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Sedimentologic Architecture of the Shoreface Prism, Relationship to Profile Dynamics, and Relevance to Engineering Concerns: Duck, North Carolina

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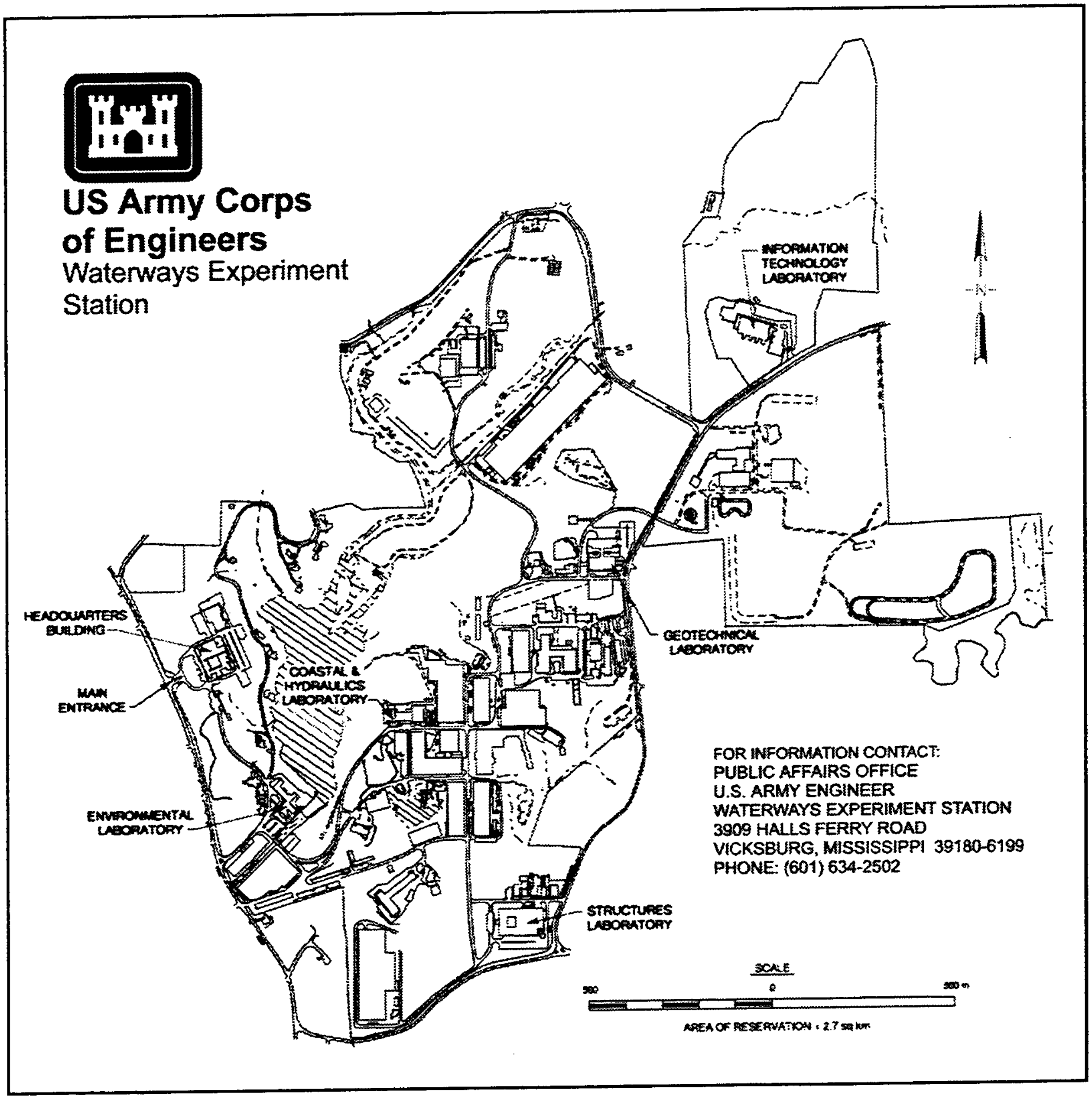

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Preface

The investigation summarized in this report was conducted by the U.S. Army Engineer Waterways Experiment Station's (WES's) Coastal and Hydraulics Laboratory (CHL) and was selected for study and funded by the Coastal Sedimentation and Dredging Program. The Program Manager is Ms. Carolyn Holmes, CHL. This program is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). The HQUSACE Technical Monitors are Messrs. John H. Lockhart, Charles Chesnutt, and Barry W. Holliday.

Work was performed under the general supervision of Mr. William A. Birkemeier, Chief, Field Research Facility (FRF), CHL; Mr. Thomas W. Richardson, Chief, Engineering Development Division, CHL; Mr. Charles C. Calhoun, Assistant Director, CHL; and Dr. James R. Houston, Director, CHL.

The report was prepared by Dr. Robert K. Schwartz, and Messrs. Derek W. Cooper and Paul H. Etheridge of Allegheny College Department of Geology, Meadville, PA. Vibracore data presented in this report were collected as part of a cooperative experiment conducted by Allegheny College and CHL, at the barrier island shoreface at the FRF at Duck, NC. Funding for this research was provided by CHL (Contract DACW39-93-009, "Vibracoring Shoreface Experiment to Determine Internal Architecture of the Shoreface Sedimentary Prism and Its Relationship to Profile Dynamics").

The vibracores used in this study were collected through the efforts of many individuals, including Messrs. Cooper, Etheridge, William Henderson, Guan-hong Lee, Craig Rankin, and J. Bailey Smith, and Dr. Schwartz. Technical and logistical support at the FRF was generously provided by Messrs. Eugene W. Bichner, Brian Scarborough, and Charles R. Townsend. Mr. Birkemeier, Chief, FRF, provided supervisory and technical support, as well as much-appreciated advice concerning field operations. Subsequent laboratory analyses were conducted at Allegheny College by Messrs. Cooper and Etheridge, and Dr. Schwartz. Beach and nearshore survey data, as well as software needs, for documenting profile dynamics at the FRF site were provided by CHL through the courtesy of Mr. Birkemeier.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin.

1 Introduction

Background and Purpose

This report examines of the relationship between subsurface sediment distribution, profile dynamics, and nearshore processes. Coastal engineers involved with the design of hard structures and the placement of sand for beach nourishment purposes necessarily make certain assumptions and utilize concepts involving profile shape (e.g., equilibrium-profile and nearshore profile closure) and sediment transfer (e.g., onshore-offshore transport). However, much is still unknown concerning the actual nature of bed conditions and sediment transport across the shoreface, especially as it relates to the geometry-based concepts of erosional lower limits, profile closeout, and profile equilibrium. Related to this is the question involving grain size and the amount of sand transported offshore beyond the depth of profile closure during major storm events. In addition, much is still unknown concerning bar morphodynamics, associated fluid processes, and sediment transfer within the nearshore. Study of the internal physical properties of the nearshore zone can provide new and significant information concerning the above topics.

Hydrodynamic processes and physical sedimentologic properties are strongly related. A systematic variation in physical attributes both at the sediment-water interface and in the subsurface occurs across the shoreface zone. These attributes, such as, profile morphology, textural trends, bedforms and internal structures, and biogenic structural patterns, represent the temporal and spatial distribution of various hydrodynamic conditions. Because of the cause-and-effect relationships, preserved subsurface properties of the system (e.g., sedimentary texture and internal physical sedimentary structures) serve as an indicator of unmeasurable or unobservable fluid processes and past bedform or bar-form elements (e.g., storm bar and trough). In relation to this, the transport of sediment is accompanied by fluid shear and deformation of the sediment-water interface. It is well established that bed geometry, or bedforms, exhibit regular variations in response to differences in flow conditions and sediment size (for example: Allen, 1984; Clifton, 1976; Clifton and Dingler, 1984; Harms et al., 1982; and Rubin, 1987). Specific physical sedimentary structures develop internal to these bedforms as a result of bedform migration and bed accretion. Preserved physical structures, and the associated textural properties, can thus be used to provide information about preexisting bed conditions and the temporal-spatial distribution of those conditions.

Because of the above, it is possible to establish the relationship between sedimentary facies (that is, a spatial assemblage of sedimentary structures, texture, and composition) and past hydrodynamic conditions which operated at various locales along the profile. More specifically, internal sedimentary structure and textural data can provide:

a. Information about preexisting bed conditions.

b. A cross-sectional "map" of the subsurface, indicating temporal and spatial shifts in energy level and profile shape.

c. In some cases, a record of the direction of sediment transport.

Vibracores which penetrate the shoreface sedimentary prism can thus afford a historical record of nearshore dynamics. In context of the above, the purpose of this study is to provide the following:

a. Baseline subsurface sedimentologic data for the Duck shoreface prism.

b. Cross-sectional maps of facies distribution.

c. A comparison between facies distribution and temporal-spatial variations in profile shape.

d. A comparison between the lower limit of surveyed elevation change (Birkemeier 1984) and the lower sedimentologic boundary of the modern marine shoreface prism.

