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Beach ridges — definitions and significance

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Abstract

Beach ridges, frequent components of Quaternary coastal plains, and other coastal landforms, have been cited as indicators of the positions of ancient seashores and associated sea levels. Numerous authors utilized the term *beach ridge* for active and relict, usually wave-built supratidal and/or intertidal forms. Wind-built ridges have been only occasionally included in the definition. The term was applied also to submerged, landward-shifting, eventually stranded bars. A consistent redefinition of the term is highly desirable. *Beach ridges* should include all *relict* strandplain ridges, whether dominated by wave/swash-built or by eolian lithosomes. All active ridge-like shore features, regardless of dimensions, morphology, and origin are excluded. Because of the resistance of coarse-clastic ridges to wave and wind erosion, swash-built gravel or coarse shell (''storm'') ridges may build several meters above the level of high tide. Swash-built high berms, even on pure sandy beaches, exceed the highest tides during episodes of wind-induced, record water levels. Frequently but not always burying underlying low-relief ''berm ridges'' of berm lithosomes, sequences of relatively steep multiple foredunes are commonly named *beach ridge* plains. The narrow, subparallel relict foredunes that form these strandplains presently are designated as *eolian beach ridges*. Beach ridges, thus, are defined as *relict*, semiparallel, multiple wave- *and* wind-built landforms that originated in the inter- and supratidal zones. Until separated from the shoreline by progradation, sandy, pebbly or shell-enriched backshore berm ridges behind an active foreshore should not be considered beach ridges. Strandplain progradation is either *continuous* or, with the inclusion of subtidal (''cat's eye'') ponds, *discontinuous*. Contrary to claims, transgressive cheniers do not represent ''true cheniers'' alone; within their overall *progradational* context, cheniers, a special category of beach ridges bracketed by subtidal–intertidal mudflats, may be transgressive or regressive in character. Landward-driven, transgressive ridges should be designated beach ridges only after they are stabilized on intertidal flats. When recognizable between clearly identifiable intertidal and overlying eolian intervals, the horizontal interface between these lithosomes in beach ridges may help the reconstruction of ancient tide/lake levels. Diagnostic sedimentary textures, structures, and fossils, however, often may be unavailable in the deposits. Along with various types of elevated terraces composed of raised marine deposits and certain coastal landforms of erosional origin that occur worldwide, beach ridges of clearly proven wave-built origin may also serve as indicators of ancient higher-than-present sea levels. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: beach ridge categories; strandplains; sea level; cheniers; foredunes; shore progradation

1. Introduction

Sequences of beach ridges are frequent components of Quaternary coastal plains. Certain beach

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Table 1
Glossary of Morphological Terms. Generalized sediment and form characteristics

Berm	Wedge-shaped, relatively narrow form at high tide/lake level; may be composed of sandy or gravelly lithosomes. It is bounded by the upper foreshore surface and the adjacent, gently landward-inclined surface of seaward (lakeward) backshore margin.
Berm ridge	Wave-built, gently sloping, often sizable sandy, shelly–sandy, or steeper gravel/boulder ridge, between the seaward (foreshore) and landward (backshore plane or beach pond) zones. In relict form it occurs between two swales. It is bounded by backshore and berm surfaces and incorporates the corresponding intertidal/supratidal backshore and berm lithosomes. Characterized by mostly landward-, in part basinward-inclined, parallel and low-angle cross-stratified bedding. Temporary, high lake/sea stand, induced by distant storm centers but no direct storm impact, may result in sediment aggradation several meters above high lake/tidal level.
Backshore, backshore plain	Supratidal, level or undulating surface between foreshore, seaward/lakeward, and backshore bluff or landward zone of extensive dune development, landward. It is influenced by occasional storm overwash and windblown sand deposition. Site of embryonic dune and subsequent foredune development.
Boulder rampart	Storm-deposited, occasionally very substantial and high supratidal gravel-boulder ridge, located on backshore and wide berm surfaces. Backshore shell concentrate ridges/mounds may form on same surfaces under similar conditions.
Backshore foredune of the multiple ridgeplain category	Formed by eolian processes usually from fine-to-medium sand by accretion of embryonic backshore/berm dunes behind the high tide zone; variable, subparallel–subhorizontal lamination to steeply inclined cross-stratification. Relatively narrow (5–15 m) and steep-sloped (5°–15°) ridges, usually with intervening saddles and relatively uneven crest elevations. Sets of relict dune ridges form multiple ridge sequences in eolian strandplain.
Swale	Elongated, relatively narrow low miniature valley forms between two wave-built berm ridges or foredune beach ridges. Its lithology and gentle or relatively steep slope angle reflect characteristics of the flanking ridges. If remnant of a backshore ‘‘cat's eye’’ inter-ridge pond, it may be underlain by shallow subtidal deposits.
Chenier ridge/chenier plain	Wave-built, sandy berm ridge and ridge set, often enriched in shell clasts; flanked by intervening and usually wider intertidal–subtidal flats. Occasionally capped by eolian sand. The landward- and seaward-inclined parallel and low-angle cross bedded layering reflect landward overwash and beach foreshore conditions.
Beach ridge	Relict, semiparallel, multiple ridges, either of wave (berm ridge) or wind (multiple backshore foredune) origin. They usually form strandplains. Active beach/shore ridge features, regardless of dimensions, shapes and origins are excluded.

ridges may serve as sensitive indicators of past sea-level and shoreline positions, even of climate stages and rates of isostatic uplift (e.g., Mason, 1990). No clear consensus exists in the literature as to what a beach ridge actually is. The broad range of often conflicting ''beach ridge'' designations, however, touch on a potpourri of wave-built intertidal, supratidal and subtidal-nearshore and eolian ridges and sundry minor forms. On lake and marine beaches these included even miniature swash-line ridgelets (Fouch and Dean, 1982: Fig. 23) and an overwashed backshore gravel sheet (Ehlers, 1988; Fig. 283).

A fresh approach is needed to establish a consistent, universally acceptable definition of *beach ridge* and its subcategories. This paper, based on the North American, Australian, New Zealand and other international literature, utilizes field work and drilling data from extensive studies carried out at locations in the coastal plains and barrier islands adjacent to the northern Gulf of Mexico.

2. Definitions of beach ridge-associated landforms

The following terms are essentially morphological in nature but associated with characteristics of sedimentary textures and structures (Table 1). Because of the great diversity of these landforms, in terms of shapes, dimensions, association with other landforms, and sedimentological composition, strict, quantitative morphometric and sedimentological parameters often are difficult to impossible to impose on them.

2.1. Berm and berm ridge

The *berm* (Figs. 1 and 2), originally denoted only as the narrow, scarp-backed and wave-cut horizontal *surfaces*, is found at various foreshore levels (Komar, 1976; Fig. 2-1). Subsequently, it came to mean wedge-shaped lithosomes, berm ridges, bounded by the upper foreshore slope and the immediately adjacent, landward-inclined berm top surface (King, 1972). Its base would be defined as the horizontal plane that intersects the foreshore slope at the level of the backshore plain (Fig. 1). Hine (1979) described berm as a shore-parallel linear body of triangular cross-section with a horizontal to slightly landward-dipping surface (berm top) and a steeper seaward-dipping slope (beach face). Berms are ephemeral, frequently recurring landforms but not always present on a given beach.

Swash currents are instrumental in accreting the landward-sloping high tidal berms above the adjacent backshore level. The ephemeral high-tidal sand berms are generally of aggradational origin, with secondary indications of erosional scarping. Increase in onshore winds during falling tide briefly stabilizes

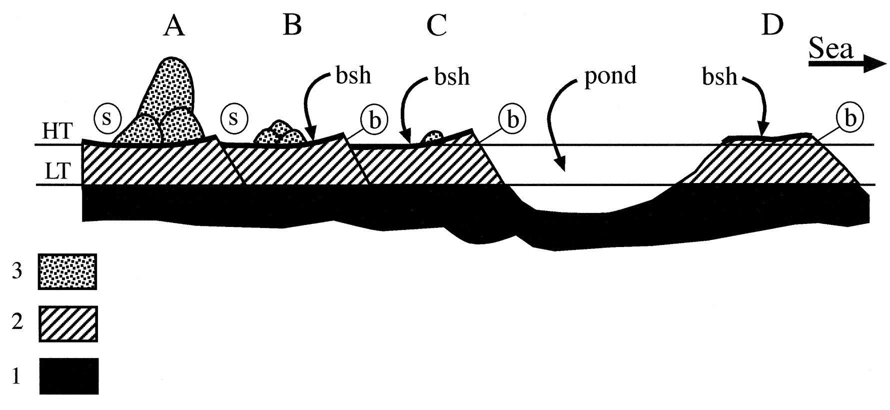


Fig. 1. Beach ridge-associated depositional facies and landforms on a prograding strandplain. Depositional facies: (1) subtidal; (2) wave-built, intertidal-to-supra-high tidal; (3) eolian. Landforms: b — berm; bsh — backshore plain; s — swale; A — foredune; B — accreting embryonic dunes on backshore plain in the early foredune stage; C — single embryonic dune on berm ridge (backshore-berm) surface; pond: spit growth-enclosed beach pond; D — pond-isolated berm ridge (intertidal–supratidal sand spit interval), without embryonic dunes; HT — high tide level; LT — low tide level.

sea level. Intermediate-level berms, in combination with scarplets, may form during such stillstands.

Berm ridges, occasionally sizable and more permanent than berm surfaces, are wave-built intertidal–supratidal landforms. These lithosomes are composed of intertidal and high tidal (swash-overwash) deposits, bounded by the backshore plane and the berm surface along its foreshore margin. After becoming inactive on prograding shores, they represent wave-built beach ridges.

