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Beach-Ridges: A Review

Matthew Taylor and Gregory W. Stone

Department of Geography and Anthropology
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

ABSTRACT

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A review of the beach-ridge literature is provided with emphasis on those composed of sand. Although confusion in the literature exists on differentiating beach-ridges from cheniers, both are viewed here as morphogenetically distinct. Several models describing the evolution of beach-ridges in diverse coastal settings have been published. Review of these models indicates that beach-ridges are deposited by swash during high or low wave-energy conditions, and may also emerge through aggradation of an offshore bar. Additionally, numerous models emphasize the role of vegetation and aeolian deposition in the stabilization, accretion, and preservation of beach-ridges.

Beach-ridges generally prograde when an abundance of sediment exists and the offshore gradient is low. Sea-level changes do not determine beach-ridge growth, but can affect the orientation and elevation of beach-ridge sets in a beach-ridge plain. Interruption, truncation, erosion of beach-ridges, and deposition of younger beach-ridges with a different orientation and shape may be caused by climate, sea-level, or sediment supply fluctuations. Thus beach-ridges are utilized in the reconstruction of sea-level, climate, and sediment budget histories.

Growth rates of beach-ridges are studied in an attempt to elucidate rates of coastal progradation. Absolute quantification of beach-ridge growth rates is limited by the scarcity of reliable *in situ* material for dating. Growth rates can also be erroneous due to erosion of some beach-ridges making up a beach-ridge plain. The study of beach-ridges has progressed from descriptions of their morphology and discussions on beach-ridge origin, to the use of these landforms in the interpretation of paleo-environments.

ADDITIONAL INDEX WORDS: *Beach-ridges, cheniers, sea-level, coastal progradation.*

INTRODUCTION

It is the objective of this paper to provide a review of published research conducted on beach-ridges primarily composed of sand-size material. Although beach-ridge studies have been conducted worldwide, a thorough literature review has not yet been published (JOHNSON, 1919; ALEXANDER, 1969; CARTER, 1986). Beach-ridges are azonal features implying local morphodynamic controls on progradation. Considerable diversity of thought exists regarding modes of beach-ridge construction (REDMAN, 1852; JOHNSON, 1919; DAVIES, 1961; BIGARELLA, 1964; CURRAY et al., 1967; PSUTY, 1967; ALEXANDER, 1969; TANNER, 1970; WRIGHT, 1970; STAPOR, 1975; CARTER, 1986; MASON, 1991). A significant number of causative mechanisms have been identified, and used to elucidate genetic models. In this paper, we carefully review what may be viewed as a disparate group of models with the objective of identifying common linkages.

It is perhaps worthy of note at the outset that confusion in the terminology used to denote beach-ridges and cheniers exists. A beach-ridge is dissimilar morphologically and stratigraphically when compared to a chenier. A chenier is a coastal ridge, which constitutes a once active beach, composed of sand and shell overlying muddy, nearshore, intertidal or marsh deposits, surrounded by mud flats and marshes (OTVOS and PRICE, 1979). The finer deposits of the swales between the chenier ridges are the dominant facies in chenier plains (at least two subparallel beach-ridges separated by a progradational littoral muddy unit). Beach-ridge plains are composed mainly of ridges without the large intervening swales (OTVOS and PRICE, 1979) (see Figure 1). As defined by STAPOR (1975), beach-ridges are "linear mound-shaped ridges roughly paralleling the coast. Ridge crests have elevations well above mean high tide, and the bottom of the adjacent troughs or swales have elevations not far from mean low tide." The native material comprising beach-ridges is usually similar in composition to the adjacent beach, however, textural differences may be apparent. Beach-ridges are progradational landforms occurring in the foreshore and considered the product of wave and wind deposition occurring at the upper limit of wave run up (SAVAGE, 1959; STAPOR, 1975; SUNAMARA, 1975; CARTER, 1986).

MODELS OF BEACH-RIDGE ORIGIN

The concept of beach-ridges was first introduced by Redman (1852, 1864) in his work on shoreline change along the south and east coasts of England. This, and subsequent work carried out in the latter half of the 19th and first half of the 20th century, resulted in early models that persist today, although in modified forms. While the work of Redman (1852) helped formulate the first causal link between storms and beach-ridge development, significant debate arose after the exposition of D. W. Johnson's text *Shore Processes and Shoreline Development,* in 1919. JOHNSON (1919) debated the importance of storm-driven waves as a mechanism for beach-

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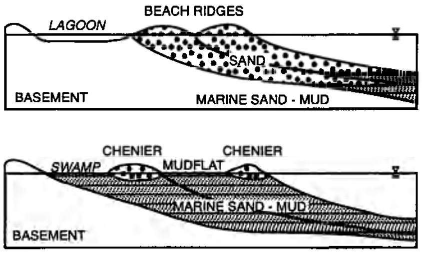

Figure 1. Structural differences between beach-ridges and cheniers (modified from Smart, 1976).

ridge development and, as an alternative, wrote on the importance of lower energy swell waves in beach-ridge origin. Both schools of thought have persisted since these early writings and have played a critical role in guiding the more recent literature. Thus, the development and subsequent modification of both models are presented below.

