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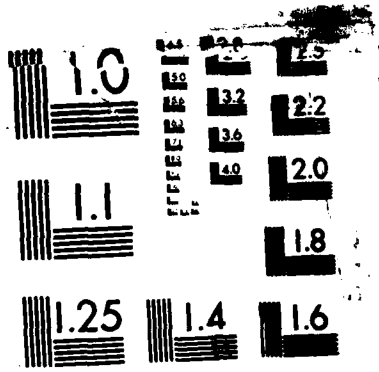

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Louisiana State University
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DELTAIC MORPHOLOGY AND SEDIMENTOLOGY WITH SPECIAL REFERENCE TO THE INDUS RIVER DELTA

J. T. Wells and J. M. Coleman

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Deltaic Morphology and Sedimentology, with special reference to the Indus River Delta

J. T. WELLS and J. M. COLEMAN
Louisiana State University,
Baton Rouge, Louisiana

ABSTRACT

The patterns of sedimentation and morphologic development of a delta result primarily from the interaction of fluvial and marine processes. Historically, the Indus River delta has formed in an arid climate under conditions of high river discharge (400×10^6 metric tons of sediment/year), moderate tide range (2.6 m), extremely high wave energy (14×10^7 ergs/sec), and strong monsoon winds from the southwest in summer and from the northeast in winter. The resulting sandy, lobate delta, lacking in luxuriant vegetation and dissected by numerous tidal channels, has prograded seaward during the last 5000 years at an average rate of perhaps 30 m/year. Morphology of the Indus Delta lies midway between that of a fluvially dominated delta (elongate, protruding distributaries) and a high-energy wave-dominated delta (beach, beach-ridge, and downdrift deposits).

Whereas sands provide a substrate for the subaerial delta, silts and clays provide material for fill in abandoned channels, delta front outer shelf deposits, and downdrift sedimentation to the east. Coarse sediments from the Indus River generally remain on the inner shelf or undergo transport to deeper water via the Indus submarine canyon. Little of the fine-grained sediment remains within the delta, since maximum river discharge occurs during southwest monsoons, resulting in transport of the muds southeast into the Ranns of Kutch.

Extensive engineering works for irrigation purposes appear to have reduced sediment load to 100×10^6 metric tons/year and may reduce it within the next 20 years to virtually zero. This decrease in sediment load, together with the extreme levels of wave energy, will cause rapid wave reworking and transgression of the Indus Delta, not unlike that experienced in other deltas in similar settings, such as the Nile Delta in Egypt and the Tana Delta in Kenya. The end product will be a wave-dominated delta, characterized as a transgressive sand body, capped by extensive eolian dune deposits.

INTRODUCTION

The 30-35 major deltas of the world display a wide range of sedimentary environments and configurations as a result of the complex interactions between marine and fluvial processes. Whereas some deltas experience low wave energy and negligible tides, others are exposed to continuous and severe wave forces or to tide ranges that may exceed 5 m. Many deltas, such as the Mississippi River delta, are dominated by silt- and clay-sized particles, whereas others, such as the Burdekin River delta in Australia, are composed almost exclusively of sand and gravel. The common attribute shared by each of these deltas, regardless of environmental setting, is the ability to accumulate fluvial sediments more rapidly than they can be removed by marine processes.

Previous research has shown that deltaic morphology and sedimentology are a function of numerous processes, most notably climate, sediment yield and type, wave power, tide range, nearshore currents, shelf slope, and tectonic activity (Coleman and Wright, 1975). Attempts to incorporate some or all of these process variables into models for discriminating delta types have resulted in at least three classification schemes. Fisher et al. (1969) proposed high constructive and high destructive delta types based on relative intensity of fluvial and marine processes. Coleman and Wright (1971) and Wright et al. (1974), using a

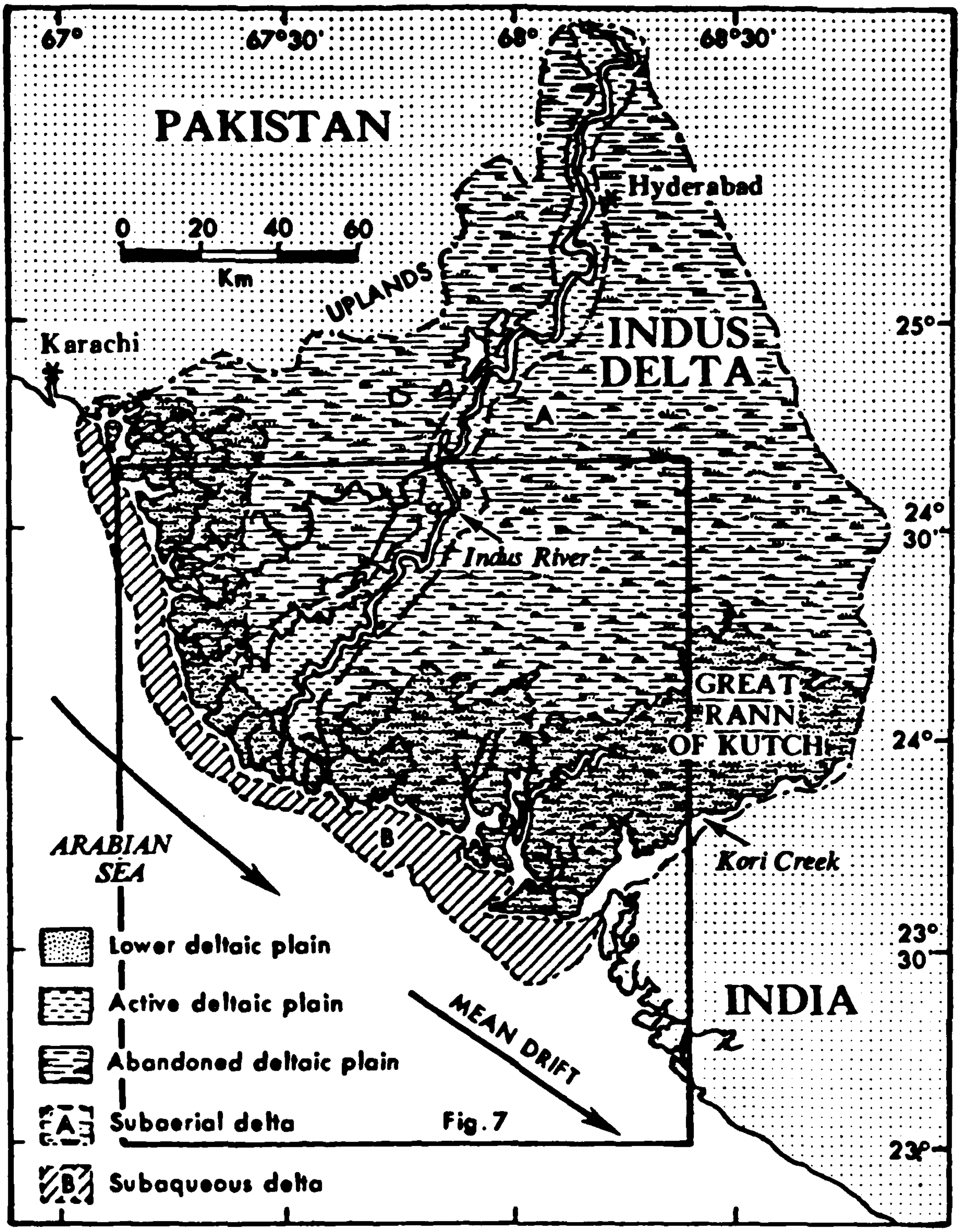

Figure 1. Index map of the Indus River delta in southeastern Pakistan showing the physiographic subdivision of the deltaic plain.

broad range of parameters, quantified the process variables, then clustered deltas into discrete statistical groupings. Most recently, *Elliott (1978)* proposed a classification scheme based on the earlier work of Galloway (1975) wherein deltas were plotted on a ternary diagram to define general fields of fluvial, wave, and tide dominance.

The most significant aspect of these more recent classification schemes is the recognition of the role of processes in producing responses. In this respect, climate is perhaps the single most important factor in determining fluvial processes and the types of sediment introduced to a given delta. At one end of the spectrum, the Indus River delta in Pakistan can clearly be included in the category of dry (arid) tropical to subtropical deltas. The environmental setting of the Indus is one of low rainfall (35 cm/year), surrounding deserts, erratic discharge, and monsoonal wind patterns. The arid climate, together with a moderate to high tide range along the coast, produces interdistributary evaporites and barren, halite-encrusted mudflats in the adjacent Ranns of Kutch (Glennie and Evans, 1976).