When actively forming on the mainland beach or on shore-parallel sand spits, an individual berm ridge is situated between the foreshore and the landward (or lagoonward) margin of the backshore. The landward margin of such a ridge may be defined by the shoreline of an elongated shore-parallel lagoon or beach (''cat's eye'') pond; (Coastal Research Group, 1969 and M.O. Hayes, pers. comm.), enclosed during the growth of a shore-parallel spit. As a series of berm ridges progrades, shore-parallel swales bracket each ridge (Figs. 1 and 2).

Sediment and form characteristics, depending on the wide range of wave and current conditions and source sediments on a given sea or lake shore, the

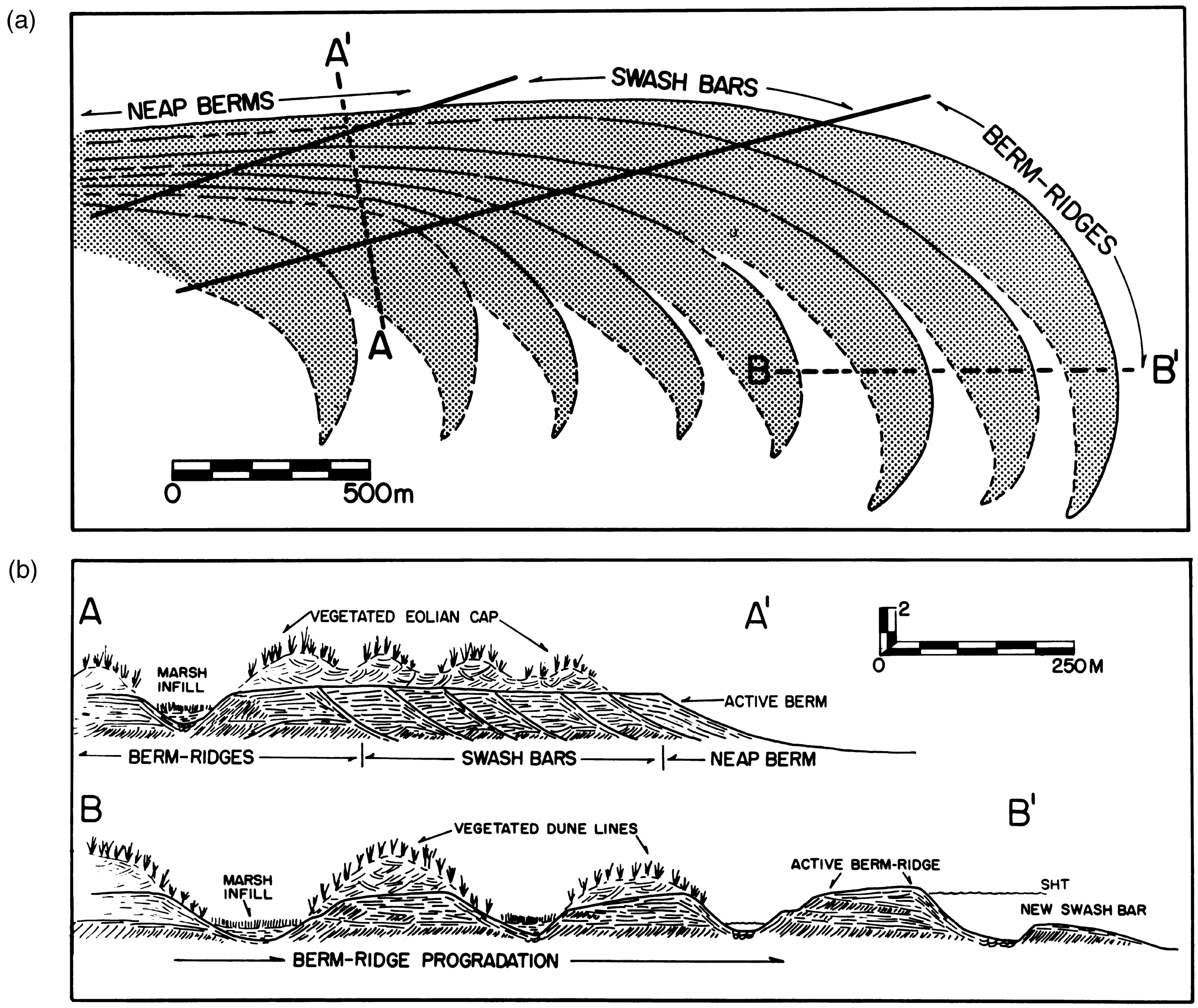


Fig. 2. (a) Zones of neap berms, welding swash bars, and berm ridges along recurved Nauset, MA, barrier spit; (b) generalized cross section across prograded neap berm, stranded swash bar and berm ridge zones; (c) landward migrating swash bar complex off the tip of barrier spit. Neap berms and berm ridges were stabilized in a progradational sequence on Nauset Spit. Photograph, courtesy of A. C. Hine (Hine, 1979).

Fig. 2 (*continued*).

upper intertidal–supratidal beach deposits in berm ridges may be composed of fine-to-coarse, even gravelly sands. Whereas sand sorting usually is good, in the presence of coarse clast fractions becomes only moderate (e.g., Thompson, 1992). Chappell and Grindrod (1984, Fig. 4) described a rare transition between sandy ridges of a regular beach ridge plain and a small adjacent chenier plain, composed of shell-enriched ridges. Reflecting the low relief and gentle seaward and landward slopes of the berm ridges, basinward-dipping, parallel laminae and low-angle (3°–5°) cross lamination characterizes the upper foreshore slope.

Subhorizontal or gently landward-dipping lamination occur on the landward berm surfaces. The highly variable berm and berm ridge dimensions, the height above still water levels and slope angles depend on wave conditions, local tidal or lake level-ranges, including wind-induced rise in sea and lake-levels along a given shore sector.

2.2. Backshore (strandplain-type) foredune

Semiparallel, narrow foredune sets usually develop along the foreshore margin landward of the high tide limit (Bates and Jackson, 1980). Relict foredunes in this category are considered in the following as *eolian* beach ridges. A host of additional foredune categories, occasionally the same name with different meanings, have emerged in the literature. Stabilized narrow ridges, located landward of foredunes, were called ''primary'' dunes by Frey and Howard (1988). This name was applied also to dunes that underwent significant landward migration (Short, 1988). Developing a new foredune classification, Hesp (1988) has modified several dune and foredune categories (Figs. 1 and 3).

Relict counterparts of various types of massive, solitary foredunes, ''established foredunes'' or ''primary'' dunes (Short, 1988; Hesp, 1988, pp. 19–22) are excluded from the present designation of beach ridges. Hesp (1984, Fig. 1) clearly illustrated the sharp contrast that exists between his massive ''established foredunes'' and a sequence of the adjacent much smaller, evenly-paced, narrow, and more symmetrical strandplain foredune ridges. With abundant sand transport from the margins of eroding dunes, the massive but solitary ''established foredunes'' (Hesp, 1988) may reach 30 m of elevation (Short, written comm., 1997). Smaller sand dunes may ''piggyback'', or aggrade on the back of these massive dunes. Eventually they merge with the underlying large dunes that gradually expand seaward (Hesp, 1988, Fig. 3). The limited number, highly uneven spacing and larger dimensions contrast sharply with the *strandplain dune* category of beach ridges.

Only elongated, shore-parallel foredunes that develop immediately behind the foreshore zone and may become part of a progradational sequence, are considered in the following.

Sediment and form characteristics, steeply landward and basinward dipping, cross-stratified fine-to-medium coarse sand layers are characteristic of beach foredune beach ridges. The relatively narrow, semiparallel, generally 3–6-m high ridges usually are bound by steep-to-moderate slopes of 5°–15°. Subparallel, sub-horizontal lamination develop when the dune layers are laid down on eolian backshore sand platforms or occur in shore-parallel cuts across foredunes (Otvos, 1999). Postdepositional biogenic (root and burrowing) activity may result in unstratified dunes (Thompson, 1992). The contrast and, thus, the interface between the backshore/berm and the overlying dune lithofacies may be pronounced on uniformly coarse or medium sandy–pebbly beaches, overlain by finer and better sorted dune sands (e.g., Table 1, in: Thompson and Baedke, 1995). If the contrast is negligible, as on uniformly fine or medium sandy beaches, the two lithofacies are difficult to differentiate and the ancient sea/lake level position hard to establish.

2.3. Swale

Another morphologic feature, is ''a long, narrow, generally shallow, trough like, elongated depression between two beach ridges, aligned roughly parallel with the coastline'' (Bates and Jackson, 1980). The gentle or steep slopes of swales that are narrow, miniature valleys between flanking beach ridges provide insight into the wave- or wind-built ridge origins (Fig. 1, Table 1). Holocene strandplain swales have steep slopes, whereas the erosionally heavily modified Pleistocene strandplain swales, as those found on the Atlantic and Gulf coastal plains, are very gently sloping. Flanked by sandy wave- or wind-built beach ridges, swales are underlain by *subtidal to supratidal sand*. Even if occasionally referred to as swales, the intervening level mudflat belts that separate individual chenier ridges and ridge sets in SW Louisiana and other localities are intertidal flats, instead. Unlike the narrow sandy swales, they greatly exceed the widths of chenier ridges and

Fig. 3. Recent foredune ridgeplains, southeastern Dauphin Island, AL. (Courtesy S.L. Douglass).

chenier ridge sets. They are floored by mud (e.g., Byrne et al., 1959; Lees, 1987).

2.4. Barrier ridge

Shore-parallel landforms, of significant width and length, backed by lagoons or bays, that consist usually of sets of berm or foredune ridges are called barrier islands, barrier spits or barrier beaches (Bates and Jackson, 1980; Carter, 1988). Holocene or Late Pleistocene ridgeplains that directly front the mainland shore of SE Alabama–NW Florida coast or south Mississippi were designated *mainland barriers* (Otvos, 1981). In an unusual recent application of the term, Adams and Wesnousky (1998) used ''barrier ridge'' and ''beach barrier'' for individual gravelly-sandy berm (beach) ridges that form the Pleistocene Lake Lahontan strandplains in Nevada.

