

# Sedimentary Characteristics of Low-Energy Carbonate Beaches, Florida Keys

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## ABSTRACT

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The recognition of carbonate-beach deposits may be important in understanding ancient stratigraphic sequences in that they can serve as an environmental reference point for interpreting adjacent facies. However, low-energy beach deposits are generally difficult to distinguish due to (1) the low contrast in energy regime from onshore to offshore and (2) extensive bioturbation which destroys primary structures (such as inclined bedding and ripple marks). Wave-induced longshore currents along three modern Florida beaches (Lower Matecumbe, Bahia Honda, and Big Pine Keys) are weak, and only small beaches are maintained. In cross-section the sand bodies appear as lenses, no more than 33 m wide and 1.5 m thick. A sedimentological study shows that these skeletal sands are marked by four distinct, but subtle, textural and compositional properties. (1) Backshore and foreshore sands contain some mud (up to 8%), but the mud content increases significantly across the shoreface and into the offshore sands (up to 25%). (2) Only the backshore sediments are moderately well sorted; most sediment deposited below mean high tide is poorly sorted. (3) Mean grain size of foreshore sands (coarse) is greater than for sands of the other subenvironments (fine to medium). Foreshore sands are also bimodal, thus accounting for their poor sorting, and these several properties result from the population of molluscs that live and die at the strandline. Waves of this zone are simply incapable of transporting these large shells. (4) One final feature of the beach sands is their low skeletal equitability, that is, the sediments are commonly composed of just one kind of skeletal grain, predominantly eurytropic gastropods or pelecypods. Results of this study indicate that a combination of petrographic characteristics is needed, because of their subtlety, to interpret low-energy beach facies in the rock record.

**ADDITIONAL INDEX WORDS:** Carbonate beach sediments, constituents, Florida Keys, low-energy environment, sedimentary model, textures.



## INTRODUCTION

Carbonate-beach deposits are rarely identified from the rock record, probably due more to non-recognition than to a real absence of the facies (INDEN and MOORE, 1983). Low-energy beach deposits, in particular, prove difficult to distinguish because they lack the patterns in lithology, texture, and sedimentary structures that are generally characteristic of beaches. Their identification, however, may be important in understanding ancient strati-

graphic sequences in that they would provide an environmental reference point for interpreting adjacent facies.

Yet modern carbonate beaches, which serve as analogues for their ancient counterparts, have not been studied in much detail. For example, although many comprehensive works have investigated the carbonate environments off south Florida (GINSBURG, 1956; SWINCHATT, 1965; MULTER, 1977; ENOS and PERKINS, 1977), beaches that fringe the Florida Keys have been mostly overlooked. The beaches are small in size and few in number. Consequently, geologists have tended to neglect this environment.

The purposes of the present study, therefore, are (1) to offer sedimentological data for three low-energy beaches of the south Florida shelf and (2) to propose a sedimentary model for such beaches. Knowledge acquired from this research should prove helpful in identifying analogous sedimentary rocks and in constructing more complete depositional models for carbonate platforms.

### GEOLOGICAL SETTING

The Florida Keys consist of an arcuate string of islands that extend for almost 400 km from Miami southwest to the Dry Tortugas. Beaches sampled for this study are located on three of the islands, Lower Matecumbe Key, Bahia Honda Key, and a small island near Big Pine Key, locally called Horseshoe Island (Figure 1). The beaches on Lower Matecumbe and Bahia Honda Keys face southeast toward the reef tract, whereas the beach on Horseshoe Island faces west-southwest into Newfound Harbor channel, a tidal-exchange channel between the Gulf of Mexico and the Atlantic reef tract.

Maximum tidal range in the Keys is approximately 70 cm along the northern outer reef arc (GINSBURG, 1956). At Tavernier Key, within the northern section of the back-reef zone and not too distant from the Lower Matecumbe beach, the mean tidal range is 66 cm (TURMEL and SWANSON, 1976). Tidal range decreases progressively to the southwest. Along the central outer reef arc, opposite the city of Marathon, the mean range is only 50 cm (GINSBURG, 1956). Farther south at Horseshoe Island, the tidal range is estimated to be 20 cm, based on

the elevation difference between small terraces at the high-tide and low-tide strandlines. In a nearby channel at the mouth of Coupon Bight, tidal range may be as high as 40 cm (HOWARD *et al.*, 1970).

Wind direction and force influence the circulation patterns of water in the back-reef zone as well as the direction of incoming waves which break on the beaches. Prevailing spring and summer trade winds blow from the east and southeast; however, winter winds are commonly from the northeast. Winds cause a general longshore drift towards the southwest along the Atlantic coast of the Keys (GINSBURG, 1956).

The outer reef arc effectively impedes oceanic swells that originate in the open Atlantic Ocean; hence, currents within the study area are mainly due to tides and local winds. Water movement through major tidal channels located between the Keys have a velocity range of 150-200 cm/sec (SCHOLL, 1966). Longshore-current velocities were measured at the three beaches of this study and averaged: 21 cm/sec at Lower Matecumbe, 24 cm/sec at Bahia Honda, and 15 cm/sec at Horseshoe Island.

### FIELD AND LABORATORY METHODS

Nine sediment samples were collected from each of the three carbonate beaches (27 samples in all) in May 1982. These nine samples were taken along three traverses that covered a large portion of each beach, and all traverses crossed the supratidal, intertidal, and subtidal zones (Figure 2). The traverses were profiled using a beach profiler described by WALLACE and PHLEGER (1979). Average

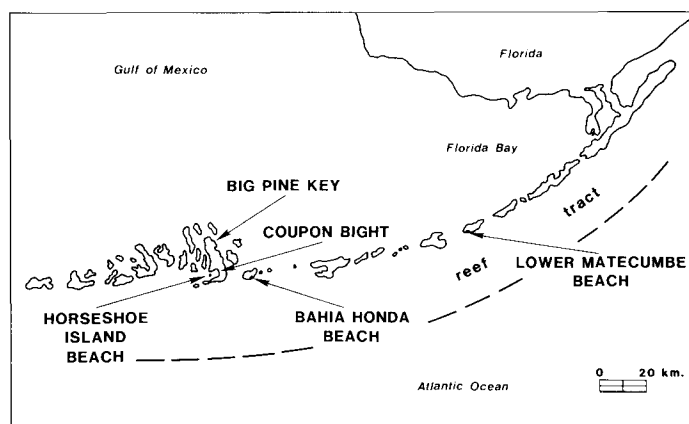


Figure 1. The South Florida carbonate shelf.

current speed was measured a short distance offshore with a Gurley current meter. At various locations along the traverses, the beaches were trenched to record sedimentary features within the sediment. Finally, the beaches were measured, described, and photographed. All work was done at low tide.

