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Source: Journal of Coastal Research, 36(sp1) : 694-707

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.694

Journal of Coastal Research	SI 36	694-707	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Global Distribution and Morphology of Deltaic Barrier Island Systems

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ABSTRACT

There are approximately 400 barrier islands on the world's deltaic plains, with a combined length of 4,100 kilometers. They make up 30% of the world's estimated barrier islands (by length). Deltaic barrier islands make up more than half of barrier islands in South America, Asia, and Africa, but only 5% in North America and Europe due to differing sea level rise history. Barrier islands are present on all types of deltas, including wave, tide, and river dominated deltas. The transgressive model of barrier island formation on the Mississippi Delta is well understood, but applies to relatively few deltaic barrier island chains. Spit formation, and to a lesser extent beach ridge accretion, on active lobes appear to be the most dominant processes of barrier island formation. A simple morphologic classification based on island length and inlet width is presented. Five island types (Nile, Mangoky, Niger, Gurupi, Mekong, and Mississippi) are described, relating island, inlet, and shoreface morphology to the relative roles of wave, tide, and fluvial processes. Human alterations to the sediment supply, extraction of hydrocarbons, and the projected near future acceleration of sea level rise poses a significant threat to many deltaic barrier island systems, many of which already display geoindicators of disintegration.

ADDITIONALINDEXWORDS: *tidal inlets, shoreface, wave energy, tidal amplitude, discharge*

INTRODUCTION

Barrier islands occupy an estimated 15,000 kilometers, or 7% of the world's open ocean shoreline (STUTZ and PILKEY, 2001). They have been observed on all continents except Antarctica, on both tectonically active and passive margins (GLAESER, 1978). Barrier island morphology is highly diverse, in response to the local wave and tidal regime (HAYES, 1979) and the regional geologic framework (DAVIS, 1994; RIGGS *et al*., 1995; FITZGERALD and VAN HETEREN, 1999).

About one-third of all barrier islands are located on deltas (STUTZ and PILKEY, 2001). Despite their abundance they have received less geologic study than coastal plain barrier islands in the U.S. and Europe. The most widely studied deltaic barrier islands are those on the Mississippi Delta (PENLAND *et al*., 1985) but their mode of formation and evolution is unique, which underscores the need to study other deltaic barrier systems more closely.

The same essential requirements for barrier island formation along coastal plains are also required for their formation on deltas. These are adequate sediment supply, low slope, and sufficient wave energy. Many deltas do not have barrier islands because these criteria are not all satisfied. The Ganges Delta has an extremely flat offshore slope due to the wide shelf and enormous sediment load, which substantially reduces wave energy necessary for island formation. However, a half dozen barrier islands are found just landward of the Swatch of No Ground, the steep submarine canyon of the Ganges that extends close to the shoreline and enhances wave energy enough for islands to form. Few Arctic deltas have barrier islands due to the reduction of wave energy by sea ice. The Doce and Sao Francisco Deltas in Brazil have wide mainland beach ridge plains but no barrier islands, which is typical of small rivers with low discharge. The Fly (Papua New Guinea) and Ord (Australia) Deltas have an extremely large tidal range that is unfavorable for barrier island formation. Most deltaic barrier islands have a spring tidal range between 1 and 4 meters, moderate to high wave energy, and a relatively narrow shelf.

For the purpose of this study, barrier islands were located and identified with topographic maps, nautical charts, aerial and space photographs, and satellite images. The definition of OERTEL (1985) was followed in identifying barrier islands. This requires five morphodynamic elements: barrier island, lagoon, inlets and tidal deltas, mainland, and shoreface. The morphologic elements were measured from maps and charts that span a large range of dates, scales, contour intervals, and data classes. The specific morphologic elements obtained from the maps are listed in Table 1.

The mainland, or delta plain width, was defined as the distance to the 100 meter contour. The width and slope was determined by averaging transects measured every 2 kilometers alongshore. Barrier island width, lagoon width, shoreface width, and shoreface slope were also measured at 2 kilometer intervals and averaged for each island.

The shoreface depth was simplistically defined as 10 meters, because that is a common depth marked on most maps and charts. Although the actual shoreface depth is highly variable it is often impossible to define with the available data and methods. The width and slope of the shoreface were measured at two – kilometer intervals alongshore and averaged for each island.

Additional data on the tidal range, wave energy, discharge, and sediment load were collected from existing sources to compare with morphologic parameters. We obtained spring tidal range estimates from the National Ocean Service (1999), maximum wave height estimates from the Land-Ocean Interactions in the Coastal Zone (LOICZ) coastal typology dataset, and river discharge and sediment load estimates from MILLIMAN and SYVISTSKI (1992). Discharge estimates exist for about three-fourths of the deltas included in this study, and sediment load estimates for about half.

Average values for the island parameters were calculated separately for each delta and are listed in Table 2. We also calculated a global average for each parameter that includes all islands. However, morphological differences between adjacent islands often do not reflect a significant change in processes, subjecting correlations to a lot of noise.

Deltas were then grouped into high, moderate and low categories of wave energy, tidal range, and discharge (Table 3). The morphologic parameters (e.g., island length, island width, inlet width, slope) were averaged within each group.

DATA

Barrier Island Distribution

Delta-associated barrier islands are found in all climates and on all continents except Antarctica. We identified 40 deltas, having 388 islands and totaling about 4,100 kilometers in length (Table 2). They comprise almost one-third of the world's barrier islands. Several of the longest continuous chains of barrier islands are located on deltas, particularly the Niger Delta.

There is a marked geographic segregation of deltaic and coastal plain barrier islands, coupled with a dramatic difference in the total number of islands. Deltaic islands are usually found along coasts with a low abundance of barrier islands, while coastal plain islands are typical on coasts with a high abundance. Over half of all islands are along the North Atlantic and Arctic coasts of Europe, Asia and North America, but deltaic islands comprise only 5% of these. In contrast, only 15% of all barrier islands are in the entire southern hemisphere, but over half of these are deltaic islands (STUTZ and PILKEY, 2001). Deltaic islands are also dominant in the Mediterranean, southern and southeast Asia, and northern Africa.

While there seems to be no definitive explanation for the differentiated pattern of occurrence, the coasts dominated by deltaic barrier islands generally have a different sea level history than coasts with abundant coastal plain islands. Sea level curves for Brazil, South Africa, Mozambique, and Australia show a higher than present mid-Holocene sea level (PIRAZOLLI, 1991) while North Atlantic coasts have continued submerging. Relative sea level fall reduces the lagoonal tidal prism and decreases the efficiency of tidal inlets , favoring mainland and baymouth barrier formation over barrier islands, and also favoring the development of deltas. These continental margins also tend to have a narrower continental shelf (GLAESER, 1978), greater mainland relief (INMAN and NORDSTROM, 1971), and larger sediment yield (MILLIMAN and MEADE, 1983) than those with large, well-developed estuaries.