2.5. Chenier ridge, chenier plain

Individual chenier ridges and ridge sets develop along shores that alternately receive large volumes of sandy and muddy sediments. As the result, these ridges/ridge sets are fronted and backed by intertidal–supratidal mudflats. The ridges, composed of sand may also include up to pebble-sized molluscan shell clasts, usually contain appreciable-to-dominant amounts of shells and shell fragments. Chenier ridges may rise several meters above normal high tide level.

3. Discussion

3.1. Definitions

3.1.1. Beach ridges

Since Johnson (1919) introduced this term for *wave-built* features, it has been in very frequent use in the coastal literature, but with great variations in meaning. As the traditional view, many claim the essentially ''marine'' (wave-built) origins of beach ridges and exclude dune ridges from the designation (e.g., Short, written comms., 1997; Taylor and Stone, 1996 and references therein). This view would admit only to an insignificant eolian veneer (''decoration'') of the beach ridge, at the most. Several writers included among ''beach ridges'' an assortment of wave-built ridge-like forms of various dimensions on *active* beaches.

The present interpretation of the designation ''beach-ridge'' or ''beachridge'' applies to stabilized, *relict* intertidal and supratidal, eolian and wave-built shore ridges that may consist of either siliclastic or calcareous clastic matter of a wide range of clasts dimensions from fine sand to cobbles and boulders. Before becoming (stabilized) beach ridges, the ridges have either a regressive (progradational) or transgressive history. Thus, before they may become (stabilized and inactive) beach ridges, *transgressive* subtidal sandy shell and gravel ridges often are driven landward over tidal flats. At this point, they cease to be regularly and substantially modified by tides and waves.

In requiring a given beach ridge to be a relict, inactive landform, one encounters a ''gray'' transitional phase in certain beach ridge plain and tidal flats between *relict* and *active* shore conditions. Strong onshore winds, high tides, and storm occasionally may still impact and modify berm beach ridges and relict foredunes, isolated from the shore by progradation. In an other example, high spring tides, with a 6–9-m high-macrotidal range, periodically invade the Gulf of California chenier plain (Thompson, 1968). Temporary stormtide-inundations; occasional wave-related and even eolian sediment transport beyond the active backshore zone landward, however, do not justify the inclusion of such effected landforms in the *active* shore zone.

If applied to landforms or structures that exist in active beach zones, the beach ridge designation would create new ambiguities and complications. Ridges on active beaches are already known as either berm ridges, storm ridges, boulder ramparts, backshore shell ridges or foredune ridges. On active beaches, devoid of wind or wave-built structures, such an approach could even stamp the perplexing ''beach ridge'' designation on the entire intertidal beach lithosome or on a sand spit body that rises from adjacent low-tidal sandflats to high tide level.

3.1.2. Beach ridge plains (''strandplains'' or ''strand plains'')

The addition of successive new beach ridges in front of the previous foreshore position creates a ridge plain. Strandplains that in the literature are commonly called ''beach ridge plains'', whether the constituent ridges in the land surface are of wave-built (''marine'') or eolian (dune) origin, appear identical in map view. The ridges, in both categories associated with beaches, *equally* merit the beach ridge designation.

Depending on factors, such as ridge dimensions, nearshore bottom gradient, and rates of sand supply, individual ridges have been added to documented strandplains at the average rate of 30–150 years per ridge (King, 1972; Chappell and Grindrod, 1984; Mason, 1990; Thompson, 1992; Thompson and Baedke, 1995; Fox et al., 1995). Calculations based on the Magilligan strandplain (Carter and Wilson, 1990, Fig. 3) and the cited twenty year old small Dauphin Island-Country Club strandplain in Alabama, yielded average growth rates of 2.5 and 1.8 yr/per ridge, respectively. The growth rate of the eighteen wave-constructed beach ridges that form a seven km wide Nile Delta strandplain (Goodfriend and Stanley, 1999) was interpreted as. 3.3 yr/per ridge.

3.2. *Wave- and wind-constructed beach ridge categories*

3.2.1. *Wave-built beach ridges*

Johnson (1919) was the first to describe beach ridges in the geological literature and he considered them to be constructed by waves along successive shore positions. Reineck and Singh (1978, pp. 291-1, 303) described beach ridges as composed at high tide level of ''rather coarser sediment'' and related to storms or exceptionally high water stages. They also used the very same term for longshore bars. Bates and Jackson (1980) designated beach ridges rather restrictively, as low mounds of beach or beach-and-dune material, heaped up by waves over the backshore beyond the present limit of storm waves or ordinary tides.

While referring to relict strand plain dunes as beach ridges, Carter (1986), who used the term very broadly to cover ''all large constructional forms of the upper beach, capable of preservation'', also applied it to landward-shifting offshore bars and to already welded swash bars and prograded berm ridges. Davis et al. (1972), Fraser and Hester (1977), Carter (1986, 1988) and Carter and Wilson (1990, p. 137), as well as others, similarly referred to onshore migrating swash bars and/or to the stranded end products as ''beach ridges''. For some time after welding to the shore, the prograding sandy berm ridges may continue to be impacted by daily beach processes.

Most North American and Australian authors considered stabilized onshore beach ridges as either of predominantly wave-built or composites of wave and wind-constructed origin (e.g., Price, 1982). Hesp (1984, 1985), Mason (1990), and Mason et al. (1997), thus, distinguished between the low-profile ''smooth, terrestrial'' berm beach ridges and dune ridges that often cover them.

3.2.1.1. Gravel-boulder (''storm''-) ridges. Storm-associated high tides and waves can build gravel beach ramparts as high as 6 m above sea level over tide-flooded backshore surfaces (Clapperton, 1990). Gravel-boulder ridges, formed during storms may be poor indicators of sea and lake levels. For a given still-water level the height of winter storm wave-built ridges, even on shores of large lakes, may vary by as much as 2–2.6 m (Adams and Wesnousky, 1998). Erosion-resistant, coarse-clastic ''storm'' ridges (Fig. 4) often occur on glaciated and other erosionally sculpted bedrock shores (Forbes et al., 1989). Permanent shingle emplacement at high tide levels is facilitated by the rapid percolation of the backwash into the highly permeable bouldery substrate (Carter, 1988). Gravel-boulder ridges deposited on wave-cut bedrock terraces may form in discontinuous tabular and tabular cross-stratified bodies, several meters thick (Adams and Wesnousky, 1998).

''Pebble-armored ridges'', pebble sheets, ''plastered'' onto sand dunes during storms have also been called gravelly ramp barriers (Orford and Carter, 1982; Mason, 1990). Following glacio-isostatic uplift in eastern Canada, Scandinavia, and other regions, depositional progradation gradually isolated such beach-stairsteps from the active foreshore zone. The ridges often overlie wave-cut bedrock terraces.

The hydraulic ratios and shapes of shell bioclasts result in higher transport and dispersal rates than with respect to larger and denser silicate rock clasts. Whereas gravel/boulder ridges accumulate during direct storm impact, this tends to flatten and disperse already existing ridges, composed of sand and lighter, platy shell clasts (Greensmith and Tucker, 1969; Rhodes, 1982, p. 217). Higher energy events enable accumulation even of bioclastic rudites (Woodroffe et al., 1983; Meldahl, 1993, Fig. 5f–g). Wide intervals between wave-built berm/backshore plain beach ridges suggested milder climatic episodes; an average storm recurrence interval of 50 years (Mason, 1990, p. 96) in western Alaska.

3.2.1.2. Sandy berm ridges. Constructive waves on predominantly sandy beaches usually aggrade berms only slightly above high tide elevation. Berm ridges, as those represented by the wave-built intertidal–supratidal portions of small shore-parallel barrier spits, underlie the beach backshore plain and its

Fig. 4. High-tidal boulder rampart, St. John's, Newfoundland (Forbes et al., 1989). (Courtesy D.L. Forbes).

seaward extension, the landward sloping berm surface (Fig. 1). Unusually high ridges (2.3 m) form during run-up by large swell waves as the sea level slowly subsides from distant storm-induced but non-erosional wave impact (Mason and Jordan, 1993). During constructive shore phases, the ridges accrete on tide-flooded, previously eroded backshore plains. In the absence of a substantial eolian sand supply that otherwise would overwhelm and bury them, berm-backshore beach ridges may remain prominent landforms. Short et al. (1989) reported on an almost exclusively swash-built ridgeplain in Australia, a rather rare occurrence on windy coasts. Berm beach ridges, without dune caps are not uncommon in tropical areas where wind energy is low (P. Roy, written comms.). Goodfriend and Stanley (1999) noted 20–30-cm high shelly sand ridges, without any eolian cover in a Nile Delta strandplain.

At the start of the celebrated Australian ''berm debate'', several workers regarded the high tidal sand berms as incipient beach ridges (Davies, 1957; Bird, 1960; Hails, 1969). Bird and Jones (1988) later proposed that if a berm survived a 15-day tidal cycle, it becomes a beach ridge. Following along these lines Psuty (1966) suggested ridge formation by berm steepening and successive cycles of accretion-erosion (wave-scarping) at a Mexican Gulf shore locality. His evidence, however, did not prove that this berm-sculpting process has been more than an ephemeral and highly localized phenomenon. No proof was offered in this region of ample eolian sand supply to show that such high-tidal ridges would persist for prolonged periods of time without being eroded or buried under eolian sands. It is unlikely that such a cyclic process, not multiple foredune growth, have formed the adjacent 20-km wide Mexican strandplain. The availability of sand and foredunes on the present Tabasco coast indeed implies that, as in the case of most Quaternary strandplains on Gulf, at least the upper and middle ridge lithosomes in that ridgeplain also represent foredune origins.