Previous Work and Related Studies

Bedforms and internal structures have been studied from a wide range of depositional environments. An extensive body of literature exists for field, laboratory, and theoretical studies concerning bedforms and sedimentary structures generated by unidirectional currents. However, there are comparatively few studies concerning bedforms and sedimentary structures produced under oscillatory or combined flow conditions, such as in shoreface systems. Similarly, detailed sedimentologic studies of modern nearshore systems are relatively few. Most have been directed towards facies characterization with hydrodynamic interpretation based upon position along the profile and upon sedimentary structures (for example, Clifton, Hunter, and Phillips et al. 1971; Davidson-Arnott and Greenwood 1976; Hunter, Clifton, and Phillips 1979; Howard and Reineck 1981; Shipp 1984; Short 1984). Even fewer studies relate bed configuration 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 (Sherman and Greenwood 1985). Equally rare are studies which examine fluid and sediment motion relative to barred-profile morphology during events (storms) for which the bed was highly active (Davidson-Arnott and Randall 1984; Greenwood and Sherman 1984; Greenwood and Mittler 1984; Schwartz and Teleki, in preparation). Rarest of all are vibracore studies of the shoreface zone where details of subsurface facies were related to profile dynamics and nearshore processes. Such vibracore studies were conducted at the following locations:

a. Kouchibouguac Bay, New Brunswick, Canada (Greenwood and Mittler 1984).

b. Topsail Island, NC (Hobson, Schwartz, and Musialowski 1980; Schwartz 1981a; Schwartz and Musialowski 1977, 1980; Schwartz, Hobson, and Musialowski 1981).

c. The Outer Banks, Duck, NC[1] (Nichols 1982; Schmittle 1982; Schweitzer 1982; Swanson 1982).

Vibracores in the 1978-79 Topsail Island and 1981 Outer Banks experiments were collected at close spacing along shore-normal transects to near-closeout depth. In addition, both experiments were conducted in the context of a profile-shape monitoring program. Both studies, from diverse coastal settings, indicated that vibracore data are well-suited to addressing concepts pertinent to coastal engineering concerns. Findings from the two experiments provided a basis for the design of the 1993 Outer Banks experiment (this study). Some of the earlier findings pertinent to this study include:

a. A correspondence between shifts in profile shape, associated nearshore processes (type and intensity), and the subsurface distribution of facies (physical structures and texture) (Schmittle 1982; Schwartz 1981b; Schwartz, Hobson, and Musialowski 1981).

b. For the Topsail shoreface, a similarity in shape and position of the erosional lower sedimentologic boundary of the shoreface prism and the lower limit of surveyed elevation change (Schwartz, Hobson, and Musialowski 1981).

c. A general correspondence between the depth of profile closure, effective limit depth for fair-weather transport, and systematic changes in the abundance of disruptive bioturbation fabric (Schwartz 1981a; Swanson 1982; Fiorina 1993).

d. A temporal association between middle-profile scour and corresponding seaward (lower-ramp) buildup during high-energy events (Nichols 1982; Schwartz, Hobson, and Musialowski 1981).

[1]Unpublished ASEX Experiment conducted by R.K. Schwartz and R. Hobson, Allegheny College, Dept. Of Geology, Meadville, PA.

e. A prevalence of storm deposits and high-energy sedimentary structures in the subsurface, particularly below the lower-ramp profile sector where low-energy bed conditions are temporally dominant (Schweitzer 1982; Schwartz 1981b; Schwartz, Hobson, and Musialowski 1981).

f. The dominance of high-energy fine-grained storm deposits near the depths of profile closure and effective limit of surf-related transport (Fiorina 1993; Schwartz, Hobson, and Musialowski 1981; Schwartz 1981 a and b) .

g. Net onshore transport of relatively coarse sediment (medium sand to gravel) over a 1-year period (Schwartz and Musialowski 1977, 1980; Schwartz 1981a) .

Physical Setting

This study, the Duck Shoreface Experiment (DSEX), was conducted during July 1993 at the Field Research Facility (FRF) of the Coastal and Hydraulics Laboratory (formerly the Coastal Engineering Research Center), U.S. Army Corps of Engineers (Figure 1) . The FRF is located near the middle of Currituck Spit along a 100-km unbroken stretch of shoreline. The "spit" is a transgressive mesotidal barrier island, approximately 800 m wide at the study site, bordered by Currituck Sound on the west. The area has a relatively straight, simple nearshore bathymetry, so that long-term profile change can realistically be considered in a two-dimensional manner (Lee and Birkemeier 1993). The shoreface consists primarily of quartz sand, with a secondary component of rock-fragment and shell gravel (Meisburger and Judge 1989). 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 sites (Birkemeier et al. 1985; Fisher 1977).

Wave energy is moderate to high, typically being higher in the winter and lower in the spring and summer. Average annual significant wave height is 1.0 m, with a standard deviation of 0.6 m, and a mean peak spectral wave period of 8.3 sec (Leffler et al. 1992). Tides at the study area are semidiurnal, with a mean range of about 1 m. Although profile shape may range from practically nonbarred to double-barred, the most common profile configuration is single-barred (Birkemeier 1984; Birkemeier et al. 1985). The zone of most active elevation change extends from the base of the beach foredune to about the 6-m water depth (Birkemeier 1985; Birkemeier et al. 1985).