Morphology

Island length and width

The average island length on the 40 deltas ranged from 2 to 65 kilometers. The average length for half of all deltas falls between 6 and 12 kilometers. Five deltas have an average island length of greater than 20 kilometers (Magdalena, Ogooue, Nile, Senegal, and Danube), while three deltas have an average island length of less than 3 kilometers (Po, Nakdong, and Olenek). The deltas with the greatest average length have a steep shoreface slope, narrow

Table 1. Geomorphologic characteristics of barrier islands

Delta Plain	Island	Inlets	Shoreface	Lagoon
Width (km) Slope (m/km)	Length (km) Width (km)	Width (km)	Width (km) Slope (m/km)	Width (km) Vegetation

Table 2. Deltaic island morphology.

Delta	Location	Islands	Total Delta Length (km)	Avg. Island Length (km)	Avg. Island Width (km)	Avg. Inlet Width (km)	Avg. Shoreface Slope (m/km)	Wave (m) *	Tide (m)**	Discharge (km3/yr)•••	Load (106t/yr)***	Yield (t/km2/yr)***
Copper	Alaska	8	93.0	9.8	1.5	1.8	No data	>5.0	3.0	32	70	1200
San Juan	Colombia	6	61.6	8.4	0.5	1.9	2.5	2.5-3.5	3.8			1000
Patia	Colombia	14	126.9	7.3	0.9	1.8	4.4	2.5-3.5	3.4			1000
Mira	Colombia	8	39.3	4.4	0.5	0.5	13.1	2.5-3.5	3.1			1000
Caravelas	Brazil	4	30.5	6.7	0.6	0.9	1.7	2.5-3.5	2.0			50
Jequitinhona	Brazil	6	66.2	10.1	0.6	0.9	3.4	3.5-5.0	2.3	13		50
Acu	Brazil	6	61.3	9.0	0.5	1.3	1.1	2.5-3.5	2.3			50
Parnaiba	Brazil	4	64.9	13.4	0.8	2.8	2.2	2.5-3.5	2.9	32		50
Gurupi	Brazil	50	571.7	6.4	0.3	5.1	1.2	2.5-3.5	4.8			10
Magdalena	Colombia	1	67.7	66.5	0.7	1.2	5.3	3.5-5.0	0.4	240	220	920
Mississippi	Louisiana	28	216.7	6.1	0.4	1.7	2.5	2.5-3.5	0.4	0	0	120
Ebro	Spain	2	32.3	13.1	1.3	3.1	6.5	2.5-3.5	No data	17	2	210
Rhone	France	4	54.6	13.4	0.3	0.2	7.6	2.5-3.5	0.2	54	56	340
Po	Italy	26	74.9	2.3	0.2	0.6	4.0	2.5-3.5	0.7	46	18	280
Danube	Romania	2	47.5	21.6	0.3	2.2	3.4	0-2.5	No data	200	40	83
Nile	Egypt	11	255.6	22.9	1.0	0.4	6.7	2.5-3.5	0.4	90	120	40
Senegal	Senegal	2	45.1	21.7	0.4	0.9	15.5	2.5-3.5	1.3	22	21	8
Saloum	Senegal	5	45.6	14.0	0.8	2.3	No data	2.5-3.5	1.1			50
Casamance	Senegal	4	42.9	10.2	0.5	0.6	No data	2.5-3.5	1.3			50
Niger	Nigeria	21	436.8	16.9	3.3	2.2	1.0	3.5-5.0	1.9	200	40	33
Ogooue	Gabon	3	139.7	44.0	3.3	1.1	2.7	2.5-3.5	1.6	150		50
Save	Mozambique	15	137.8	6.6	0.3	2.6	No data	0-2.5	3.7	5		100
Zambezi	Mozambique	11	107.9	7.1	0.4	2.7	1.7	0-2.5	3.4	100	20	35
Meluli	Mozambique	4	44.6	8.1	0.7	3.1	4.3	0-2.5	3.6	2		100
Mangoky	Madagascar	18	70.2	3.1	0.5	0.8	No data	2.5-3.5	3.4	15	10	1000
Tsiribihina	Madagascar	11	49.2	3.4	0.5	1.1	No data	2.5-3.5	3.7	31		1600
Manambalo	Madagascar	7	46.1	4.7	0.5	0.6	1.7	2.5-3.5	3.7			1000
Indus	Pakistan	22	122.4	6.3	1.0	1.3	1.3	3.5-5.0	2.5	240	100	260
Godavari	India	9	163.4	17.5	0.9	0.7	2.8	2.5-3.5	1.3	92	170	550
Mahanadi	India	7	98.3	13.3	0.7	0.8	14.7	3.5-5.0	2.0	67	31	430
Ganges	Bangladesh	6	92.5	9.2	0.1	6.2	0.4	3.5-5.0	2.7	590	520	530
Irrawaddy	Myanmar	11	130.6	7.8	0.3	4.1	0.4	2.5-3.5	1.9	430	260	620
Mekong	Vietnam	10	143.1	9.7	0.2	4.6	0.6	3.5-5.0	2.6	420	160	200
Red	Vietnam	4	21.8	4.5	0.3	1.0	2.6	2.5-3.5	2.8	170	130	1100
Sepik	Papua New Guinea	8	85.0	10.0	0.3	0.6	No data	2.5-3.5	0.6	120		3000
Tsengwen	Taiwan	6	38.9	6.1	0.2	0.4	6.2	3.5-5.0	0.7	2	31	26000
Luanhe	China	3	57.8	10.1	0.9	9.2	3.3	2.5-3.5	1.6			500
Nakdong	South Korea	3	9.2	2.6	0.2	0.5	2.2	2.5-3.5	1.7	21	10	400
Lena	Russia	13	86.9	6.1	0.2	1.0	9.7	0-2.5	0.2	520	18	5
Olenek	Russia	5	13.4	2.4	0.3	0.3	2.5	0-2.5	0.2	36	1	10

* LOICZ, coastal typology dataset
** NOAA, Tide and tidal current tables, 1999.
*** MILLIMAN and MEADE (1983) and MILLIMAN and SYVITSKI (1992); italics estimated from regional average yield

Table 3. Group classes for deltas

Parameter	Low	Moderate	High
Wave energy (max, m)	< 2.5	2.5 - 3.5	> 3.5
Tidal range (spring, m)	< 1.5	1.5 - 3.0	> 3.0
Discharge (km3/yr)	< 20	20 - 100	> 100

shelf, and low tidal range. Those with the shortest length have a wide shelf and restricted fetch, but also have a low tidal range.

The average island length is 5.9 km, 11.5 km, and 15.6 km for deltas with high, moderate and low tidal ranges, respectively. The average island length for high, moderate, and low wave energy deltas is 16.4 km, 10.7 km, and 8.6 km, respectively. Both trends agree with the general relationship expected for coastal plain barrier islands (HAYES, 1979). Average island length was not well predicted by fluvial discharge.