Berms, in addition to representing beach ridge lithosomes, have been also credited with providing *platforms* on which embryonic and, later, regular eolian dunes are subsequently able to develop (e.g.,

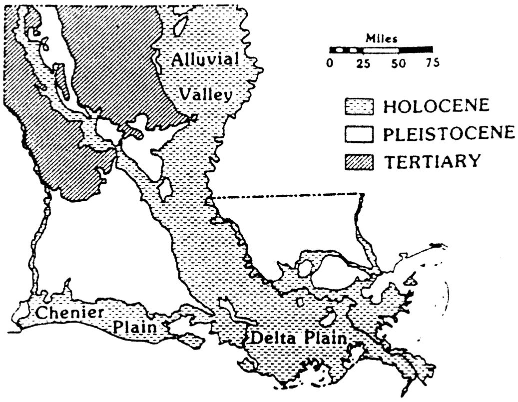


Fig. 5. Location of SW Louisiana chenier plain, northern Gulf of Mexico coast, USA (after: Penland and Suter, 1989).

Davies, 1957; Bird and Jones, 1988). Commonly, foredunes do emerge on the landward-adjacent, wide backshore surface, often after being flattened by storm-tidal beach erosion. Whereas the relatively wide, level or slightly undulating backshore plains are available for foredune construction, often this is *not* the case on narrow high-tidal berms on the backshore that do not outlast even brief episodes of wind- or wave erosion.

Berms may be absent from dissipative beach faces because of infragravity set-up/set-down. They tend to be also absent from high energy beaches (Short, 1984; written comm., 1997) and from fine sandy beaches (Komar, 1976, p. 13). Embryonic dunes on the microtidal northern Gulf of Mexico are not initiated on high-tidal *berm* surfaces. The berms usually are very narrow (2–3-m wide, at most), short-lived and, therefore, unable to support even embryonic dunes.

3.2.1.3. Chenier beach ridges (chenier ridges and ridge sets). Cheniers, also a wave-built beach ridge category, may aggrade to higher levels because of constructive waves that raise the tide. They are likely to be related to distant storms that did not result in shore erosion in the ridge area. Depending on sand availability from the adjacent foreshore at the time of formation, shell-bearing cheniers may also be veneered and/or capped by eolian sands.

Table 2
Pioneer dune-initiating plant species from worldwide beach localities

Alabama–Mississipi	*Iva imbricata*	this paper
	Panicum amarum	
Perdido Key, FL/AL	*Cakile constricta*	Gibson and Ely, 1994
	Iva imbricata	
S. Louisiana	*Panicum amarum*	Ritchie and Penland, 1990
	Cakile constricta	
	Iva imbricata	
	Croton punctatus	
Lake Michigan	*Camovilfa sp.*	Fraser and Hester, 1977
England/Ireland	*Agropyron junceiforme*	Chapman, 1964; Carter and Wilson, 1990
	Honkenya peploides	
	Cakile maritima	
Australia	*Cakile maritima*	Hesp, 1984; Jennings and Coventry, 1973; Bird and Jones, 1988
	C. edentula	
	Spinifex sericeus	
	S. longifolius	
	S. spathulatus	
Hudson Bay, Canada	*Honkenya peploides*	Ruz and Allard, 1994, 1995
	Lathyrus japonicus	
	Elymus arenarius	
N. Alaska	*Elymus arenarius mollis*	Mason, 1990
Mexico	*Okenia hypogaea*	Sauer, 1967
	Amaranthus greggi	
Surinam	*Sesuvium portulacastrum*	Augustinus, 1978

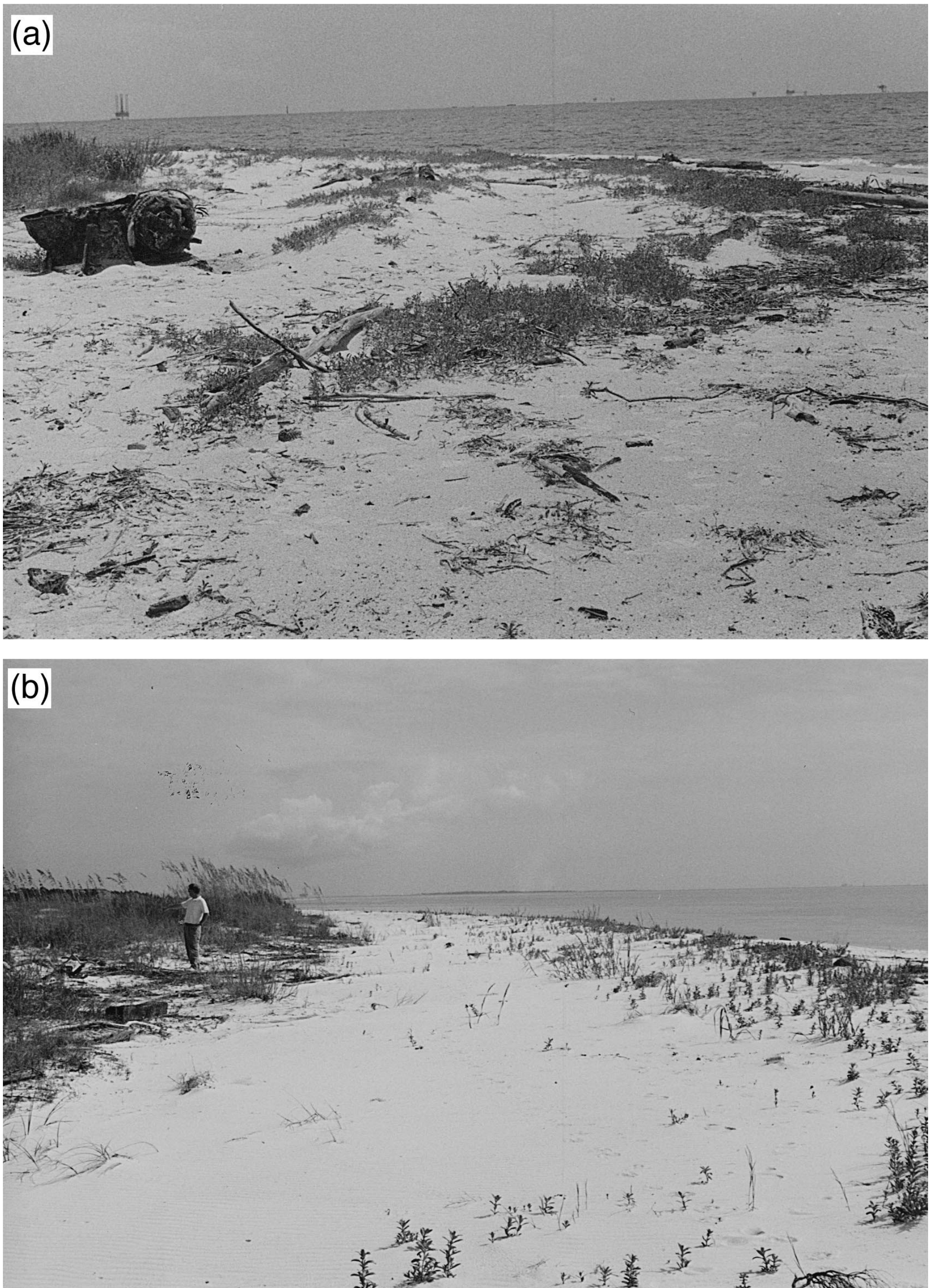


Fig. 6. (a–c) Incipient shore-parallel dune ridge development stages, southeast Dauphin Island, 1995 photo (Gulf beach: right) (a) incipient dune, formed around grass clumps (foreground). Dune ridges, in their wind-shadows, intervening swales formed. Beach progradation occurred along reemerged, buried vegetation and flotsam zones on overwashed backshore plain. Tip of cuspate Country Club strandplain (lower ridgeplain of Fig. 3); (c) established foredune beach ridge (left) faces rising incipient dune ridge (right) across wide swale.

Fig. 6 (*continued*).

A chenier plain represents *multiple* episodes of recurring ridge and mudflat formation on prograding shore sectors. At least two semiparallel chenier ridges or ridge sets, sandwiched between tidal-subtidal mudflats, must be present (Otvos and Price, 1979). A single, isolated shell ridge in a mudflat (e.g., Lee et al., 1994; Park et al., 1996) does not satisfy these criteria. A dune-capped beach backshore, backed only by an intertidal mudflat without intervening cheniers, underlain by nearshore marine sediments, and fronted by an active beach foreshore (e.g., Rhodes, 1982, Fig. 3; Woodroffe et al., 1983, and Holly Beach ridge in SW Louisiana), despite designations to the contrary, fails to meet this precondition. Mudflat progradation must bracket the ridge: a marsh-covered or barren preexisting mudflat in its rear, and a younger, possibly still active mudflat seaward. This ridge and mudflat sequence is the *chenier plain*.

Chenier ridges tend to be colonized by a climax community; ''live oak'' trees (chêne) in Louisiana. Subtidal–intertidal muds, muddy sands underlie cheniers. Mason (1990) reported on one rare *gravel* chenier in Alaska. The chenier slopes are gentle; the seaward slope in the fine–sandy cheniers in Suriname, South America, only $< 1°$ (Augustinus, 1980).

In conformity with the beach ridge designation, a chenier-beach ridge is not exposed to active beach processes on a daily basis. Occasionally, the term has been applied to isolated shell ridges, salt marsh-engulfed small barrier islands or offshore bars. In a number of instances no corroborating subsurface evidence was offered for the chenier designation, for a *chenier-type* development history of certain intertidal–supratidal ridges, and a *progradational* association with adjacent intertidal mudflats (e.g., Shuisky, 1989; ''delta front cheniers'' of Hayes, 1994, p. 295). Some of these inter-ridge mudflats, thus, may postdate both of the flanking ridge sets.