In the laboratory, samples weighing approximately 100 g were soaked in bleach for periods of up to two days in order to destroy any organic material. The samples were then wet-sieved through a 4.0 phi screen to remove all of the silt- and clay-size particles. Both the sieve residue and the silt and clay fraction were dried, after which the latter was weighed and discarded. The sieve residue was then dry-sieved using sieve sizes -2.0 phi through 4.0 phi at half-phi intervals and a Tyler Ro-Tap sieve shaker. Each sieve fraction was weighed to the nearest 0.1 gram. The percent of the sample lost was always less than 0.01%. Mean grain size, mode, and standard deviation were then calculated graphically for each of the 27 sieved samples.

To determine the sediment constituents, the very-coarse-sand and gravel-size fractions of the 27 samples were split to approximately 200 to 400 grains. These grains were then spread evenly over the bottom of a shallow 13x16 cm box lined with

graph paper. Each grain was identified and counted by examining one square at a time through a 10X-30X reflected-light microscope. The following grain types are present: foraminifers, corals, gastropods, pelecypods, *Halimeda*, coralline algae, nonskeletal grains (fragments of bedrock), miscellaneous grains (mostly echinoderms), and unknowns.

### BEACH MORPHOLOGY

The beaches of Bahia Honda, Lower Matecumbe, and Horseshoe Island (Figure 2) are small, from 0.17 to 0.47 km in length, and terminate against mangrove swamps, a rocky coast, coastal point, tidal channel, or man-made marina. Along the landward edge of each beach is a berm, generally well vegetated and built up to no more than 0.5 m above the backshore sand (Figure 3). The supratidal (backshore), intertidal (foreshore), and subtidal (shoreface) zones are commonly well defined by small terraces that have formed at the boundaries between these subenvironments. Maximum width of the beaches is 21 to 33 m.

The seaward slope of the beach surface averages between 4 and 6 degrees, and the steepest sections (4.7 to 6.9 degrees) correlate

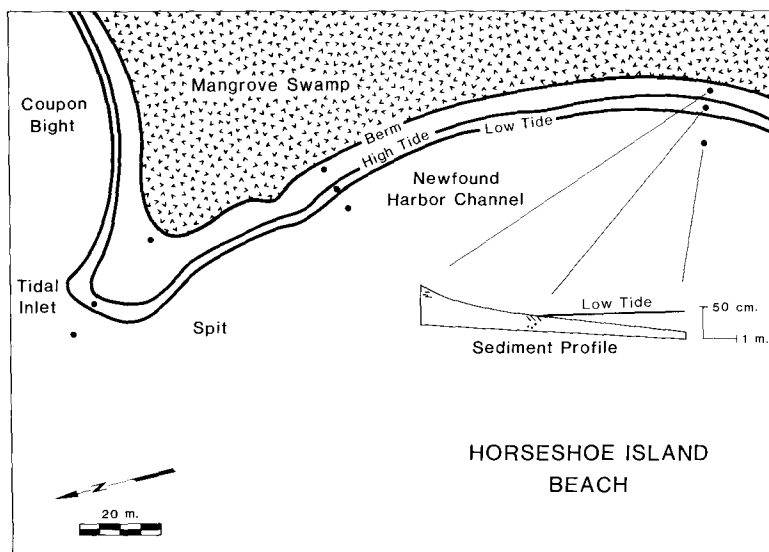


Figure 2. Map and profile view of Horseshoe Island beach. The narrow beach, which is bounded on the west by Newfound Harbor channel and on the north by a small tidal inlet into Coupon Bight, has been extended by currents into a spit. Dots mark the nine sample-collection localities. Sedimentary structures exposed by trenching include organic layers in the backshore sands and inclined bedding and carbonate-gravel layers in the foreshore sands.

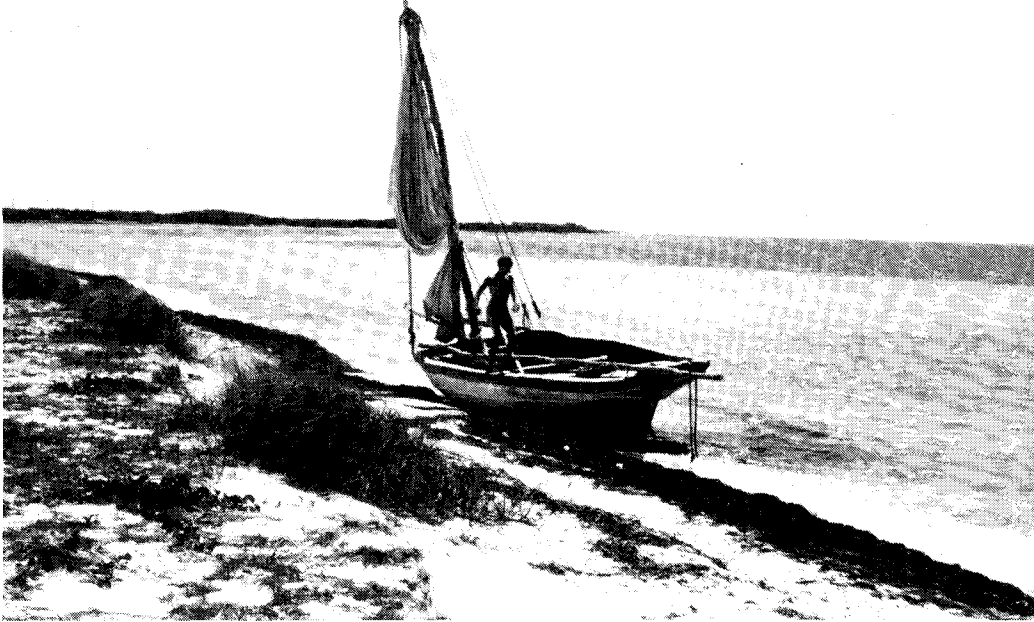


Figure 3. Bahia Honda beach, showing a berm along the landward edge of the backshore, clumps of sea grasses which accumulate at the high-tide level, the narrow foreshore, subtidal shoreface (light) and offshore zone (dark).

