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The Concept of Shoreface Profile of Equilibrium: A Critical Review

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ABSTRACT

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The concept of shoreface profile of equilibrium is the basis for most models used to quantitatively describe and predict profile response on beaches. We question the validity of the concept as used in coastal engineering. The equilibrium shoreface profile concept is based on the following assumptions: (1) underlying geology does not play a role in determining the profile shape; (2) shoreface sediment is moved only by the interaction of wave orbitals with the sea floor, unidirectional current flow is not accounted for; (3) there is no significant net movement of sediment seaward of a so called "closure depth." The equilibrium shoreface profile equation implies: (1) offshore bars do not play an important role in shoreface sediment transport; (2) grain size is the only variable determining shoreface profile shape variability; (3) the shoreface transport system is two-dimensional; and (4) all shorefaces in the world can be described by a single equation with sediment grain size as the only variable. To varying degrees, all of these assumptions fail to be met in real world situations in light of well documented oceanographic and geologic phenomena. A fundamental reexamination of the engineering methods of determining nearshore shoreface evolution is needed. As currently practiced such methods are based on poor oceanographic assumptions.

ADDITIONAL INDEX WORDS: *Beach fill, beach replenishment, cross-shore sediment transport, closure depth, sand transport, sediment transport, shoreline change.*

INTRODUCTION

The concept of an equilibrium beach/shoreface profile, especially in its shoreline engineering applications merits review for several reasons. The idea of the existence of an "equilibrium beach/ shoreface profile" has become a guiding principle behind the development of most shoreline change models. The traditional Bruun Rule (BRUUN, 1962) is essentially a simple equilibrium profile model which assumes the existence of a profile of equilibrium bounded on the seaward side by a closure depth beyond which there is no net transport of sediment. More recently, equilibrium beach profile concepts are being used by coastal engineers in the development of more sophisticated "Bruun Rules" for predicting storm-induced profile change and erosion due to elevated water levels (KRIEBEL *et al.*, 1991; HALES *et al.*, 1991). Equilibrium beach profile concepts are used in the widely applied GENESIS model of HANSON and KRAUS (1989) examining shoreline response to changes in the longshore sediment transport rate and in the SBEACH model of LARSON and KRAUS (1989) examining shoreline change due to cross-shore sediment transport.

It follows that equilibrium profile concepts and the models they spawn are now the basis for the design of most coastal engineering projects. For example, in designing a beach replenishment projection equations developed to describe the profile of equilibrium are used to determine the grain size of fill material to be used, the amount of fill material, and where on the profile to place the fill (profile nourishment). Thus, to be valid for the purpose of replenished beach design, the calculated profile of equilibrium must be close enough to the real-world shoreface profile shape, at every given project location, to justify placement volume calculations on the order of a few hundred thousand cubic meters per kilometers of beach

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length and sand transport volumes of the same order of magnitude.

In this paper we will examine in detail the concept of the equilibrium beach profile and its applications primarily as summarized by DEAN (1991).

A profile of equilibrium is defined in the *Encyclopedia of Beaches and Coastal Environments* (SCHWARTZ, 1982) as "a long-term profile of ocean bed produced by a particular wave climate and type of coastal sediment." The first qualitative mention of this concept was by FENNEMAN (1902): "There is a profile of equilibrium which the water would ultimately impart, if allowed to carry its work to completion." DEAN (1983) defined the equilibrium beach profile as "an idealization of conditions which occur in nature for particular sediment characteristics and steady wave conditions." LARSON (1991) described the equilibrium beach profile: "A beach of specific grain size, if exposed to constant forcing conditions, normally assumed to be short-period breaking waves, will develop a profile shape that displays no net change in time." DEAN (1991) listed four "well-known" characteristics of equilibrium beach profiles: (1) they are usually concave upwards, (2) the smaller the sand diameter, the more gradual the slope, (3) the beach face is usually planar, and (4) steeper waves result in more gradual slopes.

The engineering literature dealing with profile of equilibrium concepts and models recognizes that an ideal profile does not exist in the field. Rather, there is, as MOORE (1982) described, "a dynamic equilibrium that exists as the beach profile changes continuously in response to surf zone conditions." KRIEBEL *et al.* (1991) stated that "A beach profile in true equilibrium *never* exists in nature because nearshore water levels, waves, and currents are constantly changing." Data from the Field Research Facility at Duck, North Carolina, shows that only once in the last ten years of continuous monitoring has a representative profile line, #62, shown a close comparison to the profile shape predicted by the Dean equation (BIRKEMEIER, 1991). Yet LARSON and KRAUS (1989) say in the SBEACH report: "From a theoretical viewpoint, it is of minor importance if the equilibrium profile is never realized in the field due to variable waves and water level, and complex three dimensional hydrodynamic processes, as long as the concept is verified by [we assume wave tank] experiment."

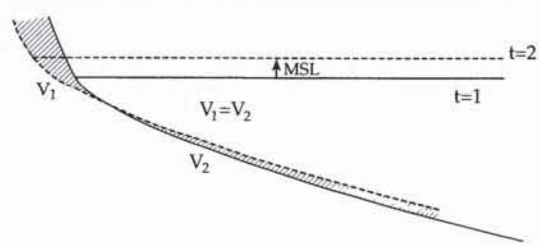

Figure 1. Translation of the original equilibrium profile (solid line) landward and upward in response to a rising sea level to establish a new equilibrium profile (dashed line). The shape of the profile does not change.

In the following discussion we examine the mathematical description of an equilibrium beach profile, its derivation, and associated concepts. We will show that this kind of simplistic attempt to model coastal processes breaks down in its real-world application and in light of well understood geological phenomena. In addition, we will show that the critical assumptions necessary for the applied engineering validity of the concept of a profile of equilibrium are strongly refuted by geologic evidence.

THE EQUILIBRIUM BEACH PROFILE EQUATION

Numerous investigators have examined the concept of equilibrium beach profiles in laboratory studies (RECTOR, 1954; EAGLESON *et al.*, 1963; SWART, 1974; VELLINGA, 1983). We will restrict this discussion to studies that examine equilibrium profiles and their application in the field. BRUUN (1954) quantified beach profiles from Mission Bay, California, and the Danish North Sea coast. He found that the average of the profiles fit the simple relationship

$$h = Ay^{2/3} \quad (1)$$

where h is water depth, y is the distance offshore, and A is a scaling parameter dependent on sediment characteristics. BRUUN (1962) developed a simple model for shoreline change in response to a rising sea level (now known as the Bruun Rule). He reasoned that the equilibrium profile described by Eq. 1 would translate landward and up without changing dimension as shown in Figure 1. This model introduced the concept of closure depth—the point on the equilibrium profile beyond which there is no significant net offshore transport of sand (even in a storm). BRUUN (1962)

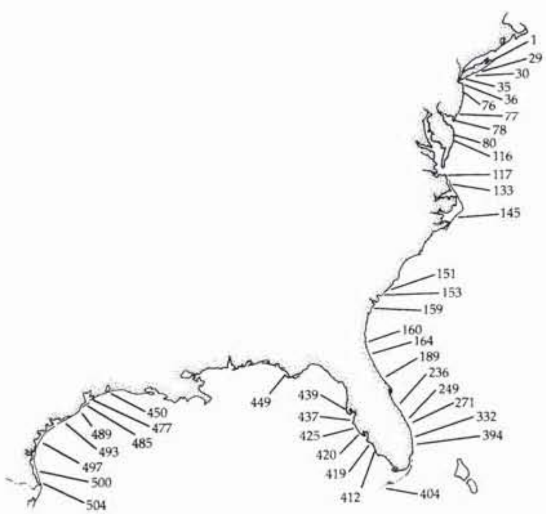

Figure 2. Locations of the 504 shoreface profiles taken by HAYDEN *et al.* (1975) and used for derivation of the equilibrium profile equation by DEAN (1977).

examined early evidence for offshore current activity capable of transporting sediment beyond the equilibrium profile closure depth. He reasoned that this loss of material from the nearshore to the offshore zone is "probably a slow process" and insignificant compared to the "short-range process of a fluctuation nature" that operates within the nearshore zone where the equilibrium profile exists. He chose 18 m (60 ft) as a "reasonable assumption" for "some kind of limit between nearshore and deep-sea littoral drift phenomena." Currently, closure depth for the U.S. Atlantic Coast is generally assumed to be at around 9 m (30 ft) in engineering project design. This is the depth where there is no measurable (within the error bars of the profiling method) change in pre- and post-storm shoreface profiles.

DEAN (1977) analyzed 504 beach profiles along the U.S. Atlantic and Gulf Coasts taken by HAYDEN *et al.* (1975) (Figure 2). He used a least squares procedure to fit to the data an equation of the same form that Bruun (1954) used:

$$h = Ay^n \tag{2}$$

n is a variable shape parameter. Dean applied the least squares fit to each of the 504 profiles. He initially determined A and n values simultaneously for each profile. These variables were determined purely empirically. This initial derivation was not physics based. The n values ranged from less than 0.1 to 1.4 (Figure 3). The A values ranged from 0.0025 to 6.31 (Figure 4). The average root mean square error expressed as a percent was 16.2%. The average value for n was 0.67 agreeing with that found by Bruun.

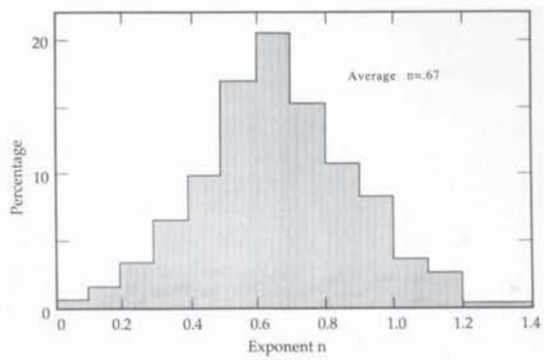

Figure 3. Distribution of n values from the initial least squares fit performed on the HAYDEN *et al.* (1975) profiles. From DEAN (1977).