Local variations in sediment supply, because of cyclic shifts in the hydrologic, weather, and geomorphic conditions, sometimes determine synchronous development of mudflats and shell ridges in small chenier plains (Thompson, 1968; Woodroffe et al., 1983). In the largest ones, fluctuations in terrestrial mud supply may result from subdelta-switching, respectively, longshore mudbank migration (Gould and McFarlan, 1959; Augustinus, 1978, 1980). Buried paleosol and grass horizons in beach ridges, including cheniers, occasionally indicate multiple episodes of vertical aggradation during interruptions in strandplain progradation (Chappell and Grindrod, 1984; Wang, 1994).

Reworked intertidal sands and shells from broad mesotidal sand and mudflats on the Gulf of California provide the source of coarse clastic sediment for emerging shore and intertidal ridges (Thompson, 1968). Winnowing of shell matter from mudflats during shore retreat does not always result in substantial shell ridges as demonstrated by the lack of sizable wave-built and shell-enriched backshore ridges along a highly erosive, 58-km long shore stretch of Louisiana, south of Grand Chenier–Pecan Island (Byrne et al., 1959; present Fig. 5). Storm-excavated inner shelf shell deposits may represent an important alternate sediment source.

In conformity with the original chenier definition (Russell and Howe, 1935, pp. 27–28) several authors (Price, 1955; Cangzi and Walker, 1989; Penland and Suter, 1989; Meldahl, 1995) defined chenier ridges as *transgressive* landforms. Prograded chenier ridges, however, are more numerous. In the classical Louisiana chenier plains the transgressive, ''true cheniers'' appear to be in a small minority. Whereas Taylor et al. (1996) reserved the beach ridge designation only for prograded cheniers, it should encompass regressive and landward-driven, transgressive cheniers.

Whereas almost all known chenier planes formed in Late Holocene, one Pleistocene chenier plain has

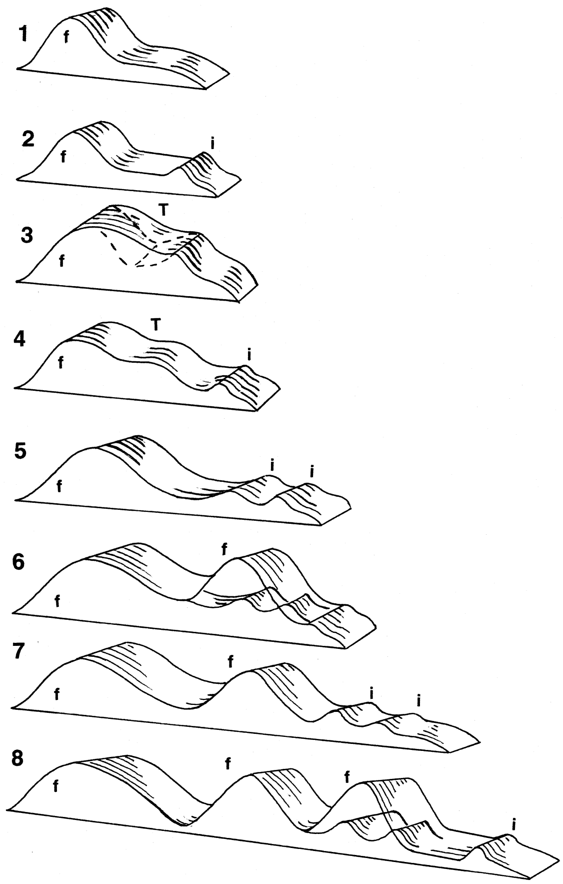


Fig. 7. Continuous dune ridgeplain progradation on micro-mesotidal shore. Incipient (embryonic) foredunes (i) merge into terrace (T) and/or foredunes (f).

also been documented. Its ridges are composed of several meters of *Chione* shell beds (Meldahl, 1993 and Meldahl, written com.).

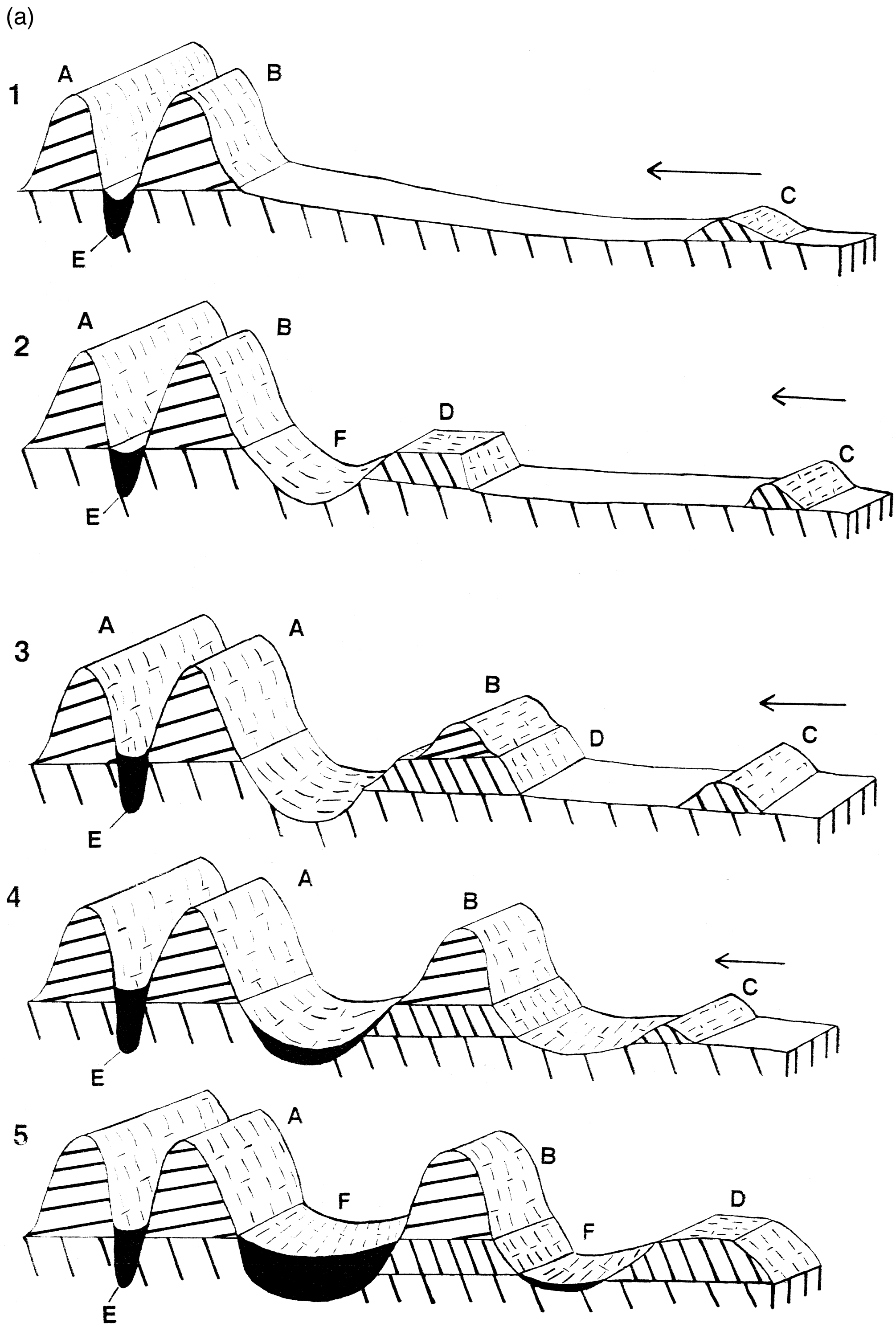
3.2.2. Eolian beach ridges: relict foredune ridges and ridgeplains

Wave-built berms and backshore zones, veneered by eolian sand, define the realm where some of the diminutive incipient (embryonic) foredunes are constructed along wracklines (swash zone debris). The emerging hardy pioneer vegetation is represented by a mere handful of plant species in any given area (Table 2). Plant growth from rhizomes, seedlings, storm-buried roots, and germinating seeds in the protection of the beach debris, within the narrow wrack zones help to promote formation and growth of embryonic dunes (Hesp, 1984; Cushman, 1964). Expanding in size while combining with adjacent small dune mounds, these swash-aligned embryonic dunes may gradually merge and develop into full-fledged foredune ridges Figs. 1, 6–8.

Cross-sections, based on drillholes (Thompson, 1992, Dott and Mickelson, 1995) revealed broad, low-relief berm ridges, formed on backshore surfaces along the lake shores. Eolian sands, including foredune ridges bury the berm ridges that become unrecognizable in the land surface. While noting that embryonic dunes may form on berms and stressing the role of vegetated *backshore* surfaces during ridge construction along stormtide lines, Hesp (1984, 1985) discounted the need for *berm* surfaces as required platforms or prerequisites for the development of embryonic and/or mature foredunes.

