COASTAL BARRIERS

D. M. FitzGerald and **I. V. Buynevich**
Department of Earth Sciences, Boston University, USA

Keywords: barrier, beach, spit, inlet, barrier stratigraphy, barrier evolution

Contents

Summary

Barriers occur on a worldwide basis but are predominantly found along Amero-trailing edge continental margins in coastal plain settings where the supply of sand is abundant. The coastal plain setting appears to be an important requirement for the wide distribution of barriers in that it provides a sediment source and a platform upon which sediment can accumulate. Barriers have many different forms but can be grouped into three major classes dependent on their connection of the mainland (barrier islands, barrier spits, and welded barriers). Barriers have formed by different mechanisms and most have migrated onshore to present position. Retrograding barrier are continuing to move onshore through rollover processes, whereas, prograding barriers are building seaward due to abundant sediment supplies and/or stable sea levels to slow rates in sea-level rise. Aggrading barriers are accreting vertically and keeping pace with rising sea level. The stratigraphy of barriers is dependent on their evolution and factors such as sediment supply, rate of sea-level rise, wave and tidal energy, climate, and topography of the land.

1. Introduction

Coastal barriers are the sites of some of the world's most beautiful beaches. They form due to the combined action of wind, waves, and longshore currents whereby thin strips of land are built a few to several tens of meters above sea level. They are called barriers because they protect the mainland coast from the forces of the sea, particularly during storms. They lessen the effects of storm waves, heightened tides, and salt spray. The bays, lagoons, marshes and tidal creeks that form behind barriers provide harborages, nursery grounds for fish and shellfish, and important sources of nutrients for coastal waters. Barriers occur throughout the world's coastlines but are most common where sediment supplies are abundant and wave and tidal energy are conducive for onshore sand accumulation. This chapter addresses the global distribution of coastal barriers, barrier types, morphology, and stratigraphy, as well as history of debate on barrier origin and the effects of hydrographic regime on the development of barrier coasts.

2. Physical Description

Barriers are wave-built accumulations of sediment that accrete vertically due to wave action and wind processes. Most are linear features that tend to parallel the coast, generally occurring in groups or chains. Isolated barriers are common along formerly glaciated coasts (e.g., northern Europe, Siberia, New England, Alaska, eastern Canada, southern New Zealand) and along high-relief coasts such as those associated with geologically young and active continental margins (e.g., parts of Pacific coast and some oceanic islands). Barriers are separated from the mainland by a region termed the backbarrier consisting of tidal flats, shallow bays, lagoons and/or marsh systems.

Barriers may be less than 100 m wide or more than several kilometers in width. Likewise, they range in length from small pocket barriers of a few 10's of meters to certain barriers along open coasts that extend for more than 100 km. Generally, barriers are wide where the supply of sediment has been abundant and relatively narrow where erosion rates are high or where the sediment was scarce during their formation. Barrier length is partly a function of sediment supply but is also strongly influenced by wave versus tidal energy of the region.

Coastal barriers consist of many different types of sediment depending on their geological setting. Sand, which is the most common constituent, comes from a variety of sources including rivers, deltaic and glacial deposits, eroding cliffs, and biogenic material. The major components of land-derived sand are the minerals quartz and feldspar. These durable grains are a product of physical and chemical decomposition of granite, the primary building block of continents. In northern latitudes where glaciers have shaped the landscape, gravel is a common constituent of barriers, whereas, in southern latitudes carbonate material, including shells and coral debris, may comprise a major portion of the barrier sands. Along the southeast coast of Iceland, as well as parts of Alaska and Hawaii, the barriers are composed of black volcanic sands derived from upland volcanic rocks. Many environments make up a barrier and their arrangement differs from location to location reflecting the type of barrier and the physical setting of the region. Generally, most barriers can be divided in three zones: the beach, the barrier interior, and the landward margin (Figure 1).

2.1 Beach

Due to continual sediment reworking by wind, waves, and tides, the beach is the most dynamic part of the barrier. Beaches exhibit a wide range of morphologies depending upon a number of factors including the sediment grain size and abundance, and the influence of storms. Sediment is removed from the beach during storms and returned during more tranquil wave conditions. During the storm and post-storm period, the form of the beach evolves in a predictable fashion.