Numerous other deltas occur in similar settings, e.g., the Nile (Egypt), Shatt-al-Arab (Iraq), Senegal (Senegal), Tana (Kenya), and Ebro (Spain). As a generalization, these, too, have deltaic plains largely devoid of vegetation that are characterized by calcretes (Ebro delta) or salinas (Nile delta). Many of the arid deltaic plains are dominated by eolian dune fields of sand that has been eroded from active and abandoned beach ridges of barrier beach shorelines (Elliott, 1978).

It is interesting to note that the Indus River delta, certainly one of the largest in the world, is not included in the classification schemes of Fisher et al. (1969), Galloway (1975), or Elliott (1978), nor does it logically fall into any of the six classification categories of Coleman and Wright (1975). In the following paragraphs we will examine the Indus Delta in more detail and uncover its important and unique characteristics by comparing it to other deltas worldwide.

THE INDUS DELTA

The Indus Delta forms a significant protuberance of clastic sediments, introduced into the northern Arabian Sea by way of the Indus River (Fig. 1). Draining the Himalaya Mountains to the north, the Indus River flows south as a braided stream in its upper valley, but displays a well defined meander belt in the lower reaches of the valley. Sediments of the meander belt consist of river bar deposits and natural levees on a landscape marked by abandoned channels and crescentic meander scars (Holmes, 1968). The complex nature of the river is shown by the numerous tributaries (and distributaries), many from previous river courses such as the Jacobabad, Nawabshah, and Nara.

In tracing the Indus River throughout historic times, Holmes (1968) has shown that the last major change in course occurred in 1758-59 when the river adopted its present course west of Hyderabad (Fig. 1). In 1819, after the lower part of this course became choked with silt, the river began delivering its discharge farther east; each successive shift in the mouth of the river produced a new locus of deposition. The present-day configuration of the delta reflects the extent of these changes in river course.

According to Holmes (1968), the head of the Indus Delta lay 55 km northeast of Hyderabad in historic times; rates of progradation during the last 5000 years appear to have been on the order of 30 m/year. Today, extensive flood protection levees line the banks of the Indus River to prevent overbank flooding and unwanted diversions in the river course. Much of the flood water is diverted through what has become one of the most extensive irrigation systems in the world.

Initial size of the sediment load, amount of discharge, and fluctuations in discharge are determined in the drainage basin to the north of the delta. It is here that the sediment and water originate. Thus the size of the drainage basin provides some measure of the size of a delta. A plot of deltaic plain area versus drainage basin area shows the Indus River to be "average" in that it lies close to the line of least-squares best fit (Fig. 2).*

The deltaic plain alone, that area from the shoreline to the alluvial valley, covers 29,500 km^2 in the shape of a broad fan (Fig. 1). The plain of the Indus Delta is slightly larger than that of the Mississippi Delta and lies midway on a scale worldwide that ranges from less than 1 x 10^3 to greater than 4 x10^5 km^2 (Fig. 3). Built by progradation where the river has become a dispersal system rather than a transporting agent, the subaerial delta has been growing most rapidly

*Data used for construction of the scatter plots and bar graphs presented in this paper were compiled by Coleman and Wright (1975). Their values were taken from numerous published and unpublished reports, maps, and data files, definitions and methods can be found in Coleman and Wright (1971) and Wright et al. (1974)

to the east as the river attempts to migrate in this direction. If permitted, all points on the Indus River south of Ganjo Takar, where it makes its last major bend to the west, are potential danger

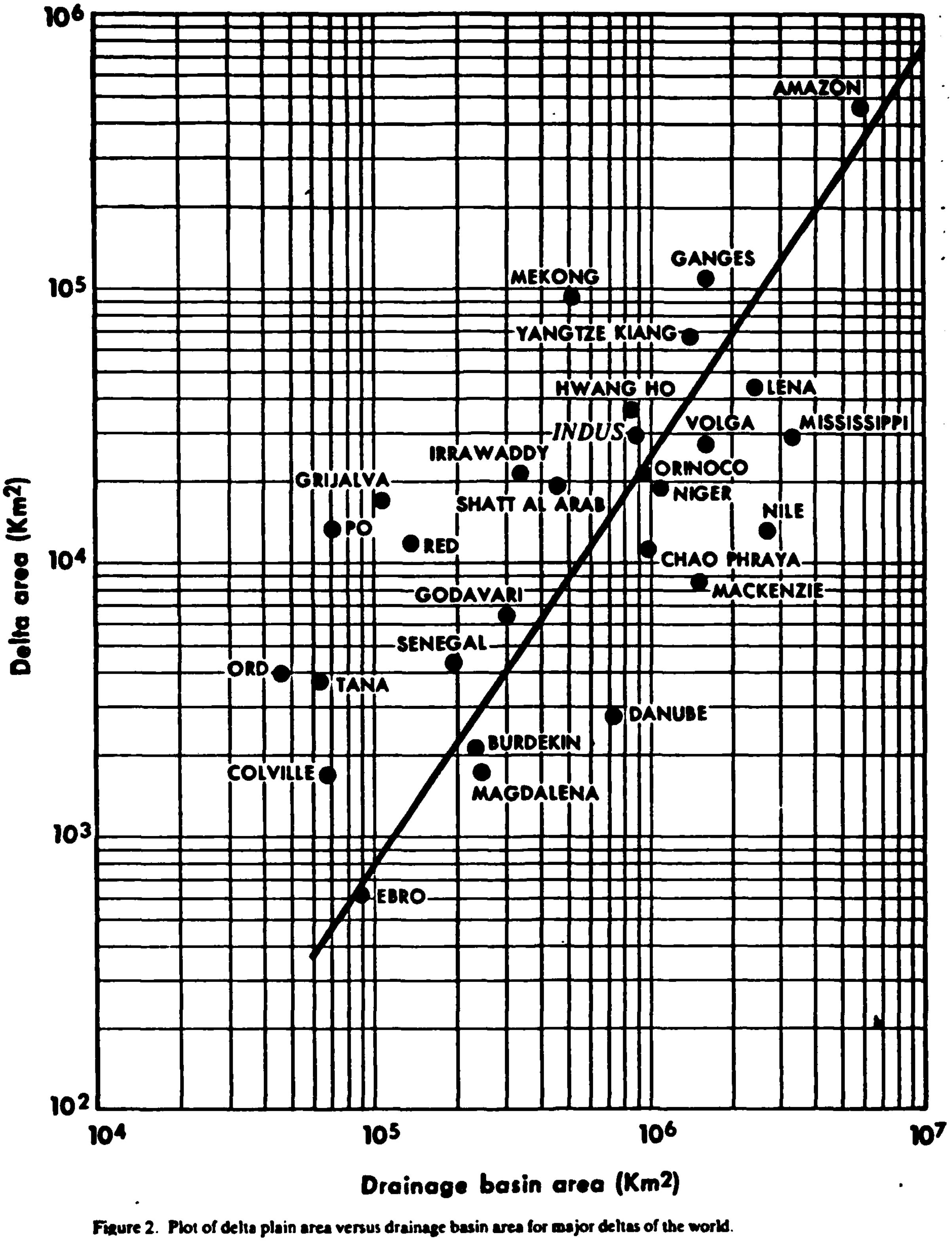

Figure 2. Plot of delta plain area versus drainage basin area for major deltas of the world.

points for a new diversion and future progradation (Holmes, 1968).