A consistent causative relationship between berm and foredune remains unproven in most of the studied shore areas along the microtidal Gulf of Mexico coast. Late Holocene and recent foredune ridge sets occur commonly on several prograded barrier islands and mainland barrier spit sectors, including small ridge plains in southeast Dauphin Island, AL (Fig. 3) and on Palm Point, FL (Otvos, 1992). What remains of the developing very narrow, and low berms along Gulf beaches after modified; reconstructed, and eroded by waves and wind often is quickly buried by wind-blown sand along shore sectors and reverts to eolian sand-veneered backshore plains. Foredunes

Fig. 8. *Iva*-constructed, isolated incipient foredune mound with scattered flotsam and an integrated initial foredune ridge in background. Rear of the Gulf backshore plain, Horn Island, MS.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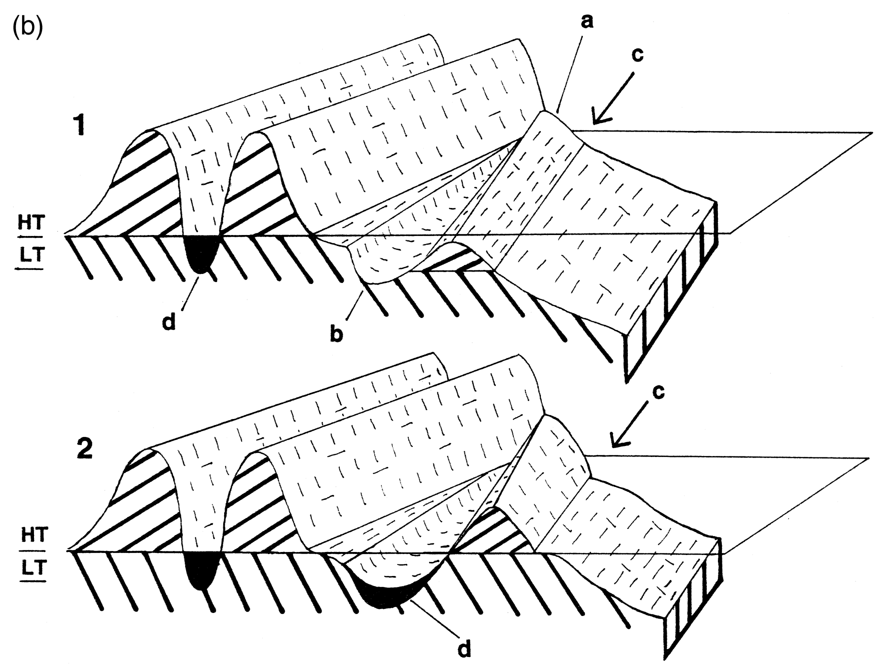


Fig. 9. (a, b) Schematic diagram of continuous and discontinuous beach ridgeplain progradation. (a) Onshore welding of berm ridges in mesotidal setting (based on Coastal Research Group, 1969 and Hine, 1979). Symbols: (A) relict foredune beach ridges; (B) active foredune; (C) landward migrating swash bar; (D) stabilized berm ridge O: new, incipient beach ridge, formed on former swash bar; (E) narrow, shallow swale and pond between continuously prograded old foredune ridges; (F) wide, pond-filled swale basin, formed behind stranded swash bar-berm ridge. (b) Development of microtidal spit-beach ridge (a), in combination with shoal emergence. Wide swale pond (b) form landward; (c) drift direction; (d) swale ponds: (top) narrow and shallow between continuously prograded relict foredunes: (bottom): wide and deep ponds, landward of new spit-beach ridge. HT — high tide level; LT — low tide level.

develop eventually through the growth and combination of embryonic dunes on these backshore surfaces.

Apart from the large chenier plain in Louisiana and the small shell-rich, berm-backshore ridge strandplains of peninsular Florida Gulf, Holocene foredune strandplains predominate. Wave-built beach ridges are not significant along northern and eastern Gulf of Mexico beaches (e.g., Otvos, 1992) because of the generally abundant littoral sand supply. Extensive eolian strandplains completely bury wave-constructed backshore-berm ridge sets on the Great Lakes (Fraser and Hester, 1977; Thompson, 1992), in Alaska (Mason et al., 1997), and at other localities (Ruz, 1989).

Although a number of workers object to the designation of relict foredunes as beach ridges, the foredune origin of the component beach ridges indeed has been recognized in numerous strandplains. McKenzie (1958), Price (1982), Hesp (1984), Fox et al. (1995) and Lichter (1997), among others, also refer to sets of semiparallel dune ridges, occasionally with clearly identifiable buried, wave-built cores, as beach ridges. Thom (1984), Nichol and Boyd (1993), and Ruz and Allard (1994, p. 71) used a related expression, ‘‘beach-ridge type’’ for relatively evenly spaced relict foredunes or cited foredune ridges as ‘‘beach ridge plain’’ components. The term ‘‘foredune ridge plain’’ (Short, 1988, Fig. 5) was also employed in Australia.

3.2.2.1. Strandplain and sand terrace development processes and modes. Strandplain progradation may be a *continuous*, smooth process when *grain-by-grain* addition of sand to the widening foreshore takes place. On mid-to-high tide levels on mesotidal foreshores where neap high tide remains below the highest foreshore levels, continuously *accreting neap berms* form a gently undulating beach plain, uninter-

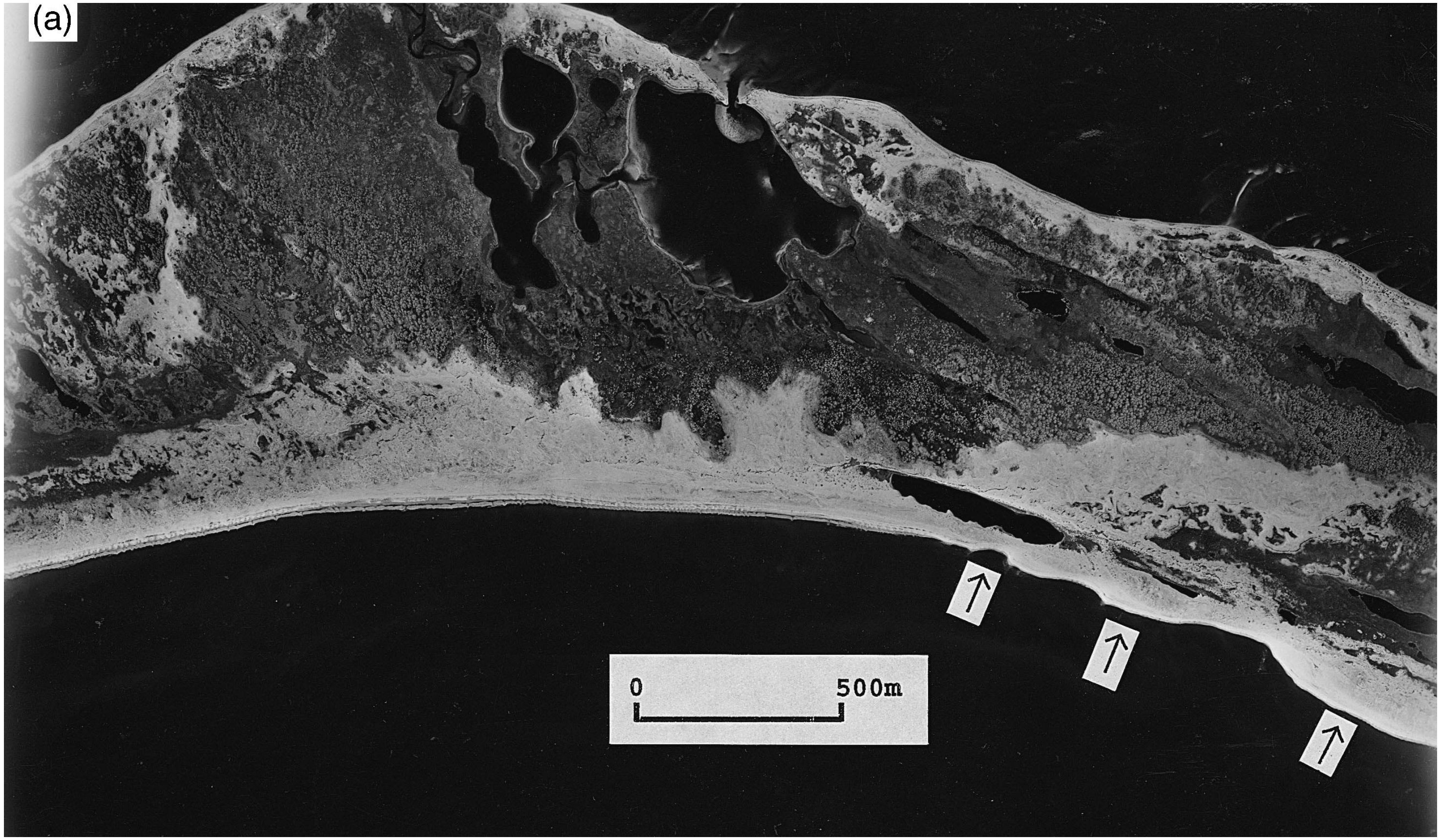


Fig. 10. (a–c) Horn Island. MS, beach ridges, (a) elongated shore-parallel spit ponds (arrows), isolated from the Gulf by new beach ridges, formed on intertidal spit platforms. Largely wooded old foredune beach ridges, separated by narrow inter-ridge and wide (spit-basin) swale ponds in interior, South shore of central island, CGS aerial photo, 1957. South central island shore. Oblique aerial photos, 1979; (b) developing swale (''cat's eye'') ponds, nearly isolated by westward prograding spits; (c) swale ponds, isolated by spit growth.