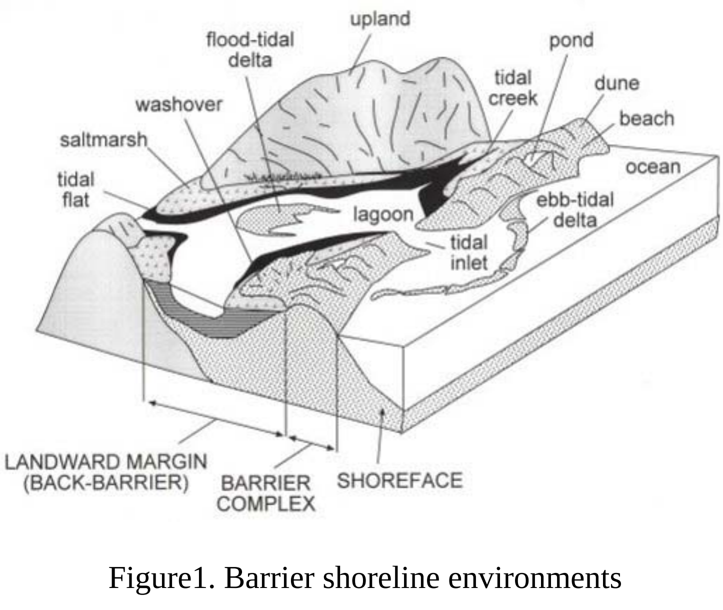

Figure1. Barrier shoreline environments

2.2 Barrier Interior

Along sandy barriers, the beach is backed by a frontal dune ridge (also called the fore dune ridge) which may extend almost uninterruptedly along the length of the barrier provided the supply of sediment is adequate and storms have not incised the dune ridge. The frontal dune ridge is the first line of defense in protecting the interior of the barrier from the effects of storms. Landward of this region are the secondary dunes which have a variety of forms depending on the historical development of the barrier and subsequent modification by wind processes. For example, devegetation of the Provincelands Spit at the tip of Cape Cod in Massachusetts, U.S.A., by early settlers led to the formation of large parabolic dunes that are up to 500m long and more than 35 m high. In other locations where barriers have built seaward through time, such as North Beach Peninsula in Washington or Kiawah Island in South Carolina , former shoreline positions are marked by a series of semi-parallel vegetated beach ridges reaching 3-7m in height. The low areas between individual beach ridges, called swales, commonly extend below the water table and are the sites of fresh and brackish water ponds or salt marshes.

2.3 Landward Margin

Along the backside of many barriers the dunes diminish in stature and the low relief of the barrier gradually changes to an intertidal sand or mud flat or a salt marsh. In other instances, the landward margin of the barrier abuts an open water area of a lagoon, bay, tidal creek, or coastal lake. Along coasts where the barrier is migrating onshore, the landward margin may be dominated by aprons of sand that have overwashed the barrier during periods of storms. In time, these sandy deposits may be colonized by salt grasses producing arcuate-shaped marshes. In still other regions, the backside of a barrier may be fronted by a sandy beach bordering a lagoon or bay. In this setting, wind-blown sand from the beach may form a rear-dune ridge outlining the landward margin of the barrier.

Barriers may terminate in an embayment or at a headland. In the case of barrier chains, individual barriers are separated by tidal inlets. These are the waterways that allow for the exchange of water between the ocean and the backbarrier environments. The end of the barrier abutting a tidal inlet is usually the most dynamic region due to the effects of inlet migration and associated sediment transport patterns.