Figure 1 shows the subdivision of the Indus Delta into an active and abandoned deltaic plain. Once the river ceases to deliver sediments as a result of artificial levees or natural diversions, this area of the delta becomes an abandoned deltaic plain. The lower deltaic plain is delineated by the

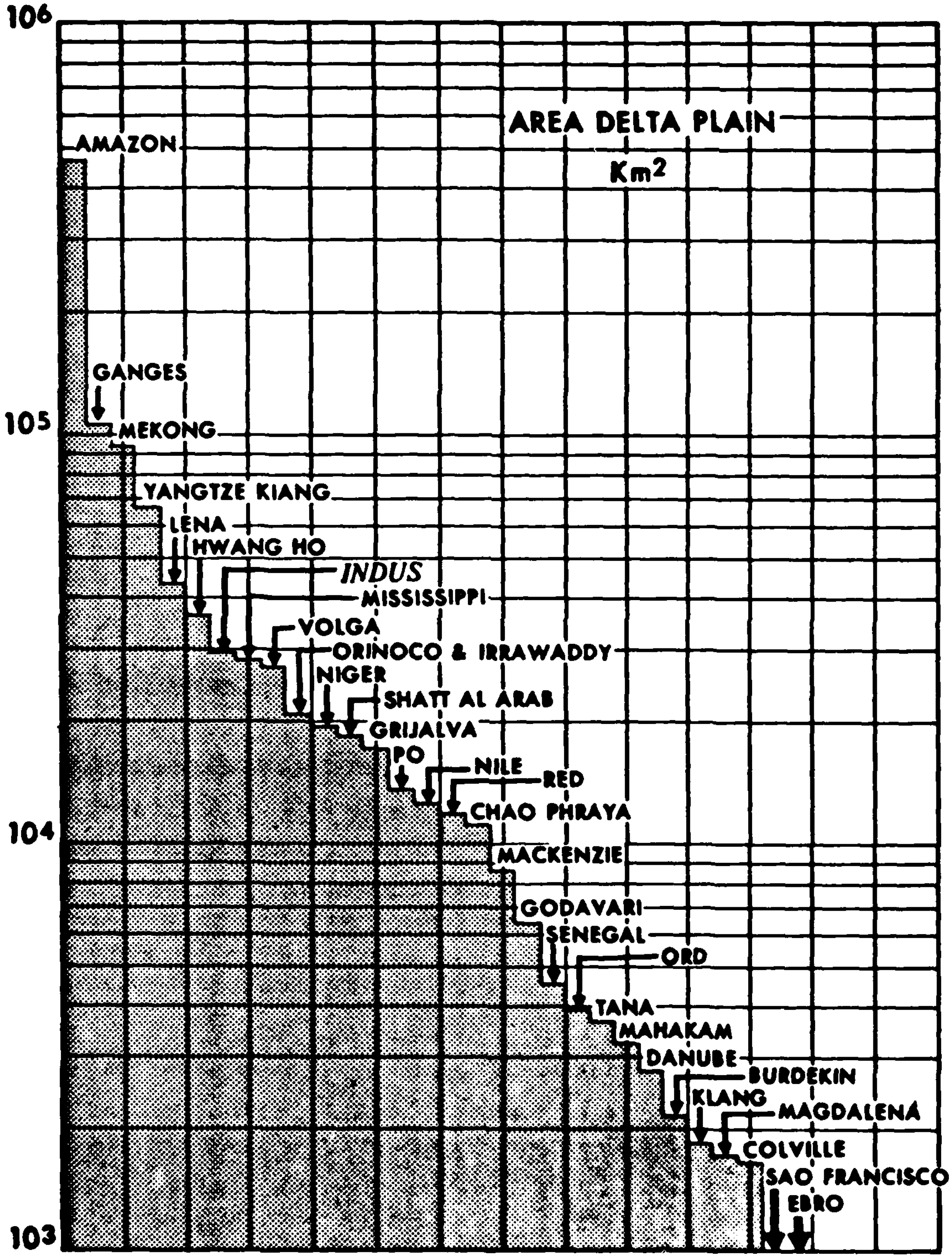

Figure 3. Bar graph of delta plain area for major deltas of the world.

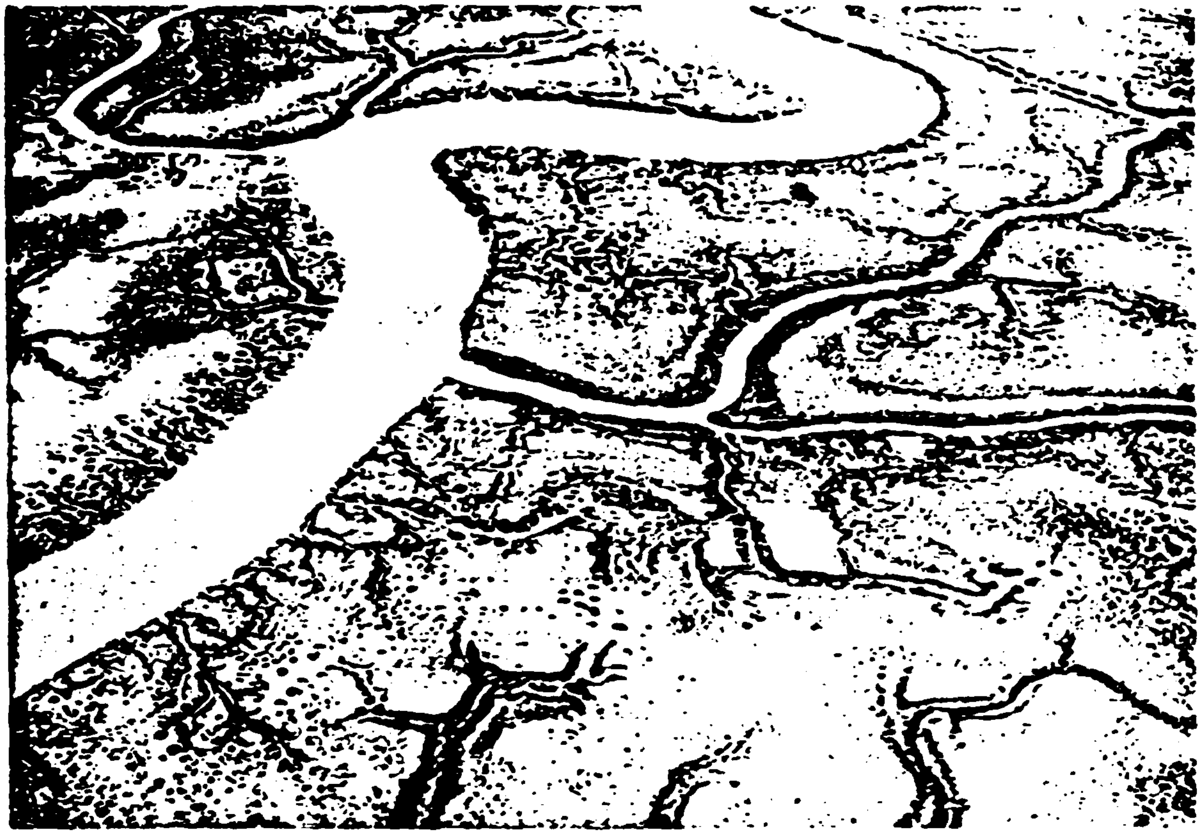

Figure 4. Mangrove-Lined tidal creeks on the lower delta plain of the Indus River.

landward boundary of saltwater intrusion, a boundary that usually does not follow that of the active/abandoned delta plain boundary. In the case of the Indus Delta, substantial storm tides from southwest monsoon winds in summer inundate vast areas of both the active and the abandoned deltaic plains with salt water. This area of lower deltaic plain is characterized by tidal creeks and small overbank splays that are lined with stunted mangroves on a sand/silt substrate (Fig. 4).

An erratic discharge, such as that of the Indus River, is characterized by a predominance of coarse sediments since little opportunity exists in these regimes for sorting of sediments prior to reaching the delta. Although average discharge of the Indus River is nearly an order of magnitude less than that of the Mississippi River (Fig. 5), it is highly erratic, with summer discharge occasionally reaching 30,000 m³/sec, nearly twice the average value for the Mississippi. Sediment discharge is usually reported to be 435-480 x 10^6 short tons (395-435 metric tons) per year (Holeman, 1968),

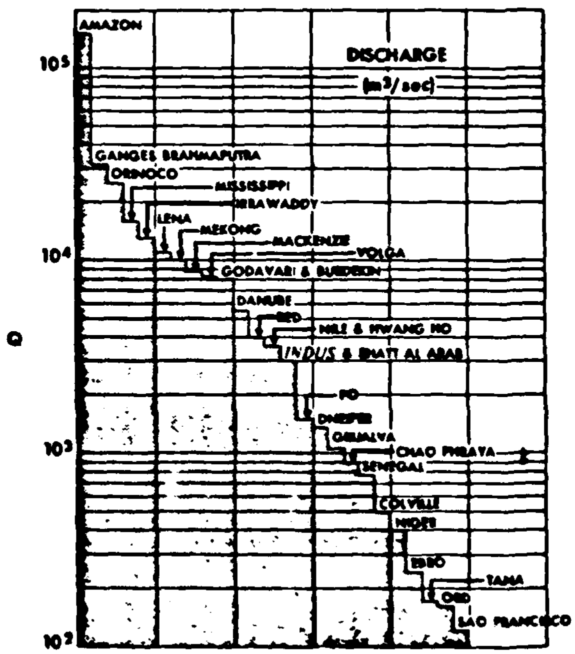

Figure 5. Bar graph of river discharge for major deltas of the world.