The average width of deltaic islands ranges from 100 meters to 3.3 kilometers. Individual islands are up to 6 kilometers wide on the Ogooue Delta. Five deltas have an average island width greater than 1.0 kilometers (Niger, Ogooue, Copper, Ebro, and Nile) though individual island widths vary greatly on each.

The Niger, Ogooue, and Copper Deltas have prominent, 3 to 6 kilometer wide beach ridge sets on most islands. Beach ridge islands are however surprisingly scarce on most deltas, although mainland beach ridge complexes are common downdrift from deltas. Eolian processes lead to the growth of wind tidal flats in arid climates on the Nile and Indus Deltas (STANLEY and WARNE, 1998; WELLS and COLEMAN, 1985).

Narrow islands are typical where there is limited fetch and a low tidal range. The Lena and Olenek Deltas in the Arctic, and the Po Delta in the Mediterranean are good examples. Narrow islands are also characteristic of deltas with both a large tidal range and a wide, flat shoreface, such as the Ganges, Mekong, Gurupi, and Irrawaddy deltas. Deltas with sediment-starved islands, such as the Mississippi, also have narrow islands.

The average width was not well predicted on the basis of wave energy, tidal range, or discharge. This is probably because deltas with barrier islands have several means of prograding. Beach ridge accretion occurs on the Niger and Ogooue Deltas. On the Mangoky Delta in Madagascar, new spits overlap in front of older islands. On the Mekong and Gurupi Deltas, narrow spits similarly grow across depositional lobes, but are separated from the former beach ridge by silt and mud.

Inlet width

Average inlet width ranged from 0.2 kilometers to 9.2 kilometers with a mean of 1.9 kilometers. Five deltas have an average inlet width of greater than 4.0 kilometers (Ganges, Irrawaddy, Mekong, Gurupi, and Luanhe).

Inlet width is significantly narrower on the low tidal range deltas than the moderate and high tidal range deltas (1.1, 2.6, and 2.0 km, respectively). The mean inlet width on high discharge deltas (2.3 km) is much larger than on moderate and low discharge deltas (1.0 and 1.5 km, respectively).

When considered in combination, the tidal range and discharge becomes a much more powerful predictor of average inlet width. Deltas with a high tidal range and high fluvial discharge have an average inlet width of 5.0 kilometers, while deltas with both low tidal range and low discharge have an average of only 1.0 kilometers.

The spacing and width of inlets on deltas is directly and indirectly influenced by the fluvial distributary network. Clearly many "inlets" serve as modern distributary channels. Most inlets on the high tidal amplitude Gurupi coast are actually funnel-shaped river mouths. Whether they should be called inlets will be subject to disagreement. Many inlets, for example on the Indus, Ganges, and Niger Deltas, were once active distributary channels but were at least temporarily abandoned. We speculate that the main difference between river mouths and inlets is that sediment bypassing around river mouths is significantly less than around tidal inlets, and may even be interrupted altogether.

Shoreface slope

The average shoreface slope measured to the ten- meter contour ranges from 0.4 m/km (Ganges, Irrawaddy) to 15 m/km (Senegal) with a mean of 2.9 m/km. The Senegal, Mahanadi, and Mira Deltas have the steepest average slope, greater than 10 m/km, while the Mekong, Ganges, and Irrawaddy Deltas have a slope of less than 1 m/km.

The shoreface slope on deltaic islands does not appear to be strongly correlated to either wave energy or tidal range alone. However, the combination of tidal range and discharge once again shows a strong correlation. The average slope for deltas with a high discharge and high tidal range is 0.4 m/km, and is 6.0 m/km for deltas with low discharge and low tidal range, a difference of one and a half orders of magnitude. The low slope offshore of rivers with high discharge is probably the result of the large sediment loads that supply fine sediment to the shelf.

Shoreface profiles are locally steepest adjacent to recurved spits. This pattern is observed on the Mahanadi, Ebro, Danube, Mississippi, and other deltas. The slope tends to locally decrease near distributaries and inlets, which is evident near the cuspate Damietta distributary on the Nile Delta.

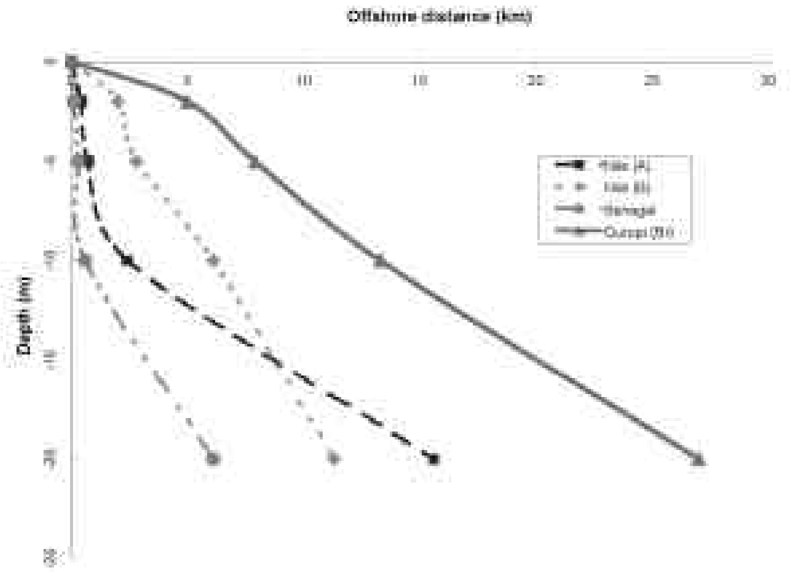

Figure 1. Deltaic shoreface shapes are steep and concave on the Nile (A) and Senegal Deltas, indicating strong wave influence, except locally adjacent to distributaries where sediment is abundant (Nile, B). The Gurupi Delta, shown in the figure, as well as the Mekong, Irrawaddy, and Ganges Deltas have a shallow inshore slope that steepens offshore due to delta foreset deposition.

A comparison of shoreface profiles is shown in Figure 1. The Nile and Senegal profiles show the typical steep, concave shape of wave-dominated barrier islands. The shoreface profiles on the Ganges, Irrawaddy, Mekong, and Gurupi Deltas deviate from this predicted shape. Rather, they exhibit a clinoform shape that is gentle inshore, rapidly steepens between 5 and 10 meters, and flattens beyond 10 meters water depth. Such shorefaces are formed and maintained by high sedimentation rates that build out a subaqueous delta front (ALLISON, 1998). Similar profile shapes occur locally adjacent to distributary mouths (e.g., Nile) where there is a direct input of sediment (Figure 1).

Lagoon

Lagoons exhibit a wide range of shapes and patterns. Eleven deltas have permanent open water lagoons, ten of which have a tidal range of less than 1.0 meter (e.g., Magdalena, Rhone, Nile). The Copper River Delta has broad, unvegetated sand and mud flats. The Nile Delta has evaporative sabkhas. The majority of deltaic lagoons, however, are fully vegetated by mangroves or salt marsh, primarily mangroves. It is usually difficult to determine from maps or photographs the difference between brackish and fresh water vegetation, since many deltas also have extensive flood plains. Because mangroves frequently mix with island vegetation, (MARTINEZ *et al*., 1995) it can be difficult merely to identify barrier islands and to determine their width.