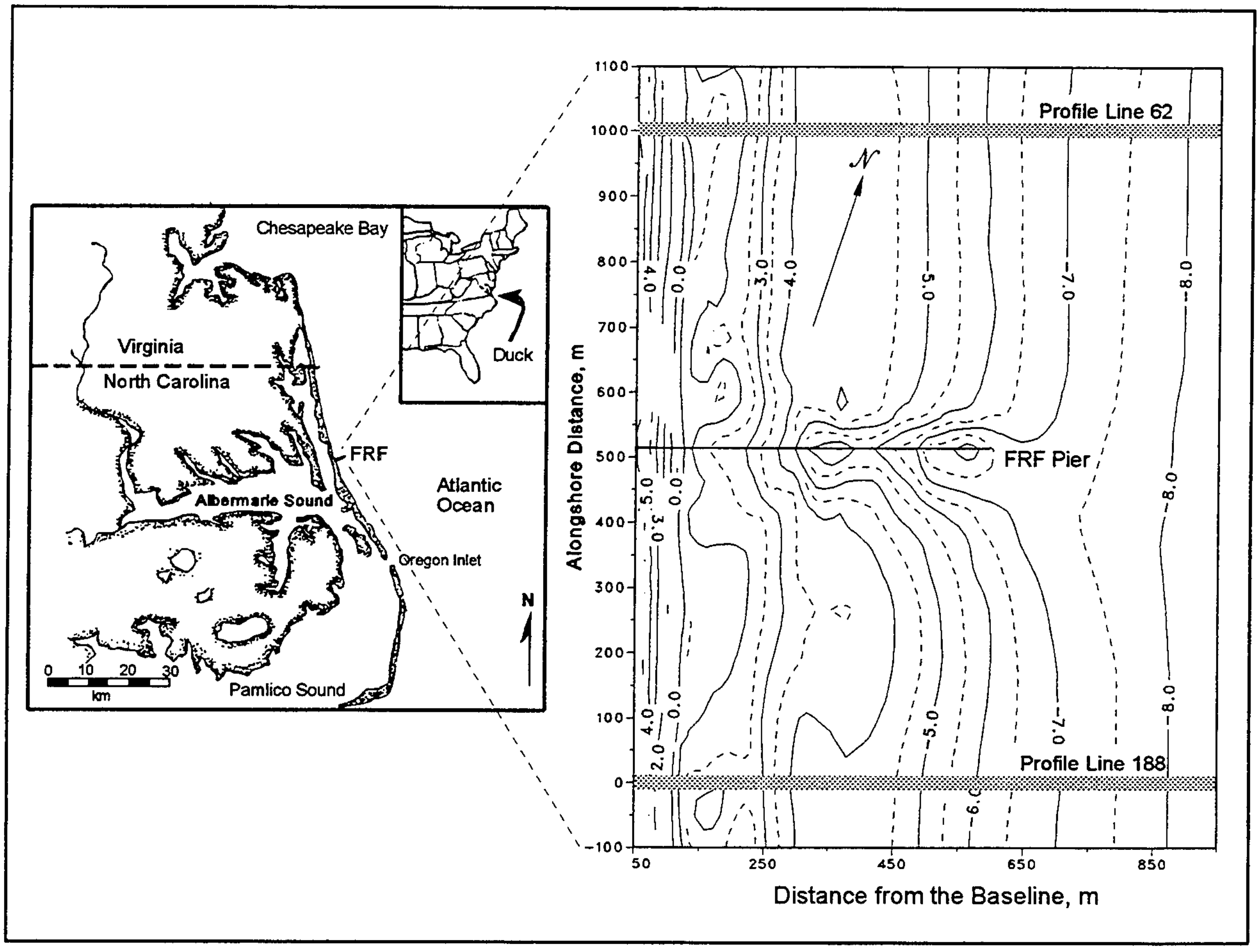

Figure 1. Location map of the study area and profile lines 62 and 188

2 Methods

Vibracore Collection and Profile Surveys

A portable vibracoring system (Lanesky et al. 1979; Thompson et al. 1991) was mounted atop the Coastal Research Amphibious Buggy (CRAB) (Birkemeier and Mason 1984) and used to obtain 49 oriented cores from the barrier island shoreface out to water depths of about 8.4 m. Vibracores were collected at relatively close spacing along two shore-normal transects, survey line 62, approximately 475 m north of the FRF pier, and survey line 188, approximately 525 m south of the pier (Figure 1). The survey lines are located near the northern and southern perimeter of the FRF research area and are beyond significant influence of the more centrally located research pier. In order to document profile shape and bathymetric change during the experiment, and thus ensure accurate positioning of vibracores, the lines were surveyed intermittently using the CRAB and a Geodimeter 140T auto-tracking survey system(Lee and Birkemeier 1993). The distance accuracy of the Geodimeter is ±10 mm in the tracking mode and angle accuracy is ±3, sec yielding a vertical accuracy of ±3.0 cm at 1,000 m. High-resolution nearshore profiles have been measured along both ranges since 1981 (Howd and Birkemeier 1987; Lee and Birkemeier 1993), thus providing extensive time-series data for comparing morphologic and bathymetric change with the subsurface sedimentologic record.

Vibracore spacing was based upon data for profile morphodynamics (Birkemeier 1984; Lee and Birkemeier 1993) and results from the 1981 ASEX vibracoring experiment. Thirty-two vibracores were obtained along line 188 at an average spacing of about 28 m (Figure 2). Vibracores were closely spaced in order to accomplish the following:

a. Provide a detailed record of subsurface sedimentologic change across the shoreface prism.

b. Allow for detailed comparisons between the distribution of subsurface sediment and changes in profile shape along line 188 since 1981.

c. Allow for eventual comparison with similar-spaced vibracores from the 1981 ASEX experiment.

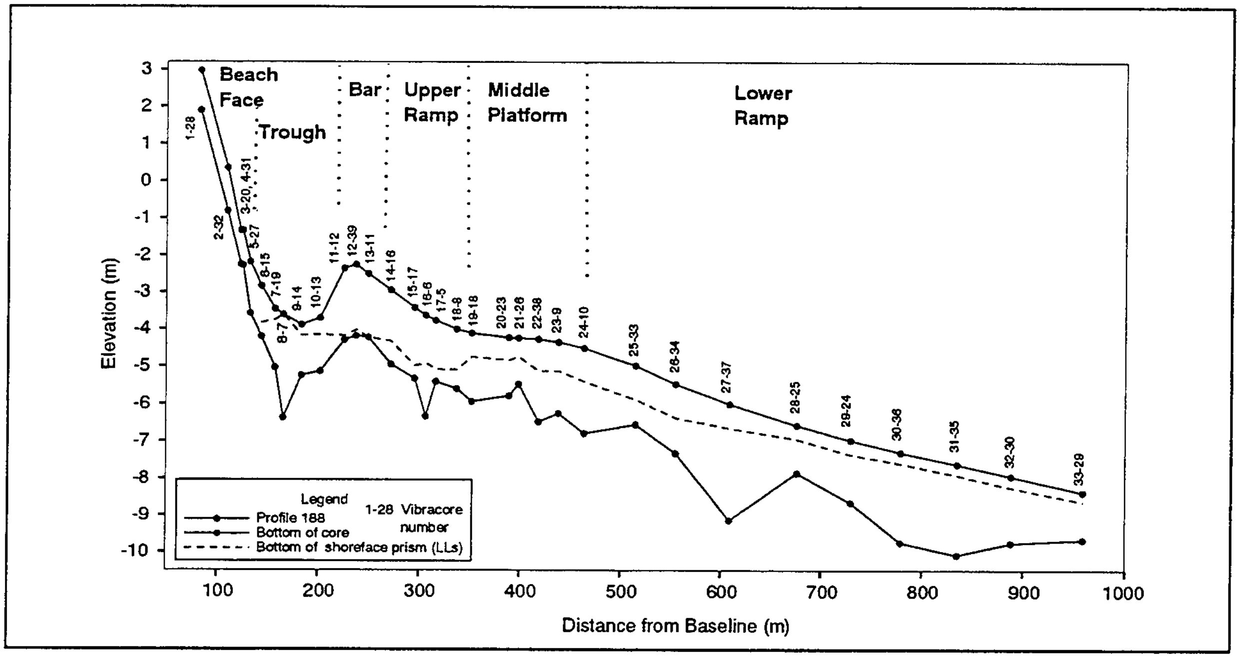

Figure 2. Shape of the cored profile along line 188 showing profile terminology, vibracore location, and depth of vibracore penetration

The ASEX vibracores documented a high degree of sedimentologic change across the inner and middle profile, in the region of shore-normal migrating bar-and-trough systems. Because of this, vibracores in this study were collected at about 17 m spacing along the inner profile and middle profile compared to about 55 m spacing along the outer profile where lateral subsurface change is less marked.

Due to time constraints, 16 vibracores were obtained along line 62 with spacings of 25 - 50 m along the upper profile and 100 m along the outer profile (Figure 3). Average spacing for cores along the entire profile was about 50 m.

Vibracore Processing and Data Collection

A longitudinal plexiglass-bound slab of sediment, ~7.6 cm wide x ~1.3 cm thick, was prepared from the center of each sediment column (Figure 4). The slabs were oriented to provide a shore-normal view of the sedimentary sequence. The slabs were x-rayed with a Pickering x-ray field unit operated at settings of 6 sec for 60 kV, and 45 mA at a distance of 46 cm from the x-ray source. Each core-slab was then described and photographed, providing an initial record of original color, texture, and sedimentary structure. Epoxy peels were prepared from the longitudinal slabs.

In the lab, grain size, internal physical structure, biogenic structure, and color were logged continuously along each epoxy core. Average sand size was visually

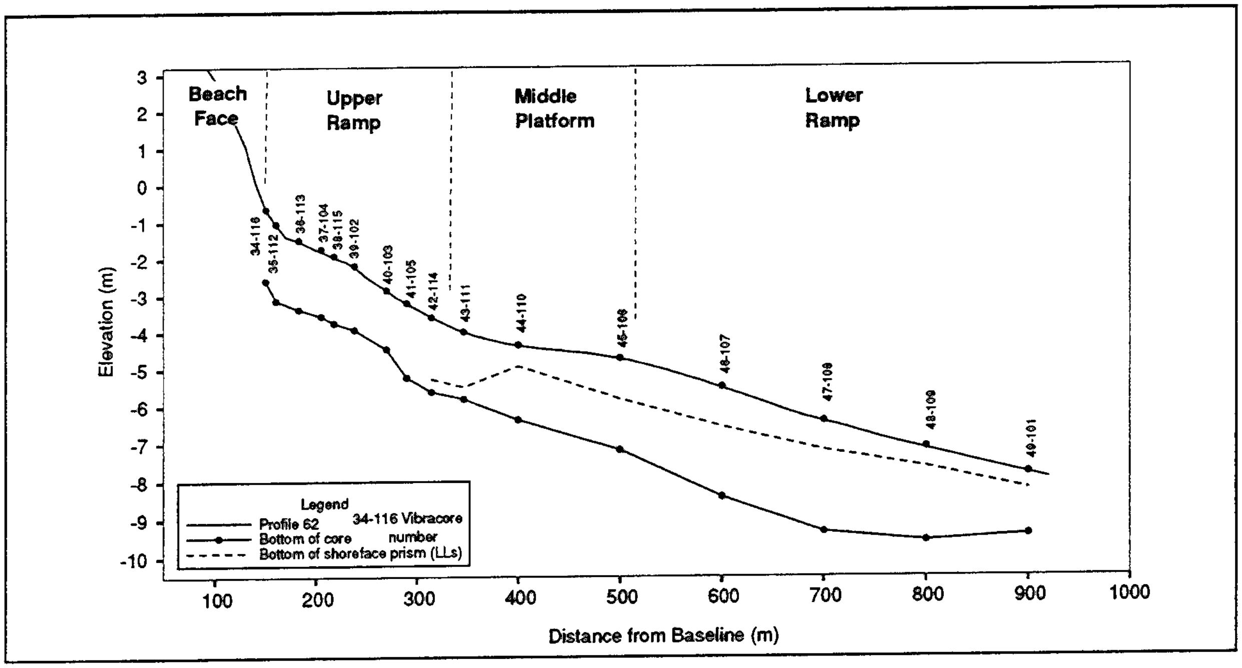

Figure 3. Shape of the cored profile along line 62 showing profile terminology, vibracore location, and depth of vibracore penetration

estimated to about one-quarter phi resolution by means of an AMSTRAT visual estimation card (Canadian-American Stratigraphic, Denver, CO). Gravel classification was based upon gravel abundance: beds with 30-90 percent gravel were classified as a sandy gravel and those with 5-30 percent gravel were classified gravelly sand. Physical sedimentary structures were classified in a manner that relates set thickness and geometry to size and cross-sectional views of two-dimensional versus three-dimensional bedforms (Table 1). The types of internal physical structures and related bedforms listed in Table 1 are based upon extensive boxcore data and, in most cases, direct observation of bedforms from previous experiments in the same study area. Although several types of medium-scale cross-stratification are evident in the boxcores, the narrow width (<7.6 cm) of vibracore sections greatly increases the likelihood that medium-scale cross-stratification will appear simply as tabular cross-stratification or low-angle parallel lamination. The relative degree of bioturbation which may disrupt, or overprint, physical structures was assigned to four categories:

a. Heavily bioturbated - greater than 70 percent overprinting by bioturbation.

b. Moderately bioturbated - approximately 40- to 70-percent overprinting.

c. Slightly bioturbated - 10- to 40-percent overprinting.

d. Non-bioturbated - < 10-percent overprinting (Fiorina 1993).