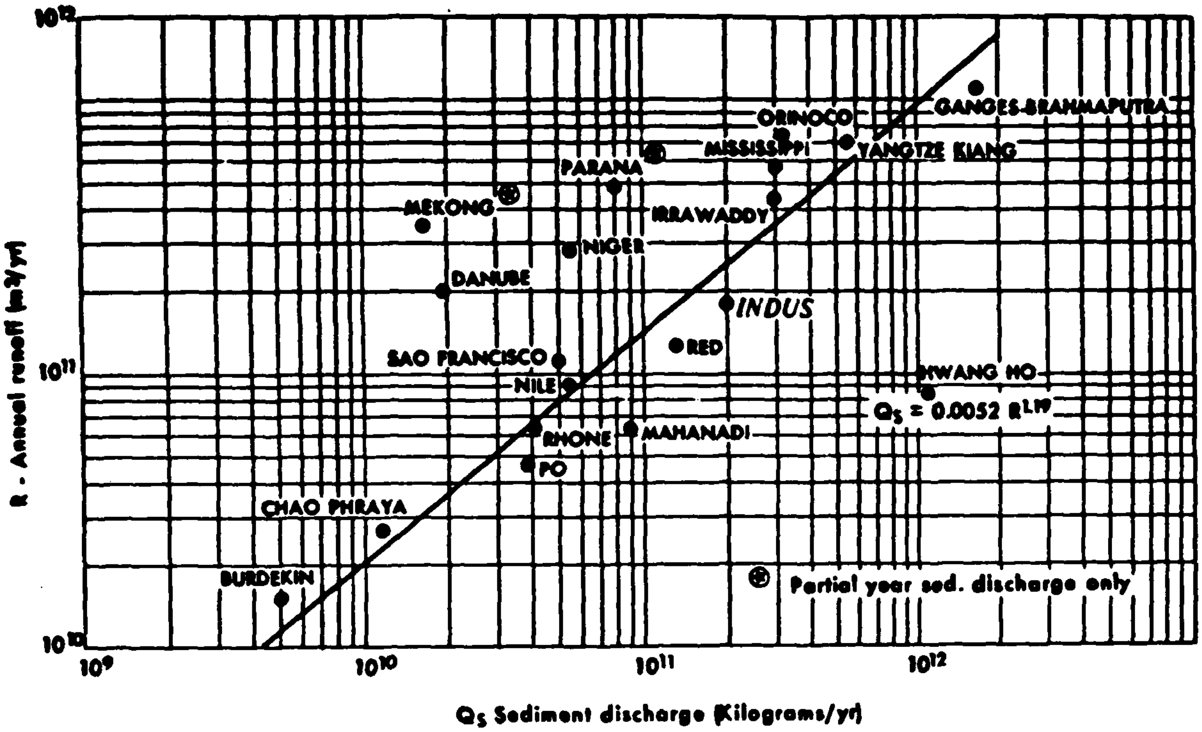

Figure 6. Plot of annual runoff versus sediment discharge for major rivers of the world.

with suspended sediment peaks during August that reach an incredible 3000 mg/l (Holmes, 1968). Of particular importance is that, as of the 1960s, sediment discharge of the Indus River was ranked (by most estimates) to be fifth or sixth highest in the world.

Figure 6 shows the relationship between annual river runoff and sediment discharge. Of the 19 data points plotted in Figure 6, nine rivers show greater runoff than the Indus, but only five have greater sediment discharge. This is largely attributable to the erodible sediments of an arid climate and to the fact that the Indus River normally experiences net evaporation over precipitation. Also, it is likely that wind-blown sands from the adjacent desert act as an additional sediment source during northeast monsoon winds

Despite the numerous changes in river course over the last 5,000 years, the Indus Delta has maintained a relatively straight shoreline. The major indentations are now formed by tidal channels, small bays, and, to the east, a large waterway known as Kori Creek (Fig. 7). One measure of crenulation and thus of subaerial complexity of the lower delta plain is the ratio between shoreline length and delta width. With a ratio of less than two "shoreline kilometers" for each one kilometer of straight coastline, the Indus Delta stands in contrast to highly crenulated deltas such as the Ganges or Mississippi (Fig. 8). Whereas high rates of subsidence (Mississippi Delta) tend to produce a highly crenulated shoreline because of the loss of a coherent delta front, high wave energy tends to produce a straight shoreline because of the strong longshore transport, which spreads sands parallel to depositional strike.

Most deltas extend seaward, well beyond the shoreline, as a platform of sediments that have been deposited subaqueously. As the delta progrades offshore, coarse particles are often deposited over a blanket of delta-front silts and clays laid down under deeper water conditions. Continued progradation produces a coarsening-upward sequence of sediments as shelf-depth waters eventually become subaerial land.

The Indus River has produced a delta that today is largely subaerial (Fig. 9). Similar to the Nile River delta, the ratio of subaerial to subaqueous delta area is nearly 10:1. A relatively coarse sediment load deposited in shallow water has been largely responsible for rapid

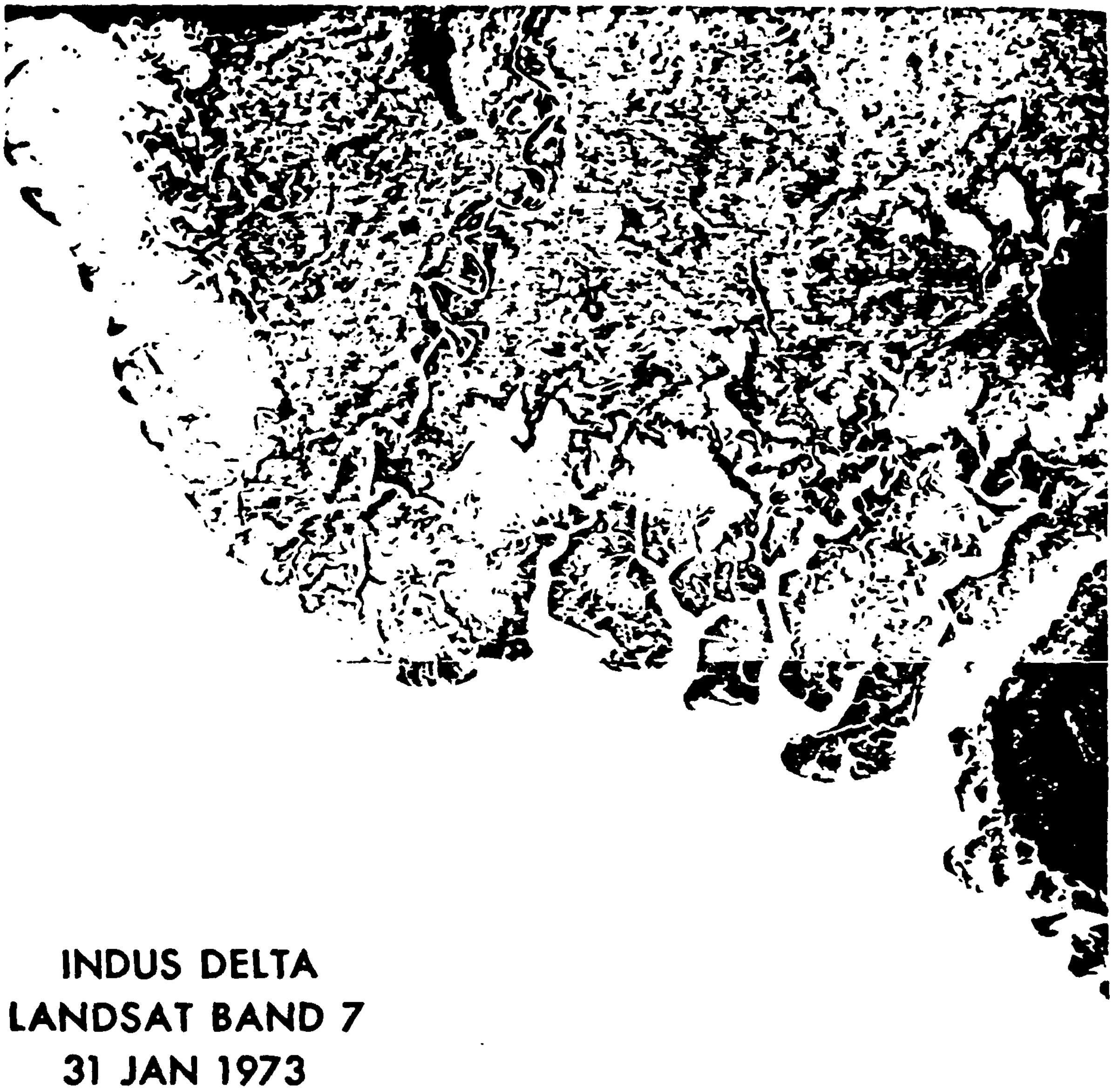

Figure 7. LANDSAT band 7 image of Indus Delta (see Fig. 1 for location).