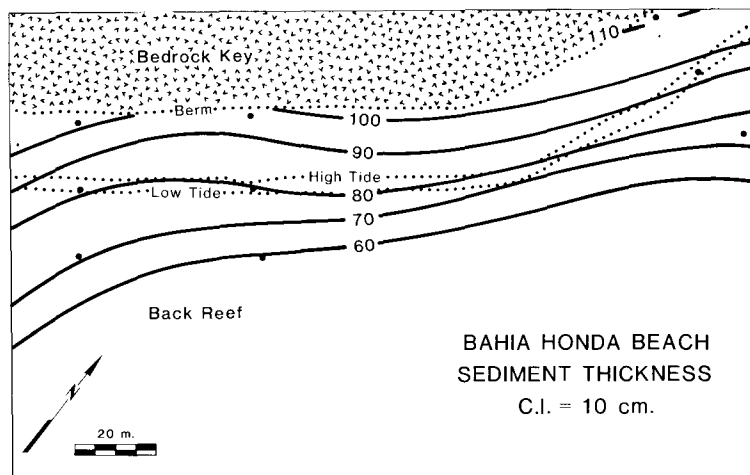


Figure 4. Contour map of sediment thickness at Bahia Honda beach. The sand constitutes a narrow, wedge-shaped body that thins seaward. Immediately southeast of the 60-cm contour line, the beach sand grades into muddy skeletal sand of the offshore environment.

with the coarsest sediments. Because coarse sediment has a high permeability, much of the water that rushes up the beach infiltrates into the sediment. With only a small backwash, the resultant beach face can stand at a steep angle (SHEPPARD, 1973, p. 127).

Surficial sedimentary features are not abundant. On Lower Matecumbe the surface is featureless except for crab mounds and tracks. At the northern end of Horseshoe Island, interference ripples are common. The major ripple set corresponds to the stronger tidal current which flows into and out of Coupon Bight. The minor set is most likely produced by the weaker current of Newfound Harbor channel. Ripples are also present at Bahia Honda. There, the rippled sand extends 16 m out from the low-tide line (shoreface). Waves from the northeast and longshore currents from the north-northeast have created interference ripples. During low tide, parts of the rippled shoreface sand lie exposed as small shoals away from the main beach.

Trenching, likewise, reveals few sedimentary features (Figure 2). Organic-rich layers, presumably representing buried sea grasses washed in by storms, are rare within the backshore sediment, and layers of carbonate gravel, also attributed to storms, occur beneath the backshore-foreshore surface. Inclined (seaward) bedding is preserved only within the foreshore sediment of Horseshoe Island. For the most part, however, the sediment is homogeneous, churned and reworked by burrowing organisms.

In profile the beach sands appear as a wedge (Figure 4). The sand veneer attains a maximum thickness of 100-150 cm near the backshore berm (determined by probing) and gradually thins seaward. The lower shoreface sediment ranges from 20 to 120 cm in thickness where it grades into muddy carbonate sands of the offshore environment.

## DISCUSSION

### Mud Content

FOLK and ROBLES (1964), in studying modern carbonate beaches of Mexico, concluded that the subtidal sediments contain the greatest percentage of fines. This fact, of course, is true for most beaches, those of terrigenous as well as carbonate sediments, and reflects decreasing hydrodynamic energy offshore. The absolute increase in mud content offshore is a function of several environmental variables, such as energy level, availability of mud, the presence of current-baffling organisms, and the

degree of biological erosion, but the relative increase can be one important indicator of beach sedimentation.

On the low-energy beaches of the Florida Keys, the backshore and foreshore sands contain some mud (sediment less than 62 microns). Mud content of the 9 backshore samples averages 3.9% and ranges from 1.0-6.6%. Similarly, that of the 9 foreshore sands averages 6.0% and ranges from 2.6-8.2%. By way of comparison, the mud content of high-energy backshore-foreshore sands in Mexico does not exceed 1.5% (FOLK and ROBLES, 1964); that of a barred shelf-edge sand of Florida ranges from 0 to 9% (SWINCHATT, 1965); and the amount of fines (sediment less than 125 microns) in a Bahamian oolite shoal averages 1.9% with an observed maximum of 5.5% (PURDY, 1963). Low-energy beach sands, therefore, are slightly muddier than typical high-energy carbonate sands.

There is, however, a continuous increase in mud content across all 9 traverses of the Florida beaches (Figure 5), from the backshore (mean 3.9%), to the foreshore (mean 6.0%), to the shoreface (mean 10.0%, range 2.6-17.2%), to the offshore (range of 9-27%, inner portion of the back-reef environment, data taken from SWINCHATT, 1965). Thus, waves and currents of this low-energy environment are sufficient to wash the sediment moderately to moderately well, particularly on the beach above mean low tide. More important, though, is the marked increase in percent mud in the offshore direction.

### Sorting

Sorting has been suggested as a discriminating characteristic of carbonate-beach sediments (FOLK, 1962; FOLK and ROBLES, 1964; UPCHURCH, 1972). UPCHURCH (1972) analyzed modern carbonate beaches of Bermuda and concluded that these sediments are similar to those of terrigenous-sand beaches in that both are well to moderately well sorted. Moreover, on beaches of Mexico, FOLK (1962) discovered that sorting values are the same for beaches with vigorous waves as for lagoonal beaches with small waves and that beach sediments of nearly all grain sizes have similar sorting values (FOLK and ROBLES, 1964). On the other hand, the present study suggests that sorting values for Florida beaches are not as good as values of other carbonate beaches nor are they as discriminating (Figure 6).

Only the backshore sands of the Florida beaches are moderately well sorted (standard deviation of grain size between 0.50-0.71  $\phi$ ). But even among the backshore sands, one third of the samples are

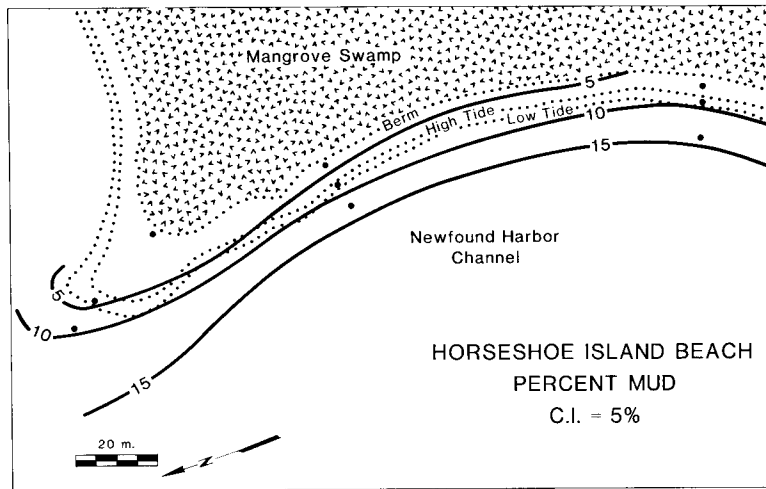


Figure 5. Contour map of percent mud (finer than 62 microns) at Horseshoe Island beach. There is a marked increase in the mud content in the offshore direction.