3. Global Distribution and Tectonic Setting

3.1 General

Barriers comprise approximately 15% of the world's coastlines. They are found along every continent except Antarctica, in every type of geological setting, and in every kind of climate. Tectonically, they are most common along *Amero-trailing Edge* coasts where low gradient continental margins provide ideal settings for barrier formation. They are also best developed in areas of low to moderate tidal range *(Tidal range is the vertical difference between high and low tide. A classification of coasts based on tidal range consists of microtidal coasts (TR < 1.5 m), mesotidal coasts (1.5 ≥ TR ≤ 3.5 m), and macrotidal coasts (TR > 3.5 m).*) (microtidal to mesotidal range) and in mid to lower latitudes. Climatic conditions control the vegetation on the barriers and in backbarrier regions, the type of sediment on beaches, and in some regions such as the Arctic, the formation and modification of barriers themselves. The disappearance of barriers toward the "zero energy" northwest ("Big Bend") coast of Florida in the Gulf of Mexico attests to the requirement of wave energy in the formation of barriers.

3.2 Tectonic Controls

The tectonic setting of the coast dictates to a large extent the sediment contribution to the coast, the width of the continental shelf, and the general topography of the coast. The tectonic coastal classification of Inman and Nordstrom can be used to illustrate these relationships and explain the worldwide distribution of barriers. *Amero-trailing edge* coastlines tend to have abundant sediment supplies due to extensive continental drainage. Their low relief coastal plains and continental shelves provide a platform upon which barriers can form and migrate landward during periods of eustatic sea level rise. The longest barrier chains in the world coincide with Amero-trailing edges and include the East Coast of the United States (3100 km) and the Gulf of Mexico coast (1600 km). There are also sizable barrier chains along the East Coast of South America (960 km), East Coast of Indian coast (680 km), North Sea coast of Europe (560 km), Eastern Siberia (300 km), and the North Slope of Alaska (900 km) (Table 1).

Location	Tectonic Setting	Approximate Length (km)
1. Atlantic Coast of North America	Amero-Trailing	3,100
2. Gulf of Mexico	Amero-Trailing/Marginal	1,600
3. North and West Coast of Alaska	Amero-Trailing	900
4. East Coast of South America	Amero-Trailing	960
5. South Coast of North Sea, Europe	Amero-Trailing	560
6. South coast of Baltic Sea	Amero-Trailing	680
7. NE Coast of Siberia	Amero-Trailing	300
8. East coast of India	Amero-Trailing	680
9. Ivory Coast, Africa	Afro-Trailing	300
10. West Coast of Australia	Afro-Trailing	650
11. SE Coast of Australia	Afro-Trailing	600
12. West-Central Coast of Mexico	Neo-Trailing	500
13. East Nicaraguan and Honduran Coast	Marginal Sea	500
14. Northern Black and Azov Seas	Inland Sea	840
15. Pacific Southernmost Coast of Mexico	Collision	150
16. Southern Washington State, USA	Collision	120
17. Copper River Barriers, SE Alaska	Collision	80

Table1. Shoreline length and tectonic setting of world's major barrier chains

The unparalleled concentration of barriers along the East Coast of the United States is undoubtedly a product of the erosion and denudation of the Appalachian Mountains, which some scientists have speculated may have once rivaled the Himalayas in elevation. The huge volume of sediment derived from the wearing down of these mountains produced the wide, flat coastal plain and continental shelf region, much of which is veneered by layers of unconsolidated sediment or easily eroded sedimentary rocks. It is the reworking and redistribution of these surface sediments by rivers, tides, and waves that are responsible for extensive barrier construction along the East Coast. Likewise, the almost continuous chain of barriers in the Gulf of Mexico is related to the wide, flat coastal plain and continental shelf of this margin. It is thought by some scientists that sediment delivery to this coast, particularly along Texas, was much greater in the past when the climate of this region was wetter.

Marginal Sea coasts contain a relatively small percentage of world's barriers even though these regions have some of the largest sediment-discharge rivers in the world, particularly along the Asian continent. While it would appear that many of these coasts have ample sediment to build barriers, the irregular topography of these margins leads to much of the sediment filling submarine valleys rather than forming barriers. In addition, the discharge from many Asian rivers has a very high suspended sediment component that may inhibit the concentration of sand-sized material. In fact, many of the marginal sea coastlines containing barriers, such as the chain found along the Nicaraguan and Honduran Caribbean coast, have no large sediment-discharge rivers associated with them. The origin of these barriers is probably tied to the reworking of previously deposited shelf sediments, similar to much of the East Coast of the United States.

