Sedimentology and morphodynamics of a barrier island shoreface related to engineering concerns, Outer Banks, NC, USA

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Received 17 June 2003; received in revised form 31 March 2004; accepted 18 May 2004

Abstract

Forty-nine vibracores were collected from a barrier island shoreface following 12.4 years of biweekly profile surveying. The sedimentologic architecture of the shoreface was linked to time-series elevation change and profile shape to determine relationships between morphodynamics, facies development, erosional processes, profile closeout, and cross-shore transport.

The modern shoreface mass, which erosionally overlies a tidal inlet-associated complex, attains a maximum thickness of 3–4 m below the beach to middle profile before pinching out seaward between 9 and 12 m depth. Concave erosional surfaces overlie by cross-stratified fine to medium sand and gravel make up most of the lower half of the shoreface prism below the beach through middle profile reflecting longshore trough incision and subsequent current-dominated aggradation. At the landward margin, gravel-rich laminae record episodic seaward progradation of beach surfaces over coarse inner-trough settings. Seaward, a parallel-laminated fine-sand facies dominates the upper part of the prism recording intermittent shoal zone buildup, including trough filling, under high-velocity plane-bed conditions. Similarly, a bioturbated parallel-laminated, fine- to very fine-sand facies makes up the entire prism below the outermost lower ramp sector, again indicating buildup under high-velocity conditions. However, accretion of the lower ramp results from major storms that cause trough scour along landward locations and simultaneous displacement of fine sand onto the lower ramp. Conversely, lower ramp erosion typically occurs during less energetic conditions as sediment is slowly returned shoreward causing inner-shoreface buildup. Close spacing of major storms during some years led to net progradation of the shoreface.

The upper and lower limits of surveyed elevation change (UL\textsubscript{e} and LL\textsubscript{e}) repeatedly develop similar limit-profile shapes over shoreface accretion–erosion cycles. The ULe reflects accretion maxima resulting from beach, bar, and lower ramp buildup. The LL\textsubscript{e} and lower sedimentologic limit (LLs) along the inner 250 to 300 m of the active shoreface are a product of storm-trough scour down to a maximum depth of \textasciitilde 5.5 m. Below the lower ramp facies, the LL\textsubscript{e} and LL\textsubscript{s} are primarily products of less energetic wave erosion down to \textasciitilde 5 m (shoreward) and 9 m (offshore) depths. The LL\textsubscript{e} closely matches the LL\textsubscript{s} documenting that \textasciitilde 90\% of the shoreface prism was reworked during the 12.4-year period whereas actual ages for erosional events indicate a potential of 2 to 4 years for complete reworking of the shoreface mass. Textural distribution indicates net long-term transport direction and loci of deposition for different sized material. The coarsest material is concentrated at landwardmost locations and well-sorted fine to very fine sand at seaward locations. Medium sand to gravel tends to remain within the trough zone, even during extreme storm events. The ULe and LL\textsubscript{e} also represent the upper and lower limits for profile closure events. A location of about 4.5 m depth at 300 to 350 m from shoreline marks the boundary.

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doi:10.1016/j.margeo.2004.05.020
between inner profile- and lower ramp-associated closure events, the boundary between trough-associated and lower ramp facies, and the lower ramp morphologic break, all of which correspond to the juncture between longshore-current- and shoaling wave-dominated zones. The lower-ramp zone of closure is a zone of seaward decreasing storm transport in which fine to very fine sand is the typical bedload material.

Keywords: barrier island; longshore trough; bar; erosion; closure; cross-shore transport; storm processes; Duck; NC; FRF

1. Introduction

1.1. Background and purpose

Coastal engineers involved with the design of shore-zone structures and the placement of sand for beach nourishment necessarily make assumptions related to concepts involving profile dynamics and sediment transport. Much is still unknown, however, concerning the actual nature of fluid processes, bed conditions, cross-shore transport, and morphodynamics, especially as they relate to beach-nearshore erosion, seaward closure of profiles, and profile equilibrium concepts. Related to this are questions involving grain size and the amount of sand transported offshore beyond calculated “limit depths” during major storm events. Detailed study of the internal physical properties of the shoreface mass and associated profile change can provide significant information concerning the above topics.

Sedimentary facies serve as a historical record of profile morphology and hydrodynamic conditions that have operated across the shoreface zone. It is well documented that a systematic variation in physical attributes occurs across the shoreface, both at the sediment-water interface and in the subsurface (for example, Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979; Howard and Reineck, 1981; Schwartz et al., 1981; Schwartz, 1982; Shipp, 1984; Short, 1984). It is also well established that bedforms and their respective internal structures exhibit regular variations in response to differences in flow conditions and sediment size (Allen, 1984; Clifton, 1976; Clifton and Dingler, 1984; Harms et al., 1982; Rubin, 1987). Thus, texture and physical structures, including erosional surfaces (Weislogel and Schwartz, 1998; Lamb and Schwartz, 1999), can be used to provide information on the temporal and spatial distribution of past fluid processes, bed conditions, and morphological features.

The barrier island shoreface at the U.S. Army Engineer Research and Development Center’s Coastal and Hydraulics Laboratory’s Field Research Facility (FRF) in Duck, NC, serves as a baseline wave-dominated model where net offshore losses are negligible with respect to the shore-normal budget (Lee et al., 1998). Beginning in 1981, a highly accurate, approximately biweekly beach and nearshore survey program was initiated at the site (Howd and Birkemeier, 1987a; Lee and Birkemeier, 1993). In 1993, closely spaced vibracores were collected across two profile lines at the FRF for the purpose of detailed sedimentologic study (Schwartz et al., 1997). The purpose of this paper is to compare the 1993 vibracore record with the ~12.4-year survey record (1981–1993) in order to address nearshore processes and demonstrate pertinence to engineering interests. The combined vibracore and long-term profile survey sets cover the same shore-normal transects and cross the most active part of the shoreface zone, that is, from the beach out to about 8.5-m depth well beyond transitory storm bar-and-trough locations. Together, the combined vibracore and survey data serve as a unique data set for the study of coastal dynamics whereby the distribution of physical properties through the shoreface, in addition to indicating hydrodynamic conditions, can be specifically linked to time-series elevation change and morphodynamics. Importantly, the combined data set serves as a historical-record approach to the study of nearshore processes compared to that of “real-time” studies (e.g., fluid motion, sediment suspension, and bed elevation experiments).

Following the introduction, the report is divided into two major sections. We first examine sedimentology of the shoreface including lower boundary and geometry of the shoreface prism, facies, and morpho-
dynamics related to nearshore processes. The combined sedimentologic findings and survey data are then used to address topics of engineering interests including lower erosional limit of the shoreface prism, depth of closure, and implications toward an “equilibrium envelope” versus equilibrium profile concept. Also included is textural makeup of the shoreface mass followed by pertinence toward cross-shore transport and beachfill design.

1.2. Previous work and related studies

Studies of beach-nearshore profile morphology are numerous (reviewed in Larson and Kraus, 1989, 1994). For the FRF site, initial documentation of long-term profile change was provided by Howd and Birkemeier (1987a) and Lee and Birkemeier (1993). Modes of profile shape and time scales of change for the long-term were examined by Birkemeier (1984) whereas Beavers (1999), Howd and Birkemeier (1987b), Lee et al. (1998) and Salenger et al. (1985) examined storm-caused change in the nearshore system. Stauble (1992) compared long-term morphologic change and surface sediment distribution. Statistical studies of temporal and spatial profile change, including long-term, seasonal and storm, have been conducted by Larson and Kraus (1992a,b, 1994). Profile change in relation to depth of profile closure has recently been evaluated by Lee et al. (1998) and Nicholls et al. (1998).

Most sedimentologic studies of modern shoreface systems have been directed toward facies characterization with hydrodynamic interpretation based upon sedimentary structures relative to position along the profile (for example, Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979; Howard and Reineck, 1981; Shipp, 1984; Short, 1984). Fewer studies relate bedforms to details of orbital flow across the profile (Clifton, 1976; Davidson-Arnott and Greenwood, 1976; Clifton and Dingler, 1984) or to orbital flow coupled with unidirectional-current flow (Drake, 1997). Equally few are studies that examine fluid and sediment motion relative to barred-profile morphology during storm events when the bed was highly active (Davidson-Arnott and Randall, 1984; Greenwood and Sherman, 1984; Greenwood and Mittler, 1984; Thornton et al., 1996). Rarest of all are vibracore studies of the shoreface where details of subsurface facies are related to profile dynamics and nearshore processes (Hobson et al., 1980; Schwartz and Musialowski, 1977, 1980; Schwartz, unpublished 1981 FRF ASEX experiment; Schwartz et al., 1981; Greenwood and Mittler, 1984). The vibracore studies indicate that the sedimentologic record of the shoreface prism linked to profile survey data is well suited to addressing coastal engineering interests and thus provided the basis for this study.

1.3. Physical setting

The FRF is located near the middle of Currituck Spit along a 100-km unbroken stretch of shoreline (Fig. 1). The “spit” is a microtidal barrier island, approximately 800-m wide at the study site and bordered by Currituck Sound on the west. Although part of a long-term transgressive system, the shore zone at the FRF is stable to slightly progradational on the several years to decade scale. The shoreline is straight, and has a simple nearshore bathymetry, so that profile change can realistically be considered in a two-dimensional manner (Lee and Birkemeier, 1993). Short-term changes along the inner profile (< 4 m depth) are complex and typically involve two-dimensional and three-dimensional bar-and-trough morphologies (Lippmann and Holman, 1990). The shoreface consists primarily of sand and a secondary component of granules and small pebbles (Meisburger and Judge, 1989; this study). Although the nearest active tidal inlet is 50 km to the south (Oregon Inlet), numerous historic inlets have occurred along Currituck Spit with the FRF being located on and near geologically filled inlet sites (Birkemeier et al., 1985; Fisher, 1977).