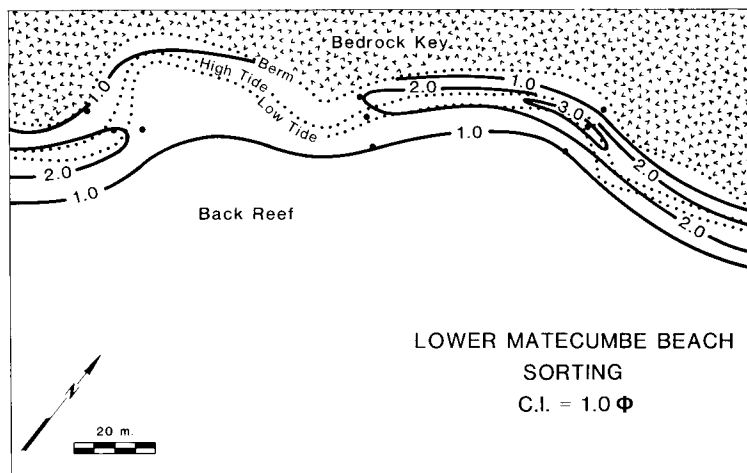


Figure 6. Contour map of sorting values (graphic standard deviation) at Lower Matecumbe beach. Sorting is generally best (moderate to poor at this beach) on the backshore and worst (poor to very poor) on the foreshore.

poorly sorted (1-2  $\phi$ ). Seven of 9 foreshore samples are poorly sorted, the remainder are very poorly sorted (2-4  $\phi$ ). Sorting values show the widest range in the 9 shoreface sediments: one is very well sorted (under 0.35  $\phi$ ), one moderately well sorted, five poorly sorted, and two very poorly sorted. Data for offshore sediments (from HURSKY, 1977, and SWINCHATT, 1965) indicate them to be moderately

to poorly sorted (values from 0.74 to 1.72  $\phi$ ).

FOLK (1962) observed that almost all of the beach sediments sampled in Mexico have a sorting value less than 0.7  $\phi$  and almost all of the subtidal sediments have a sorting value greater than 0.90. The results of our study show general agreement with those of Folk. Carbonate sands from the Florida backshore subenvironment generally have sorting

values of  $0.70 \phi$  or lower, and sands from the other subenvironments (foreshore, shoreface, and offshore) generally have sorting values greater than 0.90. The foreshore sands are commonly the most poorly sorted; however, in most cases beach sands deposited beneath the high-tide line cannot be differentiated from one another on the basis of sorting value alone.

### Mean Grain Size

Few textural data have been published on carbonate beaches of the Florida Keys. BENHAM *et al.* (1970), examining the beach at Bahia Honda Key, stated that grain size decreases offshore. FOWLER (1977) concluded that mean grain size can be useful in differentiating littoral from nearshore facies at Bahia Honda Key. HURSKY (1977) proposed that variations in grain size at two beaches on Lower Matecumbe Key were a function of hydrodynamic-energy level. In general, therefore, low-energy carbonate-beach sands are expected to follow the same trend as other kinds of beach sands; mean grain size should decrease in the offshore direction as the effect of wave activity decreases.

On closer scrutiny, the trend of grain size on Florida beaches is not so simple (Figure 7). The grain size distribution, as determined from the present study, is as follows: backshore — medium sand

(mean  $M\phi$  1.56, range 0.7 to 2.4), foreshore — coarse sand (mean  $M\phi$  0.59, range -0.6 to 1.6), and shoreface — medium sand (mean  $M\phi$  1.94, range 0.9 to 3.0). HURSKY (1977) and FOWLER (1977) established that mean grain size for offshore sediment at Lower Matecumbe and Bahia Honda beaches is fine to medium sand ( $M\phi$  1.98 and 2.04, respectively). Hence, grain size is coarsest in the foreshore subenvironment and decreases both landward and seaward.

The relative coarseness of foreshore sediments is due to the abundant gastropods and pelecypods that live within and very close to the intertidal zone. The *in-situ* production of these shells is high, but mechanical abrasion and wave transport is low due to the overall low energy of this environment and the durability of mollusc shells (CHAVE, 1964). The lack of significant abrasion on any of the skeletal material examined in this study indicates that these grains have not been transported far. Furthermore, the abundance of whole, *in-situ* molluscs causes the sediment to be bimodal (Figure 8). There are two distinct modes of grain sizes in the sediment; one fraction is presumably transported onto the beach from the offshore environment (finer skeletal sand) and a second fraction produced within the intertidal zone (coarse mollusc shells). This bimodal distribution, in turn, explains the poor sorting of foreshore sands.

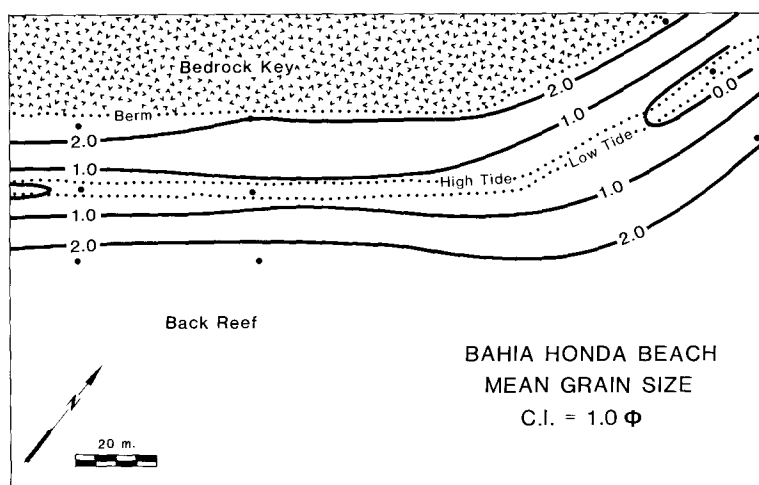


Figure 7. Contour map of mean grain size at Bahia Honda beach. Grains are coarsest in the intertidal zone, becoming finer both landward and seaward.

evenness, that is, the manner in which the individuals are distributed among the different groups present. For example, a population that contains equal numbers of individuals of species X, species Y, and species Z has a high equitability, whereas another population that is overwhelmingly dominated by individuals of species X with only a few individuals of species Y and Z has a low equitability.

The skeletal assemblages in the 15 low-equitability samples of Florida consist of more than 50 percent from one skeletal group. The dominant group may be gastropods (particularly at Horseshoe Island), pelecypods (particularly at Bahia Honda), or rarely *Halimeda* (Bahia Honda and Lower Matecumbe). The low skeletal equitability of these carbonate beaches is attributed to (1) the high physiological stress exerted on organisms that live in the near-shore environment (SANDERS, 1968; MULTER, 1977) and (2) the absence of daily currents strong enough to transport much skeletal material from the more diverse offshore communities.

#### MODEL FOR A LOW-ENERGY CARBONATE BEACH

Sediments that make up high-energy carbonate beaches are known to follow a definite trend, which allows for the development of a sedimentological model (INDEN and MOORE, 1983). Specifically,

from foreshore to shoreface to offshore, grain size decreases from coarse to fine, sorting changes from good to poor, and physical sedimentary structures give way to biological structures. Low-energy beaches, on the other hand, do not possess the obvious characteristics of their high-energy counterparts. Despite their subtlety, however, textural and compositional properties are distinct (Figure 9).