Collision coasts also have few long stretches of barriers, but in this case, it is due to an overall lack of sediment. Most of the rivers discharging along these shores have small drainage areas and contribute little sediment for barrier construction. Additionally, the narrow, steep continental shelves of these margins result in high wave energy and rapid sediment dispersal along the coast. Along parts of the California coast some of the sediment that would ordinarily accumulate along the shore is drained from the beaches during storms through submarine canyons to the deep ocean basins. The proximity of the canyons to the beaches is attributed to the narrow continental shelf. Barrier systems that do occur along the West Coast are commonly isolated and related to specific sediment sources such as nearby rivers or eroding cliffs. Two of the longest barrier chains along collision coasts are located adjacent to major river mouths including the southern Washington barriers near the Columbia River and the Gulf of Alaska barrier chain fronting the Copper River delta.

A small percentage of the world's barriers are found along *Afro-trailing* and *Neo-trailing edge* coasts due to an overall lack of sediment along these margins. There is little sediment delivery to the Neo-trailing edge margins of the Red Sea, Gulf of Aden, and Gulf of California due to the immaturity in the development of river drainage along their coasts and the very low precipitation in these regions. Similarly, much of northern coast of Africa has little river discharge of sediment due to the very arid conditions of the interior region. The extensive barrier system (300 km) that exists along the Ivory, Gold, and Slave Coasts on the west-central coast of Africa is related to the numerous moderately-sized rivers of this area.

3.3 Climatic Controls

By controlling the amount of precipitation and evaporation of a continent, climate exerts a strong influence on the size and number of rivers as well as the overall volume of sediment delivered to the coast. A river's drainage area (defined as the continental area drained by the river) is another important factor governing sediment discharge. Usually the larger the drainage area (A_d) the greater is the sediment delivery to the coast, however, there are exceptions. The Eel River in northern California releases almost twice the sediment load to the coast as does the much larger Columbia River to the north, despite having a drainage area two orders of magnitude smaller (Eel R. A_d = 9000 km^2, Columbia R. A_d = 661 000 km^2). The high sediment discharge of the Eel River is a product of the mountainous terrain it drains and a bedrock landscape that weathers easily producing abundant sediment.

In summary, barriers are best developed along continental margins where sand-sized sediment is abundant and the coastline is fronted by a moderately wide, gently-sloping continental shelf and backed by a coastal plain. Under these conditions, barriers are able to migrate onshore in a regime of slow sea level rise. Direct contribution of sediment to the coast by rivers is not enough to insure the presence of barriers as evidenced by the eastern Asian coasts where barriers are sparse. The fine-grained sediment discharged from the rivers of this region may overwhelm the ability of waves to concentrate sand and form barriers.

4. Barrier Types

Although barriers have many different forms, for ease of discussion they are grouped into three major classes based on their connection to the mainland. Barrier spits are attached to the mainland at one end and the opposite end terminates in a bay or the open ocean. Welded barriers are attached to the mainland at both ends, whereas barrier islands are isolated from the mainland and surrounded by water.

4.1 Barrier Spits

Barrier spits are most common along irregular coasts where angular wave approach and an abundant supply of sediment result in high rates of longshore sediment transport. These conditions promote spit building across embayments and a general straightening of the coast. In some instances, spit construction partially closes off a bay forming a tidal inlet between the spit end and the adjacent headland. In these instances, tidal currents flowing through the inlet prevent spit accretion from sealing off the bay.

4.2 Spit Initiation

Spit formation is due to the deflection of sediment that is moving along a beach in the surf and breaker zones into a region of deeper water commonly associated with a bay or tidal inlet. This deflection may be initiated at small protrusions of the shoreline or at major headlands. Similarly, the process may occur at the edge of embayments along an otherwise smooth coastline. The explanation of why the longshore movement of sand forms spits rather than following a pathway along the irregular shoreline lies in the fact that wave energy decreases in embayments and thus the capacity of waves to move sand is reduced.