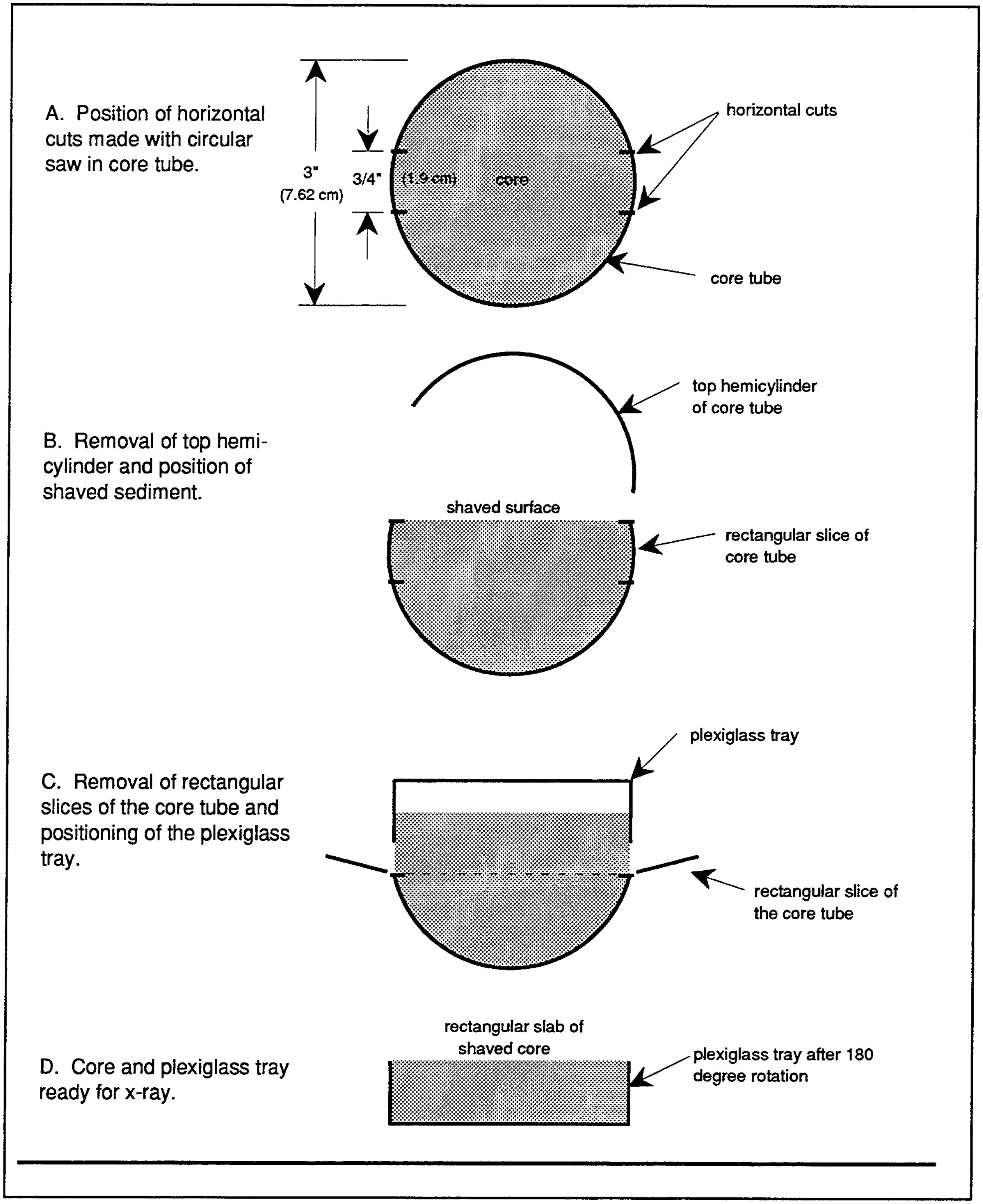

Figure 4. Schematic cross section illustrating core removal process

Table 1
Classification of Physical Sedimentary Structures and Interpretation of Associated Bedforms

<table>
<tr><th colspan="3">Internal Structure</th><th>Bedform</th></tr>
<tr><td colspan="3">Horizontal Parallel Lamination (HL[1])
(includes subhorizontal or very low angle lamination indistinguishable from HL in core)</td><td>Plane bed on horizontal to very low-angle surface (e.g., <3 degrees)</td></tr>
<tr><td rowspan="3">Small-Scale Cross-Stratification</td><td colspan="2">Trough (SSTR[1])</td><td>Small three-dimensional ripple</td></tr>
<tr><td colspan="2">tabular foreset (SSTA[1]) — planar / sigmoidal / tangential</td><td>1)[2] Longitudinal or oblique section of three-dimensional cross-stratification produced by three-dimensional ripple.
2) Asymmetric two-dimensional ripple.</td></tr>
<tr><td colspan="2">Wave-ripple (Wr[1])
1) Some combination of:
- irregular lower set boundary.
- unidirectional or bidirectional sets.
- lenticular set.
- upbuilding of truncated sets.
- asymmetric foreset aggradation.
2) - upbuilding of chevron sets.</td><td>1) Asymmetric wave ripple
2) Symmetric wave ripple.</td></tr>
<tr><td rowspan="4">Medium- and Large-Scale Cross-Stratification</td><td colspan="2">Trough (LSCS[1])</td><td>Three-dimensional ripple (megaripple).</td></tr>
<tr><td colspan="2">tabular foreset (LSCS[1]) — planar / sigmoidal / tangential</td><td>Longitudinal, oblique, or transverse section of three-dimensional cross-stratification produced by three-dimensional ripple.</td></tr>
<tr><td rowspan="2">Low-angle parallel laminae (<10 degrees)</td><td>Landward dipping and seaward dipping (LAPL[1])</td><td>Plane bed on low-angle surface (e.g., bar flank or stoss slope of large ripple).</td></tr>
<tr><td>Coset; subhorizontal and concave or convex set boundaries; variable dip directions</td><td>Hummocky bed.</td></tr>
</table>

[1] Abbreviation used. Medium- to- large-scale trough cross-stratification usually appears as tabular cross-stratification in the narrow core sections. Both types are collectively grouped as large-scale cross-stratification, LSCS.
[2] Most likely bedform.

Sediment color was determined both from freshly split cores and the epoxy peels. Color was subdivided into two basic categories: variations of yellow and variations of gray. Vertical sequences of sedimentologic data from the vibracores were computer drafted at 1-cm resolution (Appendix A). The high-resolution plots constitute a baseline data set for the study area.

Architectural Analysis of Sedimentologic Data

A hierarchical approach was used to analyze the sedimentologic data. Various levels, or groupings, of data yield different scales of information on internal makeup of the shoreface and, thus, on different scales of coastal processes. The data were treated on three levels: third-order elements - properties of individual beds, second-order elements - properties of bed sequences, and first-order elements - facies and composite textural sequences.

Third-order elements - single beds

A sedimentary bed, including details of its internal sedimentology, may be considered as a basic building block in stratigraphic sequences. A bed commonly represents a single type of depositional event, with the layer, or "bed," resulting from net accretion upon an underlying surface. The dynamic upper surface of an evolving bed may be planar or nonplanar (e.g., rippled). However, the upper surface, or contact, of a bed may not simply represent an accretion event - for example, an upper contact may represent the case where accretion is followed by erosion, resulting in the removal of original bed material or "bed condensation." This is pertinent to results of this study involving the occurrence of erosional surfaces and their correlation within vibracored sequences. Also, in some cases what appears to be a single bed may actually be a composite of beds with nonrecognizable boundaries and similar internal properties. Such cases commonly result from postdepositional biogenic reworking and disruption of sediment fabric. The approach in this study was to identify and categorize types of clearly individual beds so as to optimize interpretations.