In an attempt to attach some physical meaning to the Eq. 1 (the equilibrium profile equation), DEAN (1977) proposed several models for destructive forces acting in the surf zone that might be responsible for maintaining the profile of equilibrium. Again using an equation of the form $h = Ay^n$, he determined that $n = 2/3$ when the rate of wave energy dissipation per unit volume of the water column is equal over the profile, and $n = 2/5$ when the rate of wave energy dissipation per unit area of sea bed is equal over the profile. Al-

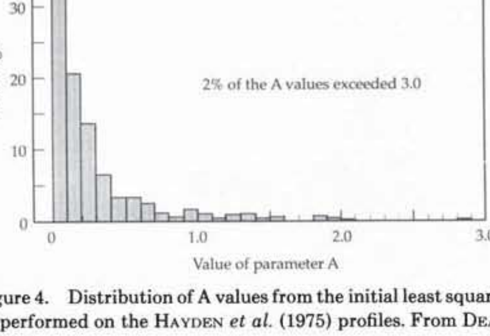

Figure 4. Distribution of A values from the initial least squares fit performed on the HAYDEN *et al.* (1975) profiles. From DEAN (1977).

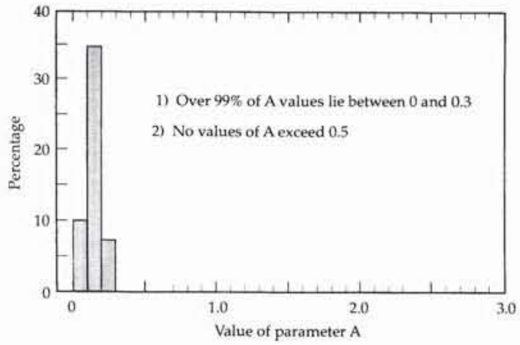

Figure 5. Distribution of A values from DEAN's (1977) second least squares fit assuming n is constant at 0.67 and that A is the only variable. From DEAN (1977).

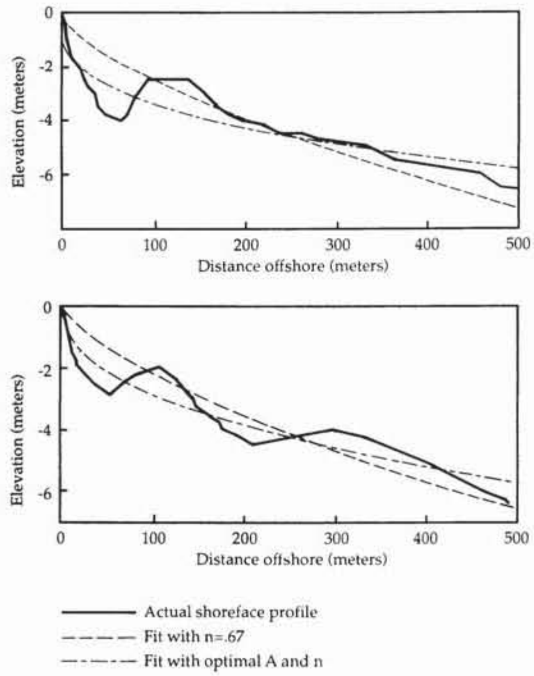

Figure 6. Least squares lines fit to two representative upper shoreface profiles from the CERC facility at Duck, North Carolina. The upper profile is Line 62 on July 1, 1981 and the lower profile is Line 62 on February 24, 1984. These profiles were taken from Howd and Birkemeier (1987). A least squares procedure was used to fit lines assuming: (1) n is constant at 0.67 and A is a variable, and (2) both n and A are variables.

though the model with $n = 2/3$ is conceptually only applicable to a saturated surf zone (a small portion of the total profile), DEAN (1977) reasoned that since this n value (2/3) matched that of the average n for the 504 profiles (0.67) the critical factor in developing a profile of equilibrium must be the rate of wave energy dissipation per unit water column volume. Furthermore, he argued that n could be made a constant at $n = 2/3$ (0.67). All of the other n values determined empirically were thus discarded. WRIGHT *et al.* (1991) stated that "the physical reasons for Dean's empirical results are unclear; other profile shapes, including those with $n = 2/5$ (WRIGHT *et al.*, 1982) and $n = 1/2$ (BOON and GREEN, 1989) have also been reported.

In recognition that the initial empirical relationship between A and n is tenuous at best—a large A and small n or vice versa could give a reasonably good fit to the same profile, DEAN (1977) redid the least squares fit of all 504 profiles fixing n at 0.67 and leaving the sediment scale parameter A as the only free variable. This provided a much smaller range of A values (99% between 0.0 and 0.3, and none greater than 0.5) (Figure 5). He cited this as the final justification for making n a constant at 0.67 and leaving A as the only variable controlling profile shape. Figure 6 is an example of two representative upper shoreface profiles off Duck, North Carolina (HOWD and BIRKEMEIER, 1987), with lines fit to the data assuming that: (1) n and A are both variables, and (2) n is constant at 0.67.

In choosing to perform a second least squares fit with n set at 0.67, Dean has discarded all of the A values from his first least squares fit and substituted an entirely new set of 504 A values. Thus, all of the originally determined n and A values (except for the average value for n) have been abandoned through selective assumptions and further mathematics. What we are left with is the assertion that beach profile shape can be calculated from sediment characteristics (particle size or fall velocity) alone. Essentially all of the world's shoreface profiles would be described by the equation $h = Ay^{2/3}$ with A values between 0.0 and 0.3.

Much work expanding on DEAN'S (1977) equilibrium profile theory has sought to better define A in terms of measurable field characteristics. MOORE'S (1982) relationship of A to sediment grain size is the most widely cited in determining project design criteria. DEAN (1987a) related A to sediment fall velocity by transforming Moore's data resulting in the equation:

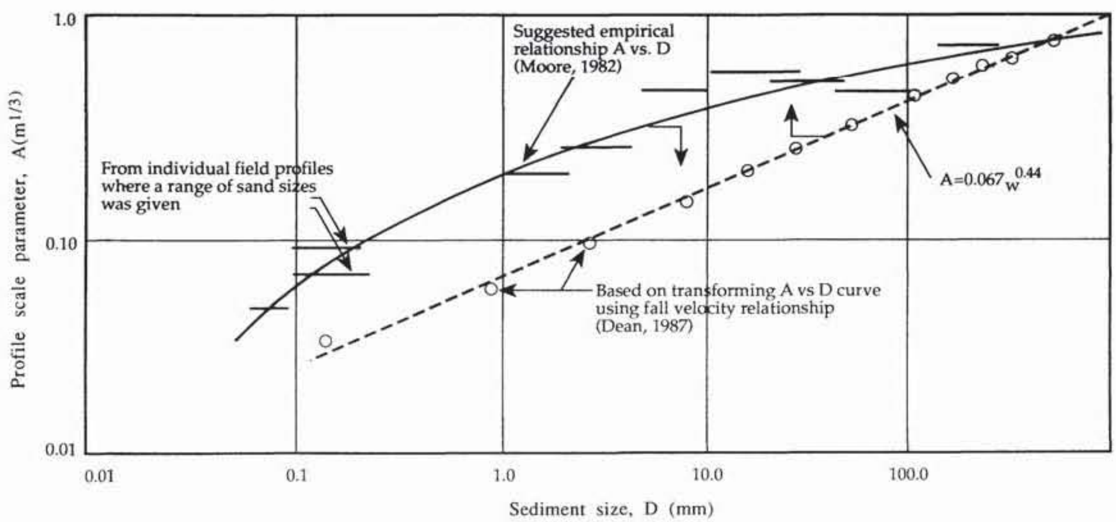

Figure 7. Plot modified from DEAN (1991) showing the relationship of A to sediment grain size based on the relationship suggested by MOORE (1982) and modified by DEAN (1987).

$$A = 0.067w^{0.44} \quad (3)$$

where w is the sediment fall velocity in cm/s. Most recently, KRIEBEL *et al.* (1991) also related A to sediment fall velocity taking into consideration the fact that "a fraction of the wave energy dissipation per unit volume due to wave breaking must equal the energy dissipation associated with suspended sand grains falling under their own submerged weight." Their resulting equation was

$$A = 2.25(w^2/g)^{1/3} \quad (4)$$

where w is the sediment fall velocity in cm/s and g is the acceleration due to gravity.

Figure 7 from DEAN (1991) shows Moore's data and Dean's transformation on a log-log plot. This

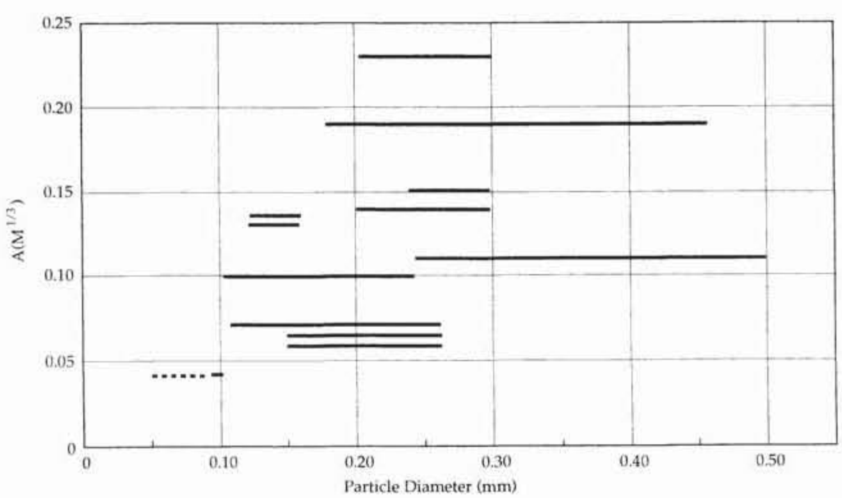

Figure 8. MOORE's (1982) original data for the sand-size range plotted on an arithmetic rather than a log-log scale showing the tenuous relationship between A and grain size. Modified from MOORE (1982).

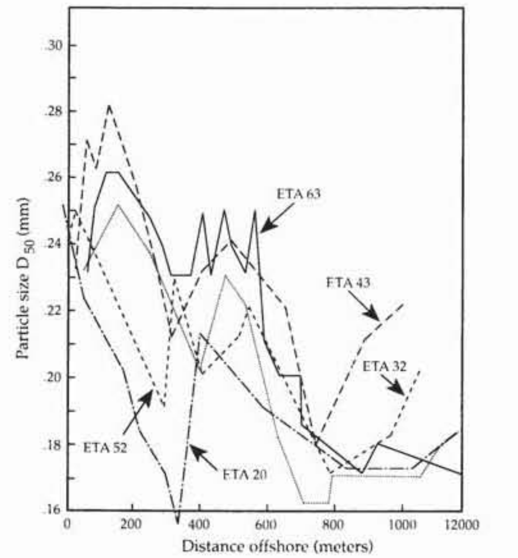

Figure 9. Particle size variation with distance offshore along five numbered profiles from the Gold Coast of Australia. The grain size variation is neither regular nor apparently predictable.