The movement of sand along a coast is a function of wave energy and breaker angle among other parameters. Consider an idealized case in which a wave crest extends a far distance along the shore such that it can be followed from where it breaks at an angle along the exposed beach to where it breaks within the bay. The section of wave breaking along the exposed beach will be higher and will expend more energy in the nearshore zone than the wave crest that breaks inside the bay. This makes sense because as the wave crest bends into the bay, it travels further than the wave breaking along the exposed coast and thus uses up more energy interacting with the seabed. Because the rate of sand movement is a function of wave height, more sand is transported along the exposed beach than inside the bay. This means that as sediment transport decreases from a relatively high rate along the exposed beach to a lower rate inside the bay, some sediment must be deposited along the way. This sediment accumulates at the edge of the embayment because this is where the change in the longshore transport rate is the greatest. It is this deposition of sediment that initiates spit growth.

Spits exhibit many different forms in addition to recurved spits, including cuspate spits, flying spits, tombolos, and cuspate forelands (King, 1972). Each of these accretionary landforms develops in specific geological settings and by particular coastal processes.

-
-
-

Bibliography

Belknap, D.F. and Kraft, J.C., 1985, Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Marine Geology, v. 63, p. 235-262. [Discusses influence of basement controls on coastal barrier evolution]

Bernard, H.A., Major, C.F., Parrott, B.S. and LeBlanc, R.J., 1970. Recent sediments of Southeast Texas: A field guide to the Brazos alluvial and deltaic plains and the Galveston barrier island complex. Bureau of Economic Geology, Univ. of Texas - Austin, Guidebook No. 11. [Classic example of a prograding barrier]

Davis, R.A., Jr. (ed.), 1994, Geology of Holocene barrier island systems. Springer-Verlag, 464 p. [Compilation of barrier studies from the United States with some global examples]

FitzGerald, D.M., and van Heteren, S., 1999, Classification of paraglacial barrier systems: coastal New England, USA, Sedimentology, v. 46, p. 1083-1108. [Discussion of barrier stratigraphy and evolution in paraglacial settings]

Hayes, M.O., 1979, Barrier island morphology as a function of tidal and wave regime. In: Leatherman, S.P., (ed.), Barrier islands: from the Gulf of St. Lawrence to the Gulf of Mexico, Academic Press, New York, p.1-28. [Classic work on barrier island morphology as a function of tidal and wave energy]

Hayes, M.O., 1994. The Georgia Bight barrier system. In: Davis, R.A., Jr. (ed.), Geology of Holocene barrier island systems. Springer-Verlag, p. 233-304. [Detailed account of how changes in wave and tidal energy, sediment supply, and basement controls affect coastal accumulation forms]

Hoyt, J.H., 1967, barrier island formation. Geological Society of America Bulletin, v. 78, p. 1123-1136 [Summary of theories of barrier island formation]

Inman, D.L. and Nordstrom, C.E., 1971, On the tectonic and morphologic classification of coasts. Journal of Geology, v. 79, p. 1-21. [Broad description of coastal morphology based on tectonic setting]

Johnson, D.W., 1919. Shore processes and shoreline development. New York: John Wiley & Sons, 584 p. [Classic volume on coastal landforms and development]

Jol, H.M., Smith, D.G. and Meyers, R.A., 1996. Digital ground penetrating radar (GPR): An improved and very effective geophysical tool for studying modern coastal barriers (examples for the Atlantic, Gulf and Pacific coasts, U.S.A.). Journal of Coastal Research, 12, p. 960-968. [Paper illustrating use of ground-penetrating radar]

King, C.A.M., 1972, Beaches and coasts. 2nd Ed. London: Edward Arnold, 570 p. [British textbook on coastal morphology and processes]

Kraft, J.C. and John, C.J., 1979, Lateral and vertical facies relations of transgressive barriers. Bulletin of American Association of Petroleum Geologists, v. 63, p. 2145-2163. [Retrogradational facies model of a barrier sequence]

Leatherman, S.P., 1979. Barrier Island Handbook. Amherst, Massachusetts, 101 p. [Book fining coastal terms]

Moslow, T.F and Colquhoun, D.J., 1981. Influence of sea-level change on barrier island evolution. Oceanis, 7, p.439-454. [Discussion of stratigraphy and evolution of Kiawah Island, South Carolina]