Beach-Ridge Formation During High Wave-energy Events

Storm waves were considered by Redman (1852) as the sole possible mechanism by which shingle could be deposited to form ridges. Storm waves of different approach orientations could result in subsequent destruction of ridges (Redman, 1852). Ting (1936) also stressed the importance of storm waves in the construction of cobble beach-ridges in South-West Jura, Scotland. Although Psuty (1967) argued that the Tabascan beach-ridge plain in the southern Gulf of Mexico was constructed by storm waves or "nortes", he noted the importance of low wave-energy events during the summer when sediment was transported to the nearshore and subsequently reworked into beach-ridges by larger storm waves (Figure 2). Psuty's conclusions were based on the internal structure of the beach-ridges mainly at one locality: an inlet bar/spit. Here landward dipping beds indicated the significance of overwash during the constructive phase. Similar conclusions were reached by Thom (1964) in a study of prograding beach-ridges on Isla del Carmen, Mexico.

The rate of beach-ridge progradation has received considerable attention and, as noted by Davis (1958a), should be carefully considered within a geographical context, particularly on considering where the early English writers (Redman, 1853; Johnson, 1919; Lewis, 1932; Ting, 1936) made their observations. These beaches, such as the Dungeness Foreland, are composed of pebbles. Thus, even during storms, it is possible that material can be deposited on the upper beach despite the increase in backwash which plays a significant role in removing sediment offshore on finer-grained beaches (Carter, 1988). Pebbles, or other coarse sediments on the beach, enhance percolation rates leading to increased deposition at the limit of wave run-up. The velocity of the backwash is severely inhibited thus reducing its capability to remove material deposited during run-up (Carter 1988). Arguments supporting the formation of beach-ridges during high wave-energy events appear convincing on coarse clastic beaches (Cushing Woods and Leahy, 1983, 1986; Mason, 1991).

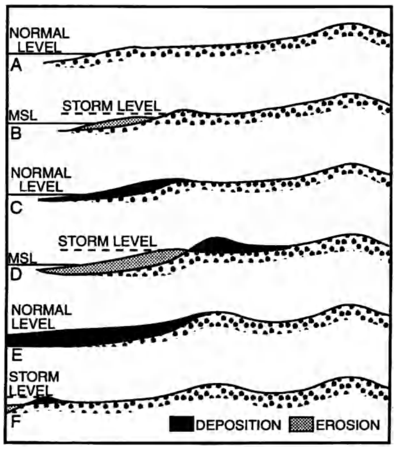

Figure 2. Beach-ridge construction according to Psuty. Sediment is deposited in the foreshore during "normal" conditions and subsequently reworked into beach-ridges by storms or "nortes" (modified from Psuty, 1967).

Construction of Beach-Ridges During Swell Conditions

A significant body of literature concludes that beach-ridges are constructed during moderate wave conditions and are not storm-related features. In his early writings, Johnson (1919) proposed the significance of swell conditions to the constructive phase of beach-ridges, whereas storm waves initiated and maintained ridge erosion. Evidence delineating the importance of swell conditions first emerged from the Australian literature in the late 1950's where the finer details of beach-ridge origin were being debated (Davies, 1958a; McKenzie, 1958; Bird, 1960; Thom, 1964; Hails, 1969; Wright, 1970; Cook and Polach, 1973; Smart, 1976; Short and Hesp, 1982). The Australian literature is somewhat confusing regarding the terminology surrounding beach-ridges. Not until 1984 was a distinction made between dune or aeolian ridges and predominately marine-formed beach-ridges (Hesp, 1984).

Davies (1958b) explained beach-ridge construction through a process of cut and fill, controlled by the dynamics and characteristics of waves and their resulting swash during storm and non-storm events. According to Davies (1958b), fill occurs during periods of constructional swell waves forming a berm. Cut is dominant during periods of erosive storm waves (Fig. 3). The berm is the only constructional feature on the beach and, therefore, may be considered an incipient beach-ridge (Fig.3). Berm deposition is followed by a period of rapid vegetation colonization which results in beach-ridge aggradation through aeolian deposition. McKenzie (1958) refuted the berm as the nucleus for beach-ridge development, and stated that if a berm was isolated from the effects of waves, it would undergo rapid deflation by wind prior to vegetation colonization and stabilization. McKenzie (1958) also suggested that the gently landward dipping slope of a berm

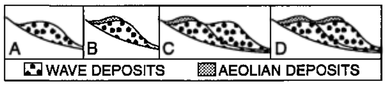

Figure 3. The wave/wind model of beach-ridge formation proposed by Davies. A: Berm is deposited in times of "fill", B: aeolian sand accumulates to form a "beach-ridge", C: another berm is built seaward, D: the second ridge is formed (modified from Davies, 1958).

is not extreme enough to account for the height differences between the crest and swale of a beach-ridge. In addition, he postulated that beach-ridges are the product of vegetation trapping sand at the toe of a foredune resulting in ridge formation and aggradation.

Thom (1964) argued that vegetation played no significant role in the construction of beach-ridges in Tabasco, Mexico; although it enhanced their preservation potential. Additionally, Thom (1964) proposed an alternative to the Davies (1958) wind/wave model, and the aeolian/vegetation model of McKenzie (1958), arguing that vegetation could be both a constructional and preservational agent. Bird (1960), on the other hand, supported the Davies model, and stated that a foredune is constructed on top of a berm. Subsequent "cut" removed some of the sediment from the foredune to form a new berm in front of the old ridge or foredune. The stabilization effects of vegetation were stressed by Bird (1960) enhancing further growth of the ridge, not the swale, as the vegetation colonized the less saline crest. Hails (1969), in his study of the Umina-Woy Woy beach-ridge system in New South Wales, Australia, supported the model of Davies (1958b). He indicated that beach-ridges originate as berms that are rapidly colonized by vegetation, thus enabling the ridge to grow in size.