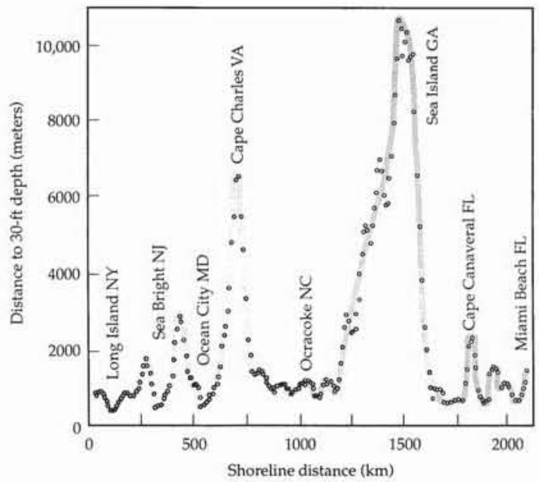

Figure 10. A five point moving average of the distance to the 30 ft contour along the coast of the Southeastern U.S. Profiles do not include cape associated shoals.

is the most common relationship used to determine A. We have several points of criticism regarding this plot. Most of the data points lie far outside the sand range. The shorefaces that we are primarily concerned with in coastal engineering lie in a narrow range between fine and coarse sand—a small portion of this plot. Plotting the relationship as log-log makes the sand-sized portion of the curve look much more reasonable than it really is. To this same end, this Figure (7), published in DEAN (1991), did not include all of Moore's data in the sand-size range. Figure 8 is an arithmetic (not log-log) plot of Moore's original data for the sand-sized range. We think that it is clear from this unenhanced picture of the data that there is no useful relationship between A and sediment grain size. Since n is considered to be a constant, this leaves no real world basis for the Eq. 1.

Another complicating factor in choosing an A to insert into the equilibrium profile equation is the variation of sediment grain size along the profile. There have been a number of recent attempts to describe the variation of A across the shoreface using one simple equation (DEAN, 1991). Figure 9 shows how grain size varies along several profiles from the Gold Coast of Australia. The variation is neither regular nor apparently predictable. How would one choose a representative A value for any of these profiles? This struggle to define A in either empirical or physical terms indicates the tenuous to nonexistent relationship between A and sediment grain size. In fact, STOCKBERGER and WOODS (1990), in their work in the Great Lakes, concluded that A could not be tied to median grain size.

However one defines A, the implication for the equilibrium beach profile theory is the same. This simple equation (with only one variable), is used to define the shape of any shoreface profile, anywhere in the world. All profiles with the same sediment grain size or fall velocity (hence the same A values) will have the exact same equilibrium beach profile shape regardless of the underlying geology or wave climate. A straightforward examination of the distance to the 30 ft contour along the U.S. East Coast from Long Island to Miami Beach indicates that there are strong and laterally consistent regional variations in shoreface slope (Figure 10). We believe that attributing this variation simply to grain size differences is unreasonable.

There has been no systematic field verification of the validity of the equilibrium profile equation; nevertheless, it has been accepted as valid and useful by many applied coastal researchers. DEAN (1991) suggested several applications of his equilibrium beach profile equation and equilibrium beach profile concepts to coastal engineering problems. The relationship was used as a basis for deriving equations that quantify shoreline response to elevated water levels and waves on natural and seawalled shorelines, and for determining fill amounts and sediment size for replenishment projects. Even if it can be assumed that the basic equilibrium beach profile equation can accurately describe the profile shape at a given project location, at a given moment (not to mention over a long period of time), there are still several fundamental, underlying assumptions implicit in the concept of the equilibrium beach profile that solid geologic evidence proves invalid. The rest of this paper will address these assumptions and their problems.

PROBLEMS WITH THE CONCEPT OF AN EQUILIBRIUM BEACH PROFILE

Equilibrium beach profile concepts have a number of underlying assumptions that must hold true in order for them to be useful and valid in their application: (1) All sediment movement must be accounted for by the interaction of incoming wave orbitals with a sandy shoreface. Sediment movement resulting from unidirectional currents is assumed to be negligible or to cancel out. (2) There must be no net loss or gain of sediment on the shoreface. More specifically, there must exist a closure depth beyond which there is no net offshore or onshore transportation of sediment—a depth of no sediment movement even during storm induced downwelling events. (3) Underlying offshore geology must not play a part in determining the shape of the profile. The shoreface is assumed to be sand-rich in all three dimensions. (4) Even assuming the ideal situation of a sand-rich shoreface, the smoothed profile generated by Eq. 1, ignoring all bars and troughs, must be a reasonable estimate of the profile shape in that Eq. 1 can be applied at any location, at any instant in time, and still produce a shape that is useful in calculating project design criteria.

We will address each of these assumptions underlying the concept of an equilibrium beach profile in turn.

Assumptions #1 and #2

(1) All Sediment Movement is Driven by Incoming Wave Orbitals Acting on a Sandy Shoreface

(2) Existence of Closure Depth and No Net Cross-Shore Transport of Sediment to and from the Shoreface

The models of shoreface profile of equilibrium discussed above are based on the assumption that the work done in entraining and moving sediment is performed by incoming incident wave orbital energy dissipation acting on a seaward sloping shoreface (BRUUN, 1954, 1962; DEAN, 1977, 1991). This work has been encouraged and "verified" by laboratory experiments employing monochromatic waves (RECTOR, 1954; EAGLESON *et al.*, 1963; SWART, 1974 and 1976; and VELLINGA, 1983). There is no consideration of unidirectional currents acting to transport sediment suspended by wave orbital action.

WRIGHT *et al.* (1991) discuss the factors that may operate to mobilize and transport sediment on the shoreface of the Middle Atlantic Bight on the East Coast of the United States. Two factors are related explicitly to incoming incident waves (as equilibrium profile theories assume): (1) sediment diffusion arising from gradients in wave energy dissipation, (2) sediment advection caused by wave orbital asymmetries. However, Wright *et al.* found that four other factors may play important roles in moving sediment: (1) interactions between groupy incident waves and forced long waves, (2) wind-induced upwelling and downwelling currents, (3) wave current interactions, and (4) turbidity currents.

WRIGHT *et al.* (1991) examined the above mechanisms responsible for onshore and offshore sediment fluxes across the shoreface. Their study used instrumented tripods deployed in the southern Middle Atlantic Bight at depths ranging from 7–17 m to directly measure and evaluate the relative contributions of incident waves, long waves, and mean flows (primarily tide- and wind-induced), to cross-shore sediment flux. Their observations were made for periods of fairweather, moderate energy, swell dominated, and storm conditions.

During the time span of their study, encompassing both fairweather and moderate energy conditions, onshore mean flows, interpreted to be related to tides, were dominant over incident waves in generating sediment fluxes. The data set for swell-dominated conditions indicated that the seaward flux from mean flows and the onshore flux from oscillatory flows were roughly equal in magnitude. During a storm, bottom conditions were strongly dominated by offshore-directed, wind-induced mean flows. This storm-generated, seaward-directed sediment flux exceeded the fluxes during fairweather and moderate energy by two orders of magnitude and exceeded that of the swell dominated case by one order of magnitude. Wright *et al.* attributed this offshore directed flow to a rise of 0.6 m in mean water level (during this particular storm) and a resultant "strong seaward-directed downwelling flow."

They found that incoming incident waves were of primary importance in bed agitation, while tide- and wind-induced currents were of primary importance in moving sediment. In other words, the incoming wave orbital energy is responsible for mobilizing the sand, but the unidirectional currents are determining where the sand is going. Tide- and wind-induced mean flows were responsible for sediment transport both onshore and offshore. Surprisingly, cross-shore sediment fluxes generated by mean flows were dominant or equal to sediment fluxes generated by incident waves in all cases and at all times.

The conclusions reached by Wright *et al.* bear heavily on the concepts of profile of equilibrium and the equilibrium beach profile equation discussed earlier. They concluded that "the directions, rates, and causes of cross-shore sediment flux vary temporally in ways that are only partly predictable." Yet, it is apparent from their data that "near-bottom mean flows [not incident waves as the profile of equilibrium models assume] play primary roles in transporting sand across isobaths on the upper shoreface." Therefore, Wright *et al.* concluded that "a fundamental implication of our results is that, at least as far as the Middle Atlantic Bight is concerned, existing models of shoreface equilibrium are seriously inadequate."

The conclusions of the Wright *et al.* study are reinforced by other hard geologic evidence for sediment deposition by offshore directed currents during storm events. Studies of both ancient and modern shoreline settings (see below) reveal evidence of seaward-directed currents flowing at high angles to the shoreline, transporting large volumes of sediment beyond the designated closure depth required by profile of equilibrium concepts.

Physical oceanographers have long recognized the processes that generate offshore directed storm currents. These concepts are founded on established fluid dynamics principles (*e.g.*, SVERDRUP, 1942; SVERDRUP *et al.*, 1942; McLELLAN, 1965; IPPEN, 1966; GADE *et al.*, 1983; POND and PICKARD, 1983; CSANADY, 1984; TOLMAZIN, 1985; PEDLOSKY, 1987). More recently, geologists have examined field evidence of offshore sediment transport during storms in light of these physical oceanographic concepts in order to formulate descriptive models of how sediment is transported across the shoreface (*e.g.*, HAYES, 1967; MACINTYRE and PILKEY, 1969; SWIFT, 1976; MORTON, 1981; CACCHIONE and DRAKE, 1982; NIEDORODA *et al.*, 1984; SWIFT and NIEDORODA, 1985; SWIFT, 1985; SWIFT *et al.*, 1986; VINCENT, 1986; SNEDDEN *et al.*, 1988).