Backshore sands are the only texturally mature sediments of the low-energy beach subenvironments. The mud content is low (less than 7 percent by weight), and the sediment is generally moderately well sorted (standard deviation of grain size between 0.6 to 0.7  $\phi$ ). Grains, however, are not rounded. If lithified, the rocks would be skeletal grainstones. This degree of maturity results from the process of wave swash, particularly that of storm surges to which the backshore is most subjected. Eolian processes acting on the exposed backshore sand may affect the sediment maturity as well. Clumps of sea grasses washed onto the backshore sand by storms may occasionally be preserved as organic-rich laminae. But like most sediment in the several subenvironments, primary structures are quickly destroyed beneath the depositional interface by burrowing organisms.

Foreshore sands are the coarsest beach sediment due to an abundance of whole mollusc shells. Eurytopic gastropods and pelecypods live in large

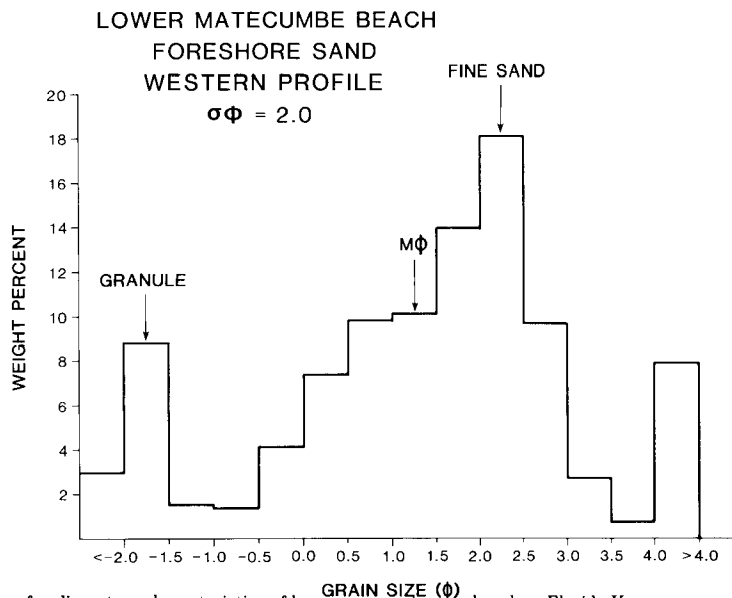


Figure 9. Summary of sedimentary characteristics of low-energy carbonate beaches, Florida Keys.



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ZONE	GRAIN SIZE		SORTING		MUD CONTENT		LITHOLOGY	PROCESSES
	Coarse	Fine	Poor	Well	Low	High		
BACKSHORE							Grainstone	Storm Surge, Biological
FORESHORE							Grainstone	Wave Swash, Biological
SHOREFACE							Grainstone to Packstone	Longshore Drift, Biological
OFFSHORE							Packstone	Biological

Figure 9. Summary of sedimentary characteristics of low-energy carbonate beaches, Florida Keys.

numbers in the high-stress environment near the level of low tide, and waves of this zone are incapable of transporting the shells. The coarse fraction of whole, *in-situ* mollusc shells (coarse sand to granules) coupled with another fraction of transported, offshore shell debris (fine sand) produce a characteristic bimodality to these sands. The mud content is low (8 percent or less), but sorting is poor to very poor (1-4  $\phi$ ); hence, the sediment is immature. If lithified, calcarenites of this facies would be classified as grainstones. Where not disturbed by infauna, foreshore sands display an inclined bedding that dips seaward at an angle of 4-6°. Rarely, layers of carbonate gravel, interpreted to be storm deposits, are preserved within the sand body.

Shoreface sands are transitional with offshore sediments. Both are composed of fine to medium sand, are moderately to poorly sorted (wide range from 0.7 to 2.5  $\phi$ ), and are fairly muddy. But differences do exist. Shoreface sands are slightly coarser. They show a low skeletal equitability and consist predominantly of eurytropic mollusc shells. Shoreface sands, too, are more mobile than offshore sands; consequently the beach surface is marked by ripple marks, the sediment contains less mud (less than 17 percent), and *Thalassia* grass is absent. Lithified shoreface sediments would be mostly texturally immature packstones. Unexpectedly, offshore sands appear to be somewhat better sorted than shoreface sands. This reversal can best be explained by (1) greater mud deposition offshore due to the baffling effect on currents by marine grasses and (2) greater biological destruction of skeletal sand (SWINCHATT, 1965). Although the sedimentary particles are not separated or selected by waves and currents, the net result is a slight improvement in overall sorting values.

Sedimentological variations are present, however, within this generalized onshore-offshore model. For example, parts of the three low-energy beaches of this study experience relatively higher wave energy than the norm. Small coastal points concentrate wave activity by refraction, and wave energy is therefore somewhat greater and more consistent. In other places the beaches change their orientation, following a turn in the coastline of the underlying bedrock, so that prevailing winds strike the beach more directly. Also, Bahia Honda and Lower Matecumbe beaches face the higher-energy Atlantic Ocean, whereas Horseshoe Island faces a tidal-exchange channel. These segments of the beaches experiencing higher wave energy respond with sedimentary characteristics more like those

described by INDEN and MOORE (1983). In particular, the mud content is less and sorting is better. The width of the beach is greater, and ripple marks on the shoreface sand are more common. Sediment thickness is also greater, but this may reflect man-made disturbances (such as construction near the Bahia Honda beach) or topographic lows on the underlying Pleistocene bedrock (FOWLER, 1977).

The northern end of Horseshoe Island beach terminates at an inlet feeding into Coupon Bight. Tidal currents moving through Newfound Harbor channel as well as through the small inlet into Coupon Bight have constructed a small spit as an extension of the beach (Figure 2), and it is thought that the energy level at this point is the highest of all three beaches studied. In contrast to other intertidal sands, that of the spit is relatively fine (medium sand) and moderately well sorted (1.0  $\phi$ ). The sediment is not bimodal. Mobility of the sand is interpreted to be great enough to preclude many molluscs, and with few organisms living in the nearshore environment, the sediment more closely resembles that of a clastic beach.

In a similar manner, parts of the beaches studied experience relatively lower wave energy than the norm. These stretches are situated within small coves along the coastline. As expected, mud content is higher, sorting is poorer, and sediment thickness is less. There is also a greater amount of coarse grains in these sands. The lower-energy stretches constitute a more favorable habitat for molluscs, and mechanical abrasion is essentially nonexistent. Hence, abundant, whole, *in-situ* mollusc shells increase the sediment's coarse fraction. These stretches of beach contain sediments more like those of the offshore environment (compare with SWINCHATT, 1965).