Average annual significant wave height is 1.0 ± 0.6 m (at 18-m water depth) with a mean peak spectral wave period of 8.3 ± 2.6 s (Leffler et al., 1993). However, wave height is seasonal with higher waves in the fall–winter period and lower waves in the spring–summer period (Larson and Kraus, 1994). Overall, wave energy is moderate to high. Storms at the study site range from infrequent events to grouped events of two or more storms with short intervals, e.g., grouped over a 10–40-day period (Lee et al., 1998). Between 1981 and 1991, 55 storms events occurred with >2-m maximum significant wave heights (Hmo), 4.0 m average Hmo and 6.8 maximum
Fig. 1. Location map of the Field Research Facility (FRF) and bathymetric map of the study area showing profile lines 62 and 188.
Storm wave periods ranged up to 24 s, but typically were in the 7–12-s range. Storm event duration averaged 49 h with a maximum of 161 h. Storm-associated longshore (surf-zone) current speeds up to 1.5 m/s (Thornton et al., 1996), wind-driven mean longshore flows up to 50 cm/s at 13 m depth (Wright et al., 1994), and seaward-directed cross-shore flows greater than 20 cm/s (Wright et al., 1991) have been recorded. In addition to incident waves causing cross-shore transport during storms, longshore and offshore mean flows can dominate (Wright et al., 1991, 1994; Thornton et al., 1996).

Tides at the study area are semidiurnal with a mean range of about 1 m and a spring tide range of about 1.2 m.

Although profile shape may range from practically non-barred to triple barred, the most common profile configurations are single and double barred (Birkemeier, 1984, 1985). The zone of most active elevation change extends from the base of the beach foredune to about 5 m water depth (Larson and Kraus, 1994).

2. Methods

2.1. Vibracore collection and profile surveys

A portable vibracoring system (Lanesky et al., 1979; Thompson et al., 1991) was mounted atop a Coastal Research Amphibious Buggy (CRAB) (Birkemeier and Mason, 1984) and used over a 1-week period to obtain 49 oriented cores from the shoreface out to water depths of about 8.4 m. The vibracores were collected at relatively close spacing along two shore-normal transects: approximately 475 m north of the FRF pier (survey range line 62) and approximately 525 m south of the pier (survey range line 188) (Fig. 1). The survey lines are located near the northern and southern perimeter of the FRF and beyond significant influence of the more centrally located research pier. Thirty-three vibracores were collected along line 188 at about 17-m spacing along the more dynamic inner and middle profile compared to about 55-m spacing along the less dynamic outer profile (Fig. 2). Due to time constraints, 16 vibracores were obtained along line 62 with spacings of 25–50 m along the inner profile and 100 m along the outer profile. A Geodimeter 140T auto-tracking survey system (Lee and Birkemeier, 1993) was used to measure bathymetry and position the vibracores. The horizontal accuracy of the Geodimeter is ± 10 mm in the tracking mode with a vertical accuracy of ± 2.1 cm (1981–1990) and ± 2.7 cm (1990–1993) at about 1300-m distance. High-resolution nearshore profiles were typically measured every 2 weeks and after most storms out to about 9 m water depth along both range lines since 1981 (Howd and Birkemeier, 1987a; Lee and Birkemeier, 1993), thus providing extensive time-series data for comparing morphologic and bathymetric change with the subsurface sedimentologic record.

Time scales of significant profile-shape change for the study area include storm, seasonal, and long-term (multi-year) (Beavers, 1999; Sallenger et al., 1985; Larson and Kraus, 1994). Storm events typically involve 1 to 3 days of severe wave activity and high rates of profile change (hourly), with net storm-profile change terminating at the end of the event (Sallenger et al., 1985). The typical time period of 14 days between consecutive surveys, coupled with post-storm surveys, allows for linking vibracore sedimentology both to net-storm and long-term profile change. Potential errors associated with a possible absence of surveys immediately before or after some storms is minimized due to slow rates of profile change associated with low wave steepness during the intervening non-storm periods. Elevation is referenced to the 1929 National Geodetic Vertical Datum (NGVD) that was 8 cm below Mean Sea Level and 42 cm above Mean Low Water during the study period. Horizontal distances are measured relative to a shore parallel baseline behind the foredune system resulting in an average beach–surf zone boundary at about 100 m from baseline.

2.2. Vibracore processing and data analysis

X-ray radiographs and epoxy peels, approximately 7.6 cm wide, were prepared from continuous rectangular shore-normal slabs along the center of each core. The slabs were oriented to provide a shore-normal view of the sedimentary sequence. Average sand size was visually estimated to about one-quarter phi resolution at 1-cm intervals down cores by use of an AMSTRAT card (Canadian–American Stratigraphic, Denver, CO). Physical sedimentary structures were classified in a manner that relates shape and thickness.
to planar, two-dimensional, or three-dimensional bedforms (Allen, 1984; Harms et al., 1982; Rubin, 1987). Taken into consideration is that trough cross-stratification can resemble traditionally defined tabular cross-stratification or low-angle parallel lamination in the narrow vibracore sections.

A hierarchical approach was used to establish the sedimentologic architecture of the shoreface on three scales: bed (third-order), bed sequence (second-order), and facies (first-order). Each scale relates to a different temporal—spatial aspect of coastal processes. Distinctive bedding types represent specific bedforms and hydrodynamic conditions on the “single event” scale. Bed sequences consist of two or more beds that sequentially make up an upward fining trend, upward coarsening trend or a systematic upward change in physical structures. Bed sequences represent a scale typically greater than that of the single event, such as, the lateral migration and superposition of bedforms or various segments of the profile. The facies groups contain assemblages of individual bedding types, bed-sequences and erosional surfaces that characterize particular environments within the nearshore zone, such as, the swash, trough, and lower ramp environments. Erosional surfaces that became preserved in the subsurface during the 12.4-year survey period were synthesized from the time-series elevation data (Weislogel and Schwartz, 1998; Lamb and Schwartz, 1999). The spatial distribution of subsurface facies and erosional surfaces constitute maps of shifts in the location of various environments, including both depositional and erosional processes, along historical profiles. Other details concerning laboratory processing and architectural analysis of sedimentologic data are presented in Schwartz et al. (1997).

Fig. 2. Shape of the cored profile along lines 62 and 188 showing profile terminology, envelope of surveyed elevation change (ULe and LLle; 1981–1993), vibracore location and the lower sedimentologic boundary (LLs) of the shoreface prism.
2.3. Profile shape and terminology

Profile terminology is based upon the morphology of components making up the shoreface and principally includes: beach, trough, bar, upper ramp, middle platform, and lower ramp (Fig. 2). The upper ramp is defined as a seaward-inclined slightly convex to slightly concave surface that merges landward with the crest of an inner bar or, under non-barred conditions, extends to the swash zone. The upper ramp is dominated by final wave shoaling and wave breaking during fair weather and by high-energy inner surf-zone conditions during storm events. The middle platform is a subhorizontal planar to slightly concave surface adjacent to the upper ramp that develops in the same zone as storm-caused middle to outer bar-and-trough systems. This zone is dominated by wave shoaling during fair weather and high-energy surf conditions during storms. The lower ramp is a seaward-inclined planar to slightly concave surface adjacent to the middle platform. A slightly convex shape, or break in slope, occurs at the middle platform–lower ramp juncture near the location of ephemeral outermost, or “distal”, storm bars. Wave shoaling processes are dominant along the lower ramp although dissipative surf conditions extend across the zone during extreme storm events.

At the time of vibracoring, one of the studied profiles (line 188) contained a well-developed longitudinal bar and trough along the inner profile whereas the other profile (line 62) was “minimally barred” (Birkemeier, 1984) or non-barred as referred to in this report (Fig. 2). The profile shapes represent two of several discrete modes of profile-shape occurrence (Birkemeier, 1984). The non-barred inner segment of profile 62 represents a state of maximum landward accretion where the inner trough has been filled and the bar form eliminated. The middle to outer segments of both profiles 62 and 188 had similar upper ramp, middle platform, and lower ramp geometries at the time of the experiment. Long-term survey data (Lee and Birkemeier, 1993; this study) document that more seaward located storm bars and troughs develop beneath the upper ramp and middle platform zones of the vibracored profiles, but not in the region of the lower ramp. In this study, it is often convenient to discuss subsurface sedimentology and coastal processes in terms of historical trough locations. Thus, the terms inner-middle, and outer-trough zone are used to indicate relative positions of occurrence in the overall zone of trough development (Fig. 2).

3. Lower boundary of the modern shoreface prism

A meaningful comparison between shoreface sedimentology and profile survey data requires accurate identification of the lower boundary, or lower sedimentologic limit (LLs), to the shoreface mass (Fig. 2). The LLs is an erosional surface between the modern shoreface prism and a previously unrecognized tidal body (Schwartz et al., 1997). Faunal remains and distinct tidal structures in the underlying body indicate that it is part of a pre-1700s inlet-associated facies complex (Fisher, 1977), including tidal delta, tidal channel, and tidally influenced nearshore components. The following properties of the contact and the procedure for demarcation are summarized from Schwartz et al. (1997).