SWIFT (1976, 1985) summarizes the offshore transport of sediment by storm-induced current action. Onshore storm winds develop a two-layered flow in the nearshore region. Water is forced landward by frictional drag from the wind in the surface Ekman layer above the shoreface. This results in an increase in sea level nearshore and a sea surface sloping downward towards the offshore—the so-called "storm surge." The oceanographic law of continuity requires that water be displaced in order to compensate for the onshore moving water. This is accomplished by a near-bottom current moving offshore underneath the onshore-directed frictional flow above. This bottom current is driven by an offshore-directed horizontal pressure gradient force resulting from the sloping sea surface induced by storm surge.

Studies in the Gulf of Mexico, using a combination of current meter and sedimentological data, have documented storm-generated, offshore-directed bottom current velocities of up to 200 cm/s and sediment transport out to the edge of the continental shelf (HAYES, 1967; MORTON, 1981; SNEDDEN *et al.*, 1988). This sediment (millions of cubic meters) was documented to have traveled seaward of the suggested closure depth for the area, yet, this movement could not have been detected by simple before and after bathymetric profiles. Although the amount of sediment transported offshore is large, it is spread over such a large area that the change in the sea bed elevation is far below that detectable by standard profiling methods. Before and after storm profiles still indicated profile closure, yet a large amount of sand was transported offshore of that profile closure.

HAYES (1967) attributed the offshore sediment deposition from Hurricane Carla to storm-surge ebb flow. While, MORTON (1981) and SNEDDEN *et al.* (1988) argued, for the same storm, that offshore currents and resultant sediment deposition were a result of storm-induced wave set-up and coastal downwelling. They also argued that although rip currents and storm-surge ebb flow may be important in the surf zone, they are insignificant in transporting sediment across the shoreface. Current meters deployed in the study by SNEDDEN *et al.* (1988) documented offshore current velocities capable of transporting fine sand at depths greater than 34 m during an extratropical storm in 1984. The storm sediments described in these studies have probably been permanently removed from the upper shoreface transport systems.

It is apparent from the replenishment history of Wrightsville Beach, North Carolina, that sand is being effectively removed from the nearshore system permanently. Figure 11 shows the cumulative volume of sand placed on the beach during the last 20 years of replenishment. If concepts of equilibrium profile are valid, then the volume of sand needed to nourish the profile should decrease over the years as it accumulates above closure depth on the shoreface. Figure 11 indicates that this is not the case. Wrightsville Beach continues to regularly require large amounts of replenishment sand. Our data indicate that this sand is not being lost only to longshore transport, but offshore as well.

On the basis of 1991 and 1992 cruises we have verified PEARSON and RIGGS (1981) observation of the offshore transport of replenishment sand from Wrightsville Beach, North Carolina, to a depth of at least 18 m. The replenishment sand, some of it originating from the back-barrier, is fine to coarse grained with an abundance of oyster shells. It has a gray to black color and can be identified as a distinct lithology from the North Carolina surficial continental shelf sediments which are brown.

Finally, geologists studying ancient shoreline settings are now recognizing evidence of seaward-directed currents flowing at high angles to the shoreline. Paleocurrent data from several ancient nearshore, inner shelf and middle shelf settings are described in LECKIE and KRYSTINIK (1989), DUKE (1990), and DUKE *et al.* (1991). These data clearly establish shore normal storm sediment transport directions.

The geologic evidence for the importance of unidirectional current flow and the offshore transportation of significant volumes of sediment is abundant and it will become more so as we being to take a closer look at this question. In addition, we believe that there is indisputable evidence against the existence of a closure depth. The physical assumptions made in the derivation of the equilibrium profile models, that all sediment

Figure 11. Replenishment history of Wrightsville Beach, North Carolina indicating that the amount of renourishment sand required has not decreased over time as might be expected if equilibrium profile concepts held true.

movement is accomplished by wave orbital interaction with shoreface sand and that there is no net offshore transportation of sediment, do not hold, in light of well understood geologic/oceanographic data.

Assumption #3

Assumption of a Sand-Rich Shoreface—Underlying and Offshore Geology Must Not Play a Part in Determining the Shape of the Profile

The concept of the equilibrium beach profile requires the acceptance of several assumptions, and of these, the most important is that the entire profile is sand rich, without excessive areas of hard bottom or mud, within the active profile. Passive margin coastlines that have limited sand supplies, such as much of the U.S. Atlantic margin, are significantly influenced by the geologic framework occurring underneath and in front of the shoreface. In fact, many east coast barrier islands are actually perched barriers in which the underlying, pre-modern sediments totally control the three dimensional morphology—dramatically influencing modern beach dynamics, shape of the shoreface, and sediment composition (RIGGS, 1979, 1985; RIGGS *et al.*, 1989).

Perched barriers cannot have a profile of equilibrium, as defined in the literature, for several reasons. The shoreface of a perched barrier will consist of relatively thin and variable layers of surficial shoreface sands on top of older, eroding, stratigraphic units with highly variable compositions and geometries and variable states of compaction and lithifaction. Depending upon the physical state, this underlying platform can act as a subaqueous headland or hardground that will dictate the shape of the shoreface profile, such as

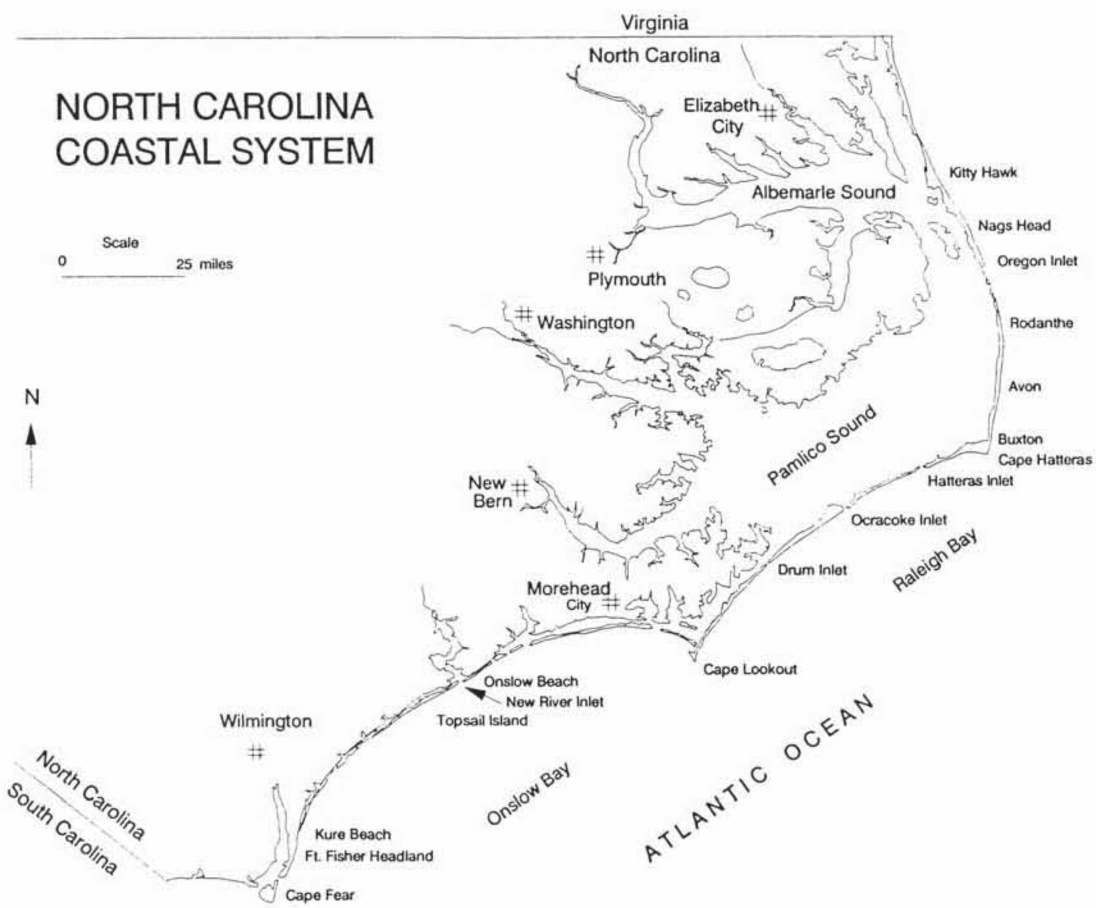

Figure 12. Map of the North Carolina coastal zone showing locations discussed in this paper.

the rock ledges on the shoreface off of Myrtle Beach, South Carolina (PAUL GAYES, *personal communication*). These zones represent fixed control points within the profiles that have nothing to do with equilibrium shapes, nor any of the properties of the seabed sediments. Paleotopographic highs composed of tight muds, limestones, or sandstones will have a much greater effect upon both the aerial shape of the barriers and shape of the shoreface than those composed of unconsolidated sands and soft muds, such as the muddy shoreface off of the Eastern Shore of Virginia (FINKELSTEIN, 1986). Second, along many parts of the coastal system, paleotopographic features occur on the innermost continental shelf. These features will modify incoming energy regimes, affecting the patterns of sediment erosion, transport, and deposition on the adjacent beaches.

In the following section we will examine in some detail the underlying geologic framework of the North Carolina coast and how these underlying rock units control the shoreface profile shape. The North Carolina example is probably typical of the importance of the interaction of underlying geology with shoreface profile shape for many barrier island chains.

The North Carolina Coast

The geology of the North Carolina coastal zone can be subdivided into two distinct provinces (Figure 12). North of Cape Lookout, the geological framework is defined totally by Quaternary sediments. A thick Quaternary sequence (50 to 70 m) fills a regional depositional basin that parallels Albemarle Sound and is called the Albemarle Embayment (WARD and STRICKLAND, 1985). Seismic data (POPENOE and WARD, 1983; POPENOE, 1985) suggest that the Quaternary section has filled the last remnants of the Aurora Embayment, a pre-Miocene depositional basin northwestward of the Cape Lookout High (an Oligocene paleotopographic high that separated North Carolina into two depositional embayments) (SNYDER, 1982; RIGGS *et al.*, 1989). South of the Cape Lookout High, the coastal zone is dominated by Tertiary and Cretaceous units. These older and more lithified, offlapping stratigraphic sequences wrap around the Carolina Platform High, a major basement structural feature that occurs between Cape Fear and Cape Romain, and crop out across much of the continental shelf in Onslow and Long Bays (SNYDER, 1982; RIGGS *et al.*, 1990). These units, along with only local, remnant Quaternary sediment units, form the basal platform upon which the modern barriers are perched in the southern province.