Second-order elements - bed sequences

A second-order grouping consists of two or more beds which sequentially make up an upward fining or upward coarsening trend or a systematic upward change in physical structure. Second-order trends represent spatial and temporal scales of events typically greater than, but sometimes similar to, that of a single bed. The lateral migration of a bedform (e.g., large ripple) or segment of a profile (e.g., bar flank), along which texture and geometry of the bed significantly vary, can result in sediment buildup and superposition of beds to make up a sequence. The repetitive migration of bedforms or a profile segment, such as a bar flank, across a given location may also result in the superposition of sequences. In either case, a second-order sequence represents a sequential change of environmental significance.

First-order elements - facies groups and composite textural sequences

Two types of first-order features are designated in this study, facies and composite textural sequences. Each of the first-order categories are made up of second- and third-order elements.

Facies groups contain assemblages of individual bedding types and bed sequences that characterize particular environments within the nearshore zone, such as the trough, bar crest-upper ramp, and lower ramp environments. Mapping the spatial distribution of subsurface facies is a means by which the geohistorical location of various environments and associated processes can be identified. In cross section, the plotted limits or boundaries of a single facies constitute a map of shifts in the location of a particular environment during the studied portion of shoreface history. Each mapped zone represents a locus of numerous depositional and erosional events for a particular type of setting, or environment, along historical profiles.

Composite first-order textural sequences are upward-fining or upward-coarsening trends which are larger in scale than those which characterize individual beds or second-order sequences. A first-order trend may contain non-graded beds and smaller-scale textural trends of a similar or opposite nature, such as a mixture of normal and inverse. A first-order trend may occur within a particular facies or extend through the facies into an adjacent facies. A lateral trend reflects the textural gradient across historical profile segments (e.g., from swash zone to trough or down the lower ramp). A vertical trend represents buildup and net change in environmental conditions resulting from the lateral shifting and aggradation of adjacent profile segments. A first-order textural trend thus represents longer term environmental (morphologic and textural) shifts in the nearshore system.

3 Profile Shape and Terminology

At the time of the experiment, the nearshore zone in the vicinity of profile line 188 contained a single well-developed longitudinal bar and trough along the inner profile (Figure 2). By contrast, the nearshore zone around line 62 was "minimally barred" (Birkemeier 1984) and is referred to in this report as non-barred (Figure 3). The shapes represent two modes of occurrence in a set of various shapes (Birkemeier 1984) which can develop along this coastal sector. The nonbarred inner segment of profile 62 represents a profile state whereby a trough form similar to that of profile line 188 has been filled and the associated bar form eliminated. The middle to outer segments of both profile 62 and 188 had similar geometries. Other profile shapes which have historically occurred along the two profiles principally involve the presence of single or multiple trough-and-bar elements in middle parts of the profiles (Birkemeier 1984). Because depositional and erosional features discussed in this report show a spatial relationship to existent and historical morphological elements of the profiles, the presentation of data is facilitated by making reference to various morphological zones.

Terminology used for morphologic zones of barred profile 188 are: *beach face, low-tide terrace, trough, bar, upper ramp, middle platform,* and *lower ramp* (Figure 3). Of those features, just *upper ramp, middle platform,* and *lower platform* pertain to the nonbarred morphology of profile 62 (Figure 4). The less familiar terms, low-tide terrace, upper ramp, middle platform, and lower ramp, are defined below. In many cases, it is important to discuss subsurface sedimentology in terms of historically seaward trough-and-bar locations. The terms *inner trough* and *inner bar* are used to indicate inner-profile positions such as those in profile 188, and the terms *outer trough* and *outer bar* are used to indicate locations along the upper ramp or middle platform.

a. *Low-tide terrace.* A relatively low-angle seaward-dipping to subhorizontal planar surface located between the more steeply dipping swash zone and an inner trough. This zone is dominated by swash processes at low tide and by surf-zone wave and current processes at high tide.

b. *Upper ramp.* A seaward-inclined slightly convex to slightly concave surface which merges with the crest of an inner bar or, under nonbarred conditions, extends to the swash zone or low-tide terrace. The zone is dominated by final wave shoaling and wave breaking during fair weather and by high-energy inner surf-zone conditions during storm events.

c. *Middle platform.* A subhorizontal planar to slightly concave surface adjacent to, and seaward of, the upper ramp. The middle platform marks the outermost zone of bar and trough development. The zone is dominated by wave shoaling during fair weather and high-energy surf conditions during extreme events.

d. *Lower ramp.* A seaward-inclined planar to slightly concave surface adjacent to, and seaward of, the middle platform. A slightly convex shape occurs at the middle platform-lower ramp juncture near the location of ephemeral outermost (storm) bars. Wave shoaling processes are dominant, although dissipative surf conditions extend across the zone during extreme storm events.

4 Lower Limit to Modern Shoreface Prism and Buried Tidal Facies

Background and Definition of Sedimentologic Lower Limit (LLs)

Bodies of sediment on the nearshore-system scale are inhomogeneous with regard to texture, composition, and internal sedimentary structures. Inhomogeneity is primarily a product of the spatial and temporal variation in physical processes and sediment supply. Accurate cross-sectional analysis of the modern shoreface prism thus requires analysis of the entire mass and identification of the lower boundary, or lower limit, to the body of material. Moreover, meaningful comparisons between surveyed profile change, coastal processes, and the sedimentary record depend upon accurate positioning of the subsurface boundary. The lower boundary, referred to herein as the sedimentologic lower limit (LLs), is the contact between the mapped modern shoreface prism and underlying tidal-associated facies.

At some coastal sites, the contact between modern shoreface sediment and underlying material of different physical and genetic aspect may be easily recognized. At this study site, many aspects of the underlying tidal sediment are similar to that of the modern shoreface mass. In a number of vibracores, the contact was not readily discernable. A two-fold approach was used to determine the stratigraphy of the vibracored mass. First, sedimentologic criteria were used to merely document the presence of material other than that of the modern shoreface. Then, correlation techniques, used in conjunction with detailed sedimentologic criteria, were used to more accurately delineate the contact between sediment masses. In the following sections, a different origin for underlying material of similar texture and composition is first established and then resolution of the contact between sediment bodies is discussed.

Underlying Tidal Body

Sedimentologic data document the presence of two major facies groups, the modern marine shoreface prism and an underlying tidally influenced facies complex. The tidal sediment primarily consists of granules to very fine sand. Thin mud beds are rare. Scattered at various locations in the lower sediment body are structures diagnostic of reversing tidal flow in high-energy to low-energy settings. Thin sequences (e.g., 10 cm) of alternating mud and sand, sometimes showing bipolar ripple foreset orientations, occurred in several cores (see Appendix A, core 26-34, 0.92-1.05 cm). Such "wavy bedding," similar to "flaser" or "lenticular bedding," is indicative of alternating slack and reversing tidal flow in muddy, low-energy settings (Reineck and Wunderlich 1968; Klein 1985).

Some fine sand sequences in the cores show rhythmic parallel laminations consisting of couplets of one thick and one thin lamination. Also rare are vertically accreted bundles of wider-spaced parallel laminations alternating with narrower-spaced laminations. The lamination couplets and the vertically accreted bundles of laminations are indicative of flood-ebb asymmetry (Reineck and Wunderlich 1968; Klein 1985) and spring-neap cycles (Boersma and Terwindt 1981; Kvale and Archer 1990), respectively.

Amalgamated medium- and large-scale unidirectional cross-stratified beds separated by reactivation surfaces occur in several cores. Such structures are commonly produced under highly asymmetric tidal current conditions, such as occur in ebb- or flood-dominated channel or bar top settings (Klein 1970; Allen 1984; deMowbray and Visser 1984; Kreisa and Moiola 1986). Upward-fining second- and third-order sand and gravelly sand cross-stratified sequences with distinct scour bases, amalgamated beds, reactivation surfaces, and large-scale bidirectional foresets indicate channel cutting and fill in a reversing flow setting.

Below fine to very fine shoreface sand of the lower ramp, relatively thin (e.g. 2-10 cm), reduced-gray shelly gravel or very coarse sand is commonly interbedded with moderate to heavily bioturbated, organic-rich , muddy, very fine gray sand. Thin shelly gravel and coarse sand interbedded with bioturbated very fine sand does not occur in deposits of known marine shoreface origin in cores from this study or those of comparable detail (Schwartz 1981b; Schwartz, Hobson, and Musialowski 1981). By contrast, this type of bedding has been documented for settings adjacent to tidal inlets where strong storm-related currents or overwash events transport coarser debris into otherwise low-energy settings.[1]

Shells in the lower sediment body were of mixed origin. Shallow marine species mixed with some brackish species indicate exchange between adjacent nearshore and back-barrier settings. *Raeta plicatella* (channeled duck clam), a delicate-shelled, normal marine salinity species, occurred rarely as unabraded whole and

[1] Personal Communication, 1994, S. Snyder, Professor, Dept. Of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC.

articulated shells with some in possible life position. Whole and fragmented sand dollar shells were abundant as transported debris in some beds. The combined occurrence of delicate, unabraded *Amygdalum papyria* (paper mussel) and the intertidal salt-marsh grazer *Ilyanassa obsoleta* (mud snail) indicate minor transport from nearby brackish settings. The scattered occurrence of abraded *Crassostrea virginica* (eastern oyster) debris may represent exhumation from underlying sediment or contemporaneous mixing between brackish and marine settings. Overall, the occurrence of definite tidal structures and presence of back-barrier shells showing minimal transport effects document a different origin for sediment lower in the vibracored section.