In a review of Australian beach-ridge literature, Hesp (1984) refuted the models of Davies (1958b), Bird (1960), and Thom (1964), and argued that beach-ridges owe their alignment to vegetation forming at the upper limit of swash. Subsequent ridge growth is accomplished by aeolian deposition (Fig 4). Based on work carried out in New South Wales, Australia, Hesp (1984) suggested that the internal structure indicates an aeolian origin for beach-ridges, and that they appear as relict foredunes. It is apparent that inconsistencies in Australian literature regarding terminology has caused confusion. More recent research on Australian beach-ridges (Hails and Gostin, 1979; Bowan and Harvey, 1986), has tended to emphasize interpretation of beach-ridge plain evolution in terms of sea-level history and sediment supply fluctuations.

Extensive work on beach-ridges was conducted and published in the United States during the 1960's and 1970's. Research and conclusions reveal that no perplexing terminology exists in the US literature, a beach-ridge is considered primarily marine in origin with occasional dune decoration (Savage, 1959; Curray et al., 1967; Psuty, 1967; Missimer, 1973; Tanner, 1970, 1973, 1974, 1987, 1988; Tanner and Stapor, 1971, 1972; Tanner and Hockett, 1973; Stapor, 1971, 1973, 1975; von Drehle, 1973; Stapor and Tanner, 1975, 1977; Chaki, 1974; Fraser and Hester, 1977). Studies of beach-ridge deposits by Ul'st (1957) at the head of Riga Bay, Latvian SSR, also indicated that beach-ridges are formed primarily by marine processes.

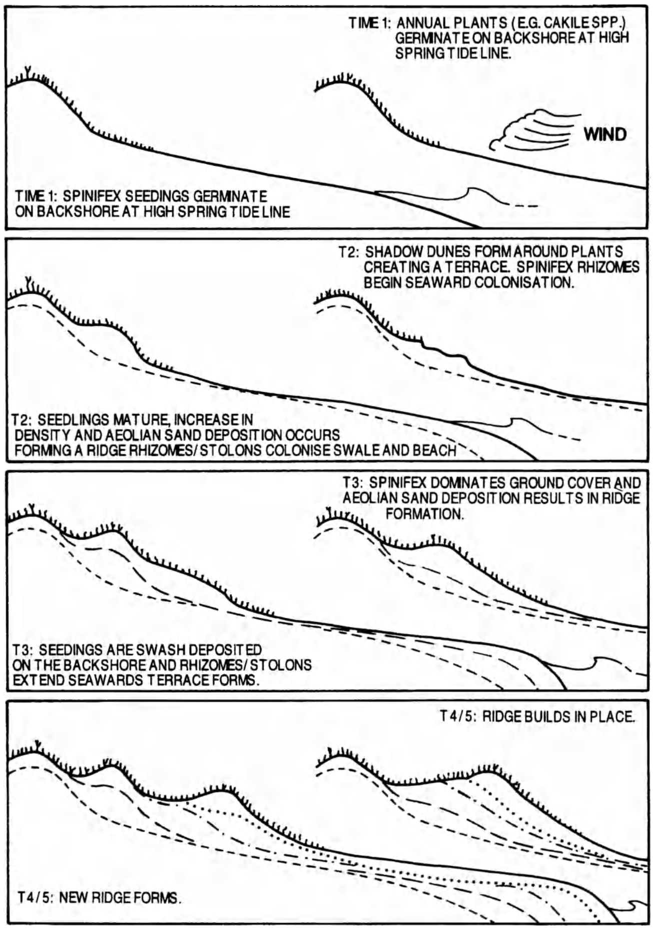

Figure 4. Beach-ridge development due to aeolian sediment transport and trapping by vegetation (modified from Hesp, 1984).

Emergent Bar Model

Drawing on data obtained along the Paraná coastal plain of Brazil, Bigarella (1965) concluded that the emergence of an offshore bar may play a critical role in ridge development. Bigarella's work shows a strong similarity between the internal stratification of beach-ridges and the structure of longshore bars formed in the laboratory. There is, however, a degree of uncertainty about the specific conditions of deposition. Observations of the Nayarit coastal plain, Mexico, by Curray et al. (1967) also indicate the potential significance of longshore bar emergence (Figure 5). The emergent bar requires low wave-energy conditions for enlargement and emergence above sea-level. Storms following immediately after bar emergence would result in removal of the sediment offshore. Curray et al. (1967) base this model on the observation that "the average spacing of beach-ridges in the strand plain is similar to the distance between the submerged bar and the

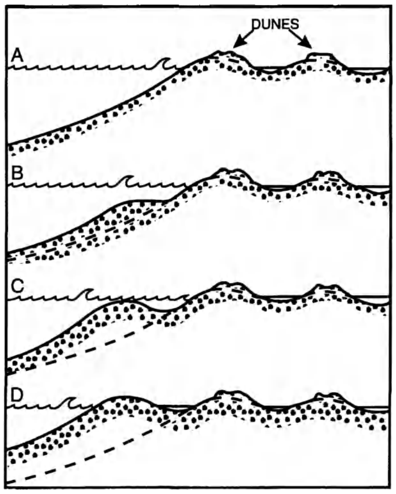

Figure 5. Emergent bar model of beach-ridge formation reliant on low wave-energy conditions for emergence above sea-level (modified from CURRAY *et al.*, 1967).

present beach-ridge." Unfortunately, data supporting this finding in the form of internal bedding in either beach-ridges or bars, were not reported.