The Pleistocene section of the entire North Carolina coastal system represents a complex record of multiple cycles of coastal deposition and erosion in response to numerous glacial-eustatic, sea-level cycles (RIGGS *et al.*, in press). During each glacial episode, fluvial channels severely dissected previously deposited coastal systems. The subsequent sea-level transgression then produced a ravinement surface that migrated landward and further eroded large portions of previously deposited coastal sediments by shoreface erosion. The fluvial channels were sequentially backfilled with fluvial, estuarine, and shelf sediments.

Present sea-level has produced a modern sequence of coastal sediments that have been deposited unconformably over the eroded remnants of Pleistocene sequences composed of different lithofacies. This modern barrier island system is stacked on top of numerous highly dissected, partially preserved, punctuated lithostratigraphic units with irregular, erosional geometries and composed of sediments ranging from tight peat and mud to indurated sandstones and gravels. Consequently, many of the North Carolina barrier islands are "perched" on top of pre-existing sediments with variable paleotopographic surfaces of variable cohesiveness. It is likely that these compositional and lithifactional differences result in varying responses to the erosional forces of waves and currents affecting the present shape of many of the Carolina barrier shorefaces.

The variable nature of the underlying geologic framework influencing shoreface profile shape along the North Carolina coast can be divided into three categories:

(1) *Subaerial Headlands* composed of semi-indurated to indurated Pleistocene or older units incised by a wave-cut platform with a perched sand beach on the platform.
(2) *Submarine Headlands* composed of semi-indurated to indurated Pleistocene or older deposits that form the platform upon which the modern barrier island is perched and either crop out on the eroding shoreface or occur on the inner-shelf as paleotopographic highs in front of the modern shoreface and thus modify the incoming wave climate in ways not accounted for in most models.
(3) *Nonheadland-Transgressive Shorefaces* commonly composed of Holocene peat and mud deposits that extend from the modern estuaries, under the modern barrier sands to crop out in the surf zone and upper shoreface.

Shoreface profiles are impacted upon in a number of ways by the geologic framework including changes in sediment sources and supply, changes in wave patterns, alteration of storm response and shoreline retreat rates, and probably most importantly, maintenance of slopes independently of shoreface sediment and wave interactions.

Subaerial Headlands

In the Fort Fisher-Kure Beach area, Pleistocene units form an extensive eroding subaerial headland. This area has no barrier island and estuarine system; rather it consists of a wave-cut platform carved into the Pleistocene units that constitute the mainland peninsula with a strandplain beach (Figure 13). MOOREFIELD (1978) mapped the distribution of the Pleistocene coquina outcrops from the surf zone on the north side of Fort Fisher seaward as an obliquely oriented, submerged "groin-like" feature. Moorefield believes that this extensive line of coquina outcrops acts as a groin in the forebeach, trapping sand transported alongshore, and as an offshore barrier on the inner shelf with significant effects upon the movement and supply of sand in this coastal system (Figure 13). Sand derived from the erosion of the rapidly receding Pleistocene shoreline south of the surf zone rock outcrops is moved

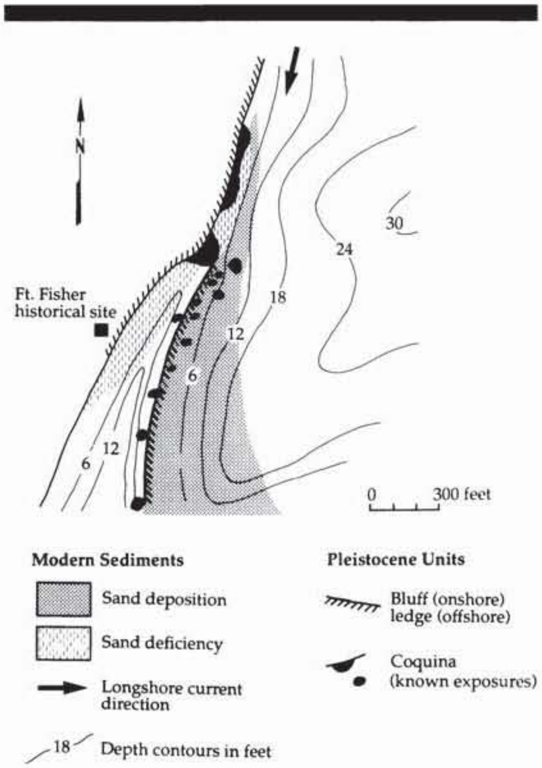

Figure 13. Map of the Kure Beach/Ft. Fisher area showing the effect of the obliquely oriented coquina ledge that is trapping sand on the shoreface and affecting the shoreface shape.

offshore during high-energy storm periods and becomes trapped seaward of the rock barrier and is prevented from moving back onto the beach during subsequent low energy periods. This subaerial headland is affecting the movement of sand and thus the shape of the shoreface. According to Moorefield, the result of this process is a net sedimentary deficiency in which the rapidly eroding bluff shoreline has retreated 370 m since the construction of Fort Fisher in 1865 with steep forebeach profiles and a receding shoreline that is rapidly consuming the historic Fort.

Submarine Headlands

Holocene and Pleistocene deposits have been vibracored under many of the shoreface sands along the Atlantic coast (RAMPINO and SANDERS, 1981; KRAFT and JOHN, 1979; PEARSON, 1979). Marsh peats, tidal flat muds, fluvial sands and gravels, bay-fill sands and muds, flood-tide delta sands, and inlet-fill sands and gravels have been cored below a thin veneer of disconformable, modern shoreface sands that are generally less than a meter thick. NIEDORODA *et al.* (1985) believed that this seaward thinning and fining veneer of modern shoreface sediments is ephemeral and easily removed from the shoreface during major storms. Thus, the erosional response and post-storm shape of the shoreface profile is at least partially controlled by the degree of consolidation of the underlying sediments. During storms, the Holocene and Pleistocene strata cropping out on the shoreface provide the immediate source of the bulk of barrier sands. This process of older units supplying sediment to the shoreface of barrier islands was termed shoreface bypassing by SWIFT (1976).

In North Carolina, the general grain size characteristics and composition of the beach sands on the barrier islands is strong evidence that relict sediments are being eroded from the shoreface (MOOREFIELD, 1978; PEARSON, 1979; CROWSON, 1980). For example, a few portions of the beaches between Nags Head and Corolla contain abnormally high concentrations of quartz and lithoclast gravel, which was mined during recent times for construction aggregate. These beach gravels occur in areas where seismic data have demonstrated the presence of abundant fluvial channels passing underneath the barrier and cropping out on the adjacent inner continental shelf (RIGGS and O'CONNOR, 1974; EAMES, 1983). The eroded gravels have been transported up the beach face and left on the subaerial beach in much the same fashion as heavy minerals left at the top of the swash zone on the storm beach. The dominance of Holocene, black-stained oysters and other estuarine fossils, as well as various Pleistocene and Tertiary fossils and rock lithoclasts on many of the mid-Atlantic beaches also support the conclusion that relict sediments are being eroded from the shoreface (PILKEY *et al.*, 1969; WEHMILLER *et al.*, 1992).

Nags Head/Kitty Hawk Area:

RIGGS *et al.* (in press) present a series of interpretive cross-sections of the Nags Head area based upon deep core holes down the axis of the barrier island (RIGGS and O'CONNOR, 1974; EAMES, 1983), shallow core holes down the shoreface (PEARSON, 1979) and tied together by a dense network of high-resolution seismic traces (EAMES, 1983) in consort with a series of Quaternary age assignments based upon amino-acid racemization of fossil mollusks (YORK, 1990). PEARSON (1979) produced three shore perpendicular, high-resolution seismic profile and vibracore transects which ran

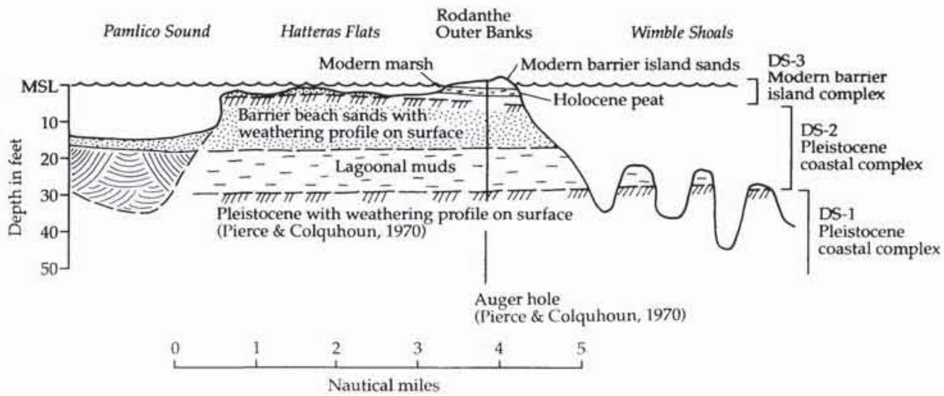

Figure 14. Geologic cross-section through Hatteras Island at Rodanthe showing the Pleistocene units cropping out on the shoreface forming Wimble Shoals.

from the shoreline out to about 3 miles offshore. The three profiles all contained two major sediment units: a modern shoreface sediment wedge, composed primarily of reworked relict sediments, that pinches out in a seaward direction, forming a thin blanket over *in situ* relict sediment units that ultimately crop out on the inner-shelf seaward of the base of the shoreface. The contact between the thin modern sand sheet and the underlying relict units is erosional and easily identified in the high-resolution seismic data. The shoreface below −8 m MSL is dominated by relict sediments that were deposited in fluvial and back-barrier estuarine environments during several previous sea-level events. Based upon diving observations and the presence of relict sediment components in surface sands, where the shoreface surface sediment wedge was thin, PEARSON (1979) concluded that the "modern sand sheet is periodically stripped away during extreme high energy periods, exposing the relict units which may experience erosion. By this mechanism, relict sediments are eroded and introduced into the modern sediment regime."

The shoreline recession rates and consequently, the resulting shoreface profiles will be quite different for shorefaces underlain by tight estuarine muds as compared to inlet fill sands. This relationship is readily apparent when the average long-term shoreline erosion data for the shoreline between Oregon Inlet and Kitty Hawk, North Carolina, (NC DEHNR; Division of Coastal Management, 1988) are plotted against the high-resolution seismic and drill hole data of PEARSON (1979), EAMES (1983), and RIGGS *et al.* (in press). Areas with the most rapid rates of shoreline recession generally occur in areas of old inlet and channel fill structures dominated by sand sediments. The type of sediment below the thin, variable shoreface sand sheet must also have a major impact upon the shape of the entire shoreface profile.