Nature and Accuracy of Contact (LLs)

An easily recognizable ravinement surface, or "disconformity," as may occur between shoreface and underlying facies was the exception rather than the rule (general case summarized by Elliot (1978); specific shoreface example by Schwartz, Hobson, and Musialowski (1981)). The texture of the tidal body is distributed laterally such that, along the inner profile, gravelly and medium- to coarse-sand tidal facies underlie shoreface facies of similar texture. Along the middle to outer profile, fine to very fine sand tidal facies underlie shoreface facies of similar texture. Some of the same internal physical structures occur in beds of similar grain size both above and below the shoreface-tidal body contact. Along the outer profile, high degrees of bioturbation occur in fine to very fine sand on both sides of the facies contact. Although intensive bioturbation activity is common in low-energy back-barrier settings, it is also typical of low-energy marine nearshore settings. A complicating factor is that meiofauna in low-energy nearshore settings can burrow deep enough to transect thin (e.g., 5- to 10-cm-thick) nearshore sand and penetrate underlying fine and very fine tidal sand. Sediment color commonly darkens downward through the cored sections. In some cases, color shows a discrete change near the contact and, in other cases, either shows no change around the contact or shows gradual change through the contact. Consequently, in a number of vibracores, accurate determination of the boundary between the facies was problematical. In order to allow for meaningful quantitative comparisons with high-resolution profile survey data, it is desirable to have sedimentologic "picks" for the boundary with an accuracy of a few centimeters or less. Criteria and procedures for establishing the tidal-shoreface contact are presented below, illustrated and annotated on vibracore plots in Appendix A, and summarized in Table 2.

In some cases, it was possible to establish a precise location for the shoreface boundary by means of recognizing an erosional contact between shoreface deposits and underlying beds or second-order sequences bearing structural properties of distinct tidal origin. The contact represents the truncation of depositional features unique to tidal processes by a later shoreface-caused erosional surface. Such high-accuracy locations could then be correlated laterally through less distinct adjacent cores. In some other cores, the base of second-order modern marine sequences were used as a minimum depth (elevation) indicator for the contact. Individual beds making up the lower part of a second-order marine shoreface

Table 2
Summary and Examples of Sedimentologic Properties at the Contact Between the Modern Shoreface Prism and Underlying Tidal Body

Below Beach, Inner Trough, and Bar Flank (Profile 188)

Texture Enclosing Contact

Gravel upon gravel. Sand upon gravel.
Gravel upon sand. Medium to very coarse sand upon finer sand.
Sand above contact is usually slightly cleaner than below contact.

Color Change Associated With Contact[1]

Gravel above contact is cleaner and brighter yellow than below; gravel below is yellowish gray with subtle clay coating on clasts.
Yellow sand above to gray shades below.

Bed Type, Second-order Sequences, Facies Enclosing Contact

Upward fining cross-stratified second-order sequence (Table 4A, type 3) of gravelly trough thalweg subfacies in erosional contact with burrowed, parallel laminated, fine-sand tidal bundles (Core 6-15).

Inversely graded gravelly bed (Table 3A, type 5) of trough thalweg subfacies in erosional contact with parallel-laminated medium-sand at top of upward-fining second-order tidal sequence. (Core 9-14)

Below Bar-Upper Ramp-Middle Platform (Profiles 188 and 62)

Texture Enclosing Contact

Sand above contact usually slightly cleaner than below contact.
Gravelly medium or coarse sand over medium or fine sand.
Fine sand over very fine to very coarse sand or gravelly sand.
Fine sand over silt-and-mud laminations.

Color Change Associated With Contact[1]

Grayish yellow to gray of various shades.
Yellowish brown to grayish brown.
Light gray to darker gray.

Bed Type, Second-order Sequences, Facies Enclosing Contact

Gravelly cross-stratified second-order sequence (Table 4A, type 3) of inner trough subfacies in erosional contact with rhythmic medium-sand tidal laminations. (Core 11-12)

Cross-stratified medium- to coarse-sand inner trough subfacies over burrowed parallel-laminated fine sand. (Cores 12-39)

Cross-stratified fine to coarse sand of various trough subfacies over partially bioturbated upward-fining coarse-to-fine sand second-order tidal dequence. Tidal sequence contains evidence for reversing asymmetric tidal flow including stacked large-scale unidirectional foresets separated by reactivation surfaces or rhythmic laminations. (Cores 14-16, 15-17, 19-18, 44-110)

Upward-fining low-angle parallel-laminated sequence (Table 4B, type 6) with coarse sand at base in erosional contact with upward-fining gravel-to-fine sand second-order tidal sequence. Tidal sequence contains evidence for reversing asymmetric tidal flow: reversed foresets, reactivation surfaces, stacked unimodal foresets. (Core 21-26)

Upward-fining cross-stratified sequence (Table 4B, type 7) with very coarse sand or gravelly sand base in erosional contact with parallel-laminated fine-sand at top of upward fining cross-stratified tidal sequence. (Code 18-8)

[1]Color change does not always occur at contact.

(Continued)

Table 2 (Concluded)

Bed Type, Second-Order Sequences, Facies Enclosing Contact (Continued)

Subhorizontal laminated fine sand of ramp-middle platform facies over thick normally graded gravelly beds. (Core 20-23)

Inversely graded and cleaner gravel bed of trough thalweg subfacies over tidal beds of similar grain size. Inverse grading and cleaner gravel due to *in* situ winnowing of tidal gravel. (Core 42-114)

Upward fining low-angle parallel-laminated second-order sequence (Table 4B, type 6) in erosional contact with tidal wavy bedding. (Core 43-111)

Below Outermost Middle Platform and Lower Ramp (Profiles 188 and 62)

Texture Enclosing Contact

In some landward cores

Thin gravelly medium to fine sand over fine to very fine sand.

Reworked granular medium to fine sand over gravelly coarse to very coarse sand.

In most cores across the lower ramp:

Slight textural coarsening above contact; most common-cleaner, slightly coarser, and better sorted fine sand over fine to very fine sand; increased clay matrix or clay coating on sand grains below.

Degree of bioturbation may be similar on both sides of contact; bioturbation anywhere results in increased clay-sized (fecal) matrix.

Color Change Associated With Contact[1]

Yellowish gray to light gray.

Light gray to darker gray.

In deepest cores: gray throughout core - no color change at contact.

Bed Type, Second-order Sequences, Facies Enclosing Contact

Horizontal laminated ramp facies overlies contact at all locations.

Upward fining horizontal laminated sequence (Table 4B, type 5) with thin relatively coarse base in erosional contact with upward fining cross-stratified (bipolar foresets) tidal sequence. (Core 24-10)

Upward fining horizontal laminated sequence with thin relatively coarse base (Table 4B, type 5) in erosional contact with heavily bioturbated fine to very fine grained sand. (Core 25-33)

Upward fining horizontal laminated sequence (Table 4B, type 5) in erosional contact with wavy bedded tidal unit containing mud and bipolar foreset sand layers. (Core 26-34)

Heavily bioturbated (no remaining primary structures), normally graded, medium-to-fine sand in erosional contact with heavily bioturbated (no remaining primary structures) upward fining gravelly tidal sequence. (Core 45-106)

Partially bioturbated to completely bioturbated fine sand overlying tidal sand of similar structural properties; contact based upon some combination of slight coarsening, cleaner sand, and color change at contact. (Cores 28-25, 29-24, 32-30, 31-35, 33-29, 46-107, 48-109, 49-101)

[1]Color change does not always occur at contact.

sequence may appear similar to other individual beds within the tidal body. However, the recognition that beds belong to distinct sequences which extend up into sediment of definite shoreface origin allows use of the base of a sequence as a minima indicator. In many of the cores, texture above the contact was very slightly coarser, cleaner, and better sorted, sometimes just due to the removal of interstitial clay. However, because of the subtlety of this type of bedding contact, as well as possible repetition in the vertical sequence, such criteria were most useful after initial correlations between cores with distinct contacts had been made.

Although sediment color could not be used as an unequivocal indicator of facies contact, it many times did correspond closely with textural and structural evidence. The upper parts of cored sequences were commonly marked by various shades of yellow or brown, including grayish brown, with a downward change to various shades of gray. The gray shades ranged from subtle whitish-gray clay coatings on yellowish gravel to light gray and dark gray sand in heavily burrowed fine sand. Other times, the color of sand and gravel in the tidal body was similar to that of overlying shoreface sediment. In heavily burrowed fine sand of the outermost profile, color was of little help, other than to identify most recently deposited or reworked shoreface material. In general, the gray colors reflect diagenetic reduction of organic material in older sediment.