Beach-Ridge Construction by Swash

Individual beach-ridge construction in Tabasco was considered by TANNER and STAPOR (1971) to be the product of swash. TANNER and STAPOR (1971) demonstrated that the internal structure of these beach-ridges, contrary to the observations of PSUTY (1967), are low angle, seaward dipping, planar beds with little aeolian sands, indicating swash construction. Additionally, STAPOR and TANNER (1971) refuted a one or two storm constructional scenario for the ridges because the internal bedding is highly complicated, indicating slow growth periods for each ridge. Their work suggested the following: 1) beach-ridges are built by processes in the swash zone; 2) storm waves play no role in beach-ridge development; 3) beach-ridges are deposited slowly, i.e. not during one high wave-energy event; 4) sea-level fluctuations are an important parameter in controlling the orientation and morphology of beach-ridge plains, not changes in energy condition; and 5) longshore or offshore delivery of sand is responsible for constructing beach-ridges, each process resulting in different ridge shape and orientation. TANNER and STAPOR (1972) stated that under constant wave conditions, a small berm will be deposited at the upper limit of swash. If constructive waves prevail, seaward progradation and increases in elevation result in beach-ridge development. Formed in this fashion, beach-ridges demonstrate predominantly seaward dipping beds.

Abnormally wide beach-ridges of Pleistocene age have been observed in Florida by VON DREHLE (1973). Although internal structures include seaward dipping beds similar to the modern ridges in other parts of Florida, the depositional mechanism of these features remains uncertain (VON DREHLE 1973).

As can be readily gleaned from the previous discussion, a widely accepted model on the origin of beach-ridges does not exist. A basic understanding of beach-ridge formation and the surrounding parameters is necessary in order to comprehend their importance in aiding interpretations of depositional environment such as sea-level, climatic conditions, wave height, sediment source, and sediment transport directions.

PARAMETERS DETERMINING BEACH-RIDGE CONSTRUCTION

JOHNSON (1919) recognized the basic parameters influencing beach-ridge construction. Beach-ridges will be prograded "whenever longshore currents of any type bring to the beach more debris than the waves there operating can remove" (JOHNSON, 1919). Johnson stated, as is seen in much of the later literature (DAVIES, 1958; BOWMAN *et al.*, 1989), that a shallow offshore bottom is also necessary to aid the formation of shoaling waves which bring the sediment onshore. This process, JOHNSON (1919) observed, would continue until the offshore profile steepened as the slope equilibrated with the existing waves. Moreover, dimensions of beach-ridges, were controlled by the size of waves and rate of sediment supply; more rapid sedimentation resulting in smaller beach-ridges (JOHNSON 1919). Formation and destruction of beach-ridges in the Netherlands was studied by DOEGLAS (1955). He considered that the direction of the wind was important in controlling the sea-level near the coast, which in turn influenced currents in the land and seaward direction. MCKENZIE (1958) pointed to the abundance of sediment provided by a fall in sea-level as an important parameter in beach-ridge formation. He stressed beach-ridge formation is not reliant on sea-level fluctuations, but on abundant sand supply and emphasized vegetation as a vital parameter in beach-ridge building and stabilization.

DAVIES (1958a) correlated storm waves with a "cutting" process due to enhanced backwash capabilities. He discussed the importance of a low gradient inner shelf, an abundance of sediment and protection from unrefracted waves as the basic prerequisites for beach-ridge initiation. NOSSIN (1964), in his work on beach-ridges in Malaysia, concluded that bathymetry of the inner shelf, the strength and direction of waves and currents, supply and nature of sediment are crucial in influencing beach-ridge construction. In a study of the Umina-Woy Woy beach-ridge system, NSW Australia, HAILS (1969) emphasized tidal range, seasonal changes in the beach offshore profile, the configuration of the adjacent bedrock coastline, and an abundant supply of sand as vital parameters in beach-ridge construction. WRIGHT (1970) investigated how sediment availability affected the pattern of beach-ridge development flanking the Shoalhaven River delta, NSW, Australia, and concluded that beach-ridge construction was controlled by two variables: 1) wave regime governed the geographic orientation of the beach-ridges; and 2) proximity to the river mouth confluences governed the type and size of sediment supplied to the beach-ridges. Analysis of beach-ridge deposits on the Caribbean coast of Costa Rica by NIEU-

Wenhuyse and Kroonenberg (1994) revealed that periodic beach-ridge progradation is related to sediment supplied by volcanic eruptions. During such eruptions, rivers draining the Costa Rican Central Cordillera transport an abundance of sediment to the coast which is then deposited as beach-ridges.

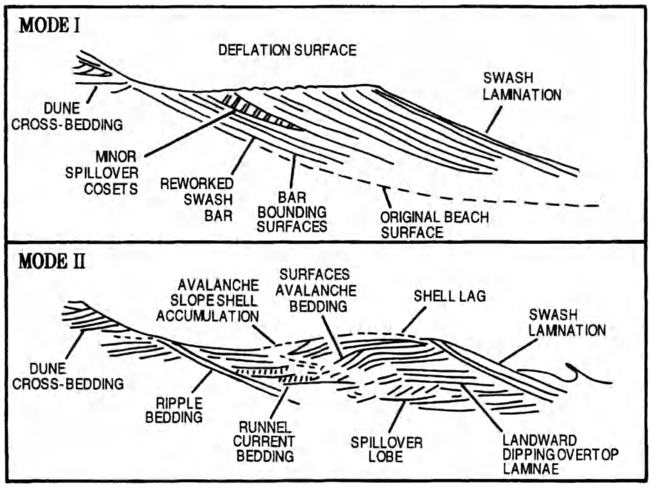

Figure 6. Differences between Type 1 and Type 2 beach-ridges shown by transverse section, Magilligan Foreland, Northern Ireland (modified from Carter, 1986).

