dominant size; asterisk, *, indicates wedge-planar]

Locality	Percent: Granule	Sand: Very coarse	Sand: Coarse	Sand: Medium	Sand: Fine	Sand: Very fine	Silt and clay
Trapichote	0.0	0.0	0.67	67.88	25.54	4.70	0.010
Puerto Ayacucho	.20	.30	5.15	62.01	25.69	5.46	.010
Río Meta*	11.16	37.39	24.78	20.73	4.64	1.01	.003
Río Meta*	.49	1.58	9.37	71.01	15.48	1.68	.004
Río Meta*	13.50	34.91	26.16	21.78	2.68	.85	.001
Río Meta*	3.87	8.76	22.47	56.15	7.57	.84	.003
Isla Babilla Flaca	14.39	50.81	28.50	4.63	.22	.89	.010
Isla Babilla Flaca	6.25	33.70	53.71	6.20	0	0	.001
Isla Babilla Flaca	3.64	11.50	63.48	21.06	.16	0	.001
Isla Babilla Flaca	5.44	43.17	42.21	8.92	0	.17	.001
Isla Babilla Flaca	3.92	13.46	52.52	29.63	.12	.11	.002
Isla Babilla Flaca	.99	1.65	17.13	77.76	1.15	.83	.005
Isla Babilla Flaca*	21.73	48.05	24.59	5.02	.30	.21	.000
Isla Babilla Flaca*	.98	1.88	26.93	68.01	1.05	.84	.003
Río Parguaza	.30	.19	6.51	70.42	17.55	4.54	.004
Río Parguaza	.30	.46	8.48	71.95	12.88	4.70	.010
Santa Maria	0	.24	.11	.12	38.92	55.19	.050
Curiquima	.16	1.14	13.15	82.53	2.92	0	.000
Curiquima	3.80	18.62	38.52	32.55	3.80	2.35	.004
Curiquima	0	.50	8.85	69.70	17.83	2.62	.005
Curiquima	.91	11.78	51.36	32.48	2.71	.61	.002
Curiquima	.45	.45	9.25	81.94	7.01	.75	.002
Cabruta*	.11	.11	2.22	36.16	6.60	3.22	.030
Cabruta*	.42	.53	11.39	80.38	2.01	3.69	.020
Río Cuchivero	.47	.95	.62	16.83	60.53	18.24	.020
Río Cuchivero	0	0	0	16.16	76.67	7.72	.005
Musinacio	7.91	45.67	38.34	7.20	.61	.25	.001
Musinacio	.13	1.56	12.21	74.41	10.99	.44	.003
Musinacio	.34	1.01	2.43	80.07	16.16	.61	.002
Musinacio	21.72	47.72	14.97	13.31	1.89	.21	.001
Musinacio	.10	.19	2.50	80.08	16.36	.66	.001

Table 2. Sediment-size classification based on Wentworth scale
[mm, millimeters]

Limiting dimension (mm)	Pieces	Aggregate	Indurated rock
	Boulder	Boulder gravel	Boulder conglomerate.
256			
	Cobble	Cobble gravel	Cobble conglomerate.
64			
	Pebble	Pebble gravel	Pebble conglomerate.
4			
	Granule	Granule gravel	Granule conglomerate.
2			
	Very coarse sand grain	Very coarse sand	Very coarse sandstone.
1			
	Coarse sand grain	Coarse sand	Coarse sandstone.
1/2			
	Medium sand grain	Medium sand	Medium sandstone.
1/4			
	Fine sand grain	Fine sand	Fine sandstone.
1/8			
	Very fine sand grain	Very fine sand	Very fine sandstone.
1/16			
	Silt particle	Silt	Siltstone.
1/256			
	Clay particle	Clay	Claystone.

Table 3. Particle-size distribution in some trough structures

Locality	Percent								Figure No.
	Pebble	Granule	Sand					Silt and clay	
			Very coarse	Coarse	Medium	Fine	Very fine		
Puerto Ayacucho	0.0	0.0	0.39	4.58	40.32	44.40	9.58	0.01	
Río Meta:									
Las Caracaras (pebbly)	0	1.84	20.68	51.19	22.56	2.88	.50	.003	6, 8
Río Apure	.17	.66	.33	.67	45.85	50.00	1.99	.003	7
Río Apure	.09	.57	3.02	14.92	58.17	22.29	.75	.002	7

Table 4. Particle-size distribution of lag deposits in sand waves and of eolian dune deposits

Locality	Percent							
	Pebble	Granule	Sand					Silt and clay
			Very coarse	Coarse	Medium	Fine	Very fine	
Lag deposits								
Isla Ceiba	14.30	38.79	12.45	12.18	12.85	8.51	0.79	0.001
Trapichote	11.42	51.58	27.87	5.79	2.72	.96	0	0
Río Meta	6.80	28.77	22.46	13.87	15.12	8.81	3.49	.010
Eolian dunes								
Punta Brava	0	0	0	.13	40.29	57.36	1.96	.003
Río Cuchivero	0	.35	.35	.18	30.50	62.36	6.38	.002