In summary, sedimentologic evidence indicates that the modern shoreface prism rests upon an inlet-associated facies complex, including tidal delta, tidal channel, and tidally influenced nearshore facies. The downward conversion to grayer colors in the cores many times indicated proximity to the facies boundary, even though the fundamental relationship may be a dependency upon age, including time of reworking, and diagenesis, rather than depositional environment. Shoreface truncation of definite tidal structures and the erosional base of definite shoreface second-order sequences allow for precise establishment of the shoreface (LLs) boundary in a number of cores. The contact could then be correlated laterally through less distinct areas in a reliable manner. 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 not distinct.

5 Geometry of Shoreface Prism

The envelope of surveyed elevation change provides an estimate of potential geometry for the shoreface sediment mass over a 12+-year period. The upper limit to the envelope of change is a composite of elevations representing maximum buildup whereas the lower limit is a composite of elevations representing maximum erosion (Figures 5 and 6). Maximum envelope thicknesses of 3-4 m occur between the beach and middle platform areas of this study. The envelope shows protracted thinning from envelopes about 1 m thick in the middle platform area to about 50 cm thick at the seaward limit of coring (900 - 950 m).

Actual profile shapes, even under conditions of maximum accretion, do not match the upper limit of the survey envelope. Although the lower sedimentologic boundary of the shoreface generally lies slightly below the lower limit of surveyed elevation change, the surveyed lower limit of erosion presents a close approximation to the shape and position of the shoreface boundary (discussed later). Therefore, at any point in time, the actual geometry of the shoreface mass is adequately represented by the lower limit of the envelope and the shape of the active profile.

The vibracored profiles along lines 62 and 188 depict two basic geometries for the shoreface prism. Vibracore profile 62 represents a state of maximum landward accretion with a shoreface-mass geometry most similar to that of the envelope geometry (Figure 5). Thickness below the beach essentially matches that of the 12+-year maximum thickness. The zone of potential inner trough development along line 62 is uniformly built up, with an average thickness of 2 m. Following local thinning of 20 - 50 cm in the region of the middle platform, the mass thickens again to about 80 cm before thinning seaward to about 30 cm at the seaward limit of coring. Vibracore profile 188 differs in the zone of maximum potential thickness, where the mass is about 2 m thick below the beach and inner bar and essentially nonexistent below the inner trough (Figure 6).

Overall, the geometry of the shoreface mass is basically prismatic, with maximum thickness in the region of inner bar and trough development. Associated

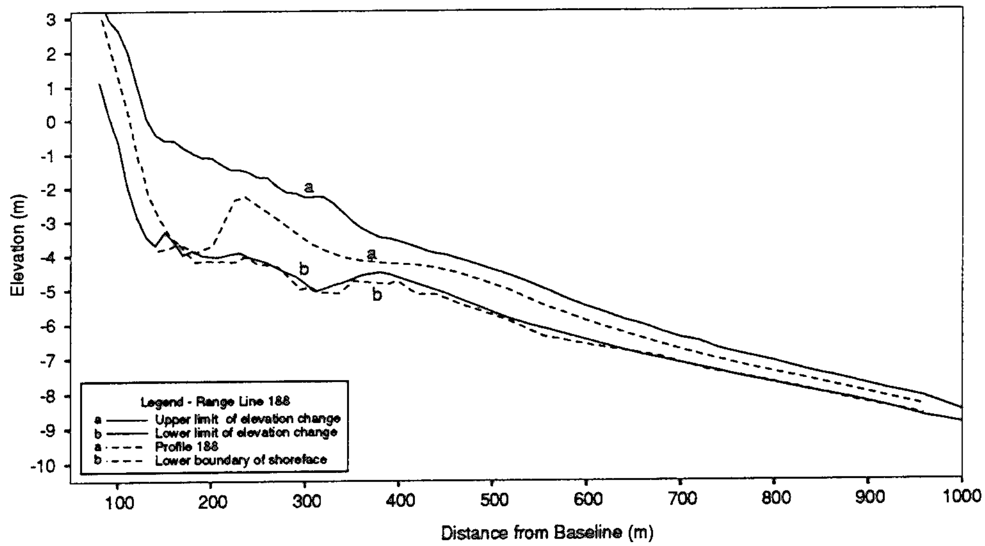

Figure 5. Profile line 188: Envelope of profile change since 1981 (solid line - a and b) compared to shape of the cored profile (dashed a) and the lower sedimentologic boundary (LLs) of the shoreface prism (dashed b)

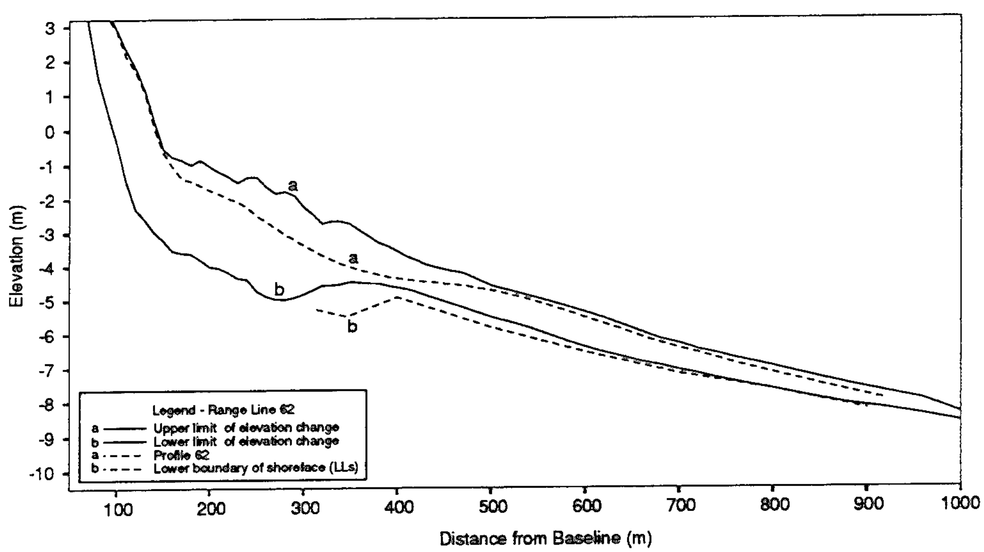

Figure 6. Profile line 62: Envelope of profile change since 1981 (solid line -a and b) compared to shape of the cored profile (dashed a) and the lower sedimentologic boundary (LLs) of the shoreface prism (dashed b)

with the lower ramp area of this study, the prism tapers slowly seaward and has geometry boundaries similar in shape to both the upper and lower limit of profile change and actual profile shapes.

6 Sedimentology of Shoreface Prism

Third-Order Elements - Beds

A number of bedding types in the vibracores are diagnostic of specific bedforms and hydrodynamic conditions related to environmental settings. In general, the shoreface prism is texturally bimodal consisting of beds in the gravel to medium-sand range and beds in the fine- to very-fine-sand range. The coarser group is representative of swash-zone and inner-trough settings whereas the finer group represents bar through lower ramp as well as historical outer trough settings. The diagnostic bed types are presented below according to texture, structure, and association with profile morphology. Physical properties and interpretations of the bed types are summarized in Tables 3 and 4.

Gravel and coarser sand beds

Several distinct bedding types in this textural group occur below the swash zone and adjacent trough of profile 188. Similar profile settings were not cored along profile 62. Structural variants include low-angle parallel laminated, medium- to large-scale cross-stratified, and horizontal- to subhorizontal-laminated beds. The following structural types generally manifest normal or inverse textural grading, but may also be nongraded.

Low-angle parallel-laminated. Normally graded low-angle parallel-laminated coarse beds occur in two locations, directly beneath the active swash zone and stratigraphically deeper in inner-trough locations.