Elevational change of individual beach-ridges has been vigorously debated, particularly in Australia. Thom (1964) proposed the seaward decrease in height of beach-ridges observed by Davies (1961) may be related to a steady decrease in availability of sediment and not a fall in sea-level. This contradicts observations made by other authors (Johnson, 1919; Davies, 1958; Stapor, 1988), who claimed a reduction in sediment supply produces larger ridges as longer periods are allowed for individual beach-ridge construction. Perhaps one of the more convincing arguments was forwarded by Tanner and Stapor (1972) who viewed wave run-up and beach slope as being critical in the initiation of sediment deposition near the maximum extent of uprush. Increased wave-energy levels and tidal range enhance beach-ridge construction, the cessation of which will only occur during a phase of reduced sediment supply (Tanner and Stapor, 1972). In a later paper, Stapor (1975) argued that the elevational change within geographically juxtaposed beach-ridge sets, may well reflect a sea-level adjustment along the northeast Gulf of Mexico coast. During a regression, new sediment sources are made available to a lowered wave base. As a transgression begins, this new sediment, deposited near the beach during the regression, is reworked into beach-ridges.

Studies of Magilligan Foreland, Northern Ireland, by Carter (1986), demonstrated that two types of beach-ridges are constructed. Type 1 is formed by gradual accretion and coalescing of swash bars by shore normal sediment transport; beach-ridges constructed in this manner exhibit seaward dipping laminae. Type 2 involved longshore sediment transport in which beach-ridges form "from the elongation and welding of nearshore bars as they pass into adjacent wave domains." Landward dipping beds are characteristic of these beach-ridges (Fig. 6). Carter (1986) suggested that regardless of type, beach-ridges are formed under certain conditions—especially on prograding coasts where sediment influx into the littoral zone is high. Abundant sediment accumulates in offshore bedforms which can then "feed" beach-ridges through onshore transport by waves.

Similar conclusions have been reached elsewhere where beach-ridge plains are located in areas where an abundant littoral sediment-supply exists. Along the northeast Gulf of Mexico, intermittent beach-ridge plains owe their location to a marked decrease in inner shelf slope along the northwest Florida and Alabama coasts (Stone, 1991; Stone et al., 1992; Stone and Stapor, this volume). A regional increase in wave-energy along this coast results in the availability of inner shelf material for onshore transport from distances up to 4km offshore (Stone, 1991). Differential beach-ridge plain elevations indicate complex sea-level stands—sediment availability relationships during the Late Holocene (Stapor, 1975). However, it is apparent that although the shoreline has maintained stability over at least the last 150 or so years, the supply of sediment to the littoral zone has decreased (Stone, 1991; Stone and Stapor, this volume). This is evident through the truncation and aeolian capping of the seaward-most ridges. What is apparent, although not yet fully documented along this coast, is that the system has crossed a sediment-supply threshold from abundance to scarcity. During the abundance phase, beach-ridge progradation occurred through a predominant supply of sediment from the shelf. During the scarcity phase a reduction in supply from the shelf is evident through the cessation of beach-ridge plain growth. However, the beach system did not experience widespread, pronounced erosion, but rather its morphology was transformed by aeolian deposition into: 1) accretion of the primary dune; and 2) aeolian capping of beach-ridges by sand transported from rapidly deflating swales. The relationship between sediment scarcity, reduction in beach-ridge plain progradation, and the initiation of dune-ridge building is also reported by Ul'st (1957) from beach ridges in the Latvian SSR.

It is evident in the North American literature that a general consensus exists on the more significant factors influencing beach-ridge construction: abundant sediment supply in the nearshore; lower wave-energy regimes—although storm waves may not always be destructive; and fluctuations in sea-level. It is clearly apparent, however, that while much of our knowledge evolved from the work of W.F. Tanner and students at Florida State University, we are perhaps biased towards a generally constructive, low wave-energy regime and micro-tidal setting of the Gulf of Mexico. Nevertheless, the Gulf of Mexico is a particularly appropriate setting for elucidating beach-ridge morphodynamics because of the high preservation potential of beach-ridge plains, particularly along the northeast and southern Gulf coastlines.

GROWTH RATES OF BEACH-RIDGES

Growth rates of beach-ridges although documented (Davies, 1958a; Curray et al., 1967; Carter, 1986), are highly variable. Generally, high rates of sediment influx are reflected in smaller ridge dimensions, whereas large beach-ridges indicate periods of reduced sediment availability (JOHNSON, 1919; DAVIES, 1958a). DAVIES (1958a) emphasized that rapid deposition resulted in low and closely spaced ridges with very regular profiles, whereas slower deposition resulted in characteristically longer ridges with wider swales and an irregular profile.