Lagoons may occupy vast areas of deltaic barrier island systems. The Sunderbans, the mangrove forest of the abandoned Ganges Delta, extend inland for tens of kilometers. Most coastal plain barrier island systems have lagoons no more than a few kilometers wide. The average width of deltaic lagoons is at least 8 kilometers. Not surprisingly, the width of lagoons is limited by the width of the delta. The largest deltas (e.g., Ganges, Niger, Nile, Indus) have lagoons 20 to 30 kilometers wide, while those on small deltas are just a few kilometers wide (e.g., Mangoky, Jequitinhona, Tsengwen).

Lagoonal channel networks show a variety of patterns. Dendritic patterns (e.g., Indus, Niger, Ganges) are considered to indicate the relative dominance of tides in the lagoonal evolution. Bifurcating or anastomosing patterns (e.g., Ogooue, Danube, Po) generally indicate the relative dominance of fluvial processes. If beach ridges or cheniers are present trellis drainage patterns are typical (e.g., Mekong, Jequitinhona).

DISCUSSION:DELTAIC BARRIER ISLAND CLASSIFICATION

Two traits were used as the basis for the classification, although additional traits can also be related to island types. The most important and obvious traits are island length and inlet width. The most widely used classification of barrier island morphology (HAYES, 1979) is also essentially based on the same traits.

Average values for island length and inlet width were calculated for each delta (Table 2) and plotted in Figure 2. Deltas plotting along the straight lines have a constant proportion of inlets to islands. Table 4 shows that on average the island length, island width, island curvature, inlet width, and shoreface slope all change systematically as the relative proportion of inlets to islands increases. However, it is important to remember that islands and inlets of variable size may have the same inlet-island proportion. In these cases (and all others) it is the actual island and inlet size that relates to the morphological features, not the relative scaling.

Based on the island length and inlet width, the five types of deltaic islands are: 1) Nile-type (long islands, narrow inlets); 2) Niger-type (long islands, wide inlets); 3) Mangoky-type (short islands, narrow inlets; 4) Mekong-type (short islands, wide inlets); 5) Mississippi-type (variable island and inlet size). Descriptions of each island type and relevant dynamic processes are provided, with tabular summaries of island characteristics in Tables 5a and 5b. All deltas are listed according to the dominant island type in Table 6.

Nile type

The Nile Delta (Figure 3) has eleven islands, stretching across more than 200 kilometers and averaging greater than 20 kilometers in length. Its inlets, including the two major Rosetta and Damietta distribuataries, average only 0.4 kilometers wide. Island widths range from 0.1 to 2.0 km, although it is highly variable. They are widest near the distributaries, where short spits of sand supplied by the river are welded as beach ridges onto the islands, and where wind tidal flats are present. A dramatic reduction of sediment supply has led to severe erosion rates of these once accreting areas, though (STANLEY and WARNE, 1998).

Table 4. Average island characteristics versus percent of shoreline occupied by inlets (Inlet %)

Inlet %		Length (km)	Width (km)	Curvature	Inlet (km)	Shoreface (m/km)	Lagoon (km)	Tidal range (m)
0-10%	N=120	14.4	1.0	1.07	0.7	4.3	13.3	1.6
10-20%	N=85	7.3	0.7	1.09	1.3	3.6	11.6	2.3
20-30%	N=63	6.6	0.5	1.14	2.2	3.4	10.5	2.5
30-50%	N=68	5.8	0.4	1.18	3.5	2.6	13.7	3.1
>50%	N=40	3.6	0.3	1.28	5.6	1.9	11.0	3.4

N= number of individual islands
Curvature= Actual shoreline length / Chord length

Table 5a. Types of deltaic barrier islands and delta morphology

Deltaic Island type	Examples	Delta type (Galloway, 1975)	Delta shoreline
Nile	Senegal, Godavari, Jequitinhona	Wave-dominated	Cuspate, straight
Mangoky	Mira, Tsiribihina	Mixed (wave)	Arcuate
Niger	Copper, Indus, Zambezi	Mixed (tide)	Arcuate
Mekong	Irrawaddy, Gurupi, Ganges	Mixed (river)	Wide lobes
Mississippi	Po, Lena	River-dominated	Branching lobes

Table 5b. Morphologic characteristics of deltaic barrier islands

Island type	Islands	Inlets	Slope	Wave	Tide	Discharge
Nile	Long, width var.	Narrow	High	Moderate to High	Micro	Low to High
Mangoky	Short, narrow, overlap	Narrow	Moderate	Moderate to High	Meso	Low to Moderate
Niger	Length var., wide	Wide	Moderate	Moderate to High	Meso	Moderate to High
Mekong	Short, narrow, curved	Wide	Low	Low	Meso to macro	Low to High
Mississippi	Length var., narrow	Variable	Low	Low to Moderate	Micro	Moderate to High

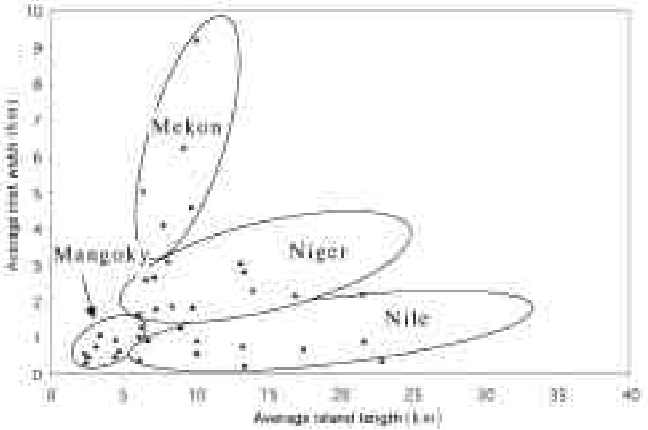

Figure 2. Plot of the average island length and average inlet width for all deltas. (A) Nile type islands plot near the X axis with the greatest island lengths and narrow (< 1 km) inlets (Note: Magdalena and Ogooue Deltas not shown to reduce graph size. Average lengths and widths are 66 km/ 1.2 km and 43 km/ 1.1 km, respectively). (B) Niger type islands have somewhat shorter islands and inlet widths from 1 to 3 km. (C) Mangoky type islands plot along a similar trend as Niger type islands but have shorter island lengths (about 5 km) and inlets (< 1 km). (D) Mekong type islands have inlets greater than 3 km and lengths from 5 to 10 km. Mississippi type islands are not grouped due to their variability, which is related to a distinct evolutionary stage of development.