Although erosional, the contact was not clearly indicated in all cores by the truncation of underlying beds, shell lag, or a discrete change in sediment color above the ravinement surface (Reading and Collinson, 1996, pp. 220–224). Problematically, similar sediment size and equivocal bedding structures flanked the contact in a numbers of cores. For example, below the inner-trough zone, gravelly and medium- to coarse-sand of both bodies usually occurred in direct contact and, seaward, fine to very fine sand of both bodies commonly occurred in direct contact. Compounding the problem was the occurrence of thin (e.g. 2–10 cm) shelly gravel or very coarse-sand tidal layers directly, or buried a short distance, below the LLs of the middle to outer shoreface prism. Because of stratigraphic proximity to the LLs, it would be easy to mistakenly assume that the coarse layers represent an erosional shoreface lag (Swift, 1968) or storm deposits within the shoreface prism. In some, but not all cases, color showed a discrete change near the contact from yellow to brown or shades of gray for underlying, unworked, and chemically reduced sediment. In heavily burrowed fine sand of the outermost profile, color was of little help other than to identify the uppermost few centimeters of most recently deposited modern sand. Con-
sequently, the following procedure was utilized to demarcate the LLs.

Maximum erosion depth derived from the elevation series data for each core location served as a minimum depth indicator for the LLs. In some cores, the truncation of sedimentary structures or bed sequences unique to tidal processes was used to establish a precise location for the shoreface (LLs) boundary. Where this was not possible, the base of an unequivocal shoreface bed sequence was used as a minimum depth indicator for the LLs. In many of the cores, texture above the contact was only slightly coarser than below, but slightly cleaner and better sorted due to the lack of interstitial clay. The lower boundary for the shoreface prism was extended across the nearshore zone by using definite contacts and correlating laterally through geologically reasonable contacts at intervening sites. The accuracy within cores ranged from $\pm 1$ cm for sedimentologically distinct contacts to an estimated accuracy of $\pm 2-3$ cm for cores where the contact was indistinct.

4. Geometry of shoreface prism

The envelope of surveyed elevation change provides one estimate of potential geometry for the shoreface sediment mass over a 12-year period (Fig. 2). Maximum envelope thicknesses of 3–4 m occur between the beach and middle platform areas.
The envelope shows protracted thinning from about 1 m thick in the middle platform area to about 50 cm thick at the seaward limit of coring at 900 to 950 m from baseline (800–850 m from shoreline).

However, actual profile shapes, even under conditions of maximum accretion, never match the upper limit of the survey envelope (ULe) whereas the LLs generally lies slightly below and closely approximates the lower limit of surveyed elevation change (LLe). Therefore, at any point in time, the actual geometry of the shoreface mass is represented by the lower limit of the survey envelope and the shape of the active profile. Profile shapes at the time of vibracoring depict two basic geometries for the shoreface mass. The geometry below line 62 represents a state of maximum accretion with buildup of the beach, inner trough, and lower ramp zones, approaching that of the upper envelope (Fig. 2). The geometry below line 188 shows much less buildup in the beach and lower ramp zones with essentially zero thickness in the inner trough zone.

Overall, the geometry of the modern shoreface mass is basically prismatic with maximum thickness in the bar-and-trough-associated zone. Seaward, below the lower ramp, the prism slowly tapers seaward and has boundaries similar in shape to both the upper

![Diagram](image-url)

Fig. 4. Facies below beach and inner-trough margin of line 188. Examples of second-order bed sequences and first-order textural trends through facies are indicated by solid arrows and dashed arrows, respectively. Average grain size at a 1-cm interval is indicated by the horizontal scale whereas relative sand vs. gravel abundance in an entire bed is indicated by color shading. Vibracores are schematically positioned relative to each other with actual NGVD elevations listed with each core.
and lower limit of profile change as well as to measured instantaneous profiles.

5. Facies and relationship to nearshore processes

Five facies groups are designed for the shoreface prism: swash, swash-trough transition, trough-associated, upper ramp–middle platform, and lower ramp (Fig. 3). Included in the trough-associated group are five subfacies related to various trough and bar settings.

5.1. Swash facies

A medium-to-coarse sand and gravel lens directly underlies the swash zone along line 188 (Figs. 4 and 5). The lens thins and coarsens seaward from about 60 cm of medium coarse sand in the upper foreshore to about 10 cm of sandy gravel at the inner trough margin. Similarly, sediment texture along the active sediment–water interface coarsens downslope across the swash zone (Fig. 6). Internally, the swash facies contains seaward-dipping erosional surfaces (Fig. 7) and repetitive smaller scale upward fining bed sequences that make up an overall upward-fining trend. Although dominated by parallel-laminated sand and gravel beds, large-scale cross-stratified sand and gravel is mixed within lower and seaward parts of the facies.

Swash zone runup and backwash occur across a seaward sloping planar surface. Parallel lamination develops under high shear-stress plane-bed conditions, typically during backwash (Clifton, 1969; Clif-
ton et al., 1971), with seaward textural coarsening being a product of the downslope (backwash) increase in flow strength, inter-particle dispersive-shear sorting (Schwartz, 1975, pp. 42–44; 1982, p. 846), and overall increase in energy at the surf–swash transition. The upward fining bed sequences and intervening erosional surfaces reflect episodic erosion followed by progradation of the beach whereby higher energy and coarser grained lower swash zone settings are superposed by lower energy and finer grained upper swash zone settings (Fig. 8). Cross-stratified beds in lower parts of the facies indicate the presence of large-scale ripples in subaqueous settings downslope from an extant swash zone. Elevation data show that, following maximum erosion events between 1981 and 1987, a complicated history of net accretion resulted in development of the cored swash and underlying swash–trough transition facies (Fig. 9). Major erosional events were associated with ephemeral trough development in foreshore locations substantiating the setting for cross-stratification development. An example of short-duration profile buildup that would result in the above facies relationships is shown in Fig. 10.

Fig. 6. Grain size along the sediment–water interface of line 188 at the time of the 1993 DSEX and 1981 ASEX Experiments.
5.2. Swash–trough transition facies

A 40- to 60-cm-thick seaward-dipping gravel-dominated lens directly underlies the swash facies (Fig. 3). It becomes exposed, or intermittently buried by fine to medium sand, along the upper flank of the longshore trough. By contrast with the swash facies, this facies is characterized by net upward coarsening (Fig. 4). Internally, the unit contains seaward-dipping erosional surfaces that lead into trough shaped erosional surfaces (Fig. 7) as well as repetitive upward coarsening bed sequences that are primarily composed of inversely graded horizontal to low-angle parallel-laminated beds. Other bedding types include normally graded
cross-stratified and non-graded parallel laminated beds.

The transition facies represents accretion of the swash–inner trough margin in advance of a prograding beach (Fig. 10). The seaward terminus is spatially linked to grain sizes and bedforms observed in the swash–trough transition area of an active profile. Medium sand to gravel is often concentrated in this zone followed by seaward fining into the upper part of the trough flank (Fig. 6), thus accounting for net upward coarsening with progradation (Fig. 8). Planar bed surfaces and scattered medium-scale to large-scale three-dimensional current-dominated ripples account for the development of parallel-laminated and cross-stratified beds. Similar to the overlying swash facies, stacked bed sequences and alternating beds of sand and gravel indicate a number of trough-erosion events with subsequent net accretion following erosional maxima between 1981 and 1990 (Fig. 9).

5.3. Trough-associated facies

Extending from below the swash–trough transition facies to the landward margin of the lower ramp, most of the shoreface prism is dominated by facies associated with trough and bar development (Fig. 3). Five subfacies are designated: inner-, middle-, and outer-trough, inner-bar flank, and distal bar. The group as a whole is a composite of thin (<0.9 m) laterally and vertically stacked concave-shaped erosional-based lenses that represent trough-scour events followed by trough filling (Fig. 7) (Schwartz et al., 1997; Weislogel and Schwartz, 1998; Lamb and Schwartz, 1999). The inner-, middle-, and outer-trough zones are marked by different maximum depths for trough
erosion. The three subfacies merge laterally making up an irregular concave-shaped composite body up to 2.2 m thick and approximately 300 m wide (Fig. 3). Although bars and troughs concomitantly develop and migrate across the profile, the upper parts of bar deposits are largely eliminated from the sediment record due to their shallower bathymetry and high erosion potential. At the time of vibracoring, the only sedimentologically active parts of the trough facies included the longshore trough and bar along line 188 and a narrow low-relief trough-like feature adjacent to the beach along line 62. Structural properties common to the entire trough-associated facies group are presented below followed by individualized treatment of different subfacies.

A mixture of low-angle parallel-laminated cross-stratification and normally graded medium- to large-scale cross-stratification characterizes the entire trough-associated group (Figs. 11–14). Less common are subhorizontal parallel-lamination and small-scale trough cross-stratification. Both the horizontal and low-angle parallel-laminated beds represent accumulation upon very low-angle to subhorizontal surfaces during intermittent sheet-flow (upper-regime plane bed) (Clifton and Dingler, 1984) conditions. Based upon the occurrence of variable foreset orientations and erosional contacts below many medium- to large-scale cross-stratified beds, the cross-stratification is interpreted to be trough, or “three-dimensional”, produced by the migration of three-dimensional ripple forms (megaripples) (Rubin, 1987) with slightly concave scour pits preceding the ripple front. Such ripples, with orientations oblique and parallel to bar-and-trough axes, are typical for trough settings at this site and other coastal sites (Davidson-Arnott and Greenwood, 1976; Greenwood and Mittler, 1984; Drake, 1997). The relative abundance of cross-stratification documents that current-dominated lower-regime flow is commonly associated with trough infilling.

5.3.1. Inner- and middle-trough subfacies

The inner-trough subfacies occupies an approximately 175-m-wide shore-parallel zone within the...
normal concave-shaped base and a maximum subsurface depth of \( \sim -4.2\) m (Lamb and Schwartz, 1999). Larson and Kraus (1994) report that the center of mass for inner bars typically occurs at about 215 m from baseline, slightly seaward of the center of the subfacies. Along line 188, the subfacies underlies the swash and swash–trough transition facies and emerges at the active sediment–water interface along the inner flank of the longshore trough (Fig. 3). There, the unit thins and makes up the active bed of the trough before thickening again as it projects beneath the bar and upper ramp. Along line 62, the inner trough subfacies makes up the lower 2/3 to 3/4 of the fully accreted inner profile (Fig. 3).