Nummedal, D., Oertel, G., Hubbard, D.K., and Hine, A., 1977. Tidal inlet variability – Cape Hatteras to Cape Canaveral, Proc. of Coastal Sediments '77. ASCE, Charleston, SC, 543-562. [Variability in wave and tidal energy as it pertains to coastal morphology in the Georgia Bight]

Reinson, G.E., 1984. Barrier island and associated strand-plain systems. In: Walker, R.G., (ed.), Facies Models, Geoscience Canada Reprint Series 1, p. 119-140. [Models of barrier stratigraphy]

Reinson, G.E., 1992, Transgressive barrier island and estuarine systems. In: Walker R.G., and James, N.P., (eds.), Facies models: response to sea level change, Geological Association of Canada, p. 179-194. {Discussion of factors controlling transgressive barrier and estuarine systems and resulting sedimentary signature]

Roy, P.S., Cowell, P.J., Ferland, M.A. and Thom, B.G., 1994. Wave-dominated coasts. In: Carter, R.W.G., and Woodroffe, C.D. (eds.), Coastal Evolution: Late Quaternary shoreline morphodynamics, Cambridge University Press, p. 121-186. [Detailed chapter on the stratigraphy, processes and evolution of wave-dominated coasts]

Schwartz, M.L., 1972, Spits and bars. Stroudsburg, PA. Dowden, Hutchinson and Ross, 452 p. [Compendium of papers dealing with spits and bars prior to 1970]

Schwartz, M.L., 1973, Barrier islands. Stroudsburg, PA. Dowden, Hutchinson and Ross, 451 p. [Compendium of papers dealing with barrier islands prior to 1972]

Tanner, W.F., 1995. Origin of beach ridges and swales. Marine Geology, v. 129, p. 149-161. [Discussion of beach ridge types and their classification and origin]

Thom, B.G., 1984, Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. Marine Geology, 56, p. 137-158. [Paper dealing with different barrier stratigraphic sequences along the Australian coast]

van Heteren, S. and van de Plassche, O., 1997. Influence of relative sea-level change and tidal-inlet development on barrier-spit stratigraphy, Sandy Neck, Massachusetts. Journal of Sedimentary Research, v. 67, p. 350-363. [Paper detailing the stratigraphic evolution of Sandy Neck, Massachusetts]

van Heteren, S., FitzGerald, D.M., Barber, D.C., Kelley, J.T. and Belknap, D.F., 1996. Volumetric analysis of a New England barrier system using ground-penetrating radar and coring techniques. Journal of Geology, v. 104, p. 471-483. [Volume determination of a barrier system in Saco Bay, Maine based on ground penetrating radar data and sediment cores]

Van Heteren, S., FitzGerald, D.M., McKinlay, P.A., and Buynevich, I.V., 1998, Radar facies of paraglacial barrier systems: coastal New England, USA. Sedimentology, v. 45, p. 181-200. [Classification of barrier facies based on their ground penetrating radar signature]

Zenkovich, V.P., 1967. Processes of coastal development. Oliver and Boyd, Edinburgh. [One of the original books on coastal landforms and processes of evolution]

Biographical Sketches

Duncan M. FitzGerald is a marine geologist in the Department of Earth Sciences at Boston University where he teaches courses in sedimentology, marine geology, and coastal processes. He received his Ph.D from the University of South Carolina and for the past 25 years has been conducting geologic research throughout the world, extending from the coastal zone to the inner continental shelf. During the past decade his research has centered on the hydraulics and sediment-transport characteristics of tidal inlets and estuaries and the morphostratigraphy of coastal sedimentary accumulation forms.

Ilya V. Buynevich is a Research Geologist at the Coastal and Marine Geology Program, U.S. Geological Survey, Woods Hole, and a Guest Investigator at the Woods Hole Oceanographic Institution. He holds a Ph.D in geology from Boston University and conducts research on stratigraphy and evolution of coastal barriers, with the focus on marginal marine sedimentary sequences as archives of environmental change. His recent studies emphasize the use of high-resolution onshore and marine geophysical methods in coastal research.