Table 6. Deltaic barrier island classification

Delta	Location	Island Type
Manambalo	Madagascar	Mangoky
Mangoky	Madagascar	Mangoky
Mira	Colombia	Mangoky
Nakdong	South Korea	Mangoky
Red	Vietnam	Mangoky
Tsiribihina	Madagascar	Mangoky
Ganges	Bangladesh	Mekong
Gurupi	Brazil	Mekong
Irrawaddy	Myanmar	Mekong
Luanhe	China	Mekong
Mekong	Vietnam	Mekong
Lena	Russia	Mississippi
Mississippi	Louisiana	Mississippi
Olenek	Russia	Mississippi
Po	Italy	Mississippi
Copper	Alaska	Niger
Indus	Pakistan	Niger
Meluli	Mozambique	Niger
Niger	Nigeria	Niger
Parnaiba	Brazil	Niger
Patia	Colombia	Niger
San Juan	Colombia	Niger
Save	Mozambique	Niger
Zambezi	Mozambique	Niger
Acu	Brazil	Nile
Caravelas	Brazil	Nile
Casamance	Senegal	Nile
Danube	Romania	Nile
Ebro	Spain	Nile
Godavari	India	Nile
Jequitinhona	Brazil	Nile
Magdalena	Colombia	Nile
Mahanadi	India	Nile
Nile	Egypt	Nile
Ogooue	Gabon	Nile
Rhone	France	Nile
Saloum	Senegal	Nile
Senegal	Senegal	Nile
Sepik	Papua New Guinea	Nile
Tsengwen	Taiwan	Nile

The shoreface is steep and concave in profile (Figure 1). Several open lagoons back the islands, with widespread salt and mud flats due to high evaporation rates.

Nile Delta type barrier islands are characteristically long and straight with narrow inlets, with less than 10% of the shoreline occupied by inlets. They generally occur on deltas that are wave-dominated (GALLOWAY, 1975). Although the Nile has eleven islands, there may be as few as one or two on Nile-type deltas. Nile-type islands average 14 km long, two to five times the average length of the other delta island types. Conversely, the average inlet width of 0.7 km is two to eight times smaller than all other delta types. Distributary mouths are usually narrow and cuspate (e.g., Godavari, Jequitinhona, Ebro) or diverted by long spits (e.g. Senegal, Ogooue). Nile type islands also have the widest (1.0 km) and straightest islands, and the steepest shoreface slope (4.3 m/km).

The spring tidal range averages 1.6 meters, well within microtidal conditions. Although deepwater wave energy is variable, nearshore energy is usually high due to the steepness of the shoreface. River influence is only important adjacent to distributary mouths, which are usually very few. Because there are few river mouths, most inlets are tidal, and island chains may extend alongshore beyond the delta plain.

Niger type

The Niger Delta has 21 barrier islands stretching over 300 kilometers. It is located on a narrow and moderately steep shelf facing large swells from the South Atlantic. The tidal range increases from 1.4 meters in the northwest to 2.0 meters in the southeast. The average island length is 16

Figure 3. Nile Delta, Egypt. The Rosetta Branch has built a cuspate mouth (left), while long barrier islands enclose restricted, hypersaline lagoons (center). The wide portion of the island has been created by a combination of overwash and eolian processes. Landsat 7 ETM+ browse image, EROS Data Center.

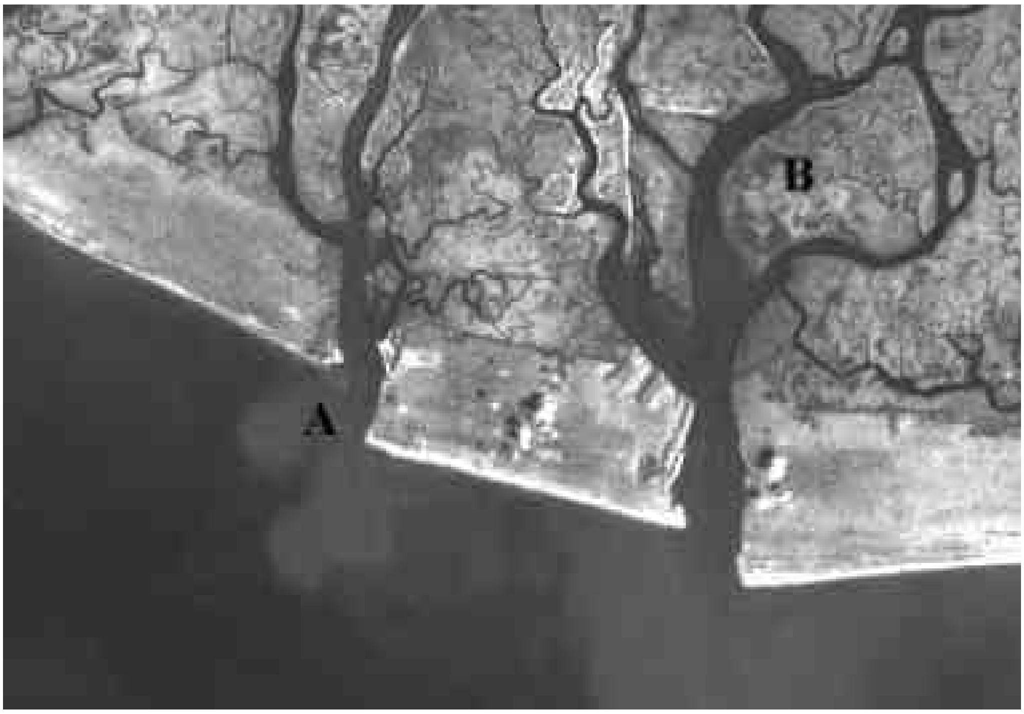

Figure 4. Niger Delta, Nigeria. These inlets are characteristically wide due to the large tidal prism. Downdrift islands are significantly offset seaward (A), due to wave refraction over the ebb tidal delta. These unusually wide islands are the result of beach ridge progradation, although they are presently subject to severe erosion. Mr. SID image from NASA Scientific Data Purchase (http://zulu.ssc.nasa.gov/mrsid/)

kilometers and width 3.3 kilometers, with extensive beach ridge sets. The average inlet width is 2.0 kilometers, substantially wider than the Nile. Many islands have a characteristic drumstick shape and display significant downdrift offset across tidal inlets (Figure 4).

Niger type islands are morphologically diverse, ranging from 5 to 15 km in average island length and 1 to 3 kilometers in average inlet width. Inlets occupy anywhere between 10 to 25 % of the delta shoreline. Wave energy is moderate to high and the average tidal range is upper microtidal to low mesotidal. The Niger, Copper, and Indus Deltas in particular have numerous drumstick-shaped islands typical of island systems significantly influenced by both waves and tides. Island width and shoreface slope is slightly less on average than on Nile type islands but greater than Mangoky and Mekong type islands. Beach ridges are common features due to the energetic waves and relatively steep slope, particularly at locations where ebb swash bars weld to the shoreline. Niger type islands are often located on deltas with large delta plains, creating a large tidal prism that leads to wide inlets. On such large deltas river discharge occurs through only a few of the inlets at any one time, leaving most inlets predominantly influenced by tides.