advancement of the subaerial delta. Although the shelf widens near Karachi to 100-160 km and has a shelf break at 130 m (Closs et al., 1974), the Indus submarine canyon restricts subaqueous delta development by funneling sediment hundreds of kilometers offshore to the Indus cone (Nair et al., 1982).

Tides have been of at least moderate importance in developing the morphology and sedimentology of the Indus Delta. With a tidal excursion of 2.6 m, the Indus Delta can be included in the 2-3-m mesotide-range category that characterizes many Asian deltas, e.g., the Irrawaddy, Mekong, Shatt-al-Arab, and Chao Phraya (Fig. 10). The role of tides in the Indus Delta has been to produce 1) limited flooding and the formation of evaporites, 2) substantial mixing of riverine and seawater, 3) bell-shaped river mouths and intricate tidal creeks, and 4) bidirectional sediment transport patterns.

Flooded soils and saltwater intrusion have been long-standing problems in the lower Indus

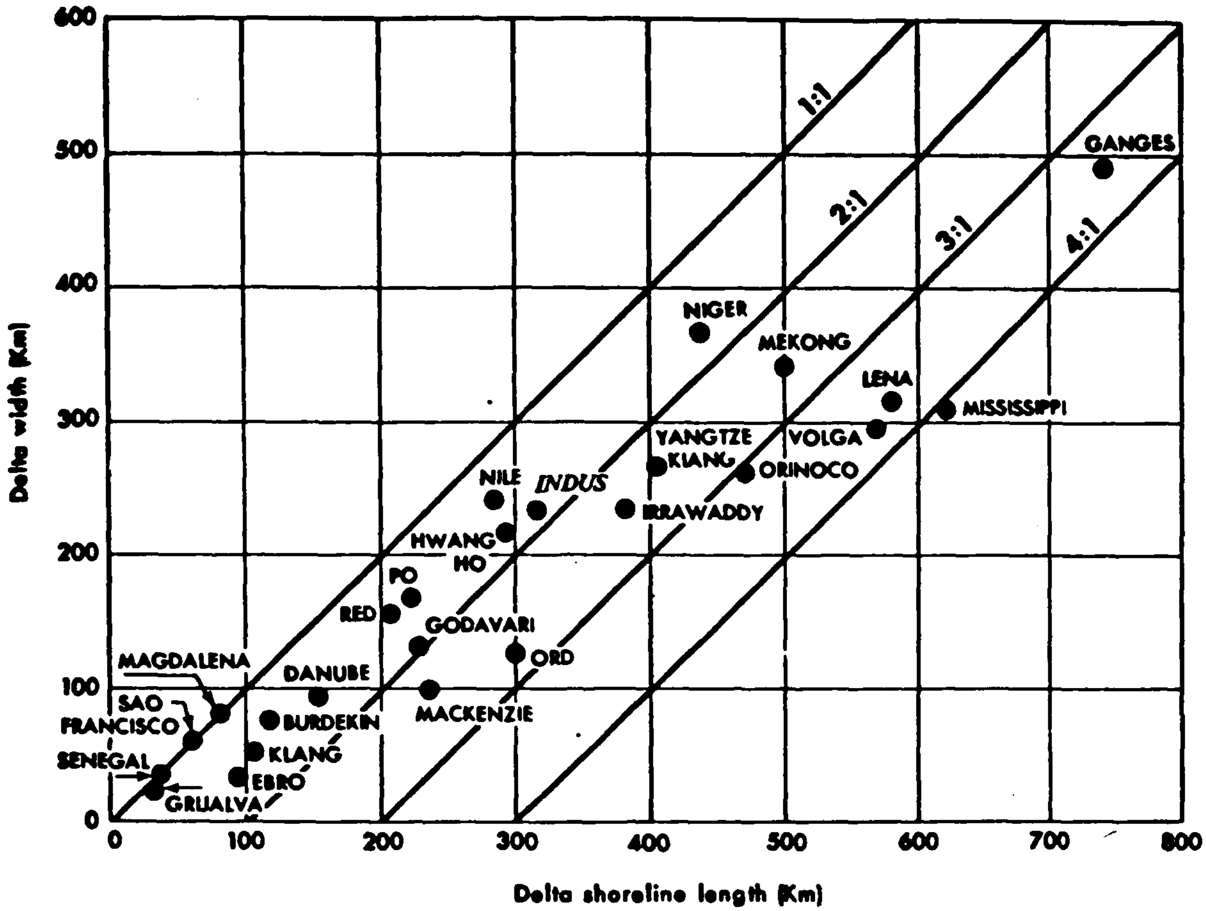

Figure 8. Plot of delta width (straight line distance between lateral extremes) versus shoreline length (digitized) for major deltas of the world.

Delta. Although the area of the lower delta plain (and hence the area of saltwater intrusion) is extensive (Fig. 1), much of this land, such as the Ranns of Kutch, receives its saltwater flooding from sea level elevation associated with the southwest monsoon winds in summer. Likewise, the formation of evaporite deposits is most pronounced in areas subject to the rhythm of annual rather than daily flooding. The degree to which density stratification is affected by tide is unknown. What is known is that tides extend the zone of marine and riverine interactions both vertically and horizontally. With a shelf gradient on the order of 0.1 degree, tides of 2.6 m range would provide an intertidal zone 1,500 m wide. Morphologically, there appears to be a slight tendency toward the formation of bell-shaped river mouths (Fig. 7) that are so common in macrotide-range deltas such as the Ord River delta, and a strong tendency for the development of intricate tidal creeks (Fig. 4) such as those of the Ganges River delta. Finally, tides are most important sedimentologically in producing reversals in current direction, thus leading to the bidirectional transport of sediment.

Waves have been the single most important process variable in shaping the Indus Delta. Figure 11 shows that, at a water depth of 10 m, the Indus Delta receives the highest average wave energy of any major delta in the world. Intense monsoonal winds arriving from the southwest during May through September are responsible for annual maxima in wave energy that produce such an abnormally high average energy level. Nearshore wave energy, however, shows only weak correlation with offshore wave energy. At the shoreline, for example, the Indus Delta assumes a wave energy ranking of fourth highest, an order of magnitude less than the Senegal and Magdalena deltas (Fig. 12). Nearly three orders of magnitude