The middle-trough subfacies occupies an approximately 125-m-wide concave-shaped tract, the base of which extends to a maximum depth of \( \sim -5.0\) to \(-5.5\) m, a deeper stratigraphic level than that of both the inner- and outer-trough subfacies (Fig. 3). Thicknesses up to about 1.0 m are preserved above the basal erosional surface (LLs). The subfacies then thins seaward terminating against a higher elevation convex-shaped erosional sector of the LLs. Bars associated with middle-trough zone scour develop seaward at an average location of about 400 m from baseline (Larson and Kraus, 1994).

Both the inner and middle trough subfacies are characterized by upward and seaward textural fining trends. Both subfacies fine upward from a thin (\(<50\) cm), discontinuous, coarse unit that extends along the base of the facies tract. The coarse basal unit thins and fines seaward from a relative abundance of gravelly and coarse-to-very coarse sand beds at innermost locations to thin beds of finer sand and scattered gravel in outermost locations (Figs. 11–14). Laterally and vertically stacked upward fining bed sequences, 5–60 cm thick, occur within the subfacies. Each upward fining bed sequence is marked by an erosional base and contains normally graded beds.

The inner- and middle-trough subfacies reflect medium- to large-scale three-dimensional ripple and plane-bed development along the troughs and asso-
associated bar flanks of past profiles (Fig. 15). The textural trend along the sediment–water interface of an active current-dominated trough is one of textural fining away from the deeper axial zone, or thalweg, toward the trough flanks (Fig. 6). The greater degree of coarsening near the base of the shoreface prism is related to coarsening along the axial zones of the more deeply scoured troughs. Upward-fining bed sequences within the facies represent trough scour events and initial coarse deposition along axial zones followed by filling from finer adjacent areas (Fig. 8). The history of inner- and middle-trough subfacies development is marked by repeated erosional and depositional events showing two end-member styles of elevation change (Fig. 9) (Clemenich and Schwartz, 1998). Patterns of rapid erosion decrease followed by relatively slow accretion represent storm trough scour with subsequent bar encroachment and trough filling. Patterns of rapid accretion and relatively slow erosion represent rapid storm bar development at the site of a previously scoured trough, followed by a slower rate of bar migration away from the site. Overall, the higher energy and more active inner-trough zone is marked by elevation series showing a higher frequency of cut-and-fill events than for the middle trough zone (Fig. 9).

5.3.2. Outer-trough subfacies
Concave erosional surfaces mark an outer zone of low-relief trough scour located directly below the middle platform (Fig. 7). The zone is about 120 m wide, contains thin (<25 cm) trough-fill sequences, and extends to a maximum subsurface depth of ~4.5 m. The subfacies is sedimentologically less distinct than the inner- and middle-trough subfacies due to its relative thinness, deformation of physical structures in the uppermost part of vibracores, and physical similarity to surrounding upper ramp-middle platform deposits (Fig. 14). In contrast to the inner-
and middle-trough subfacies, the outer-trough subfacies does not typically rest upon the erosional base (LLs) of the shoreface prism, but occurs at a higher stratigraphic level where it cuts into underlying distal bar or lower ramp facies. A dominance of parallel-laminated beds with overall depositional features similar to those of the middle platform facies is characteristic. Although fine sand is far dominant, thin (cm-scale) medium sand-rich beds and very thin (< 1 cm) coarse-sand and granule-rich stringers occur.

Fig. 12. Facies below the active bar and upper ramp along line 188. See Fig. 4 caption for explanation of symbols and core position.
throughout the facies (Figs. 5, 12, 13, and 14). Normally graded beds and upward fining bed sequences above erosional surfaces are characteristic.

Similar to sequences within the inner and middle subfacies, upward fining beds and bed sequences in the outer-trough subfacies reflect trough scour followed by filling. However, the shallower depth and low relief of outer troughs in this commonly high-energy zone allowed for a dominance of plane bed deposition (further discussed under upper ramp-middle platform facies). The shallower depths of scour, compared to the middle-trough zone, resulted in minimal trough-related erosion at the base of the shoreface prism allowing for a higher elevation,
convex-shaped segment of the LLe and LLs. Larson and Kraus (1994) report that extreme storm waves, about 1% of all waves at the study site, break at about 4.5 m depth which closely corresponds to the seaward margin of outer-trough scour.

5.3.3. Distal bar subfacies

A lens-shaped subfacies related to bar development underlies and extends seaward from the outer-trough subfacies (Figs. 3 and 14). Although sedimentologically similar to the middle-trough subfacies, the landward part of the distal bar subfacies only locally rests upon the base of the shoreface prism (LLs). Seaward, the facies overlies lower ramp deposits.

Bar deposition is concomitant with trough scour. Fig. 16 illustrates that as troughs are scoured in response to storms, excavated sand is simultaneously displaced seaward resulting in the buildup of a low-relief bar. A comparison of time-series elevation change with the cored distal bar facies illustrates a sequence of bar depositional events and intervening fair-weather erosion (Fig. 17). The basal contact of the distal bar sequence correlates with a pre-storm erosional maximum (E2) into lower ramp deposits. The subsequent E2–A2 storm-bar accretion sequence was truncated by the A2–E3 erosion series, with erosional maximum E3 marking the upper contact of the remnant distal bar sequence. The profile change illustrated in Fig. 16 occurred between erosional maximum E2, accretional maximum A2 and erosional maximum E2 in Fig. 17. The illustrated profile change is representative of those associated with all other rapid accretion events in the distal bar zone (Fig. 9).

Overall, the combined core and elevation data for middle and outer troughs and outer bars demonstrate several facets of nearshore processes. Trough scour in the middle-trough zone results in seaward bar deposition that can include deposition toward, and upon, the lower-ramp. Outer-trough scour results in farthest seaward bar development and usually even thicker sediment accumulation upon the adjacent lower ramp. Overall, the distal bar subfacies consists of erosional remnants of storm-associated bars that developed

Fig. 14. Facies below the middle platform of line 188. See Fig. 4 caption for explanation of symbols and core position.
under widespread surf conditions with depth–velocity combinations sufficient for plane-bed and large-scale current ripple development. The seaward limit of the distal bar facies (500–550 m from baseline and ~5.3 m depth) documents the seawardmost development of bar morphologies associated with longshore-dominated combined flow. There, bar-flank deposits merge with, and become, lower-ramp facies. The distal bar facies limit also corresponds to the break-in-slope between the middle platform and lower ramp demonstrating a dependency between longshore-current-related sediment transfer to outer bars and subsequent fair weather-modified profile shape. Based upon measurements of surf-zone width and current motion during extreme storm events at the FRF, it is known that appreciable shore-parallel flow can extend beyond the distal bar limit. Surf zone widths of about 1000 m with shore-parallel velocities up to 1 m/s at depths of 8 and 13 m (1 m above the bed) have been documented. Nonetheless, profile survey data show no evidence for bar and trough development beyond a 500 m distance–5 m depth limit indicating the absence of fluid kinematics leading to zones of shore-parallel trough scour and simultaneous bar deposition.

5.3.4. Inner bar-flank subfacies

A fine-sand lens dominated by landward-dipping parallel lamination mantles the landward-facing flank of the inner bar along profile 188 (Figs. 3, 11, and 12). The lens is inclined subparallel to the frontal profile of the bar form, thins from 40 to 80 cm thick at flank locations, and pinches out along the trough and bar crest. Although the dominant structure is low-angle landward-dipping parallel lamination, intermixed structures include medium- to large-scale cross-stratification, small-scale trough cross-stratification, and, near the bar crest, subhorizontal lamination. The subfacies consists almost entirely of fine sand with scattered occurrences of coarse to very coarse sand and granule stringers (Fig. 5). Upward fining from the underlying inner-trough subfacies is followed by slight upward coarsening into the upper part of the bar. Similarly, textural data from along the sediment—

Fig. 15. Comparison of facies distribution below the bar and upper ramp with representative surveyed troughs at inner- and middle-trough locations. Arrows mark the thalweg of troughs at the labelled times.
water interface document initial fining from the trough axis to mid-flank area followed by slight coarsening at the bar crest (Fig. 6).

The inner bar-flank subfacies is primarily a product of wave-driven bar migration over a 2-month period (Fig. 18). Lens geometry represents form-parallel accretion upon the frontal (landward) profile of the bar. Trough-to-flank fining reflects a decrease in current-energy away from the trough axis with internal upward fining due to bar migration and flank accretion (Fig. 8). Similarly, flank-to-crest and internal upward coarsening are associated with continued bar buildup and increased wave energy toward the bar crest. Landward-dipping sub-parallel lamination represents high shear-stress plane-bed conditions along the bar-trough flank whereas the smaller-scale cross-stratified beds document the ephemeral migration of small-scale to medium-scale three-dimensional ripples during periods of lower velocity current-dominated flow.

5.4. Upper ramp–middle platform facies

Directly below the upper ramp-to-middle platform shaped segments of the profile, a predominantly parallel-laminated fine-sand facies makes up much of the upper half of the shoreface prism (Fig. 3). The facies overlies, and locally encloses, thin lenses of sedimentologically distinct trough facies. In addition, trough-shaped erosional surfaces (Fig. 7) with dominantly parallel-laminated fill are common. Rare, but intermixed in the facies, are small- and medium-scale trough cross-stratified and low-angle parallel laminated beds. Although parallel laminated beds of the upper ramp dip seaward at several degrees, dip is typically indistinguishable in the several centimeter-wide cores and thus similar in appearance to lamination below the middle platform. Irrespective of location, the mm-scale parallel laminations typically show small differences in grain size between laminations and at lamination boundaries. Overall, fine sand is far
dominant in the upper-ramp and middle platform region (Fig. 5). Scattered occurrences of medium sand-rich beds and very thin (<1 cm) coarse-sand and granule-rich stringers occur throughout the facies, particularly above erosional surfaces and at the base of upward-fining bed sequences (Figs. 12–14). An overall trend of weak upward coarsening, containing the smaller scale upward-fining bed sequences, extends through the facies. Overall, the facies boundaries define an irregular concave-shaped lens with a maximum thickness up to 1.3 m below the upper ramp. This facies, in combination with the enclosed and similar appearing outer-trough subfacies, thins seaward to about 30–40 cm thick where it merges with parallel laminated sand of the lower ramp.