Mangoky type

The Mangoky Delta (Figure 5) faces Mozambique Channel on the west coast of Madagascar. It is located on a narrow, steep shelf, and the islands are backed by a narrow band of mangroves and small, branching distributary channels. The river systems of Madagascar, including the Mangoky, are small but drain steep hinterlands and carry high sediment yields (MILLIMAN and SYVITSKI, 1992).

Mangoky type islands are similar to Niger type islands only in that the relative proportion of inlets to islands is between 10 and 25%. Similar islands occur on two other Madagascar deltas (Manambalo and Tsiribihina), and the Mira Delta on the Colombian Pacific coast. Mangoky type islands are much shorter than Niger type islands, averaging 3 to 10 km, and inlets are much smaller, averaging 0.5 to 1.0 km. While the wide Niger Delta inlets are stable, those on the Mangoky show evidence of alongshore migration. The dramatic decrease in inlet width exists despite a 3.5 to 4.0 meter spring tidal range on the Mangoky, Mira, and Tsiribihina Deltas. Since Mangoky type deltas are small, the lagoonal area contributing to the tidal prism is much smaller than, for example the Niger. The inlets are generally active distributary mouths, as opposed to the tide-dominated inlets on the Niger Delta.

Wide, regressive islands are not common among Mangoky type islands as they are on the Niger. As new islands form at active river mouths they grow laterally through the accretion of recurved spits, sometimes overlapping older islands but rarely welding to the existing shoreline (Figure 5). The older islands become preserved as cheniers as lagoonal and marsh/mangrove sediment is deposited between the islands (Figure 5). The overlapping morphology indicates consistently oblique waves and strong longshore transport. The sheltered downdrift flank of the Mangoky Delta, like the Mira Delta (MARTINEZ *et al*., 2000), has a noticeably flatter slope and shorter islands.

Mekong type

The Mekong Delta in Vietnam (Figure 6) consists of several wide distributary channels separated by broad depositional lobes with chenier plains extending tens of kilometers inland. The arcuate lobes are 5 to 10 kilometers wide each, and prograde at rates of up to 40 meters per year (COLEMAN *et al*., 1986). In addition to a large discharge and sediment load, ranking eighth and tenth in the world, respectively (MILLIMAN and MEADE, 1983), the delta has a spring tidal range of 2.6 meters. Wave energy is low due to the wide dissipative shelf, despite strong seasonal monsoon winds. Due to the shallow bathymetry, the shoreface extends more than 20 kilometers to the 10- meter contour.

Mekong-type islands are not distinctive in length (5 to 10 km) but are narrower and much more arcuate than all other deltaic island types. Their chief characteristic is their wide inlets, averaging nearly 5.0 km, occupying between 30 and 50% of the delta shoreline. The inlets are maintained either by high river discharge (e.g., Mekong, Irrawaddy), high tidal range (e.g., Ganges Gurupi) or both. Another distinguishing trait is the excessively gradual shoreface slope of 0.5 to 1.0 m/km. The slope increases between 5 and 10 meters water depth then flattens (Figure 1). These clinoforms are maintained by foreset progradation, even where shoreline erosion is severe on the Ganges Delta (ALLISON, 1998). Although the Mekong and Irrawaddy Deltas are rapidly prograding, the abandoned Ganges Delta is rapidly eroding, and the Gurupi Delta islands are thought to be slowly transgressing over formerly prograding tidal flats (SOUZA and EL-ROBRINI, 1998).

The islands on the Mekong Delta, in Figure 6, are sandy (NGUYEN *et al*., 2000) but there is little information regarding their dynamics. They appear to originate as narrow (< 50 m) spits at the mouths of the channels and build in front of the existing lobe shoreline, but are confined between the large distributary mouths (Figure 6). It appears the mechanism that is actively forming the Mekong Delta islands eventually results in the preservation of cheniers, but not through the same depositional sequence as Louisiana cheniers (AUGUSTINIUS, 1989; PENLAND and SUTER, 1989). The islands are forming on active rather than inactive depositional lobes, and their length is constrained by the distributary spacing. The islands appear to form prior to or coeval with fine grained deposition behind the spit, and as mud flats accrete on the foreshore. The mud flats

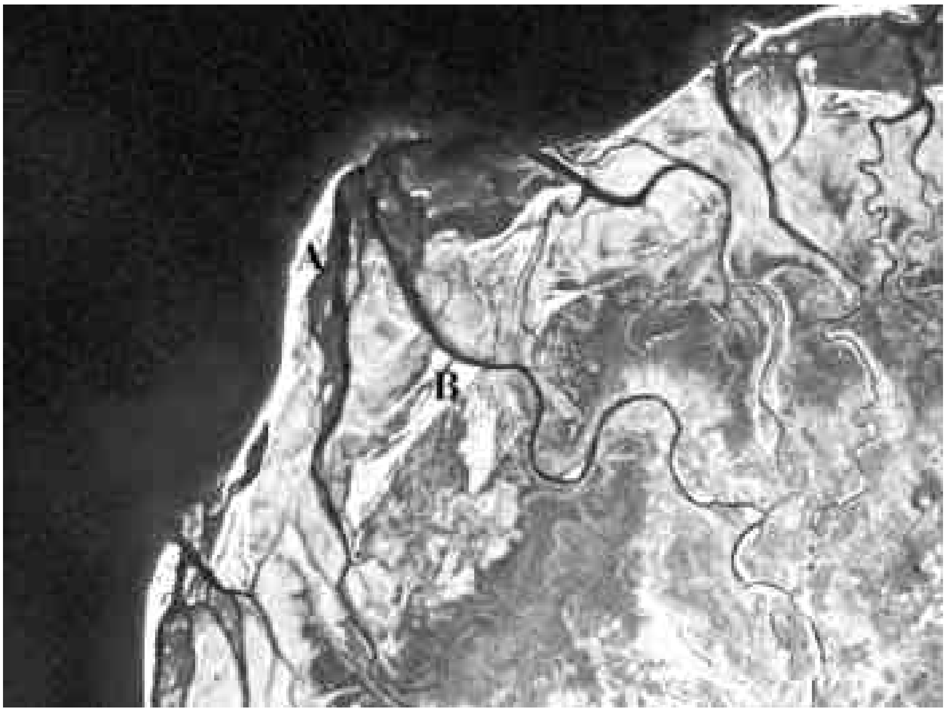

Figure 5. Mangoky Delta, Madagascar. Islands forming adjacent to active distributaries are strongly prograding to the north (toward top page) (A), diverting tidal channels. Former islands are eventually surrounded by lagoon deposits and mangroves (B). Mr. SID image from NASAScientific Data Purchase (http://zulu.ssc.nasa.gov/mrsid/).