Table 5. Average size and uniformity of sand grains

Locality	Structure type	Mean grain size (phi units)	Size class	Graphic standard deviation (phi units)	Sorting classification
Trapichote	Tabular-planar.	1.84	Medium sand	0.57	Moderately well sorted.
Trapichote	Nonstratified	-.08	Very coarse sand ...	1.60	Poorly sorted.
Puerto Ayacucho	Tabular-planar	1.84	Medium sand	.59	Moderately well sorted.
Puerto Ayacucho	Nonstratified	2.77	Fine sand	.76	Moderately sorted.
Puerto Ayacucho	Trough festoon	2.12	Fine sand	.70	Moderately well sorted.
Puerto Ayacucho	Lens	.25	Coarse sand	1.11	Poorly sorted.
Isla Ceiba	Tabular-planar	1.14	Medium sand	.65	Moderately well sorted.
Río Meta	Trough festoon	1.28	Medium sand	.38	Well sorted.
Río Meta	Wedge-planar	1.58	Medium sand	.52	Moderately well sorted.
Río Meta	Wedge-planar	.15	Coarse sand	1.05	Poorly sorted.
Río Meta	Wedge-planar	1.10	Medium sand	.85	Moderately sorted.
Río Meta	Trough festoon	.55	Coarse sand	.75	Moderately sorted.
Río Meta	Trough festoon	2.33	Fine sand	.41	Well sorted.
Babilla Flaca	Tabular-planar	-.26	Very coarse sand ...	.75	Moderately sorted.
Babilla Flaca	Tabular-planar	.10	Coarse sand	.65	Moderately well sorted.
Babilla Flaca	Tabular-planar	.58	Coarse sand	.59	Moderately well sorted.
Babilla Flaca	Tabular-planar	.05	Coarse sand	.67	Moderately well sorted.
Babilla Flaca	Tabular-planar	.67	Coarse sand	.60	Moderately well sorted.
Babilla Flaca	Tabular-planar	1.27	Medium sand	.39	Well sorted.
Babilla Flaca	Wedge-planar	-.38	Very coarse sand ...	.78	Moderately sorted.
Babilla Flaca	Wedge-planar	1.17	Medium sand	.46	Well sorted.
Río Apure	Trough festoon	1.94	Medium sand	.41	Well sorted.
Río Apure	Lens	1.73	Medium sand	.33	Very well sorted.
Río Apure	Trough festoon	1.53	Medium sand	.64	Moderately well sorted.
Río Apure	Trough festoon	2.00	Fine sand	.41	Well sorted.
Río Apure	Wedge-planar	2.16	Fine sand	1.19	Poorly sorted.
Parguaza	Tabular-planar	1.70	Medium sand	.56	Moderately well sorted.
Parguaza	Tabular-planar	1.60	Medium sand	.61	Moderately well sorted.
Santa Maria	Tabular-planar	3.18	Very fine sand	.45	Well sorted.
Curiquima	Tabular-planar	.65	Coarse sand	.90	Moderately sorted.
Curiquima	Tabular-planar	1.63	Medium sand	.52	Moderately well sorted.
Curiquima	Tabular-planar	1.24	Medium sand	.30	Very well sorted.
Curiquima	Flow toes	.51	Coarse sand	.90	Moderately sorted.
Curiquima	Tabular-planar	1.36	Medium sand	.36	Well sorted.
Curiquima	Horizontal	1.62	Medium sand	2.63	Very poorly sorted.
Cuchivero	Tabular-planar	2.55	Fine sand	.62	Moderately well sorted.
Cuchivero	Eolian dune	2.26	Fine sand	.48	Well sorted.
Cuchivero	Eolian dune	2.09	Fine sand	.31	Very well sorted.
Cuchivero	Tabular-planar	2.39	Fine sand	.40	Well sorted.
Cabruta	Wedge-planar	6.99	Medium silt	5.50	Well sorted.
Cabruta	Wedge-planar	1.40	Medium sand	.54	Moderately well sorted.
Musinacio	Tabular-planar	-.03	Very coarse sand ...	.73	Moderately sorted.
Musinacio	Tabular-planar	1.49	Medium sand	.47	Well sorted.
Musinacio	Tabular-planar	1.70	Medium sand	.34	Very well sorted.
Musinacio	Tabular-planar	1.69	Medium sand	.35	Well sorted.
Musinacio	Flow toes	.95	Coarse sand	.74	Moderately sorted.
Musinacio	Flow toes	1.37	Medium sand	.76	Moderately sorted.

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★ **U.S. GPO:** 1989 673-047/86,084