The parallel laminations reflect upper-regime plane-bed conditions, including the possible occurrence of low-amplitude (mm-scale) bedwaves, associated with subcritical to supercritical orbital or wave-dominated combined flow (Clifton, 1976; Paola et al., 1989; Best and Bridge, 1992). The bar, upper ramp, and middle platform, at a depth range of about 2.0–
4.0 m, are zones across which strong wave shoaling and high-energy dissipative surf frequently occur. During fair-weather wave conditions, the sediment–water interface is usually covered by a seemingly planar bedform zone at shallower depths and a wave-rippled zone at greater depths. During higher energy periods, e.g., wave height >1.2 m and wave periods of 8–11 s, sheet-flow conditions would extend across the entire middle sector of the profile (Clifton and Dingler, 1984). Supporting evidence for high shear-stress development of parallel lamination across the middle profile includes: (1) correspondence between diver-observed “plane-bed” conditions and parallel lamination in box cores from the same site during earlier experiments (unpublished 1981 ASEX experiment), (2) the continuity of parallel laminated bedding types from the high-energy bar/upper ramp across the middle platform, and (3) the occurrence of small concavo-convex shells in a plane-bed (high shear-stress) stable orientation.

A widespread upper ramp to near-horizontal middle-profile shape follows the earlier occurrence of storm-related trough scour and bar deposition in the same location. Long-term profile buildup and overall energy increase is documented by upward coarsening through the facies. However, enclosed erosional surfaces and upward-fining bed sequences document continued, but relatively shallow, trough scour-and-fill events during the ramp-platform buildup phase. Although low-energy waves and currents intermittently act upon the upper ramp-platform sector of the profile, the shallow depth favors plane-bed development as well as higher energy reworking of low-energy ripple-bed products. Overall, aggradation under high-velocity plane-bed conditions, such as, >80–100 cm/s (Komar and Miller, 1975; Clifton and Dingler, 1984), most reasonably accounts for parallel lamination development.

5.5. Lower ramp facies

A seaward dipping and thinning prism of bioturbated, parallel-laminated, fine to very fine sand underlies the lower ramp (Figs. 3 and 19). Thickness ranges from 1.1 m at the landward margin of the ramp to 0.25 m in the seawardmost cores at ~8.4 m depth. Unpublished seismic reflection data from the study site document that the modern lower ramp prism continues to thin seaward and pinches out between 9 and 12 m depth. The slightly concave lower boundary of the lower ramp prism is similar in shape to measured lower ramp profiles (Fig. 7) (Lamb and Schwartz, 1999). The parallel laminations are similar to those of the middle platform sector including the occurrence of small concavo-convex shells in a plane-bed (high shear-stress) stable orientation. Where there has been a high degree of bioturbation, bed contacts...
and internal structures range from partially to totally obscured and sediment appears to be homogenous. Although rare, small-scale trough cross-stratified beds (<4–5 cm thick), including some with stacked offshore-oriented foresets, are preserved in the seaward-most cores.

Overall, the lower ramp facies is marked by a lateral seaward trend of textural fining, darkening from yellow to gray, increased bioturbation fabric and increased organic content. At the landward margin, the lower ramp facies encases the distal bar subfacies. Proximal to the distal bar subfacies, scattered pebbles and rare biodisrupted granule stringers locally occur within fine sand of the lower ramp facies (Figs. 14 and 19). A vertical sequence through the facies consists of slight upward coarsening, upward lightening of color, decreased bioturbation fabric and decreased organic content.

During fair-weather wave conditions, the sediment–water interface along the lower ramp is usually covered by active to inactive small-scale two-dimensional wave ripples. However during large storms, the lower ramp becomes energetic and, sometimes, part of a dissipative surf zone (Lee et al., 1998) with high-velocity sheetflow conditions along the bed (Beavers, 1999). Minimum velocities of 70–80 cm/s are required for plane-bed development in very fine to fine sand (Harms et al., 1982; Clifton and Dingler, 1984). Given the above, and the similarity of parallel laminations in the lower ramp to those of the upper ramp–middle platform sector, high-velocity plane-bed conditions during storm events are interpreted to be

Fig. 19. Facies below the lower ramp of line 188. See Fig. 4 caption for explanations of symbols, core position, and vertical scale. Although not shown, cores 29 and 31 exhibit patterns similar to the adjacent cores.
responsible for lamination development and profile buildup in this zone. Conversely, the paucity of wave-ripple structures suggests that temporally dominant fair-weather wave transport tends to result in sediment removal, subelevation of the ramp, and development of ramp-shaped erosion surfaces. At the same time, biogenic reworking and structural overprinting is maximized during fair-weather periods. An exception for ramp erosion occurred during an extreme storm event in October 1993 when wave period was unusually long (20 s) and the surf zone extended completely across the lower ramp.

The temporal association of storm buildup and fair-weather erosion along the lower ramp is corroborated by Lee et al. (1998). Furthermore, Fig. 20 illustrates that, during a lower ramp accretion trend (E1–A1 in Figs. 17 and 21), a number of large troughs were simultaneously scoured in the middle-trough zone. Both the trough-scour events and associated net lower-ramp buildup resulted from a close succession of major storms (12/02/86, 1/1/87, 1/26/87, 2/17/87, 3/10/87, and 4/26/87; Lee et al., 1998). During each trough-scour event, sand was displaced seaward onto the lower ramp. Conversely, during the subsequent lower ramp erosion trend (A1–E2), landward profile sectors underwent net accretion due to a dominance of fair-weather (landward) transport. Lee et al. (1998) document that major storms were more tightly grouped during the lower-ramp accretion trend and that wave power for individual storms, as well as cumulative storm wave energy, greatly exceeded that for storms occurring during the erosion trend. The nature of profile change shown in Fig. 20 is representative of that associated with all other accretion-erosion trends for the lower ramp region (Fig. 9). Thus, the internal seaward trend of decreasing grain size primarily reflects decreasing energy and seaward-transport along the lower ramp of past storm profiles. The lateral increase in bioturbation and organic content also reflect a seaward decrease in energy and increase in biogenic reworking during subsequent low-energy conditions. The upward coarsening and

![Fig. 20](image-url)
upward decrease in bioturbation through the facies sequence record net long-term energy increase at a given site as the ramp prograded and shallower lower ramp settings were superposed upon deeper and lower-energy ramp settings. The restriction of scattered gravel and coarse sand stringers to the landwardmost part of the lower ramp facies, that is, adjacent to the seaward margin of the distal bar and outer-trough subfacies, indicates only minor seaward displacement of coarser material beyond trough-and-bar settings during some storm events. The rare occurrence of small-scale trough cross-stratification is consistent with the measured episodic occurrence of offshore-directed mean flows (Wright et al., 1991; Beavers, 1999).

A comparison of elevation and storm-event data with lower ramp stratigraphy provides further details concerning the history and dynamics of lower ramp buildup and erosion. The time-series elevation data document the occurrence of repetitive long-term (e.g., 700–1300 day) erosion trends across the lower ramp (Fig. 22) (Clemenich and Schwartz, 1998). Labeled E1 through E5 in Fig. 22 are “time lines” approximating a series of successively shallowing erosional maxima that occurred throughout the study area (Weislogel and Schwartz, 1998; Lamb and Schwartz,
An E time line, although not strictly synchronous, represents a widespread lower-ramp erosional surface similar in shape to those shown in Fig. 20 (E1 and E2). E1 marks the deepest surveyed erosional level to occur across the lower ramp during the 12.4-year survey period. Erosional surfaces E2 through E5 cut downward into preceding storm-accretion sequences, but, for the most part, to progressively shallower depths resulting in only partial removal of the post-December 1986 depositional record. Shown in Fig. 23 are correlations between the erosion-surface time lines and lower-ramp stratigraphic record demarcating four major phases of storm-related accretion that occurred between December 1986 and February 1993. Although a number of major storm events with various amounts of corresponding ramp buildup occurred between 1981 and 1993 (Lee et al., 1998), a fair weather-dominated erosional trend culminating in late November–early December 1986 (E1) resulted in removal of most of the preceding lower ramp deposits (Fig. 22). The successively shallower erosional maxima (E2, E3, E4, and E5), which culminated in 1987, 1989, 1991, and 1993, resulted in partial truncation and, thus, remnant preservation of storm-related accretion trends (Fig. 21). Seaward of the middle part of the lower ramp (seaward of core 28), erosional surface...
E5 cut below surface E4 resulting in total removal of the 1993 record leaving just the three older storm-accretion sequences (Fig. 23). The relationship between upward coarsening and shallowing is demonstrated on two different scales in core 30 (Fig. 21). Net upward coarsening through the core corresponds to net shallowing caused by storm-related accretion during the preceding 6.4-year period. In addition, upward coarsening between the E1–E2 and E2–E3 bedding contacts represent the truncated 1986–1987 and 1989 storm-accretion trends, each of which were products of closely spaced, or “grouped”, major storm events (Lee et al., 1998). The occurrence of lower ramp facies below E1 along the inner part of the ramp (Fig. 23) is related to a deeper level of lower ramp erosion with subsequent storm deposition pre-dating the survey period.