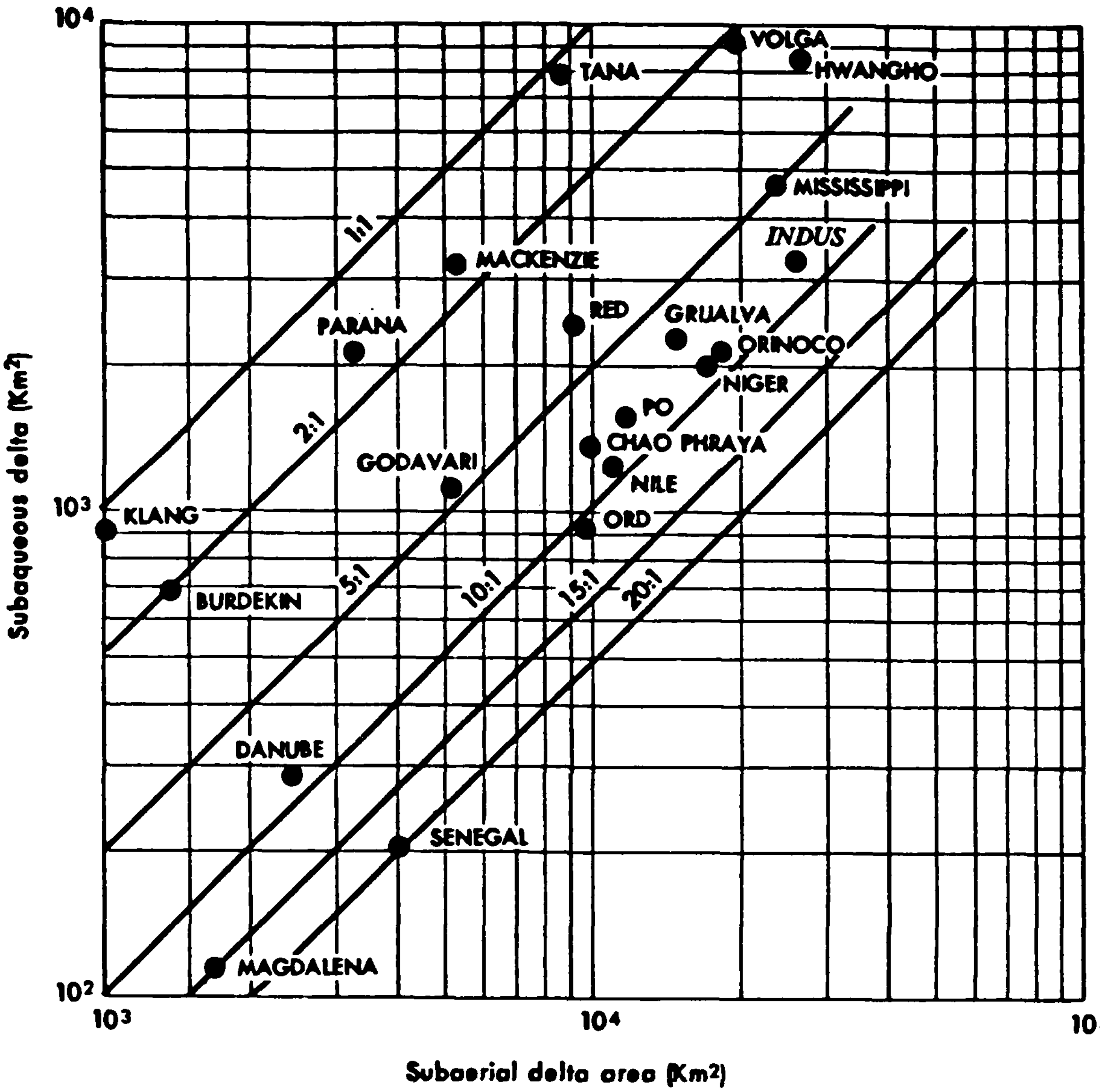

Figure 9. Plot of subaqueous delta area (below mean sea level) versus subaerial delta area (above mean sea level) for major deltas of the world.

greater than the Shatt-al-Arab Delta at the lower end of the scale, the Indus Delta receives more wave energy at the shoreline in a single day than the Mississippi Delta receives in a full year. The change in relative position of the Indus Delta (Fig. 11, 12) is a function of offshore slope, since the amount of wave energy at the shoreline depends mainly on the subaqueous profile; the flatter the slope, the greater the attenuation of deepwater wave energy. Figure 13 shows this relationship in a plot of offshore slope versus wave power at the delta shoreline.

The major effect of incoming wave energy is to sort and redistribute sediments. Waves induce strong longshore currents, straighten shorelines, and produce interdistributary beaches and beach-ridge complexes. In general, an increase in nearshore wave energy (relative to discharge) leads to a shoreline with gentle arcuate protrusions and a uniformly advancing delta front. However, as pointed out by Wright (1978), nearshore wave climate alone is insufficient to explain the degree to which delta morphology is wave dominated. Thus the Indus Delta, even with extreme levels of

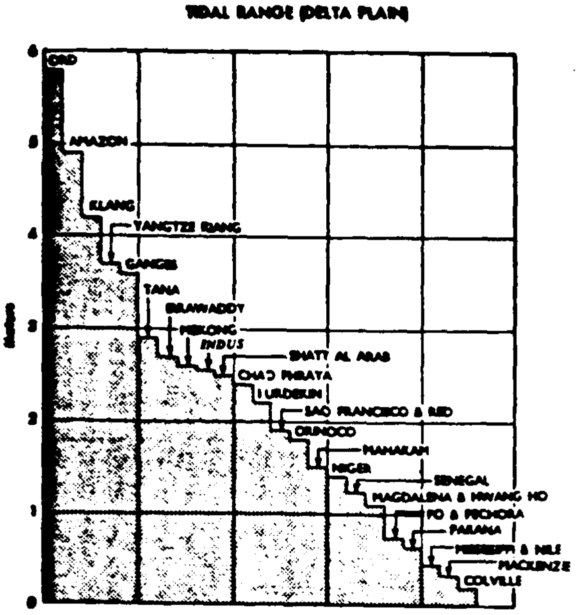

Figure 10. Bar graph of the tide range for major deltas of the world.

wave energy, differs substantially from true wave-dominated deltas such as the Sao Francisco. High discharge from the Indus River has been able to provide sediments to the receiving basin at a rate sufficient to keep pace with the sediment-reworking ability of waves. This is reflected morphologically by the lack of extensive beach and beach ridge deposits and the presence of a broad, arcuate, and moderately indented shoreline.

Dispersal of Sediments

Terrigenous input from the Indus River dominates sediments in the northern Arabian Sea. Sediments are characterized by coarse size, low $CaCO_3$ content, and an abundance of quartz and feldspar. Except for the outer shelf, which has a band of calcium-carbonate-rich sediment, most of the shelf off eastern Pakistan has uniform carbonate content, ranging from 14% to 19% (Stewart et al., 1965). High concentrations of illite and chlorite are common in the clay fraction; toward India, montmorillonite increases, but kaolinite remains virtually absent in northern Arabian Sea sediments (Stewart et al., 1965). The Persian Gulf and Red Sea are not considered to be important sources of sediment to the Indus shelf, but significant contributions may be derived from the dustbearing winds blowing off Africa in summer and northern India in winter. Beyond the shelf, the median size of sediment decreases to that of silts and clays on the slope, rise, and adjacent sea floor (Kolla et al., 1981).

Sediments discharged by the Indus River into the northern Arabian Sea may be transported farther offshore, accumulate on the continental shelf offshore of the delta, or may be transported by longshore currents to the southeast. Much of the coarse sediment is carried directly offshore to the Indus Fan by way of the Indus submarine canyon (Islam, 1959). The head of the canyon, referred to as The Swatch, is remarkably well aligned with the Kahr distributary of the Indus River and lies only 6.5 km offshore in 35 m of water. As a funnel-shaped feature more than 15 km wide at its head, the canyon provides a direct conduit for offshore transport of sediments. That much of the sediment from the Indus River has followed this route to deeper water is shown by the extent of the Indus Fan, the largest physiographic feature in the Arabian Sea. The Murray Ridge, to the west of the Indus Fan, serves as a sediment dam, thus preventing deposition of Indus River material in the Gulf of Oman.

The size and shape of the Indus Fan suggest that turbidity currents have been important in its formation (Heezen and Laughton, 1963). Transport of Indus River sediments as far as 1500 km into the pelagic regions of the Arabian Sea has resulted in the accumulation of unconsolidated sediments within the Indus Fan (Ewing et al., 1969). Tongues of exceptionally high bottom-water turbidities 1000-1500 km offshore, together with low $CaCO_3$ bands in the easternmost fan (Kolla et al., 1981), support the concept of deep turbid-layer flows. Despite the massive accumulation of terrigenous sediments in the distal fan, the regional increase in $CaCO_3$ at the shelf edge suggests a sedimentary contribution by the Indus River that is highly restricted on some parts of the outer shelf (Nair et al., 1982).