Figure 6. Mekong Delta, Vietnam. Depositional lobes (Aand B) are separated by wide distributary channels. New islands are forming in front of each lobe, and the narrow lagoons are not yet filled with fine sediment. Note the wide chenier plain extending inland on each lobe. As the delta continues to prograde, the present islands will become cheniers. NASA JSC Photo Collection, STS059-94-86.

provide a platform for the next island to form. The exceptionally wide chenier plain on the Mekong Delta suggests that the present distributary system has remianed in a relatively stable location for a long period of time. The variability of the sediment supply, which is necessary for chenier formation, may occur on a seaonal to decadal time scale, as a result of increased discharge and wave energy during the monsoon, or due to interannual to decadal climatic variability.

The Rio Gurupi coastal stretch actually consists of several dozen funnel shaped river mouths, separated by long (10-20 km) peninsulas vegetated by mangroves (Figure 7). Small, curved, sandy islands have developed at the tips of the peninsulas, numbering more than 50 over a 300- kilometer stretch. They are somewhat wider than islands on the Mekong Delta and some contain vegetated dunes (BEHLEING *et al*., 2001). The spring tidal range is virtually 5.0 meters, making it the greatest tidal regime known to contain sandy barrier islands. The distinctive convex curvature of these islands is probably related to the wide inlets. In the Arctic islands adjacent to wide inlets are exposed to waves approaching from oblique angles, resulting in rotation of the islands (SHORT, 1979). Like the Mekong Delta, there is a dearth of information about the coastal dynamics, particularly about the islands. The present islands are thought to be transgressive, although preserved beach ridges and cheniers on the peninsulas indicate long term progradation since the mid Holocene (SOUZAand EL-ROBRINI, 1998).

Mississippi type

The barrier islands of the Mississippi Delta are morphologically diverse and rapidly evolving (Figure 8). Based on shape alone the islands are highly variable and have no distinguishing features and could fit under other types. However it would seem inappropriate not to provide a distinct class for these islands, considering the level of knowledge already accumulated, and their unique sequence of formation and evolution.

Mississippi Delta islands form as a result of erosion and/or subsidence of abandoned portions of the delta (PENLAND *et al*., 1985), and are the only type of deltaic islands to form transgressively. The Lena, and possibly the Po Delta, appears to follow a somewhat similar evolutionary path of transgression and subsidence (RUZ *et al*., 1992; CENCINI, 1998). The islands happen to form on predominantly river-dominated deltas with low wave energy and tidal range, and thus do not form on the active depositional lobes. Because of their rapid evolution, island and inlet morphology is highly variable. While inlets at advanced stages of evolution on the Mississippi are several kilometers wide, those just forming a just a few hundred meters (Figure 8). Similarly, island lengths are not consistent, as those on the Po Delta are just 2.5 km while those on the Mississippi are as long as 20 km. All islands are narrow and transgressive, with abundant washover deposits.

THE FUTURE OF DELTAIC BARRIER ISLANDS

The present morphology of deltaic barrier islands is not necessarily indicative of present-day processes. Many deltaic islands probably formed prior to dramatic reductions of sediment supply and discharge as a result of hydroengineering projects and have incurred more rapid subsidence stemming from drilling activities. The wide beach ridge islands on the Niger Delta are eroding at an average of 20 meters per year (IBE, 1996), as are portions of the Nile Delta (STANLEY and WARNE, 1998). Such rapid changes result from the dependence of the islands on a continuous sediment supply.

The disintegration of many deltaic barrier island systems is a distinct possibility in the coming century and it may have potentially disastrous consequences. Accelerating wetland loss is predicted in Louisiana as a continued result of barrier island disappearance (STONE and MCBRIDE, 1998). Dramatic wetland loss in the Po Delta has occurred since 1940 as the barrier islands have slowly been dissected (CENCINI, 1998). The break-up of the Nile Delta would result in extensive flooding, abandonment of fertile land, and displace thousands of people. Other deltas likely to suffer enhanced erosion rates in the immediate future are the Zambezi and Indus (MILLIMAN and SYVITSKI, 1992).

CONCLUSIONS

There are approximately 400 barrier islands on the world's deltaic plains, with a combined length of 4,100 kilometers. They make up 30% of the world's estimated barrier islands (by length). Deltaic barrier islands make up more than half of barrier islands in South America, Asia, and Africa, but only 10% in North America and Europe due to differing sea level rise history. Barrier islands are present on all types of deltas, including wave, tide, and river dominated deltas.

Deltaic barrier islands were classified based on island length and inlet width. Five island types are represented by the Nile, Mississippi, Niger, Mangoky, and Mekong Deltas. Other morphologic characteristics, including island width, island curvature, and shoreface slope can also be related to island type. Island types are influenced by variation of waves, tides, and fluvial discharge.

- Nile- type islands are long, straight islands with narrow inlets and steep shoreface slope, forming under high wave and low tidal energy with variable river discharge.

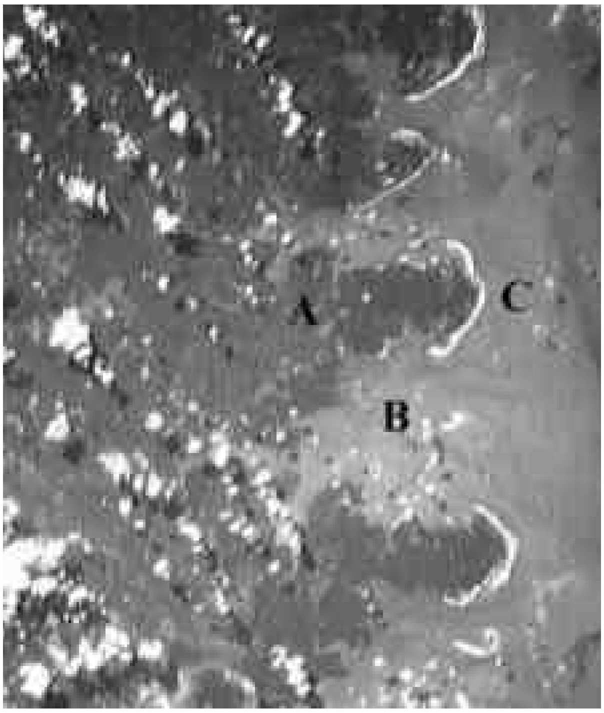

Figure 7. Gurupi Delta, Brazil. Numerous long peninsulas covered by mangrove forest (A) are separated by wide, funnel-shaped estuaries (B). The thin bright, arcuate strips at the tip of peninsulas are barrier islands (C). NASAJSC Photo Collection, STS068-201-95.

Figure 8. Mississippi Delta, Louisiana. Image shows portions of the delta at different stages of island evolution. (A) The active branching lobe of the Mississippi with no barrier islands. (B) Recent splay deposits built by the active lobe being reworked by waves; some new islands have already formed here. (C) Grand Isle is adjacent to an eroding, older abandoned distributary lobe. (C) NASA JSC Photo Collection, STS095-74-86_2.