Many studies of beach-ridge growth aided by C-14 dating have been completed. CURRAY et al. (1967) used this method to illustrate variations in progradational rates of beach-ridge sets within the Nayarit beach-ridge plain. This, they suggested, indicates fluctuations in the sediment supply, indicating that beach-ridge building varied between 12 to 16 years for each ridge. Based on radiometric dating, MISSIMER (1973) calculated a ridge growth rate of between 8–15 years per ridge along Sanibel Island, Florida. TANNER and STAPOR (1971) and STAPOR (1975, 1988, 1991) indicated that beach-ridge plains undergo complex histories of intermittent growth reflected by the different orientations of beach-ridge sets. No absolute time for individual beach-ridge formation is proposed by STAPOR (1988), but he discussed, as did JOHNSON (1919) and DAVIES (1958), that differences in beach-ridge morphology indicate different rates of progradation.

Rates of beach-ridge plain progradation can be obtained using archaeological dating in areas where a well defined lithic or ceramic chronology exists (STAPOR, 1975; DEPRATTER and HOWARD, 1977). This technique is particularly useful when geologic material for dating is scarce. Radio carbon dates from habitation sites on a beach-ridge plain south of the Savannah River, Georgia, were used by DePratter and Howard to define progradation of 10-km for this section of the coast over the last 4500 years.

BEACH-RIDGES AS INDICATORS OF DEPOSITIONAL-ENVIRONMENTS

Beach-ridges can provide records of past wave regimes, climate conditions, sediment supply, sediment source, and sea-level change (CURRAY et. al., 1967; STAPOR, 1975; FAIRBRIDGE and HILLAIRE-MARCEL, 1977). JOHNSON (1919) recognized that beach-ridges have value as indicators of relative sea-level change and proposed that beach-ridges becoming progressively higher inland, may indicate isostatic emergence. Beach-ridges decreasing in elevation landward, indicate land submergence. Individual beach-ridge elevations, DAVIES (1958a) stressed, do not reflect sea-level change because elevation is governed by wave height and duration of the construction period. DAVIES (1961) stated that where beach-ridges reflect changes in sea-level, the evidence will be obvious, such as an overall tilt of the beach-ridge plain.

PSUTY (1967) indicated that the Tabascan beach-ridge plain demonstrates through truncation and differing orientation of each ridge set, an interruption in the sequence of deposition. This view is also held by STAPOR (1975, 1988), TANNER (1988), and CURRAY et al. (1967). CURRAY et al. (1967) suggested that erosion and truncation of older beach-ridge sets was a function of climatic cooling which caused a change in wind direction, wave regime, longshore drift and thus orientation of beach-ridges. The authors interpreted the evolution of the Nayarit strand plain in terms of climatic change, estimating cool/stormier weather periods and periods of hotter/calmer weather. Beach-ridges on the east side of Hudson Bay, according to FAIRBRIDGE and HILLAIRE-MARCEL (1977), have a 45 ± 5 year cyclicity. The relative uniformity of this isostatically-emerged beach-ridge plain is a consequence of the Double Hale solar magnetic cycle which influences a 45 year interval between major storm cycles in the area.

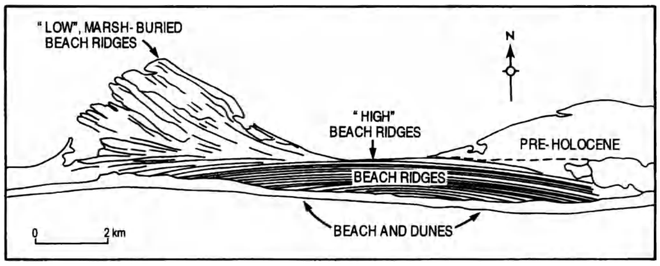

Figure 7. Truncating beach-ridges in Baldwin County, Alabama, which display differing orientations and elevations, interpreted by Stapor (1975) as indicative of fluctuations in sea-level (modified from STAPOR, 1975).

HAILS (1969) proposed that the Umina-Woy Woy beach-ridge plain, Broken Bay, New South Wales, reflects construction during a fall in sea-level in the Holocene. However, HAILS and GOSTIN (1979) presented conclusive evidence from the pebble beach-ridges in the Upper Spencer Gulf, South Australia, that high sea-level and wave energies existed in the Pleistocene and early Holocene epochs. The orientation and sedimentological composition of these ridges suggest that they were built under conditions that are not operative today (HAILS and GOSTIN, 1979). Strong arguments are presented (STAPOR, 1975, 1988, 1991; TANNER, 1988; and STAPOR and TANNER, 1977) against fluctuating wave-energy levels as the agent forcing truncation and erosion of beach-ridge sets. STAPOR (1975) stated that the continued lateral continuity and distinct difference in elevations of beach-ridges of known ages reflect fluctuations in sea-level with energy conditions remaining fairly constant (Fig 7). The orientation of beach-ridges can assist in reconstructing paleo-littoral drift processes (STAPOR, 1973 1975; TANNER, 1974, 1987; STONE, 1991; STONE and STAPOR, this volume).