Coarse sediments that are discharged to the northwest or southeast of the Indus canyon will continue to accumulate in the delta or on the inner continental shelf. The protrusion of the Indus Delta and the wide shelf southeast of Karachi are certainly the result of extensive terrigenous sedimentation during the Holocene. Although the percentage of sediment load retained in the delta and inner shelf environments is unknown, seasonal events appear to be quite important in retention of sands because of the in-phase relationship between flood stage discharge and

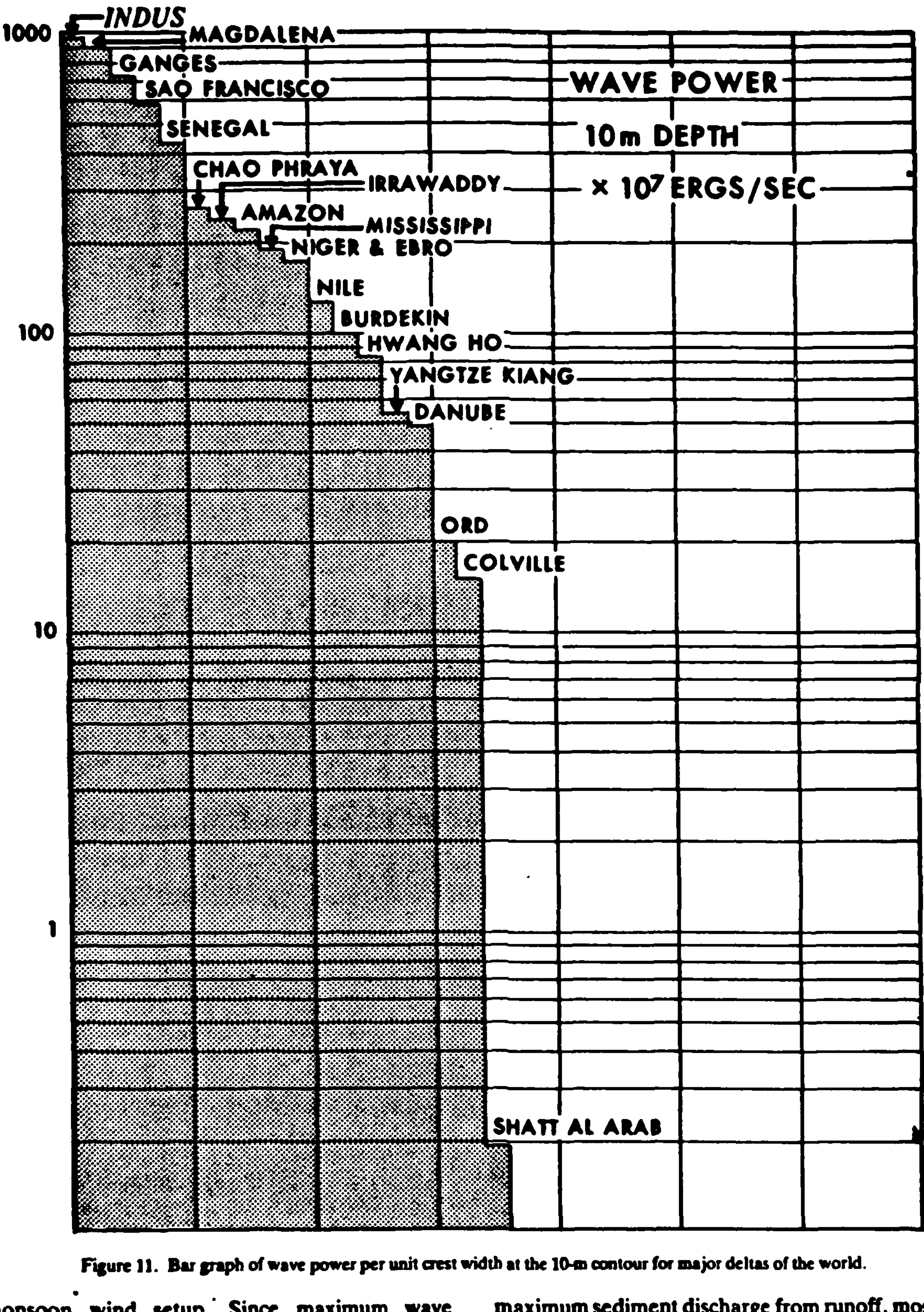

Figure 11. Bar graph of wave power per unit crest width at the 10-m contour for major deltas of the world.

monsoon wind setup. Since maximum wave energy from the receiving basin coincides with maximum sediment discharge from runoff, most of the sediments introduced to the shelf are

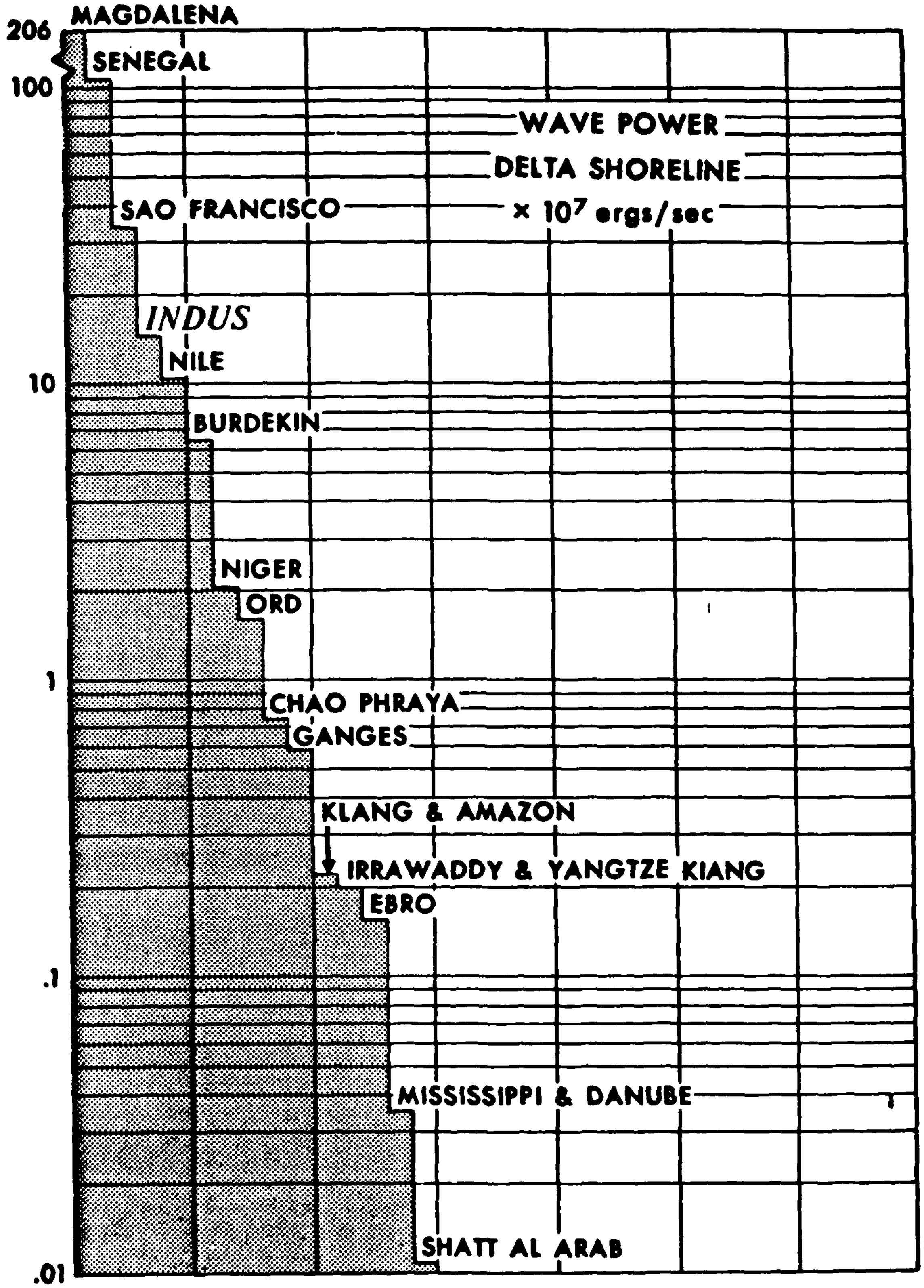

Figure 12. Bar graph of wave power per unit crest width at the delta shoreline for major deltas of the world.