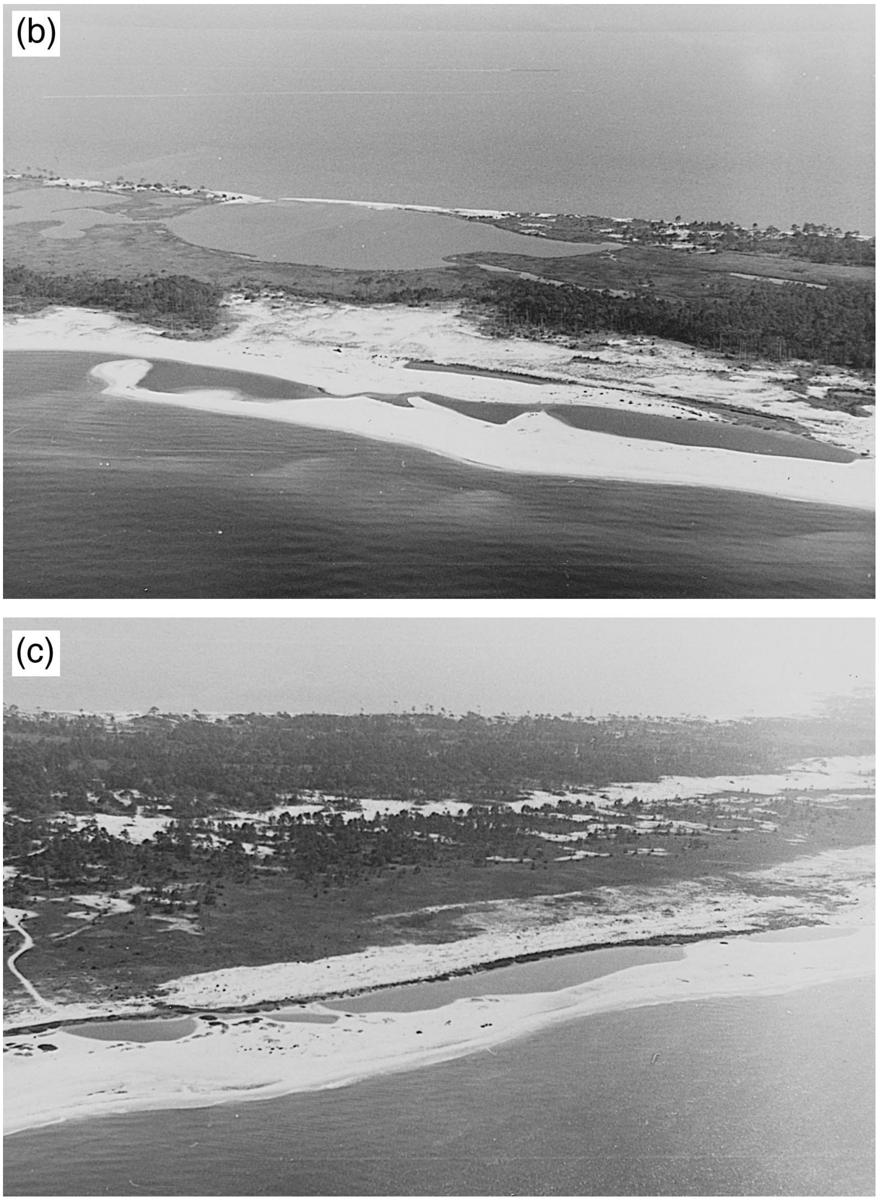


Fig. 10 (*continued*).

rupted by inter-berm swales (Fig. 2a,b; Hine, 1979, Fig. 17A). Along the low-microtidal Gulf of Mexico beaches, increased sand supply results in steady foreshore outbuilding and consequent progradation of narrow, closely-spaced foredune ridges (e.g., the small Dauphin Island and Palm Point strandplains; Otvos, 1992).

Discontinuous progradation involves either the stranding and remolding of landward migrated mesotidal swash bars on the foreshore (e.g., Hine, 1979; Carter, 1986; Fig. 2) or *spit growth* from and downdrift reattachment to the beach in microtidal settings (Figs. 9 and 10, and Otvos, 1981). Both processes result in elongated ponds. Gradually filled by eolian and washover sands and fronted by a new foredune ridge, such ponds gradually may become wide supratidal inter-ridge swales.

Holocene strandplain ridges on the northern Gulf of Mexico are spaced between 20 and 80 m. apart. Ridge crests rise 3–5 m above the swale floors. In contrast, the Late Pleistocene Sangamonian strandplain ridges, subjected to prolonged erosion and swale infilling occur at 150–400-m intervals and rise only 0.5–1.2 m above the inter-ridge swale floors. Similar sharp contrasts between the Holocene and Pleistocene strandplain morphologies were also noted in Australian ridge plains (Smart, 1976; Roy et al., 1992).

As observed on the Gulf shore of Horn Island, MS, inland-directed eolian sand transport may be essentially unhindered by older dunes on a 50–60 m wide storm-leveled backshore plain. Following the hurricane, a number of incipient dune ridges emerge nearly simultaneously at varying distances from the foreshore. Development of dune ridges in this case also excludes any role in dune localization, occasionally played elsewhere by preexisting intertidal berm ridges.

Level eolian sand terraces, *instead of ridge-swale sequences*, form when sand supply and progradation keep up with vegetation growth. Rates of beach progradation and/or eolian sand supply are low and plant growth intensive (Hesp, written comm., 1994). Ruz and Allard (1994) reported wind-blown sand filling the inter-dune swales and Mackenzie (l958, p. 214) described the role of *Spinifex* growth in the formation of a broad eolian terrace, instead of sets of dune ridges.

3.3. Ancient sea level markers: coastal sediments and landforms

3.3.1. Beach ridges — markers of ancient sea levels?

Based on Holocene beach ridge elevations, recent publications (e.g., Stapor, 1975; Stapor et al., 1991; Donoghue and Tanner, 1992) claimed Gulf of Mexico record marine highstands at elevations above present high tide levels. The diagnostic sedimentological and morphological indicators and limitations on use in interpreting ancient sea level positions, however, often have not been adequately addressed (Otvos, 1995, 1999).

The utilization of sandy beach ridges as sea-(lake-) level indicators presupposes a recognizable interface between the wave-built foreshore and the overlying eolian lithosome within a given ridge. This indeed has been the case in the Lake Michigan strandplain ridges (Fraser and Hester, 1977; Thompson, 1992) where low-angle sand and gravel cross beds and trough-cross-bedded lacustrine sands of wave-built origin underlie land snail-bearing, cross-bedded, in part massive, structureless dune sands.

Sediment granulometry and structures by themselves, however, may not always provide sufficient proof of foreshore and eolian facies within a given beach ridge. To illustrate this problem, 350 plots of skewness and kurtosis of foreshore and eolian sand-sheet/foredune samples from active Mississippi and Alabama mainland and island beaches revealed a complete overlap between plots from wind and swash-deposited sands. This result runs counter to common assumptions about a consistent granulometric separation between dune and ''beach'' (foreshore) sands (Otvos, 1999), especially with regard to the skewness values. On southeast Dauphin Island, AL, eolian sands, even when deposited in a tall precipitation ridge well inland from the foreshore source, were not transported far enough from the source to substantially modify granulometry (Fig. 11).

Elevation values and sedimentary structures from beach ridges that rise well above the present levels of high tides were presented somewhat unconvincingly as evidence for Mid/Late Holocene highstands in the Gulf of Mexico (Stapor, 1975; Stapor et al., 1991; Donoghue and Tanner, 1992). In contrast with steep eolian cross-bedding, low-angle cross-strata and parallel laminae are often accepted as diagnostic of intertidal or shallow subtidal depositional facies. When deposited over level wave-built or eolian terrace surfaces, near-horizontal laminae and low angle ($< 15°$) seaward-dipping eolian cross-strata that closely mimic foreshore lamination may be incorporated into foredunes, eolian interdune zone, sand eolian sand terraces (Fraser and Hester, 1977, p. 1101; Hesp, 1988, p. 30; Olsen and Larsen, 1993, p. 406; Otvos, 1995, 1999; Ruz and Allard, 1995, Mason et al., 1997). As noted, steeply dipping (10°–

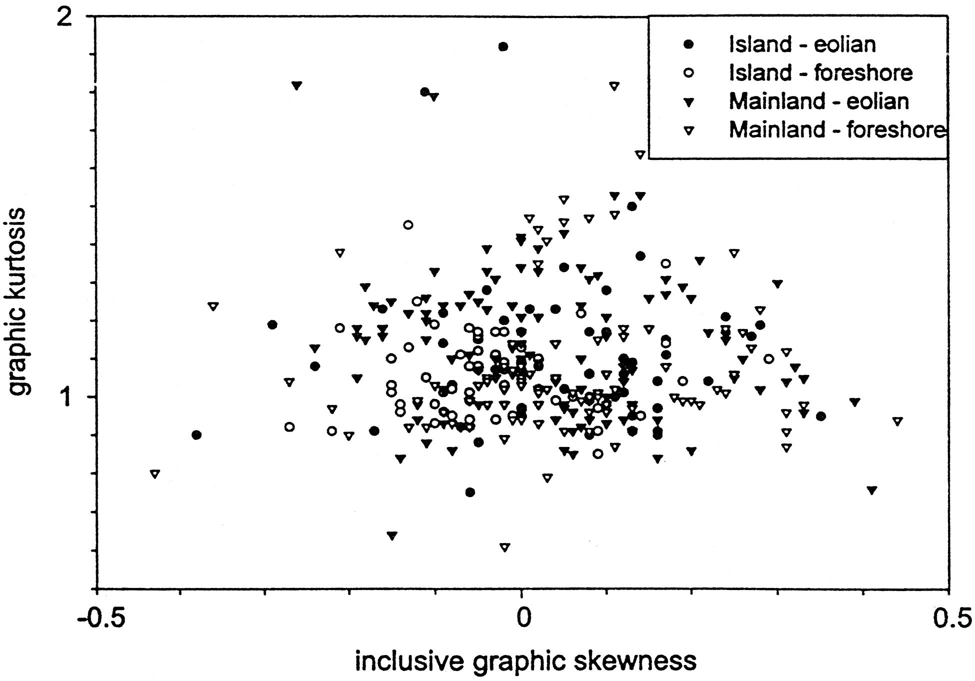


Fig. 11. Skewness vs. kurtosis plots, based on samples from mainland and island foreshore and foredune/eolian backshore environments. Mississippi mainland and barrier island beaches. Notice complete overlap between eolian and foreshore sand plots.