TANNER (1974, 1987) concluded that individual beach-ridge shape and orientation is an indicator of littoral-drift processes and sources of sediment. Beach-ridge plain shape may also indicate fluctuations in sediment supply. Shorter seaward ridges may represent a general decrease in sediment supply. Longer seaward ridges may be indicative of a general increase in sediment supply to the beach-ridge plain. TANNER (1974, 1987) suggested that parallel or near parallel beach-ridges are indicative of shore-normal transport and deposition. Additionally, TANNER (1974) indicated that as beach-ridge taper increases, especially in cases of bi-directional taper, the importance of shore-parallel littoral-drift increases. Beach-ridge curvature, concave or convex, according to TAN-

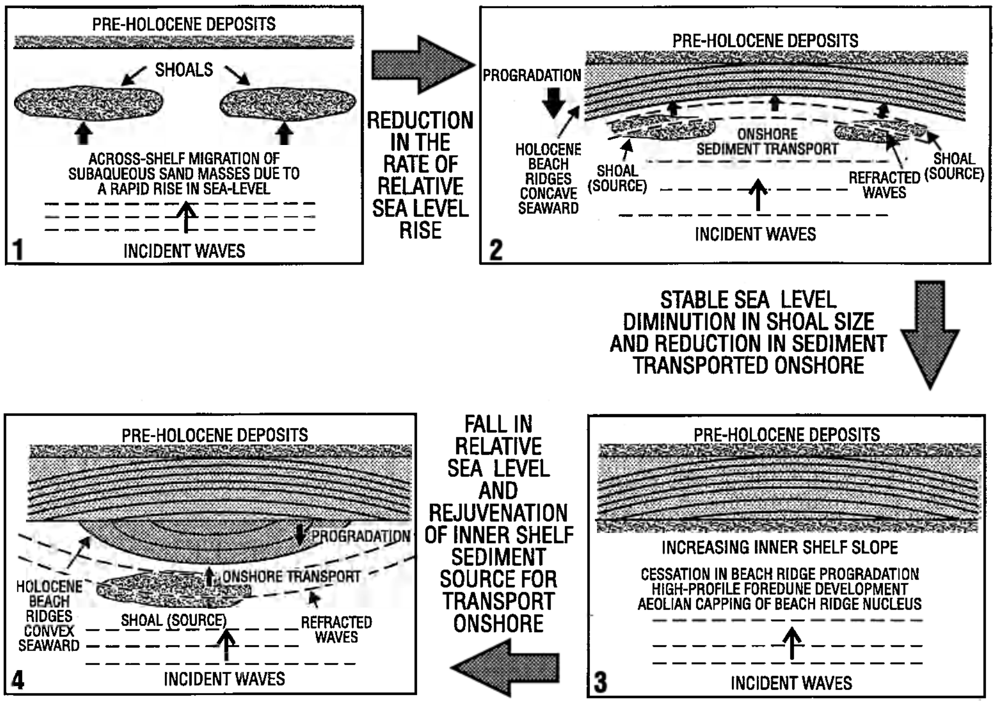

Figure 8. A conceptual model for the development of concave and convex seaward beach-ridge deposits along a low gradient inner shelf.

NER (1974), is an indication of features such as headlands, shoals, or capes, which affect wave refraction.

Although the critical links between sea-level and beach-ridge development are still debated (*cf* STAPOR, 1975; CARTER, 1988), it is evident that a reduction in the rate of sea-level rise during the mid Holocene permitted onshore transport processes to dominate the littoral system along low-gradient inner shelves. Drawing from the work of STAPOR (1975) and STONE (1991), it is apparent that changes in the geometry of beach-ridges along the N.E. Gulf of Mexico coast can be partially explained by variations in sea-level stands. An abundance of sediment on the inner shelf in the form of subaqueous shoals may have provided a source of sediment for direct transport onshore (Fig. 8). Subsequent seaward progradation of beach-ridge plains would have decreased during a period of sea-level stability during which the inner-shelf slope began increasing. The cessation of sediment supply from offshore would result in the development of higher-profile foredunes, transgressing the seaward margin of the beach-ridge plain. A subsequent fall in sea would be required to rejuvenate the offshore source of sediment, resulting in geometric switches from concave seaward to convex beach-ridge plains (Fig. 8).

TANNER (1991, 1992a,b, 1993) and TANNER et al. (1989), suggested that useful information for reconstruction of the Gulf of Mexico sea-level curve may be obtained from granulometric analysis of beach-ridge sediments. TANNER (1991) stated that wave-energy density in the surf zone is an inverse function of kurtosis on nearly straight beaches. Kurtosis values have been shown by TANNER (1991, 1992b) to vary between beach-ridge sets of distinctive elevations within a beach-ridge plain. Low kurtosis values (near the Gaussian K = 3) are found on the topographically higher ridge sets indicating higher wave-energy. Higher kurtosis values are representative of topographically lower beach-ridge sets and reduced wave-energy. Changes in kurtosis values across set boundaries with distinctive elevations indicates a change in wave-energy. Variation in wave-energy levels, TANNER (1992b) concluded, do not represent fluctuations in general storminess, but are indicative of changes in water-level. Rise in sea-level provides a substantial increase in wave energy along the coast as less energy is lost from shoaling waves before breaking.

MASON (1991) proposed that beach-ridge complexes are a "proxy record of climatic fluctuations" and that "differences in storm frequency and intensity explain variations in the sedimentation regime". Additionally, MASON (1993) demonstrated from many examples around the world how archaeological data from coastal settlements can be utilized with care to aid in the dating of coastal progradation of beach-ridges and cheniers. Beach-ridges can also be used to help correlate cultural deposits in or on beach-ridge plains (MASON, 1993). CUSHING WOODS and HEALY (1983, 1986) regard beach-ridges as significant aids in understanding paleo-geography as the ridges record shoreline position through time. CUSHING WOODS and HEALY (1986) correlated geographically separated sets of beach-ridges along the Baja California Norte Coast of Mexico to demonstrate that the shorelines may have prograded at similar time periods. MOSELY et al. (1991) argued that beach-ridges have important cultural im-