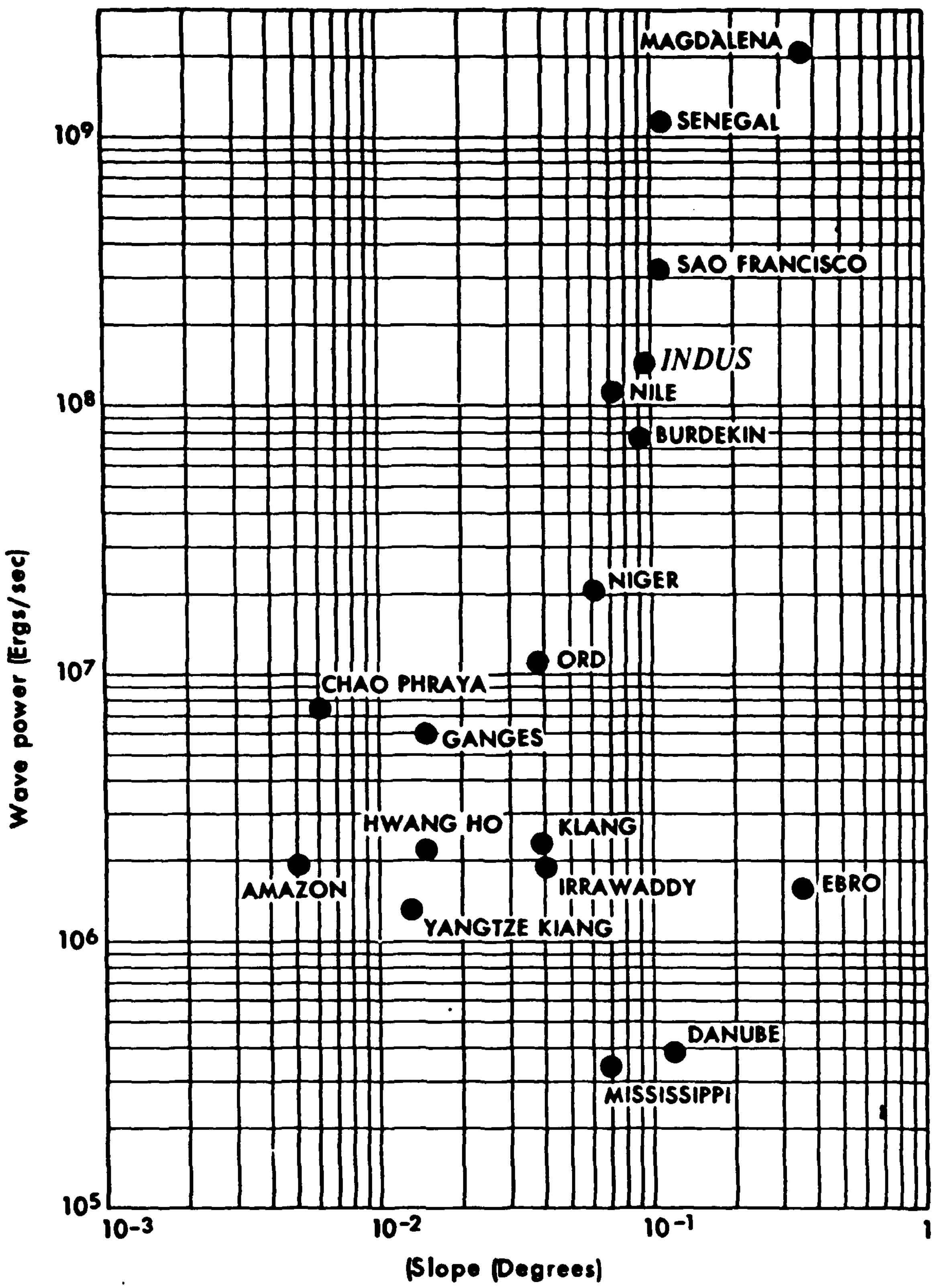

Figure 13. Plot of wave power at the shoreline versus offshore slope for major deltas of the world.

Figure 14. Wind-blown sands along the western margin of the Indus Delta.

immediately reworked and dispersed. Even more important, however, is the fact that the monsoon winds force surges of waters into the lower delta, effectively moving the receiving basin 20-30 km inland, thus promoting retention of sand within the subaerial delta.

Dispersal of sands by longshore currents appears to be relatively minor. As pointed out previously, extensive beach ridges, spits, and other downdrift sand deposits do not have a widespread occurrence. On the other hand, development of extensive mudflats on the north shore of the Gulf of Kutch and within the Ranns of Kutch indicate that transport to the southeast of silts and clays is significant (Glennie and Evans, 1976). The salt-covered deserts of the Ranns of Kutch and the broad Gulf of Kutch embayment receive their fine-grained sediments from storm-tide floods of the southwest monsoon after sediments are transported southeast by wave-and wind-induced longshore currents. Nair et al. (1982) have shown that surface tidal currents of 1.5 - 2.5 knots at the mouth of the Gulf of Kutch serve as a barrier to the transport of sands as bedload and coarse mica as suspended load, thereby restricting accumulation of nearly all delta-derived sediment to the northwest areas of the India-Pakistan shelf.

Future of the Indus Delta

The future of the Indus Delta is uncertain. Extensive irrigation works during the 20th century have diverted much of the water and sediment away from their natural receiving basin. According to Milliman and Meade (1983), discharge from the Indus River is now only 100 x 10^6 metric tons/year, a value that reflects a fourfold decrease from previous estimates of discharge. Continued upstream diversions may, in fact, decrease discharge to nearly zero by the turn of the century (S.C. Snedaker, personal communication).

The immediate effect will be an attempt by waves to rework and straighten the shoreline of the existing delta front. As this happens, the "discharge effectiveness' will decrease, i.e., the ratio of discharge per unit width of river mouth to the nearshore wave power per unit width of wave crest (Wright, 1978) will fall from its present value of 1.1×10^{-2}, ultimately reaching a value on the order of 10^{-6} to 10^{-8}. The Indus Delta will then rapidly begin taking on the morphology of a wave-dominated delta.

The loss of discharge is critical for two reasons. First, the Indus Delta, throughout historic times, appears to have retained more sediment for subaerial land-building processes than has been transported by littoral processes. That is, the delta has been able to prograde under conditions of extreme wave energy only because of the high sediment discharge that was deposited rapidly and retained by the delta because of its coarse size. Second, the loss of discharge will cause the delta to become a transgressive sand body, dominated by wind-blown sand deposits. The most likely scenario for the next 25-50 years will be 1) cessation of subaqueous and subaerial delta-front progradation, 2) initial transgression of delta-front sands, 3) increase in wind-blown sands as a result of the loss of vegetation, and 4) establishment of a transgressive beach, dominated by eolian dunes. Figure 14 illustrates that early establishment of eolian sands on the western margin of the Indus Delta near Karachi has already begun.

Similar patterns of deterioration have been observed in other arid deltas subject to loss of discharge and vegetation through activities of man. Perhaps the two best examples are the Nile Delta in Egypt (Academy of Scientific Research and Technology, U.A.R., 1976, 1977; Coleman et al., 1981) and the Tana Delta in Kenya (United Nations Food and Agricultural Organization, 1967), both in advanced stages of deterioration. In the case of the often cited Mississippi Delta, presently experiencing one of the highest rates of land loss of any delta in the world, subsidence, lower overall discharge, and less sand in the sediment load are primarily responsible (Wells et al., 1983). To accurately predict the future of any delta, but particularly a delta such as the Indus, which is undergoing drastic reductions in discharge, will require a better establishment of the sediment budget, littoral processes, and patterns of sediment dispersal.

ACKNOWLEDGMENTS

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The patterns of sedimentation and morphologic development of a delta result primarily from the interaction of fluvial and marine processes. Historically, the Indus River delta has formed in an arid climate under conditions of high river discharge (400×10^6 metric tons of sediment/year), moderate tide range (2.6m), extremely high wave energy (14×10^7 ergs/sec) and strong monsoon winds from the southwest in summer and from the northeast in the winter. The resulting sandy, lobate delta, lacking in luxuriant vegetation and dissected by numerous tidal channels, has prograded seaward during the last 5000 years at an average rate of perhaps 30m/year. Morphology of the Indus Delta lies midway between that of a fluvially dominated delta (elongate, protruding distributaries) and a high energy wave dominated delta (beach beachridge, and downdrift deposits).

Whereas sands provide a substrate for the subaerial delta, silts and clays provide material for fill in abandoned channels, delta front outer shelf deposits, and downdrift sedimentation to the east. Coarse sediments from the Indus River generally remain on the

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22b TELEPHONE (Include Area Code): (504) 388-2396

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