Finally, the texture of low-energy carbonate-beach sediments is a function of skeletal-grain type as well as wave and current action. In the nearshore environment, disintegration of skeletal hard parts produces many different grain sizes (FOLK and ROBLES, 1964). Gastropods, for example, are mostly whole; they have not suffered any reduction in grain size. Consequently, almost all samples in which gastropods dominate (those with more than 50 percent of the skeletal material consisting of gastropod shells) contain at least 15 percent by weight very coarse sand and gravel and as much as 48 percent. Corals (mostly *Porites*) typically break into large bioclasts, and the two samples in which corals dominate contain 35 percent very coarse sand and gravel. Conversely, the disintegration of *Halimeda*

produces a large fraction of micron-sized particles, and the four beach samples dominated by *Halimeda* fragments have less than 15 percent very coarse sand and gravel. Any effects of wave and current activity on sedimentary texture — such as removing the lime-mud matrix and sorting the sediment — are additional to those of skeletal-grain types and their disintegration patterns.

#### SILURIAN EXAMPLE OF A LOW-ENERGY CARBONATE BEACH

A core from the Silurian Salina Formation (McKenzie equivalent) in western West Virginia has recovered a limestone interpreted to be an ancient beach deposit (SMOSNA and WARSHAUER, 1978). The unit is 30 cm thick and consists of ostracode grainstone-packstone (Figure 10). Ostracodes overwhelmingly dominate the rock (42 percent of the rock volume or 97 percent of the skeletal assemblage); hence, the sediment had a very low skeletal equitability. Several genera of ostracodes may be present, but *Leperditia* is most abundant. *Leperditia* were eurytropic organisms, being tolerant of a

wide range of environmental factors (particularly elevated salinity and periodic subaerial exposure), and often they lived in shallow, restricted waters (WARSHAUER and SMOSNA, 1977). Valves are generally disarticulated, implying transport, although some are articulated. Only a few were broken in the depositional environment, but several have been crushed by post-depositional compaction. A number of ostracode valves are stacked one inside another, thought to have been produced by agitation of the sediments. Other fossils include whole gastropods, bryozoan fragments (*Homotrypa*), and brachiopods. Micrite envelopes on some shells imply the presence of endolithic algae or fungi (BATHURST, 1975). Shells are generally oriented parallel to bedding, though not necessarily concave-side down.

Sorting of the sediment is visually estimated to be poor. All sizes of ostracodes are present, including juveniles and adults. Peloids (6 percent) also display a wide range in size from very fine sand to coarse sand. Peloids consist of both fecal pellets and small erosional intraclasts. Like the carbonate-gravel layers in the modern beaches of Florida, the

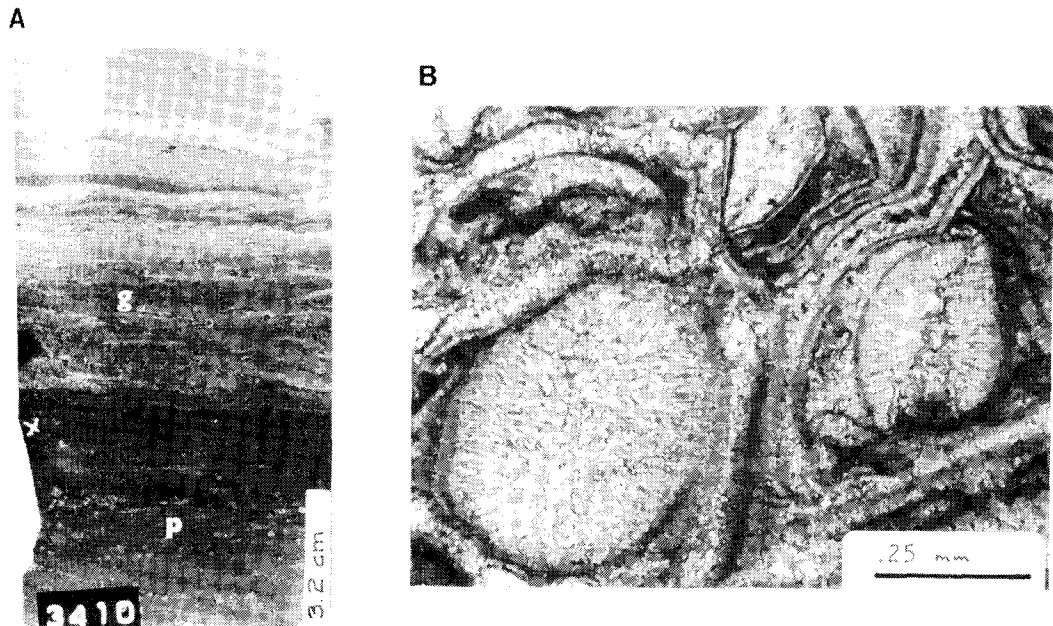


Figure 10. Ostracode grainstone-packstone in the Silurian Salina Formation, from a well in West Virginia (subsurface depth 3,410 feet), interpreted to be an ancient low-energy beach sand. A. Core photo shows lower dark packstone (p) grading upward to rippled grainstone (g). Beach deposit is overlain by stromatolitic dolomite (s) of sabkha facies. B. Photomicrograph of tightly packed ostracode shells, calcite cement, and dolomitic matrix.

intraclasts are concentrated in layers, probably as storm deposits. Some carbonate matrix is present (9 percent), but this has been subsequently dolomitized (now aphanocrystalline to finely crystalline dolomite) or rarely replaced by chert. In one place, the matrix has a geopetal structure where mud filled only the lower portion of a whole ostracode shell. Small amounts of clay minerals are dispersed in the dolomitic matrix.

The rock was originally quite porous (39% of total rock volume); however, all porosity has been occluded by finely crystalline calcite cement. Calcite cement increases upward in this unit as the mud

content decreases. Ripple marks are the only sedimentary structure, and in contrast to the Florida beach sands, bioturbation is absent. Other evidence illustrates that the Silurian epeiric sea was hypersaline, and an elevated salinity may be responsible for the lack of burrowing infauna. The unit is capped by small flat stromatolites, constructed by blue-green algae.

By comparison to modern beaches (in terms of lime-mud content, sorting, skeletal equitability, paleoecology, level of abrasion, and sedimentary structures), the 30-cm Salina unit is interpreted to be a low-energy beach sand.