6. Sedimentology and morphodynamics related to engineering interests

6.1. Lower limits of the shoreface prism and erosional processes

The lower limit of surveyed elevation change (LLe) is a shore-normal profile representing maximum erosion, or total reworking depth, of the shore-
face mass over the 12.4-year survey period (Fig. 7). The lower sedimentologic limit (LLs), or lower geologic boundary, of the prism is a shore-normal profile of the erosional contact between modern shoreface deposits and underlying tidal deposits representing reworking depth on the open time scale. The geometry, origin, and age of the LLe and LLs profiles are addressed below. In addition, a comparison of the spatial and temporal properties of the LLs with various duration-dependent LLe profiles is used to estimate the potential for total shoreface-mass reworking.

6.2. Geometry of the LLe and LLs profiles and erosion depth

6.2.1. Line 188

The shape and position of the LLe profile along line 188 are very similar to that of the LLs profile with the LLs occurring only a relatively small distance below, or coincident with, the LLe (Fig. 7). Both profiles document an overall seaward trend of increasing depth of erosion and decreasing differences in elevation. Differences of 0–50 cm between the LLe and LLs occur landward of the lower ramp below the trough-associated facies zone. Differences of 10–30 cm occur below the inner part of the lower ramp with both profiles becoming coincident along the outer half of the lower ramp. More than 90% of the shoreface mass lies above the LLe.

Smaller-scale zones of distinctive geometry make up parts of both the LLe and LLs profiles. From below the beach to middle platform (100 to 400 m from baseline), an approximately 300-m-wide, irregular-concave sector occurs along the base of the inner- and middle-trough subfacies (Figs. 3 and 7). Maximum downward erosion to ~−4.0 m below the middle-trough zone compared to ~−4.0 m below the inner-trough and ~−4.5 m below the outer-trough zones. The concave sector consists of even smaller concave-shaped profile segments.

The basal erosional surface of the outer-trough facies occurs above a convex-shaped rise in elevation of both the LLe and LLs and only locally reaches LLe depths near the top of the convexity (Fig. 7). Seaward, the outer-trough erosional base rises above lower ramp deposits and becomes divergent with the slightly concave, seaward descending, LLe and LLs profiles below the lower ramp. Maximum lower-limit erosion along the lower ramp extends from about −4.8 to −5.0 m NGVD at 400 to 450 m from baseline to about −8.0 to −8.2 m NGVD at 900 m from baseline.

6.2.2. Line 62

The basic form and depth of the LLe and LLs profiles along line 62 are similar to those of line 188 (Fig. 7). Because of insufficient vibracore penetration, LLs data are not available between the beach and upper ramp (landward of 300 m). However, an irregular, strongly concave LLe sector occurs in that zone, along the base of the subsurface inner- and middle-trough subfacies, similar in shape and depth to that of line 188. LLs data between 300 and 400 m document a deeper and older extension of the concave trough-associated zone. Seaward of 400 m, in the ramp-associated zone, about 87% of the cored shoreface mass lies above the LLe.

6.3. Physical evolution of lower-limit profiles

The origin of the LLe can be established by linking LLe depths at various locations along the profile to facies and corresponding (date-specific) morphodynamics. The uniformity in shape, position and facies relationships for the LLe and LLs indicate a similar type of origin for both types of limit-depth profiles.

6.3.1. Trough-associated sector

Surveyed profiles document that a composite of shore-parallel scour events associated with the development of longshore troughs accounts for the 250–300-m-wide concave-shaped erosional surface that constitutes most of the landward part of the LLe (Weislogel and Schwartz, 1998; Lamb and Schwartz, 1999). The smallest-scale concave segments along this sector of the LLe correspond to concave segments of individual surveyed troughs.

Overall, the concavity of the trough-associated LLe reflects greater downward erosion potential along the central region of storm-widened surf zones than along marginal areas. The convex-shaped rise in the LLe and LLs is a result of decreased scour potential associated with outer troughs and marks the seaward limit for trough-associated limit-depth scour and the beginning of the erosional system associated with lower ramp limit depths.
6.3.2. Lower-ramp sector

The limit-depth profiles below the lower ramp are a composite of remnant segments of lower-ramp profiles developed at the end of long-term (e.g., 700–1300 day), fair weather-dominated, lower-ramp erosional trends (Fig. 22). Individual lower-ramp erosional surfaces are widespread alongshore (>1 km) and slightly concave offshore (Lamb and Schwartz, 1999) accounting for the shape of the composite limit-depth profiles. Facies and elevation series data document that lower ramp erosional trends are terminated by storm-associated trough scour events in more landward locations that result in sediment transfer onto the lower ramp.

6.3.3. Internal prism

Preserved at higher elevations within the shoreface prism are younger erosional surfaces similar in form and lateral extent to underlying trough- and lower-ramp-associated sectors of the LLe and LLs (Fig. 7). The repetition of similar shapes for the LLs, LLe, and younger internal erosional surfaces further substantiates cause and indicates a potential for relatively rapid development of a basic “equilibrium” shape for composite erosion-limit surfaces.

6.4. Age of lower limits and shoreface reworking

6.4.1. Trough-associated zone

At the time of vibracoring, the LLe in the trough-associated zone was a composite of numerous time segments ranging in age from several months to about 12.5 years (Fig. 24). However, most trough-associated segments of the LLe developed between 1981 and 1987, prior to post-1987 net buildup of the shoreface. Although the LLs along line 188 descends below the LLe at many locations in the trough-associated zone, the LLs and LLe profiles also coincide at a number of locations.

Fig. 24. Age of the lower limit of surveyed elevation change (LLe) along lines 62 and 188.
locations demonstrating potential for full downward erosion to LLs depths along all trough-zone locations (Fig. 7). Although some of the LLs departure below the LLe may be pre-survey, it is most likely that maximum downward scour events were simply missed by post-storm surveys due to high recovery rates after trough scour in the surf zone.

6.4.2. Lower ramp zone

Most of the LLe below the lower ramp of lines 62 and 188 resulted from a 3.5-yr erosional trend that culminated during the fall of 1986 (Figs. 9 and 24). Short segments also represent 0.8- to 1.8-yr erosional trends that culminated during fall 1981, winter 1982–1983, and winter 1988–1989.

Seaward of about 600–700 m, the 1982–1983 and 1986 LLe-profile segments along lines 62 and 188 coincide with the LLs profile establishing the most recent ages for the respective LLs segments (Fig. 7). Landward, where the lower ramp portion of the LLs descends below the LLe, slightly deeper pre-survey (pre-1981) erosion is indicated. Because erosional surfaces in the lower ramp zone tend to subelevate very slowly compared to those in the trough-associated zone, it is unlikely that LLs development below the LLe was simply missed due to survey frequency.

6.4.3. Reworking history

Reworking history of the shoreface mass can be addressed by means of comparing LLe age and depth at a given location with corresponding LLs depth. At the time of this study, the age of profile segments making up the LLe along lines 62 and 188 ranged between <1 and 12.4 years (Fig. 24). In the trough-associated zone, separate troughs cut down to LLe depths along short segments of lines 62 and 188 at least 27 times over the 12.4-year period. Below the lower ramp, ramp systems cut down to LLe depths along relatively wide segments only five times over the same period. The rapid downward scour of troughs during storms compared to slow rates of net fair-weather erosion across widespread ramp systems accounts for the higher incidence of limit-depth events in the trough-associated zone. Based upon similarity of the LLe and LLs profiles and the demonstrated capacity for erosion down to LLs depths a number of times during the study period, the maximum age for some LLs segments that lie below LLe segments is judged to be <13–15 years. The potential for erosion down to LLs depths was decreased during the last 6 years of the study period as the shoreface underwent net buildup, including over 40 cm of accretion at the seaward limit of measurement (Lee and Birkemeier, 1993; Lee et al., 1998; Nicholls et al. 1998). Overall, based upon combined core and lower limit data, most or all of the shoreface mass is fully capable of being reworked on the decade scale.

Reworking potential can be further addressed by means of a cycle-based consideration of survey data rather than by simply comparing the LLs with the 12.4-year LLe record. Time-series elevation data show that the shoreface is characterized by repetitive patterns of accretion and erosion (Fig. 9). Exceptionally well-defined large-scale accretion–erosion trends occur in phase across the lower ramp zones (Fig. 22) (Clemenich and Schwartz, 1998). Four erosional maxima and three intervening accretional maxima demarcate three large-scale ramp accretion–erosion “cycles” between 1982 and 1992. As demonstrated in this study, erosion in one hydrodynamic zone is inextricably linked to deposition in another. Fundamental to this aspect of morphodynamics, or mass exchange, is that simultaneous sets of coastal processes do not allow for synchronous shore-wide buildup or erosion toward limiting values.

The accretion–erosion cycles may be used to derive upper and lower limits of elevation change for each cycle period (Fig. 25). The upper and lower limits for each cycle are similar in shape to each other and to those of the full survey period thus reflecting similar cause. Moreover, the shapes of all lower-limit profiles (cyclic and 12.4-year cumulative) are basically similar to the shape of the LLs, further demonstrating similar cause for the LLe and LLs. Duration for cycle E0–E1 is about 3.97 years, E1–E2 about 2.38 years, and E2–E3 about 2.72 years compared to the 12.4-year survey period. There is no systematic correspondence between envelope thickness, depth of erosion, and duration of the three cycles. Rather, envelope thickness and erosion depth is dependent upon the frequency, grouping, magnitude, and duration of erosional and depositional conditions, that is, storm vs. fair weather, that occur within the cycle period. The full-survey envelope is thicker than that of individual cycles as it consists of maxima and minima for the entire 12.4-year period and includes the full component of net profile accretion.
Although conservation of mass does not hold for shoreface systems, each cycle indicates a return to similar erosion and accretion limit-profile shapes and a tendency for return towards limiting values. It is reasonable that cycle duration serves as an estimate of potential reworking time for a stationary system, that is, a shoreface which is not undergoing net accretion or erosion. Accordingly, the time-series data indicate that the mass under a stationary system may be completely reworked within a period of 2 to 4 years or less.