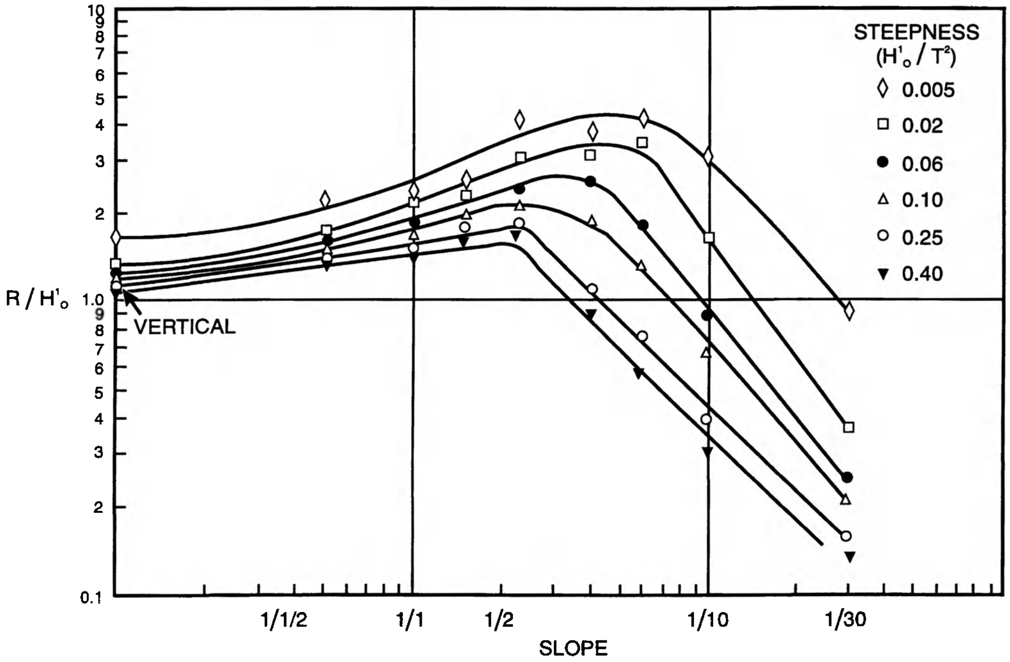

Figure 9. The relationship between relative wave run-up (R/H), beach slope, and deep water wave steepness and height (modified from SAVAGE, 1959).

plications along the arid Andean Coast and are indicative of "abnormally stressful conditions." The ridges are a consequence of major tectonic events which loosen terrestrial sediment. Transport to the coast of the previously released sediment may occur during later El Niño Southern Oscillation (ENSO) events when abnormally high rainfall is experienced in this arid environment. These beach-ridges may thus record a history of ENSO events during the late Holocene, and could be significant for ENSO event prediction.

BEACH-RIDGE STUDIES IN THE LABORATORY

Limited work has been conducted on beach-ridge formation in the laboratory. In one of the earliest laboratory studies, SAVAGE (1959), determined the relationship between relative wave run-up (R/H), beach slope, and wave steepness in a wave tank. As shown in Figure 9, Savage (1959) demonstrated that run-up increases with decreasing slope for a given wave steepness prior to a rapid decline. In situations where the slope achieved by the foreshore of the beach-ridge does not reach the slope maximum (Fig. 9), the height of beach-ridges would be governed by the maximum slope of the foreshore and run-up.

SUNAMARA (1975) concluded that the interaction of swash and beach material determine beach-ridge construction. This mechanism is difficult to observe in nature and in the laboratory due to the complexity of phenomena in the swash zone. Swash is governed by deep water waves and submarine slope, so these two factors along with beach material must be considered in the calculation of an empirical formula to explain beach-ridge construction (SUNAMARA 1975).

$$H_0/L_0 = C(\tan \beta)^{-0.27} (d/L_0)^{0.67} \quad (1)$$

where H_0 = deep water wave height, L_0 = deep water wave length, $\tan\beta$ = submarine slope, d = median or mean diameter of beach material, C = constant with a value of 3.

From this equation Sunamara indicated that beach-ridges will occur with higher probability at places having a gentler submarine slope, or larger material size, other factors remaining constant.

Beach-ridge formation models in the laboratory are simple when compared to beach-ridge formation processes in nature. SAVAGE (1959) stressed that models of beach-ridge construction do not exactly emulate natural processes, but they do embody the basic principles involved in beach-ridge construction and lead to a better understanding of beach-ridge formation in nature.

CONCLUSIONS

1) The study of beach-ridges has progressed from simple descriptions of their structure to utilizing these coastal landforms to aid in the interpretation of past sea-levels and climate.

2) Current models explaining beach-ridge evolution suggest that beach-ridges are formed by swash during high or low wave-energy conditions, the emergence of offshore bars, or through a combination of wave and wind deposition. Despite the diversity of models, explicable given the azonal nature of beach-ridges, most models require an abundance of sediment and a low offshore gradient as necessary parameters in beach-ridge plain evolution.

3) Absolute rates of individual beach-ridge building are considered "estimates" until dating methods improve. Relative rates of beach-ridge progradation, however, are often in-

dicated by change in beach-ridge dimensions: Smaller, closely spaced ridges indicate rapid progradation; ridges of larger dimensions and greater spacing point towards relatively slower rates of growth.

4) Geometry, orientation and elevation of beach-ridge sets and plains are good indicators of past sea-levels, morphodynamic and climatic conditions.

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