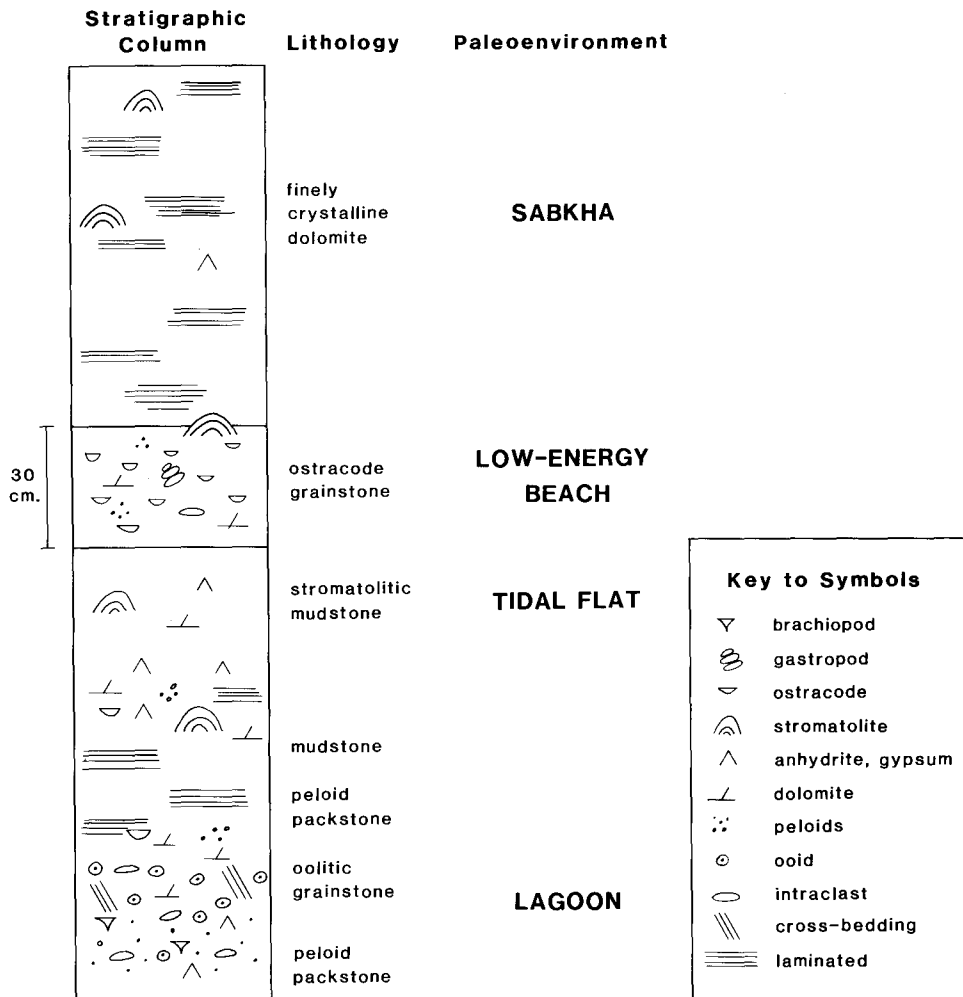


Figure 11. Stratigraphic column of upper Lockport Dolomite (lagoonal facies) and lower Salina Formation (peritidal facies) in a well from West Virginia. Thirty-centimeter unit near the middle is a Silurian low-energy beach deposit.

The Silurian beach unit caps a regressive, near-shore stratigraphic sequence of limestones and dolomites (Figure 11). Sixty centimeters below in the core (in the uppermost Lockport Dolomite) is a restricted lagoonal deposit. This unit, although partly dolomitized, is a pellet-intraclast grainstone-packstone. Fossils include ostracodes, brachiopods, and stromatolites. The intraclasts are erosional rip-ups and grapestones. Transported ooids are also present. Small amounts of evaporite minerals (anhydrite and gypsum) occur as nodules and scattered crystals. Overlying this unit and directly beneath the beach sand is a stromatolitic mudstone. Small stromatolite domes, anhydrite crystals, very finely crystalline replacement dolomite, and cryptalgal structures attest to a muddy tidal-flat environment.

Sedimentation on the Lockport-Salina shelf thus produced a shallowing-upward sequence from muddy lagoonal sands to tidal-flat muds. The carbonate shelf must have exhibited some topography, and perhaps the tidal-flat muds accumulated on a small bank or island. A slight change in the environmental setting, like a change in wind direction, then created a low-energy beach around the margin of the exposed mud bank. At this time the ostracode grainstone was deposited. The thin beach sand was later blanketed by sabkha dolomites typical of the Salina Formation.

## SUMMARY

A sedimentary model has been constructed for low-energy carbonate beaches based on lime-mud content, sorting, mean grain size, skeletal equitability, ecological relationships, and sedimentary structures. Petrographic characteristics of sands from the four subenvironments vary only slightly, because of the low contrast in energy across the beach; still the various subfacies are distinct (Figure 12). In general, backshore sands are well sorted and contain little mud. Foreshore sands are coarsest, and the mud content is also low. Sorting is poor due to a bimodal distribution of large *in-situ* shells and finer transported bioclasts. Shoreface sands are transitional with offshore sediments: moderately to poorly sorted and fairly muddy. The skeletal assemblage of all three beach subfacies is commonly one of low equitability, and the sediment is dominated by eurytrophic molluscs. With an increase in energy level, sands of low-energy carbonate beaches more closely resemble those of clastic beaches in terms of textures and structures. With a decrease in energy level, they resemble offshore lime sediments. The model presented in this paper, developed from a study of Recent sediments of the Florida Keys, serves as a good analogue by which to interpret a Silurian low-energy beach deposit of West Virginia.

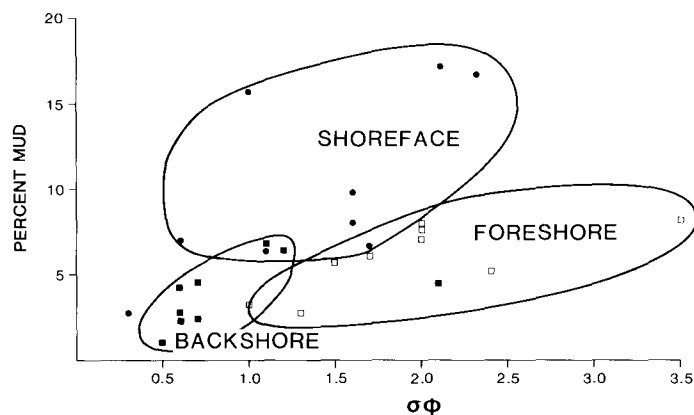


Figure 12. Plot of percent mud versus sorting values for 27 beach samples of this study. Backshore = black squares, foreshore = open squares, shoreface = black circles. With only a few exceptions, the three beach subenvironments can be fairly well differentiated.

## ACKNOWLEDGMENTS

William Grady of the Holiday Isle Tiki made helpful and important contributions to many aspects of this investigation. Financial support was provided by Appalachian Basin Industrial Associates and West Virginia University.