6.5. Depth of profile closure and coastal processes

Results from this study clarify the relationship between aspects of the profile closeout concept and coastal processes. Depth of closure ($D_c$) is a widely used coastal engineering concept that addresses the seaward limit of appreciable depth change along the shoreface (Hallermeier, 1978, 1981; Larson and Kraus, 1994; Nicholls et al., 1998). $D_c$ is used to infer a seaward limit to significant cross-shore transport and is thus of major importance to sediment budget studies, the design of beach-nearshore nourishment projects, and coastal evolution models. The concept is based upon the observation that repetitive beach-nearshore profiles show a decline in elevation variability over increasing depth, eventually reaching a depth beyond which elevation changes are small. For similar purposes, the seaward limit depth to the littoral zone ($d_l$) may be estimated using incident wave conditions (e.g., Nicholls et al., 1998). For any given locale, $D_c$ is not fixed and varies depending upon oceanographic climate (including storm-event
grouping), time scale of consideration, and superposition of long-term net advance or retreat of the shoreface system (Nicholls et al., 1998). Closure values can be determined in terms of the event scale, such as, closure resulting from a single storm event, and the cumulative time scale, which addresses net elevation change over the longer term.

Nicholls et al. (1998) considered closure events in terms of accretional and erosional cases. Accretional cases were classified on the basis of closeout occurrence associated with sequential onshore bar movement and inshore accretion. As demonstrated in this study, inshore accretion is associated with simultaneous erosion along the bar crest and seaward-facing bar flank or ramp. Thus, closure values for the accretional cases actually mark a landward-migrated limit of negligible elevation difference between two profiles associated with erosion surrounding, and seaward of, the accretional closure location.

Erosional cases were classified on the basis of closeout occurrence associated with sequential bar movement in the offshore direction and seaward deposition. Also demonstrated in this study is that erosion occurs along the trough of a seaward-displaced bar with simultaneous deposition along the bar and seaward-facing bar flank or ramp. Thus, closure values for the erosional case actually mark a seaward-migrated limit of negligible elevation difference between two profiles associated with deposition primarily landward of, and surrounding, the erosional closure location.

Using a depth-change criterion of \( \Delta h < 6 \) cm, Nicholls et al. (1998) calculated a total of 156 accretional and erosional event-closure values along lines 62 and 188 for the 12.4-year period. The relationship between closure values, limits of elevation change, and facies distribution along both profile lines is shown in Fig. 26. Other than for rare nearshore-wide dissipative events, when closure does not occur within survey limits, the group of closure values range between about 2 and 8 m water depth over distances of about 200 to 900 m from baseline (100 to 800 m from shoreline). This \( \approx 700\)-m-wide zone of depth change thus extends from potential inner bar-and-trough and upper-ramp settings out to relatively deep lower-ramp settings. The combined erosional and accretional closure locations occur as two groups, an inner group with a relatively wide elevation range and an outer group with a relatively narrow elevation range. The elevation ranges correspond to the general thickness of the profile envelope. Maximum and minimum elevation values for the closure events approach the upper and lower limits of elevation change indicating that the limits of elevation change also represent a maximum estimate of event-closure over the long term. Included in the 12.4-year envelope is the net shoreface buildup factor marked by over 40 cm of accretion at the seaward limit of measurement (Nicholls et al., 1998). Thus, the limits of elevation change over shorter time intervals, such as, between E0–E1, E1–E2, and E2–E3 in Figs. 22 and 25, serve to better indicate the range of closure by reducing the net buildup or erosion factor inherent in long-term surveys.

The boundary between the inner and outer closure groups occurs at about 4.5 m water depth and 400 to 450 m from baseline which corresponds closely to the morphologic break between the middle platform and lower ramp sectors of the profile and to the boundary between the trough-associated facies and the beginning of the lower ramp facies. Within the inner group, accretional closure values become dominant in the landward direction and in the upper half of the profile envelope. Within the outer group, erosional closure values become dominant in the seaward direction and almost solely existent beyond 600 m and 4 to 5 m depth. The facies evidence documents that the inner region is frequently dominated by longshore-current processes whereas the lower ramp region is dominated by shoaling wave processes. Larson and Kraus (1994) also report that at: (1) \( < 4.5 \) m depth, about 1% of all waves break (i.e., major storm waves); (2) \( \approx 4.5 \) m depth, elevation change through time becomes markedly greater; and (3) \( > 4.5 \) m, vertical accretion upon the lower ramp is a typical response to extreme storm events. The large elevation range at \( < \approx 4.5 \) m is due to trough scour and bar growth. Overall, the depth-distance factor of about 4.5 m and 400–450 m from baseline (300–350 m from shoreline) serves to indicate the average boundary between two major components of the nearshore morphodynamic and transport system. The dominance of accretional events in the upper-landward direction and erosional events in deeper seaward locations simply reflects end points in the spatial segregation of processes that cause maximum accretion in the shoreward and offshore directions.
In some cases, the vibracored shoreface prism contains a physical record of the conditions associated with closure events. Many closure values of the inner group plot in association with the trough-and-bar and upper ramp-middle platform facies groups. However, surveys over the 12.4-year period show that closure did not develop in association with trough-and-bar settings, but rather with upper ramp-middle platform or outer bar-lower ramp settings that temporarily developed in more landward locations. Conversely, closure values of the outer group were indeed associated with deposition of distal bar and lower ramp facies. Those facies therefore contain a physical record of the conditions associated with closure development. Accretional closure is represented by erosional bed contacts in cores located seaward of the accretional closure location whereas erosional closure is represented by depositional features.

The combined facies data and profile dynamics associated with closure events in the outer zone corroborate findings from Lee et al. (1998) and Nicholls et al. (1998) that erosional closure is associated with storm events and offshore transport and that accretional closure is associated with swell-dominated shoaling and onshore sediment transport. Of the inner- and outer-closure groups and the types of closure...
events, erosional closure in the lower ramp is of primary importance with regard to sediment budget considerations as it is associated with the offshore displacement of sand, most of which subsequently undergoes shoreward recovery (Nicholls et al., 1998). Sedimentologic data from this study further documents that buildup across the lower-ramp (an erosional closure event) is typically associated with storm-associated accretion along lower ramp surfaces under high-velocity (e.g., >80 cm/s) wave-dominated conditions. Unpublished seismic data from the FRF indicate that the modern shoreface prism generally pinches out between 9 and 12 m depth at the study site. Boxcore data from other studies at this site (Fiorina, 1993; Beavers, 1999) also document the continuation of lower ramp facies to those depths and a dominance of parallel laminated bedding. Based upon the near-parallel style of ramp-profile buildup, dominance of plane-parallel internal bedding, correlative ramp-buildup time series over very widespread areas (>1 km), and seaward-tapering facies geometry, it is evident that storm-associated ramp accretion occurs in a thin and very widespread manner extending much beyond erosional closure and survey capability of the CRAB (~9 m depth). Because of the direct relationship between plane-parallel bedding, shear stress, turbulence and transported load, the bed across the lower ramp must be highly active during major storm events with significant amounts of sediment in motion. Although orbital velocity alone is capable of producing plane-bed conditions across the lower ramp during storms, additional shear is commonly contributed by superimposed mean flows (e.g., Wright et al., 1991, 1994; Thornton et al., 1996; Beavers, 1999).

6.6. Textural distribution within the shoreface prism and cross-shore sediment transport

Data from this study provide a substantive basis for evaluating cross-shore transport in the nearshore zone. The shore-normal arrangement, close spacing, and penetration depth of vibracores along two profile lines allow for a three-dimensional consideration of sediment texture making up the shoreface mass as opposed to partially representative surface (e.g., grab) or near-surface (e.g., box core) samples. As discussed, the lower-limit age data indicate that essentially all of the shoreface mass is reworked on the decade scale with a major likelihood of reworking within any 2- to 4-year period. The physical structures within all of the facies, as well as fluid motion measurements from other studies (e.g., Beavers, 1999), document shear stress and turbulence conditions capable of entraining and transporting any sized nearshore particle during high-energy events. Consequently, the entire prism can be thought of as transported sediment load for the modern system. Important topics concerning cross-shore transport involve the spatial distribution of sediment size within the shoreface mass, sorting processes, transport direction and redistribution of mass.

The composite grain size distribution for the entire shoreface prism consists of a dominant subpopulation in the medium- to very fine-sand range and a minor subpopulation in the gravel to very coarse-sand range (Fig. 5). Fine-grained sand is ubiquitous and makes up the bulk of the shoreface mass. However, a distinct spatial trend in grain size occurs through the prism. The coarsest and most poorly sorted sediment, making up relatively thick gravel and medium- to coarse-sand beds, is concentrated at landwardmost locations in the swash, swash–trough transition, and basal inner-trough facies (Figs. 4, 5 and 11). Diminished amounts of relatively coarse material occur seaward, but are largely restricted to the trough-associated facies group (Figs. 5 and 11–14). Within this facies group, gravel and very coarse sand are relatively abundant in the inner-trough subfacies with seaward diminishing amounts of the coarse subpopulation and overall textural fining occurring through the middle-trough, outer-trough and distal bar subfacies. In spite of the relative abundance of coarse material in the trough-associated facies group, the trough-associated facies are dominated by the finer subpopulation that in itself exhibits seaward fining from medium- and fine-sand dominant in the inner-trough subfacies to fine-sand dominant in the outer-trough and distal bar subfacies. Farther seaward, almost the entire lower ramp (>99%) consists of unimodal, well sorted, seaward-fining fine to very fine sand. Although rare, seaward decreasing, thin (usually <1 cm), medium-sand- to granule-rich zones do occur within the lower-ramp vibracores, usually at <6 m depth and adjacent to the trough and distal bar subfacies. By
comparison, detailed time-series studies of the sediment–water interface document that very small amounts of medium-sand to small-pebble sized material can be deposited at locales along the lower ramp during extreme storm events (Stauble, 1992; Beavers, 1999). Continued seaward fining of fine- to very fine-sand extends beyond the limits of this study out to at least 2000 m from baseline and 14 m water depth (Fiorina, 1993, unpublished boxcore data). Wright et al. (1991), reports a change to a muddy fine-sand bed, with the fine sand bound in fecal pellets, at about 15 m depth. Similarly, regional geophysical, side scan, and vibracoring studies confirm that the lower ramp along the Outer Banks barrier system is restricted to depths landward of 15 m and consists of fine to very fine sand (Snyder, 1998, personal communication; Rice et al., 1998).