Rodanthe-Buxton Area:

The Rodanthe-Buxton segment of the Outer Banks is characterized by the following features:

(1) A major change in the orientation of the barrier island occurs at Rodanthe (Figure 12).
(2) Paleotopographic features occur on the inner shelf in front of each of several minor capes or headlands and intersect the lower beachface at acute angles. These features include Wimble Shoals (extending from Rodanthe to Salvo) and Kinnakeet Shoals (extending from Little Kinnakeet to Avon) (Figures 14 and 15).
(3) In Pamlico Sound south of Rodanthe, the backside of the barrier island is characterized by the Hatteras Flats, a broad and very shallow platform bounded by a vertical scarp up to three meters high (Figure 14).
(4) Minor cape structures occur on the barrier beach at the towns of Rodanthe, Avon, and Buxton with rapidly receding, cuspate-shaped barriers occurring between the capes (Figure 16).

The change in shoreline characteristics from Rodanthe to Cape Hatteras may be directly due

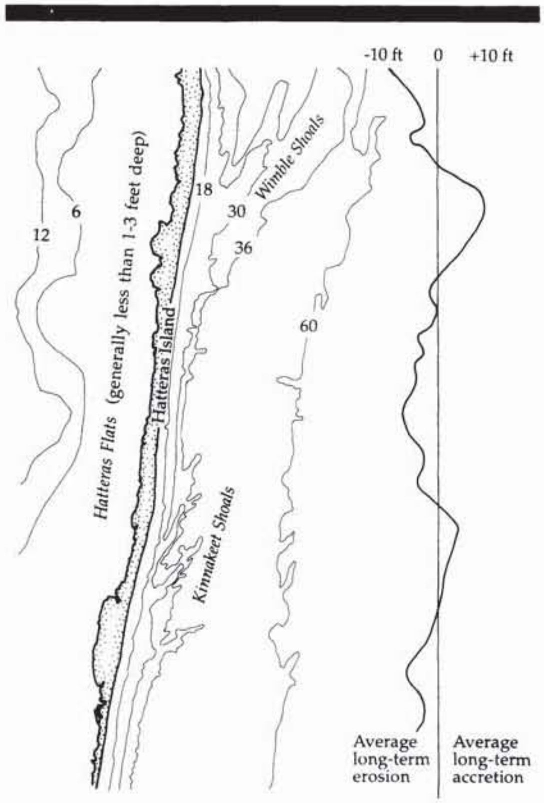

Figure 15. Offshore bathymetry of the Hatteras Island shoreface and North Carolina Department of Environment, Health, and Natural Resources (1988) long-term average annual erosion rates. Note the accretion and gradual slopes associated with the shoals and the erosion and steeper slopes associated with the intervening areas.

to the paleotopographic expression of gently dipping Pleistocene sediments in the shallow subsurface along the southern edge of the Albemarle Basin. PIERCE and COLQUHOUN (1970) also recognized the uniqueness of this portion of the coast. Based upon 20 (9 to 26 m deep) auger holes along the barrier islands between Oregon Inlet and Cape Hatteras, they interpreted this same section of barrier as an "eroded and modified primary barrier." They differentiate "primary barriers" from "secondary barriers" on the basis of the substrata upon which the barrier occurs. Primary barriers are built upon pre-existing sediments that form paleotopographic highs and have been exposed to weathering; whereas, secondary barriers built out over contemporaneous marine sediments as prograding shoals or spits (PIERCE and COLQUOHOUN, 1970).

PIERCE and COLQUHOUN (1970) described a Pleistocene unit with a distinct soil profile on top that occurred at about −40 ft. (11.4 m) below MSL in the middle of the Pea Island Wildlife Refuge and systematically rose southward to −30 ft (8.6 m) below MSL at Rodanthe and −18 ft (5.1 m) below MSL at Avon. These sediments are interpreted to represent depositional sequence 1 in Figure 14. They are overlain by sediment units labeled "lagoon" and "barrier beach" facies of PIERCE and COLQUHOUN (1970). We interpret these to represent depositional sequence 2, which is also a pre-Modern sea level event that contains a weathering profile. This is overlain by the Holocene depositional sequence 3, a very thin (0 to 3 meters) modern barrier island sand sheet on top of a very thin Holocene backbarrier marsh peat and estuarine sand unit that crops out in the modern surf zone at Rodanthe.

These major morphological features and associated changes in the character of the barrier islands, including the shoreface, are interpreted to be products of the underlying geologic framework. Recently acquired high-resolution seismic data within Pamlico Sound demonstrates that the Quaternary sediments rise and thin southward out of the Albemarle Embayment and onto the Cape Lookout High (S.W. SNYDER and S.R. RIGGS, *unpublished data*). These seismic profiles display major Quaternary reflectors that rise from depth beneath Roanoke Island to outcrop in the area extending from Rodanthe southward to Buxton. The structural orientation of semi-indurated to indurated units cropping out in the Rodanthe to Buxton area could explain (1) the change in orientation of the barrier island, (2) geometry of the Hatteras Flats on which the modern barrier island appears to be perched (Figure 14), (3) the orientation and morphology of associated inner-shelf shoals (Figure 15), and (4) the shape of the shoreface.

Wimble and Kinnakeet Shoals are a series of ridges that are oriented NNE-SSW at about 25° to 30° angles to the barrier. These offshore Pleistocene hardbottom features have up to 20 feet of relief and rise up between 22 and 30 feet below sea level. These shoals have not been cored or sampled directly, however, fathometer traces over them demonstrate that they are essentially scarped hardbottoms rather than constructive depositional sand bars as inferred by SWIFT *et al.* (1973). Also, commercial fishermen work these rocks for reef-fish species and commonly obtain pieces of

Figure 16. Air-photo of the Rodanthe and Kinnakeet headlands and the cuspate embayment between.

Pleistocene, carbonate-cemented sandstones in their nets when fishing around the flanks of Wimble Shoals.

If the long-term average annual erosion rates of the NC DEHNR (Division of Coastal Management, 1988) are plotted against offshore bathymetry and shoal structures, there is a very strong relationship. Figure 15 displays the plot of average annual rates of shoreline accretion and erosion from Rodanthe to Cape Hatteras. Not only are the irregularities in the shoreline profile exactly opposite the north end of each shoal system, but the only areas of shoreline accretion occur opposite the major portion of the shoal structure with major shoreline recession on both the updrift and downdrift reaches. Similar patterns exist along the coast north of Oregon Inlet to the Virginia line.

In addition, nearshore topographic features such as Wimble and Kinnakeet Shoals can have dramatic impacts upon the energy regime effecting the adjacent shoreface through wave refraction and wave setup. The small headlands that occur at the towns of Rodanthe, Avon, and Buxton are separated by cuspate-shaped barrier beaches (Figure 16). Bathymetric charts suggest fairly steep and deep shoreface profiles directly off the headlands with the shape probably being controlled by outcropping units in the shoreface. Whereas, in the cuspate portion of the barriers adjacent to the headlands, the shoreface profiles are relatively broad and shallow.

In short, Wimble and Kinnakeet Shoals are permanent features that dramatically impact the shape of the shoreface profile. They are not, nor can they be, in equilibrium with incoming wave energy. This area can never have the simple concave equilibrium beach/shoreface profile described by the equilibrium beach profile equation.

Onslow Beach-Topsail Island Areas:

The morphology of the inner shelf in west Onslow Bay, North Carolina, presents a dramatic example of the relationship between carbonate rock

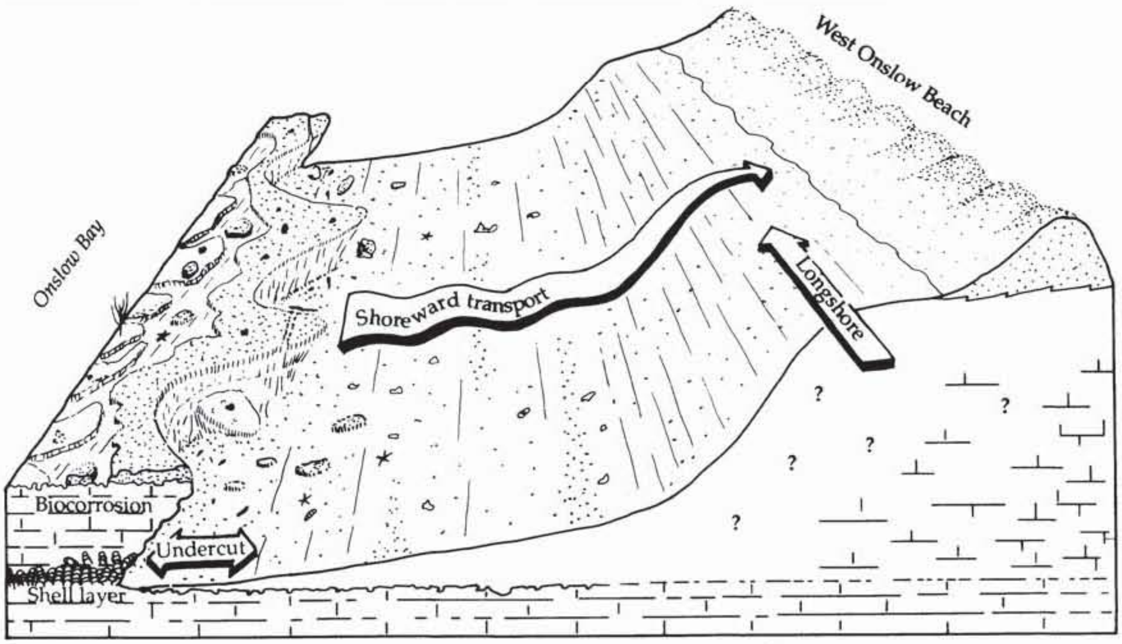

Figure 17. Schematic of the shoreface off West Onslow Beach showing the shoreward facing coquina scarp controlling patterns of beach sedimentation, as well as the shape of the shoreface.

exposures, shoreface profile shape, and the adjacent modern coastal sediment transport systems of Topsail Island and Onslow Beach. The New River Inlet coastal area protrudes seaward forming a small bulge in the coastline of central Onslow Bay. This shoreline bulge is the product of a rock headland composed of the Silverdale Formation of Oligocene age; an indurated unit that ranges from a sandy, pelecypod moldic limestone to a calcareous-cemented quartz sandstone.