## LITERATURE CITED

- BATHURST, R.G.C., 1975. *Carbonate sediments and their diagenesis*. Amsterdam: Elsevier, 658p.
- BENHAM, S.R.; BOYCE, R.L.; DREXLER, W.W., and HAMILTON, M., 1970. A carbonate sand beach, Bahia Honda Key, Florida. *Geological Society America Abstracts*, 2, 194.
- CHAVE, K.E., 1964. Skeletal durability and preservation. In: J. Imbrie and N.D. Newell (eds.), *Approaches to paleoecology*. New York: John Wiley, 377-387.
- ENOS, P. and PERKINS, R.D., 1977. Quarternary sedimentation in South Florida. *Geological Society America Memoir* 147, 198p.
- FOLK, R.L., 1962. Sorting in some carbonate beaches in Mexico. *New York Academy Sciences Transactions*, Series 2, 25(2), 222-244.
- FOLK, R.L. and ROBLES, R., 1964. Carbonate sands of Isla Perez, Alacran reef complex, Yucatan. *Journal of Geology*, 72, 255-292.
- FOWLER, T.A., 1977. Local variations in the modern carbonate depositional environment, Bahia Honda Key, Florida. Unpublished M.S. thesis, University of Texas at Arlington, 97p.
- GINSBURG, R.N., 1956. Environmental relationships of grain size and constituent particles in some south Florida carbonate sediments. *Bulletin American Association Petroleum Geologists*, 40, 2384-2427.
- HOWARD, J.F.; KISSLING, D.L., and LINEBACK, J.A., 1970. Sedimentary facies and distribution of biota in Coupon Bight, Lower Florida Keys. *Geological Society America Bulletin*, 81, 1929-1946.
- HURSKY, M.J., 1977. Grain size distribution and constituent particle analysis of nearshore carbonate sediment of Lower Matecumbe Key, Florida. Unpublished M.S. thesis, University of Texas at Arlington, 93p.
- INDEN, R.F. and MOORE, C.H., 1983. Beach environment. In: P.A. Scholle, D.G. Bebout, and C.H. Moore (eds.), *Carbonate Depositional Environments*. Tulsa, Oklahoma: American Association Petroleum Geologists, 211-265.
- MULTER, H.G., 1977. *Field Guide to Some Carbonate Rock Environments, Florida Keys and Western Bahamas*. Dubuque, Iowa: Kendall/Hunt, 415p.
- PURDY, E.G., 1963. Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary facies. *Journal of Geology*, 71, 472-497.
- SANDERS, H.L., 1968. Marine benthic diversity: a comparative study. *The American Naturalist*, 102, 243-282.
- SCHOLL, D.W., 1966. Florida Bay: a modern site of limestone formation. In: R.W. Fairbridge (ed.), *The Encyclopedia of Oceanography*. New York: Reinhold, 282-288.
- SHEPARD, F.P., 1973. *Submarine Geology*. New York: Harper and Row, 517p.
- SMOSNA, R. and WARSHAUER, S.M., 1978. The evolution of a carbonate shelf, Silurian McKenzie Formation, West Virginia: a cluster analytic approach. *Journal of Sedimentary Petrology*, 48, 127-142.
- SWINCHATT, J.P., 1965. Significance of constituent composition, texture, and skeletal breakdown in some recent carbonate sediments. *Journal of Sedimentary Petrology*, 35, 71-90.
- TURMEL, R.J. and SWANSON, R.G., 1976. The development of Rodriguez bank, a Holocene mudbank in the Florida reef tract. *Journal of Sedimentary Petrology*, 46, 497-518.
- UPCHURCH, S.B., 1972. Discrimination analysis of Bermuda carbonate strand-line sediment. *Geological Society America Bulletin*, 83, 87-94.
- WALLACE, W.J., and PHLENGER, C.F., 1977. *Field Guide and Laboratory Manual for Oceanography*. Belmont, California: Wadsworth, 207p.
- WARSHAUER, S.M. and SMOSNA, R., 1977. Paleoecologic controls of the ostracode communities in the Tonoloway Limestone (Silurian; Pridoli) of the central Appalachians. In: H. Löffler and D. Danielopol (eds.), *Aspects of Ecology and Zoogeography of Recent and Fossil Ostracoda*. The Hague: Junk, 475-485.

## □ RESUMEN □

El estudio de los depósitos de playa carbonatados puede ser importante para la comprensión de las secuencias estratigráficas, puesto que pueden servir como punto de referencia ambiental para la interpretación de las facies adyacentes. Sin embargo, los depósitos de playa de baja energía son generalmente difíciles de distinguir debido a (1): el bajo contraste en el régimen de energía desde la costa hacia mar abierto y (2): a gran alteración biológica que destruye las estructuras primarias (como pueden ser los ripples). Las corrientes longitudinales inducidas por el oleaje a lo largo de tres modernas playas de Florida (Lower Matecumbe, Bahia Honda y Big Pine Keys), son débiles y sólo mantienen pequeñas playas. En sección transversal, las masas de arena aparecen como lentejones, que como máximo tienen 33 m de anchura por 1.5 m de espesor. Un estudio sedimentológico muestra que estas arenas bioclásticas se pueden distinguir mediante cuatro propiedades, precisas pero sutiles, texturales y de composición. Los resultados de este estudio indican que es necesario una combinación de las características petrográficas, debido a su sutileza, para interpretar las facies de baja energía de los testigos de roca.

## □ ZUSAMMENFASSUNG □

Das Erkennen der Carbonatstrandablagerungen mag wichtig zum Verständnis der uralten stratigrafischen Reihen sein, indem sie als einem Umweltpunkt zur Auswertung der anliegenden Fazien dienen. Die mit niedriger Energie gespeiste Strandablagerungen sind jedoch schwer zu unterscheiden, weil (1) das Energiesystem einen niedrigen Gegensatz zwischen dem Gebiet auf dem Strand und das hinaus dem Strand hält und (2) das umfassende Bioverwornen die anfängliche Tektonik (wie Neigungsschichtungen und Kräuselungsbezeichnungen) zerstören. An drei heutigen Strände in Florida (Lower Matecumbe, Bahia Honda, Big Pine Keys) vorbei sind die von Wellen verursachte Strömungen schwach; nur kleine Strände unterhalten sind. Im Querschnitt erscheinen die Sandkörper wie Linsen, ebensowenig wie 33 m breit und 1.5 m dick. Eine sedimentologische Forschung zeigt daran, dass diese Skelettsande von vier deutlich aber subtile Struktur- und Gestaltungseigenschaften bezeichnet sind. Aufgrund der Feinheit der Strandfazien zeigen die Ergebnisse dieser Forschung daran, dass eine Vereinigung der petrografischen Eigenschaften gebracht ist, um die mit niedriger Energie gespeiste Strandfazien im Steinzeugnis auszuwerten.