Although only small subsets of the entire shoreface mass are active at a single point in time, the combined textural and lower-limit elevation data document that the net product of both fair weather and storm transport has been size sorting of the entire mass with the coarsest of material concentrated at landwardmost locations and well-sorted fine to very fine sand at seawardmost locations. Similar textural trends and facies associations within the previously vibracored shoreface prism at this study site (Schwartz, unpublished 1981 ASEX experiment) and along Topsail Island, NC (Schwartz et al., 1981) attest to the existence of fundamental cross-shore sorting processes in low- to moderate-energy wave-dominated shoreface settings. The near restriction of medium sand and coarser material to beach and trough-associated facies reflects a tendency for confinement of such sized material within this inner zone even during major storm events when significant amounts of fine sand are displaced seaward and deposited upon the lower ramp (this study and Beavers, 1999). Supporting evidence for seaward storm displacement of coarse material being largely restricted to <4-m depth at this study site, and in association with seaward bar-and-trough displacement, is provided by Stauble and Cialone (1996). Local sources of coarse material do occur immediately below the erosional lower boundary of the modern shoreface prism at this site and the Topsail Island site (Schwartz et al., 1981). However, erosional and depositional features within the shoreface prism at both sites substantiate that the underlying coarse material is exhumed and effectively transported rather than simply remain in situ as a lag concentrate. That medium to very coarse sand can be selectively transported landward from outer parts of a nearshore zone and retained within the surf zone over short (non-storm) to long (mixed storm and fair weather) time scales has been documented in nearshore tracer (Ingle, 1966; Judge, 1975, pp. 34–36) and sediment disposal studies (Vera-Cruz, 1972; Mikkelsen, 1977; Schwartz et al., 1981, pp. 285–286; Schwartz and Musialowski, 1977, 1980).

Overall, the textural distribution of the shoreface mass is a product of size-dependent sorting processes associated with cross-shore sediment transport. With regard to beach nourishment, the relative shore-normal retention of placed sand may be somewhat predictable by considering the grain size distribution of placed material relative to textural distribution throughout the shoreface mass. The major abundance of coarse to medium sand in shorewardmost parts of the shoreface mass indicates that similar-sized placed material would be retained in beach and inner trough settings for the greatest amount of time. In spite of some coarse material being displaced seaward in storm-widened surf zones, the strong landward concentration within the prism also indicates net landward return. Placement of fine sand upon, or immediately adjacent to, the beach would result in relatively rapid and major losses of beach fill toward middle profile and lower ramp settings where it is of greatest natural abundance and where storm buildup of fine to very fine sand is typical. Evidence from this study indicates that fine sand transported onto the outer profile will be returned shoreward at very slow rates during fair weather with long-term cross-shore adjustment depending upon storm-event frequency and magnitude. As is well established, longshore transport is intrinsic to the surf zone or, in terms of this study, to settings landward of the morphologic break between the middle platform and lower ramp sectors of the profile, the boundary between the trough-associated and lower ramp facies groups, and $D_c \approx 4.5$ m (at 300–350 m from shoreline). Consequently, net shore-parallel loss of nourishment material along this inner zone is relatively large.
7. Conclusions

The combination of detailed facies, time-series elevation, and profile-shape data served as a means of linking sedimentological properties of the shoreface prism to nearshore processes, age and history of development. The integrated data sets also provide significant insight concerning topics of engineering interest including the envelope of profile change, temporal and spatial aspects of erosion and deposition, conditions associated with profile closure, and cross-shore sediment transport. Overall, the geologic information provides a framework and constraints for engineering concepts based solely upon physical principles or quantitative aspects of profile change. More salient findings of this study pertaining to shoreface dynamics and engineering interests are summarized below.

7.1. Morphodynamics, erosion, and deposition

Longshore trough and bar development is a product of simultaneous storm current-dominated scour and deposition, respectively, along longshore parallel tracts within the surf zone. Thornton et al. (1996) provide supporting fluid-motion evidence that linear bar and trough formation is associated with strong longshore currents during times of storm waves. Longshore troughs develop in one or multiple locations landward of the lower ramp. In general, the zone within which significant trough scour can occur is between 250 and 300 m wide and extends from the beach foreshore to about 5.5 m water depth (Fig. 27). The outermost longshore bar and conjoining lower-ramp facies are typically deposited upon a fair weather-related erosional ramp surface. Trough scour and concomitant distal bar-lower ramp buildup are temporarily offset from lower ramp erosion and inshore accretion. The seaward limit of the trough-associated facies also corresponds to the break-in-slope between the middle platform and lower ramp, thus indicating a dependency between profile morphology and longshore current-dominated processes. Erosion in the lower ramp zone is usually associated with lower energy or fair-weather conditions during which waves

![Diagram](image_url)

Fig. 27. Schematic diagram summarizing morphology of the shoreface, preserved erosional surfaces, cross-shore transport between the inner profile and lower ramp, and properties associated with the boundary between the wave-dominated lower ramp and longshore-current influenced inner shoreface. Asterisks indicate data from Larson and Kraus (1994).
move fine sand to landward parts of the shoreface. A rare exception can occur during extreme storm events as evidenced by the 1991 Halloween event when surf zone conditions extended across the entire lower ramp causing lower ramp erosion. Similar relationships between profile morphodynamics and trough-associated versus lower-ramp facies have been documented for the Topsail Island shoreface in southern North Carolina (Schwartz et al., 1981) indicating a fundamental behavior for wave-dominated marine shoreface systems.

7.2. Limit shapes

Actual beach-nearshore profiles can never fully coincide with either the upper limit of accretion or lower limit of erosion. Although segments of an extant profile may coincide with segments of the upper or lower limit of profile change, other segments of the extant profile necessarily occur in opposite directions and sometimes coincide with the opposing limit. Fundamental to this is the nature of coastal processes whereby erosion in one sector is linked to accretion in an adjacent sector, not allowing for pervasive buildup or erosion toward limiting values. Therefore, in addition to the use of envelopes for volume calculation or project design, a perspective of interdependent zonal buildup and erosion across the shoreface must be maintained.

7.3. Profile closure

Data from this study clarify the link between the profile closure concept and coastal processes. The upper and lower limits of elevation change mark the limits of event-closure occurrence over the long term. At the study site, a closure value \( \Delta \) of about 4.5 m water depth at 300 to 350 m from shoreline marks the boundary between middle profile- and lower ramp-associated closure groups, the boundary between trough-associated and lower ramp facies, and the lower ramp morphologic break, all of which correspond to the juncture between longshore-current and shoaling wave dominated zones (Fig. 27). During storms, fine to very fine sand accretes in a thin, widespread, seaward-tapering manner along the lower ramp, much beyond calculated closure locations.

7.4. Cross-shore transport

The entire shoreface prism can be thought of as a relatively short term (~2–10-year scale) composite of transported load. The combined textural, facies and morphodynamic data indicate an inner and outer domain for the shoreface transport system. Medium sand and coarser material are largely restricted to the beach and trough-associated facies whereas fine sand, although mixed throughout the prism, dominates with very fine sand in the lower ramp system. Thus, the net product of both fair weather and storm processes has been size sorting across the shoreface. During fair weather periods, the lower ramp typically subelevates as sand slowly undergoes net shoreward transport. During major storms, fine to very fine sand is displaced seaward onto the lower ramp in spite of velocity conditions capable of entraining and transporting coarser material. There is no evidence for significant amounts of material coarser than fine sand being lost seaward to, or beyond, the lower ramp zone. By contrast, the near restriction of medium sand and coarser material to the beach and trough-associated zones indicate net shoreward transport of coarser material acted upon by lower ramp-associated processes. With regard to beach nourishment, coarse- to medium-sand fill would be selectively transported into, and preferentially retained within, beach and inner trough settings whereas fine sand fill would undergo relatively rapid and major losses toward middle profile and lower ramp settings during major storm events. Because longshore transport is intrinsic to the surf zone, net shore-parallel loss of any sized fill material is comparatively large along the inner profile.

Acknowledgements

This study represents a collaboration between the Department of Geology at Allegheny College and the Field Research Facility (FRF) of the US Army Engineer Research and Development Center’s Coastal and Hydraulics Laboratory (CHL). Funding was provided by the CHL Coastal Sedimentation and Dredging Program under the Geologic Analysis of Shelf/Beach Sediment Exchange work unit (Contracts DACW39-93-009 and DACW39-98-M-0381). The data used for this study resulted from the combined
efforts of the dedicated staff of the Field Research Facility, Allegheny College participants, in particular, D. Cooper, P. Etheridge, B. Henderson, and C. Rankin, and, especially, J. B. Smith (Dewberry and Davis; formerly of CHL) who served as the CHL co-supervisor and contract monitor. Permission was granted by the Chief of Engineers to publish this information.

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