The Silverdale Formation crops out just at or slightly below sea level in the mouth of the New River estuary. It occurs extensively in the dredge spoil islands where the Intracoastal Waterway was dredged through the shallow and narrow estuarine areas behind east Topsail Island and west Onslow Beach. This same rock forms large paleotopographic features on the inner shelf with the rock cropping out over approximately 50% of the sea floor around New River Inlet (Crowson, 1980). Crowson mapped a series of prominent rock scarps that occur just seaward of the lower shoreface and on either side of New River Inlet. These arcuate rock outcrops have up to 5 meters of relief above the surrounding seafloor with the tops in about 5 meters of water, which is somewhat above the toe of the lower forebeach (Figure 17). The steep scarps are subparallel to the beach and face landward with smooth rock surfaces that dip gently away from the beach.

These submarine scarps probably rise high enough in the shallow water column to cause some refraction of storm waves and possibly to effect the patterns of erosion and deposition on the adjacent beaches. These scarps also represent a major source of "new sediment" during storms when abundant gravel (up to boulder-size grains) off the rock scarps, and possibly from the shoreface, are delivered to the beach and rapidly broken down to sand-sized components in the surf zone (Crowson, 1980). At the very least, this subaqueous outcropping of the Silverdale Formation is the primary control on the shape of the lower shoreface.

Nonheadland-Transgressive Shoreface

There are many examples of estuarine peat and clay deposits cropping out in the surf zone along the North Carolina beaches. These deposits, believed to be exclusively Holocene in age, have been observed cropping out intermittently along major portions of the barrier islands from Nags Head to Buxton and from Drum Inlet to Cape Lookout. PIERCE and COLQUHOUN (1970) found that in many instances along the northern Outer Banks, these peats were continuous from just below low-tide level on the front of the beach into the present-day marsh on the west side of the barrier. Peat and clay occurred extensively along the entire eroding south shoreline of Oregon Inlet, extending from the modern marshes on the west, seaward into the surf zone on the east side of Pea Island.

At West Topsail Island, a 0.5 meter thick peat crops out periodically in the surf zone and can be traced laterally around New River Inlet to a modern backbarrier salt marsh. Underlying the peat is a tight gray clay of unknown thickness. Storm erosion produces large boulders (up to 0.7 meters across) of both peat and the gray clay. Along with the Oligocene rock fragments from the offshore scarps, this material which is rapidly abraded into granule- and sand-size sediment components on the beach, represents a significant portion of the post-storm beach sediment. Peat and clay outcrops have been documented on many barriers along the Atlantic coast (KRAFT, 1969; HAYES, 1976; HOYT and HENRY, 1967).

The extent or distribution of these estuarine peat and clay deposits cropping out in the surf zone within the North Carolina beach system has not been determined. However, a large portion of the Outer Banks have been occupied by inlets during the recent past. These portions of the barriers are underlain by thick accumulations of inlet fill sands and shell gravels. Any other non-inlet portion of the barrier system would have been involved in barrier island migration in response to rising sea level during the Holocene. We estimate that about 50% of the barrier beaches could be underlain by a framework of older estuarine sediment units composed of peats and clays. Obviously, these sediments have very different compositions, densities, cohesiveness, and resistance to erosion and transport than normal beach sands. Consequently, their presence can have significant effects upon various factors such as the beach width, slope and shoreface profile, as well as, rates of erosion and recession.

We believe that a detailed survey of the world's shorefaces would show that the sand rich shoreface required by the equilibrium profile model is an exception rather than the rule. Instead, most shorefaces are underlain by older, consolidated or

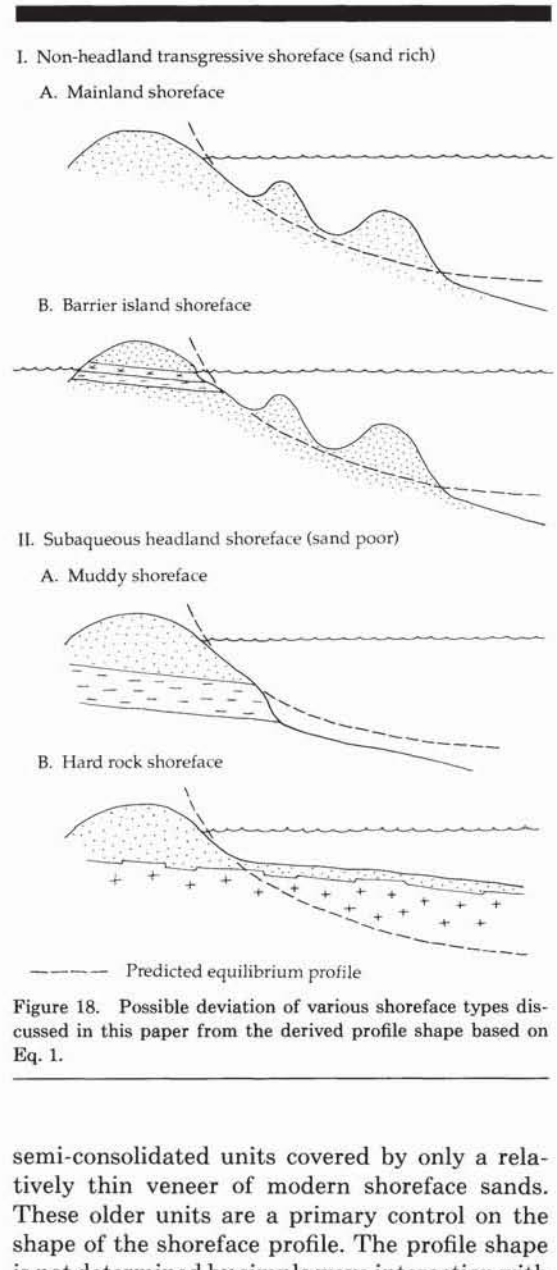

Figure 18. Possible deviation of various shoreface types discussed in this paper from the derived profile shape based on Eq. 1.

semi-consolidated units covered by only a relatively thin veneer of modern shoreface sands. These older units are a primary control on the shape of the shoreface profile. The profile shape is not determined by simple wave interaction with the relatively thin sand cover. Rather, the shape of the shoreface in these sediment poor areas is determined by a complex interaction between underlying geology, modern sand cover, and highly variable (and often highly diffracted and refracted) incoming wave climate. Figure 18 is a summary of how the underlying geology may control the shape of the shoreface based on the previous discussion.

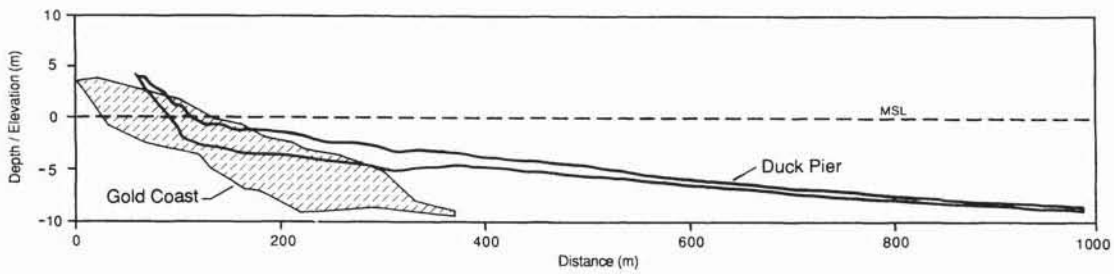

Figure 19. Plot of the shoreface profile envelopes (representing several years of profile variation) from Duck, North Carolina (HOWD and BIRKEMEIER, 1987) and the Gold Coast of Australia showing the persistant difference in shoreface slope between the two areas that cannot be simply explained by grain size differences.

Assumption #4

If a Shoreface is, in Fact, Sand-Rich, the Smoothed Profile Described by the Equilibrium Profile Equation (Ignoring Bars and Troughs) Must Provide a Useful Approximation of the Real Shoreface Shape

To examine the dynamics of a sediment-rich shoreface, a shoreface not strongly impacted by underlying geology, we should probably look elsewhere than the U.S. East Coast. The beach system of the Gold Coast in Queensland, Australia, fits this category. One of us (Smith) has studied this coastline in great detail for more than 20 years, including a thousand or so high-resolution shoreface profiles. As compared to the U.S. Atlantic and Gulf Coasts, the Gold Coast shoreface is highly sediment-rich to well beyond a depth of 30 meters. One simple measure of the difference between the U.S. Atlantic Coast barrier island shoreface and the Australian Gold Coast shoreface is the smoothness of bathymetric contours on navigational charts. U.S. Atlantic Coast charts show much more irregular contours compared to the smooth Gold Coast contours on charts of similar detail.

Without any underlying geological control along the Gold Coast, the shoreface and beach sediment body are highly dynamic. For example, the width of the dry beach displays a short term variability that readily reaches and often exceeds 35 meters per day (SMITH and JACKSON, 1992). Likewise, the shoreface out to a depth of 20 meters is highly dynamic as the shoaling zone shoreface passes through a never ending cascade of profile shapes that vary by the hour, tide, day, month and year (Figure 19). The shoaling zone is never in equilibrium, but tries to attain a temporary, dynamic, semi-equilibrium state under the ambient wave train at every point of time. We adopt the fluvial and river mechanics term "regime" to define the ambient dynamic equilibrium profile shape in the ever changing cascade of shoreface profiles. The sand-rich Gold Coast shoreface shape cannot be described by one equilibrium profile; rather, it is best described by an ever changing regime profile.

Along the Australian Gold Coast, the shoreface offshore of the currently active wave shoaling zone is heavily affected by what we refer to as "memory" effects. The shape of the shoreface below the zone of immediate wave shoaling has been dictated by higher energy events occurring at sometime in the past. During fair weather, the upper shoreface is in dynamic equilibrium or "in regime" with current conditions, while the lower shoreface still has a shape that was imparted by the last storm event with some modification by various unidirectional flows. The local shoreface profile shapes are entirely controlled by relative wave energy "thresholds"; for the sediment properties have not changed at all. Thus principal changes to the shoreface profiles of the Gold Coast are driven by wave power history with some modification by currents, and not by sediment size, or its parameter A, as defined within the equilibrium profile concept.