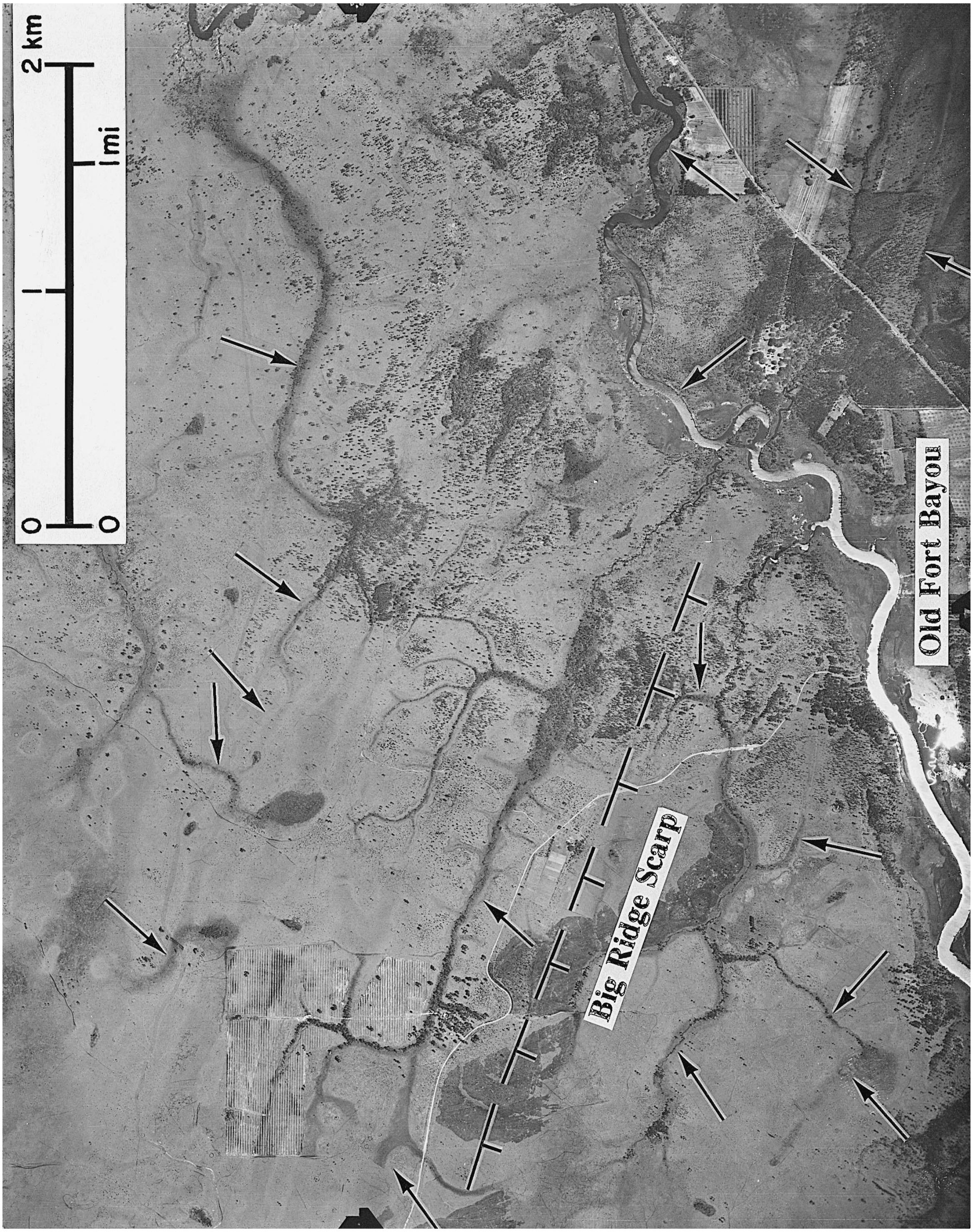
30°) cross-strata are not exclusively diagnostic of dune sands. Inclined cross-strata, capped by near-horizontal intertidal layers and washover deposits from waning storms, may represent the core of a given berm ridge. Steeply inclined-to-near horizontal foredune ridges may subsequently be draped over such berm deposits (e.g., Mason et al., 1997, Fig. 8; Otvos, 1999).

3.3.2. Ridge crest elevation and sea level

The crest elevations of certain northern Gulf beach ridges, alleged to be indicators of Holocene record sea-levels (Stapor et al., 1991) provide even less evidence. The steep, relatively high Late Holcene beach ridges in the Apalachicola mainland coast and St. Vincent Island strandplains of NW Florida, clearly indicate foredune origins. Certain shell-enriched, 2–3-m high ridge sets on the peninsular Florida Gulf coast may have formed during unusually high, storm-associated wind tide stages. In sharp morphological contrast with the steep relict foredune ridges (Otvos, 1995, 1999), the swash-built shelly–sandy backshore berm ridges, including Louisiana cheniers and shell-rich beach ridges on the peninsular Gulf coast of Florida, do *not* necessarily record Mid- and Late Holocene eustatic highstands.

As noted (Table 1), sandy *berm ridges* are subdued, flat-topped features of gentle slopes (e.g., Mason et al., 1997). During record high tide episodes, associated not with direct, erosive storm impact but with constructive waves from glancing, relatively distant storm centers and/or subsiding record high tides, the ridges have aggraded up to a few meters above mean sea level. Interpretations of sea/lake levels from *wave*-deposited clastics at record high elevations would require detailed regional field studies beyond routine sediment analysis. This could determine whether the raised water levels were associated with brief storm-related episodes or prolonged, eustatic phenomena.

Shell-enriched coastal ridges that formed only in the last century on the Gulf shores of Florida are comparable in elevation to some of the prehistoric alleged highstand beach ridges; earlier ridge generations in the same strandplains (Stapor et al., 1991; Otvos, 1995, 1999). Mostly wave-built, 1.5–3 m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Big Ridge Scarp
Old Fort Bayou

high beach ridges, including those in the SW Louisiana chenier plain provide little convincing indication for the alleged Late Holocene highstands. Regionally widespread, elevated intertidal salt marsh deposits along and above the present, protected Gulf estuarine shores would have provided the decisive evidence. Such a proof, however, is lacking.

3.3.3. Terraces, lineaments and scarps

Unlike uplifted, fossiliferous marine terraces on Pacific mainland and island shores, commonly with datable coralgal deposits, erosional and tectonic landforms that only superficially resemble coastal marine features are not infrequent on the northern Gulf of Mexico coastal plain. They provide no conclusive evidence for coastal marine origins (Otvos, 1995, Fig. 5; 1999; Otvos and Howat, 1997).

Certain Gulf-facing bluffs and creek interfluves in Pliocene and Pleistocene northeastern Gulf coastal plain areas have often been attributed to wave-cut scarps, littoral barriers, beach ridges, and relict beaches. Alleged coastal features that mimic elongated beach ridges, often include shallow-etched parallel and rectangular fine grooves or coarser, more deeply incised elements of drainage networks. The features are of joint fracture origin and were imprinted by tectonic forces into level alluvial coastal plain surfaces. The absence of marine coastal deposits and material proof for marine erosional processes, and the presence of fresh water peat-bearing alluvial floodplain deposits decisively argues against beach ridge or other coastal marine origins. Rectangular lineament configuration and sag pond-like lows, such as along the toe of the Big Ridge escarpment in coastal Mississippi (Fig. 12) indicates the tectonic (fault and joint) nature of these features (Otvos, 1981, 1999).

4. Conclusions. Inclusionary and exclusionary criteria for beach ridge designation

In the face of a plethora of conflicting designations, beach ridges are redefined as intertidal–supratidal, narrow, relict landforms. This essentially morphological designation is reserved for coastal ridges that became isolated from the daily impact of shore erosion and accretion processes through shore progardation. Beach ridges are wave-built berm ridges, including transgressive and regressive cheniers, and relict foredune ridges. Almost all beach ridge lithosomes include at least a measure of intertidal and eolian components. In contrast with the subdued berm ridge morphology, Holocene eolian strandplain ridges (relict multiple, subparallel foredunes) have steeper slopes. Under favorable conditions the ancient sea level may be reconstructed by the horizontal interface between *intertidal* sediments and the *eolian sand cap* within a given beach ridge.

Regardless of morphology, dimensions, and developmental history, all active wave-constructed and eolian shore landforms are excluded from the beach ridge designation. Also excluded are sundry inactive coastal dunes, even those designated as ''foredune'' in the literature, if they do not conform to the criteria of multiple eolian strandplain ridges.

In the absence of significant differences in the granulometric parameters and sedimentary structures between intertidal and capping eolian deposits within a beach ridge precludes reconstruction of a past sea level from vertical ridge sequences. Episodic storm-tide-related record sea levels may build sturdy boulder ramparts, shell-rich sandy, occasionally even sandy berm ridges well above present elevations of the ''highest high'' tides. Holocene equivalents of such *supratidal* wave-built ridges, whether capped by eolian sand or not, do not reflect ancient long-term positions of sea level.

Alleged shoreline indicator landforms of Late Pliocene and Quaternary ages on the northeastern Gulf of Mexico coastal plain that superficially may mimic shore barriers, beaches, wave-cut bluffs and barrier spits are common in the literature. These features have often been interpreted, however, as fluvial surfaces, erosional scarps, bluffs, and interfluve ridges. Tectonic lineaments, including fractures, have been overprinted on alluvial deposits that were not laterally associated with any open marine

Fig. 12. East end of Big Ridge Scarp (toe: dashed lines with teeth). Fine-textured, rectangular drainage lineaments occur north of it. Ocean Springs Quadrangle, Jackson County, MS. US Department of Agriculture aerial photo map, 1942.

littoral, inshore and nearshore units in the surface or the shallow subsurface (Otvos, 1995).

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