- Mangoky- type islands are short, narrow islands, often with significant overlap, with narrow inlets and moderate slope, and form under moderate to high wave and tidal energy with low river discharge.
- Niger- type islands are relatively long and wide with large inlets and moderate slope, forming under moderate to high wave and tidal energy, with a larger tidal prism than Mangoky- type islands, and typically higher river discharge.
- Mekong- type islands are short, narrow, curved islands with wide inlets, very low slope and form under low wave and high tidal energy with high or low river discharge.
- Mississippi- type islands are narrow with variable island length and inlet width and a low slope, forming mostly on abandoned lobes of deltas in low wave, low tide settings. Their morphology is heavily influenced by rapid transgression and disintegration due to a limited sediment supply.

Deltaic barrier islands form by a variety of mechanisms, including erosion of abandoned lobes and spit formation on active lobes. Sediment supply directly affects how islands form and evolve. The future of deltaic barrier islands will be severely impacted by human activities that reduce the fluvial sediment supply and induce rapid subsidence rates. Rapid morphologic response of deltaic barrier islands should be expected and is already apparent on deltas such as the Mississippi, Niger, Nile, and Po. The morphologic traits of barrier islands on these deltas were likely formed under dramatically different conditions than those prevailing today.

LITERATURE CITED

ALLISON, M.A., 1998. Historical changes in the Ganges-Brahmaputra Delta front. *Journal of Coastal Research*, 14(4), 1269-1275.

AUGUSTINIUS, P.G.E.F., 1989. Cheniers and chenier plains; a general introduction. *Marine Geology*, 90(4), 219-229.

BEHLEING, H., COHEN, M.C.L., and LARA, R.J., 2001. Studies on Holocene mangrove ecosystem dynamics of the Braganca Peninsula in north-eastern Para, Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 167, 225-242.

CENCINI, C., 1998. Physical processes and human activities in the evolution of the Po Delta, Italy. *Journal of Coastal Research*, 14(3), 774-793.

COLEMAN, J.M., ROBERTS, H.H., and HUH, O.K., 1986. Deltaic landforms. *In*: N.M. SHORT and R.W. BLAIR, Jr. (eds.), *Geomorphology from space: a global overview of regional landforms*. Washington, D.C., NASA.

DAVIS, R.A., 1994. Barriers of the Florida Gulf Peninsula. *In*: R.A. DAVIS (ed.), *Geology of Holocene Barrier Island Systems*. Springer-Verlag, New York, pp. 167-206.

FITZGERALD, D., and VAN HETEREN, S., 1999. Classification of Paraglacial Barrier Systems: Coastal New England, USA. *Sedimentology*, 46, 1083-1108.

GALLOWAY, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. *In*: M.L. BROUSSARD (ed.), *Deltas: Models for exploration*. Houston Geological Society, pp. 87-98.

GLAESER, J.D., 1978. Global distribution of barrier islands in terms of tectonic setting. *Journal of Geology*, 86, 283-297.

HAYES, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. *In*: S.P. LEATHERMAN (ed.), *Barrier islands*: From the Gulf of St. Lawrence to the Gulf of Mexico. New York: Academic Press, pp. 1-29.

IBE, A.C., 1996. The Niger Delta and sea-level rise. *In*: J.D. MILLIMAN and B.U. HAQ (eds.), *Sea-level rise and coastal subsidence*. Netherlands: Kluwer Academic Publishers, pp. 249-267.

INMAN D.L., and NORDSTROM, C.E., 1971. On the tectonic and morphologic classification of coasts. *Journal of Geology*, 79, 1-21.

MARTINEZ, J.O., GONZALEZ, J.L., PILKEY, O.H., and NEAL, W.J., 1995. Tropical barrier islands of Colombia's Pacific Coast. *Journal of Coastal Research*, 11(2), 432-453.

MARTINEZ, J.O., GONZALEZ, J.L., PILKEY, O.H., and NEAL, W.J., 2000. Barrier island evolution on the subsiding central Pacific coast, Colombia, S.A. *Journal of Coastal Research*, 16(3), 663-674.

MILLIMAN. J.D. and MEADE, R.H., 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology*, 91(1), 1-21.

MILLIMAN, J.D. and SYVISTSKI, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *Journal of Geology*, 100, 535-544.

NATIONAL OCEAN SERVICE , 1999. *Tide and tidal current tables*. National Oceanic and Atmospheric Administration, Silver Springs, MD, CD-Rom.

NGUYEN, V.L., TA, T.K.O., and TATEISHI, M., 2000. Late Holocene depositional environments and coastal evolution of the Mekong River Delta, southern Vietnam. *Journal of Asian Earth Sciences*, 18, 427-439.

OERTEL, G.F., 1985. The barrier island system. *Marine Geology*, 63, 1-18.

PENLAND, S. and SUTER, J.R., 1989. The geomorphology of the Mississippi River chenier plain. *Marine Geology*, 90(4), 231-258.

PENLAND S., SUTER, J.R., and BOYD, R., 1985. Barrier island arcs along abandoned Mississippi River Deltas, *Marine Geology*, 63, 197-234.

PIRAZZOLI, P.A., 1991. *World atlas of Holocene sea-level changes*, Elsevier Science Publishers, Amsterdam, The Netherlands, 300p.

RIGGS, S.L., CLEARY, W.J., and SNYDER, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology*, 126, 213-234.

RUZ A.-H., HEQUETTE, A., AND HILL, P.R., 1992. A Model of Coastal Evolution in a Transgressed Thermokarst Topography, Canadian Beaufort Sea. *Marine Geology*, 106:, 251-278.

SHORT, A.D., 1979. Barrier island development along the Alaskan-Yukon coastal plains. *Geological Society of America Bulletin*, Part II, (90) 77-103.

SOUZA, F.P.W.M., and EL-ROBRINI, M., 1998. Sea-level changes and sequence stratigraphy of the Braganca coastal plain, northeastern Para, Brazil. *Boletim do Museu Paraense Emilio Goeldi. Serie Ciencias da Terra*, 10, 45-78.

STANLEY, D.J, and WARNE, A.G., 1998. Nile Delta in its destruction phase. *Journal of Coastal Research*, 14(3), 794-825.

STONE, G.W., and MCBRIDE, R.A., 1998. Louisiana barrier islands and their importance in wetland protection: Forecasting shoreline change and subsequent response of wave climate. *Journal of Coastal Research*, (14)3, 900-915.

STUTZ, M.L. and PILKEY, O.H., 2001. A review of global barrier island distribution. *Journal of Coastal Research* Special Issue 34, pp. 15-22..

WELLS, J. T., and COLEMAN, J. M., 1984. Deltaic morphology and sedimentology, with special reference to the Indus River Delta. *In*: *Marine Geology and Oceanography of the Arabian Sea and Coastal Pakistan.* New York: Van Nostrand Reinhold, pp. 85-100.