What is the importance of the offshore storm bars and troughs that occur on sediment-rich beaches? Figure 20 shows the impact of offshore bars on the rate of sediment transport based entirely on incident band models (DEIGAARD *et al.*, 1989). Figure 21, from the Gold Coast, shows a typical double storm bar beach configuration induced by a tropical cyclone wave train in 1974. The offshore sediment-rich shoreface has three separate shoaling regions with the ambient waves

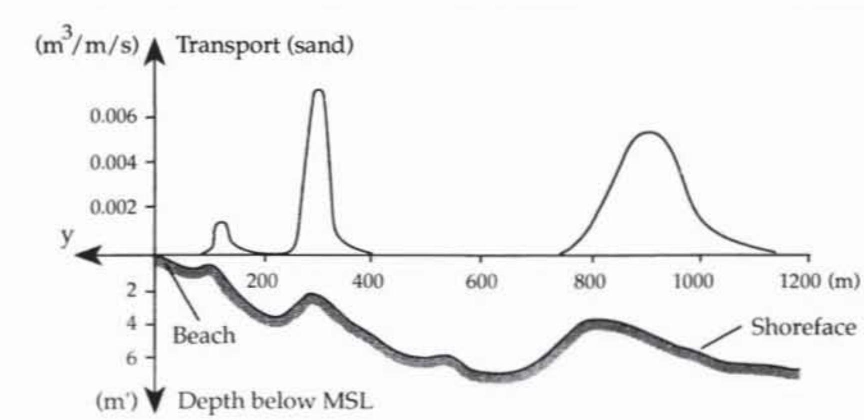

Figure 20. Plot showing the increase in sediment transport over bars on the shoreface based entirely on incident band wave models, ignoring mean currents. From DEIGAARD *et al.* (1989).

breaking three times, twice on the outer bars and a third time on the beach proper. The impact of this treble breaking upon the inner shoreface profile and shape is profound. Inside of each breaking point, the waves reform at approximately half their breaking height, so the wave energy is reduced to approximately one quarter of its pre-breaking state. In these terms, the double bar features of Figure 20 result in a wave break reaching the shoreline with significantly less energy than the waves breaking on the outer bar. Equilibrium profile concepts ignore these crucial shoreface bars and troughs and presumes that some "mean" profile, averaging out the bars and troughs, holds a

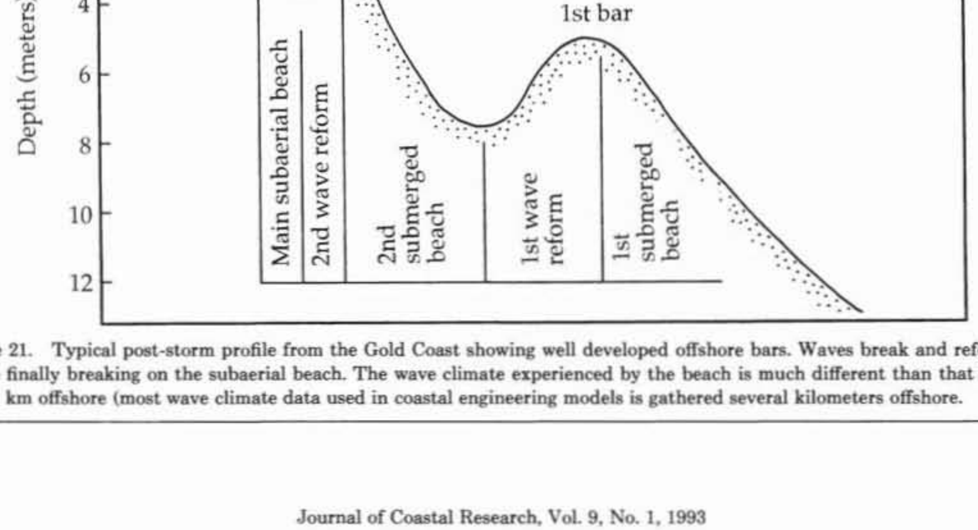

Figure 21. Typical post-storm profile from the Gold Coast showing well developed offshore bars. Waves break and reform twice before finally breaking on the subaerial beach. The wave climate experienced by the beach is much different than that measured only 1 km offshore (most wave climate data used in coastal engineering models is gathered several kilometers offshore.

much more important value. Alternatively, we suggest that it is the seaward shoreface shape up to the crest of the outer bar that is the most important factor for the absorption of incoming wave energy. If the volume of available sediment on the shoreface is not large enough to form that outer bar, then the inshore beach will be eroded and the sediment taken offshore to form the outer bar, provided enough sand is available. In summary, even in the situation of a sandy coast with sufficient sediment supply, the smoothed profile shoreface shape predicted by the equilibrium profile equation inadequately describes the true profile shape, ignores the effects of bars, and oversimplifies wave-shoreface interactions.

SUMMARY AND CONCLUSIONS

(1) Does the Shoreface Profile of Equilibrium Exist in Nature?

Yes, from a large scale viewpoint there are regionally consistent shoreface slopes that are probably in equilibrium with a large number of oceanographic and geologic factors. For example, the Gold Coast shoreface profile envelope is clearly steeper than the Duck, North Carolina, profile envelope (Figure 19). The Georgia shoreface profiles are clearly much more gentle than those off northern North Carolina (Figure 10). But we believe that these variations are controlled by factors more numerous than those described by the equilibrium profile equation. In the few places where extensive profiling has occurred (Duck Pier and The Gold Coast, Australia) the concept of an identifiable and precise shoreface profile of equilibrium appears to have no engineering validity. For the sandy Gold Coast the "regime profile" concept appears to best fit reality.

(2) Is It Reasonable to Assume that an Average or Least Squares Fit Profile at a Given Location is a Profile of Equilibrium?

No. Any technique that takes out the actual topography of the shoreface, including the all-important offshore bars, no longer describes a current that has been formed by or will interact with wave orbitals and bottom currents.

(3) Are the Ancillary Assumptions of the Profile of Equilibrium Valid?

Assumption #1: There is no significant net loss of sand seaward of closure depth.

Invalid. There is abundant field evidence, backed up by theory, that large volumes of sand may be frequently moved far seaward of the so-called closure depth. Such movement can occur during both fairweather and storm conditions, but the large scale seaward flux of sand is mainly in response to a storm event. The concept of no net seaward movement of sand is virtually insupportable on any time frame.

Assumption #2: All sand movement is caused by interaction of wave orbitals with the surface sediment cover.

Invalid. The field evidence and the physics of nearshore water movement clearly and unequivocally indicate that bottom currents are important movers of sand on the shoreface. Even in cases where the wave orbitals are primarily responsible for mobilizing the sand, bottom currents frequently determine where the sand will go.

Assumption #3: Shoreface profile shapes are not affected by the underlying geological units.

Invalid. It is clear that the profiles of many, if not most shorefaces are impacted by the underlying geology. Presumably only sand rich shorefaces such as those on the Gold Coast of Australia are not directly impacted by shoreface stratigraphy. Overwhelming evidence suggests that the shape of most of the U.S. East Coast and Gulf Coast barrier island shoreface profiles are impacted to varying degrees by pre-modern deposits.

(4) Is the Profile Described by Eq. 1 a Profile of Equilibrium?

No. It describes some sort of average shoreface profile cross section, but its meaning is not clear. A lot of field work will be needed to determine the validity and significance of this equation. The most fundamental problems with the equation are the assumptions that only wave orbitals move sediment, that underlying shoreface geology is unimportant, and that differences in profile shape from place to place are due only to variations in grain size.

(5) Is the Shoreface Profile Shape as Determined by the Application of Eq. 1 Sufficiently Close to Reality at All Sites to Be Useful in Quantitatively Predicting the Behavior of Sand?

No. If the shape does not precisely mimic the profile at a given location, volume calculations and calculations concerning the effect of wave orbital interaction with the seafloor will be wrong.

Limits of application for the profile of equilibrium equation have not been suggested. Hence, it is applied to all types of shorelines. It is virtually inconceivable that a single equation can describe in a useful way all shoreface profiles in the world or even all barrier island shorefaces. In this paper we discuss a number of examples of its failures and shortcomings. We strongly doubt its universal or even local utility. However, the final answer as to the utility of the equation, must come from extensive field measurement of a sort not currently under way in North America.

(6) Are the Ancillary, Implied Assumptions of the Profile of Equilibrium Equation Valid?

Assumption #1. Wave climate variations are not responsible for variation in profile shape (only grain size, represented by A, controls profile shape).

Invalid. Clearly wave climate among many factors, plays a role in determining profile shape. Other things being equal, high wave energy should result in gentler profiles and low wave energy should result in steeper shorefaces.

Assumption #2. The shoreface is a two dimensional system which ends in the seaward direction at closure depth and in the landward direction on the upper beach.

Invalid. Sand is lost and gained, laterally, from offshore and from onshore.

Assumption #3. Offshore bars do not play a significant role in determining profile adjustment to wave orbital interaction.

Invalid. Clearly offshore bars are profoundly involved in the shoreface sand transport system. They strongly influence the distribution of wave energy on the shoreface and hence control the wave orbital interaction with the seafloor surface.

In summary, we question the validity of the concept of shoreface profile of equilibrium as used in standard coastal engineering practice. We question even more strongly the validity of using one equilibrium profile equation to describe all shoreface profiles. A large number of very fundamental oceanographic/geologic assumptions are not met and the concept and equation have not been field tested.

As a consequence of the failure of this concept, as currently defined, a number of engineering models and concepts which depend on it as a basic assumption, are brought into serious question. These include the Bruun Rule (BRUUN, 1962), Genesis (HANSON and KRAUS, 1989), and SBEACH (LARSON and KRAUS, 1989). All of these design equations must be reevaluated in the context of modern oceanographic and geologic understanding of the nearshore zone.

BRUUN (1992) states that "Dean's as well as Bruun's assumptions may be more academic than real in a highly 3-dimensional and irregular environment. That they gave the same result may be incidental, but neither Dean's nor Bruun's results should be extended beyond their capacity. . . . a beach/bottom profile is a very dynamic feature subject to considerable variances. Its behavior may be better described in statistical, rather than in physical terms." We agree.

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