Normally graded - swash associated (Table 3, type 1). Normally graded gravel or medium to very coarse-grained sand beds were common directly beneath the active lower foreshore zone (Figure 7a). The beds are 5 - 25 cm thick and coarsen laterally downslope (seaward). Similarly, sediment texture along the surface coarsened downslope across the swash zone (Figure 8). Internal structures are usually poorly defined or indiscernible in vibracore sections due to the coarse grain size and to fabric distortion from coring. However, the pervasive occurrence of crudely to well-defined seaward-dipping parallel lamination has been

Table 3

Diagnostic Bed Types (Third-Order Elements) in Gravel and Relatively Coarse Sand

Grain Size Group	Bed Type	Dominant Structure	Bed Texture	Thickness (cm)	Occurrence and Comments	Bed Origin
GRAVEL AND COARSE SAND	1	Low-Angle Parallel Lamination (LAPL)	Normally graded. Pebbly gravel & very coarse to medium sand. Ex. Fig. 7A & B.	5 - 25	Occurs directly below swash zone; laminae dip and coarsen seaward.	Aggradation of seaward coarsening planar swash-zone surface.
	2		normally graded. Pebbly gravel & very coarse to medium sand. Ex. Fig. 7A & B.	5 - 8	Relatively rare. Buried below bar and upper ramp in lowermost part of shoreface prism.	Current dominated flow. Aggradation upon low-angle surface in base of trough.
	3		Inversely graded subhorizontal (HL) or very low angle lamination. Pebbly gravel & very coarse to medium sand. Ex. Fig. 7C & D.	10 - 40	(1) Buried below, & seaward of, swash zone & type 1 beds. (2) Along active landward flank of inner trough.	Aggradation of subhorizontal to very low angle, seaward-fining, planar surface near surf-swash juncture.
	4	Medium- to Large-Scale Cross-Stratification[1] (LSCS)	Normally graded. Pebbly gravel & very coarse to fine sand. Fig. 7E, F, G.	5 - 20	At trough depths: (1) Buried below swash zone and below type 1 & 3 beds. (2) In inner trough along active bed. (3) Buried below bar and upper ramp in lowermost part of shoreface prism.	Current-dominated flow. Bed aggradation associated with migration of relatively large 3-dimensional ripple. Local coarsening down ripple front produces normal grading.
	5		Inversely & inverse-to-normally graded. Pebbly gravel & very coarse to coarse sand. Fig. 7H.	8 - 25	Relatively rare. Along basal part of shoreface prism: (1) In coarse inner trough along active bed. (2) Below bar or upper ramp. Associated with type 4 beds.	Current-dominated flow in trough. Bed aggradation associated with migration of relatively large 3-dimensional ripple. Coarsening down ripple front preceded by fining onto down-flow surface produces inverse-to-normal grading.
	6	Horizontal Lamination (HL)	Normally graded & non-graded. Gravel to coarse sand. Ex. Fig. 7B.	5 - 7	Relatively rare. In lower & landwardmost parts of shoreface prism. Associated with type 4 & 5 beds.	Aggradation upon near-horizontal planar surface along base of trough.
	3		Inversely graded - see type 3 above			

[1]Usually appears similar to tabular cross-stratification in narrow cored section. The actual structural type is most likely trough cross-stratification.

Table 4
Diagnostic Bed Types (Third-Order Elements) in Relatively Fine Sand

Grain Size Group	Bed Type	Dominant Structure		Bed Texture	Thickness (cm)	Occurrence and Comments	Bed Origin
FINE SAND	7	Horizontal Lamination (HL)	Non- to slightly biotur-bated	(1) Normally graded fine above thin coarser base (2) Couplets of thin "non-graded" coarse & thicker fine (3) Non-graded fine (See Figures 11 D & F)	2-30	Most common directly below upper ramp & middle platform. Erosional lower contact common below coarser basal layer.	Aggradation upon subhorizontal to horizontal planar surface under high velocity conditions. Erosional base and overlying unit indicate high energy scour, waning flow & accretion
	8		Biotur-bated	Fine to very fine sand. Grading indiscernable. (See Figures 11 K and L)	2-20	Below lower ramp thinner offshore. Laminae moderately to completely overprinted by bioturbation	Aggradation upon planar surface under high velocity conditions. Extensive biogenic reworking during subsequent fairweather
	9	Low-Angle Parallel Lamination (LAPL)		Texture similar to type 7. (See Figure 11 B (top) and H)	3 - 30	Landward dipping below active landward flank of bar. Landward & seaward dips in lower prism below bar through middle platform. Erosional lower contact common.	Aggradation upon low-angle planar surface, e.g., bar flank, under high velocity conditions. Erosional base and overlying unit indicate high energy scour, waning flow & accretion
	10	Medium- to Large-Scale Cross-Stratification (LSCS)		Normally graded or nongraded. Fine sand or fine-sand dominant with coarser base. (See Figures 11 F, G, & J)	3 - 20	In lower half of prism below bar, upper ramp & platform. Associated with type 9. Erosional lower contact common. Usually appears similar to tabular cross-strat.; most likely trough cross-strat.	Current-dominated flow. Migration of large 3-D ripples; normal grading due to coarsening down ripple front. Erosional contact due to scour event or localized ripple-trough scour
	11	Small-Scale Trough Cross-Stratification (SSTS)	Non-biotur-bated	Fine to medium sand. (See Figure 14, core 10-13, 0.25m)	< 5	Scattered occurrence in lower part of shoreface prism. Erosional lower contact common.	Low velocity current-dominated flow. Migration of small 3-D ripples.
	12		Biotur-bated	Fine to very fine sand. (See Figure 11 L)	< 5	Rare below lower ramp. Slightly to completely overprinted by bioturbation fabric.	Same as 11. Biogenic reworking during subsequent low energy.

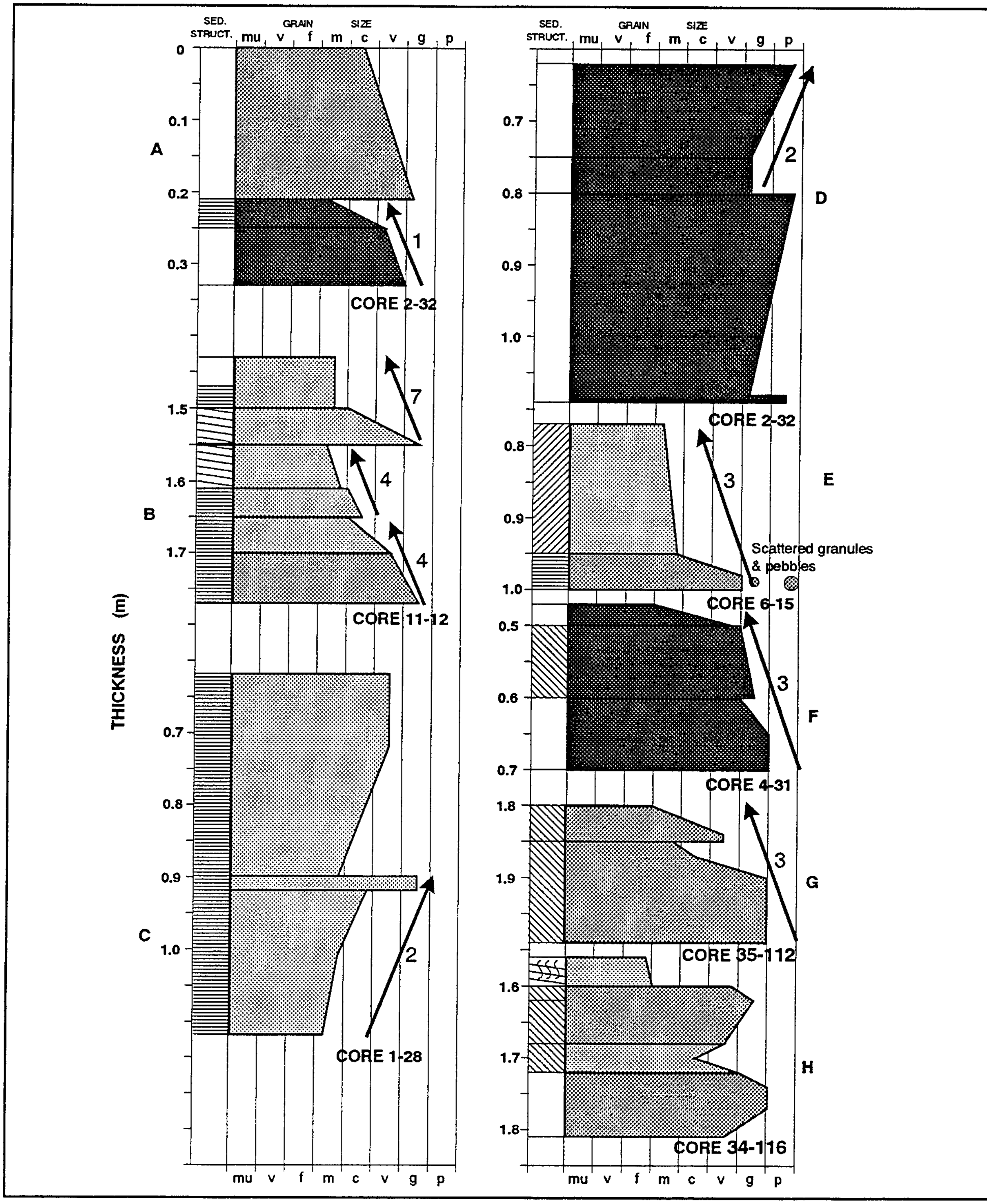

Figure 7. Bedding types in gravel and relatively coarse sand below beach and inner trough locations: A and B - normally graded horizontal and low-angle parallel-laminated; C and D - inversely graded; E, F, and G - normally graded cross-stratified; H - inverse-to-normal grade cross-stratified. Examples of second-order sequences are identified by solid arrows and type numbers (Tables 5 and 6). A key to other symbols is located in Appendix A.

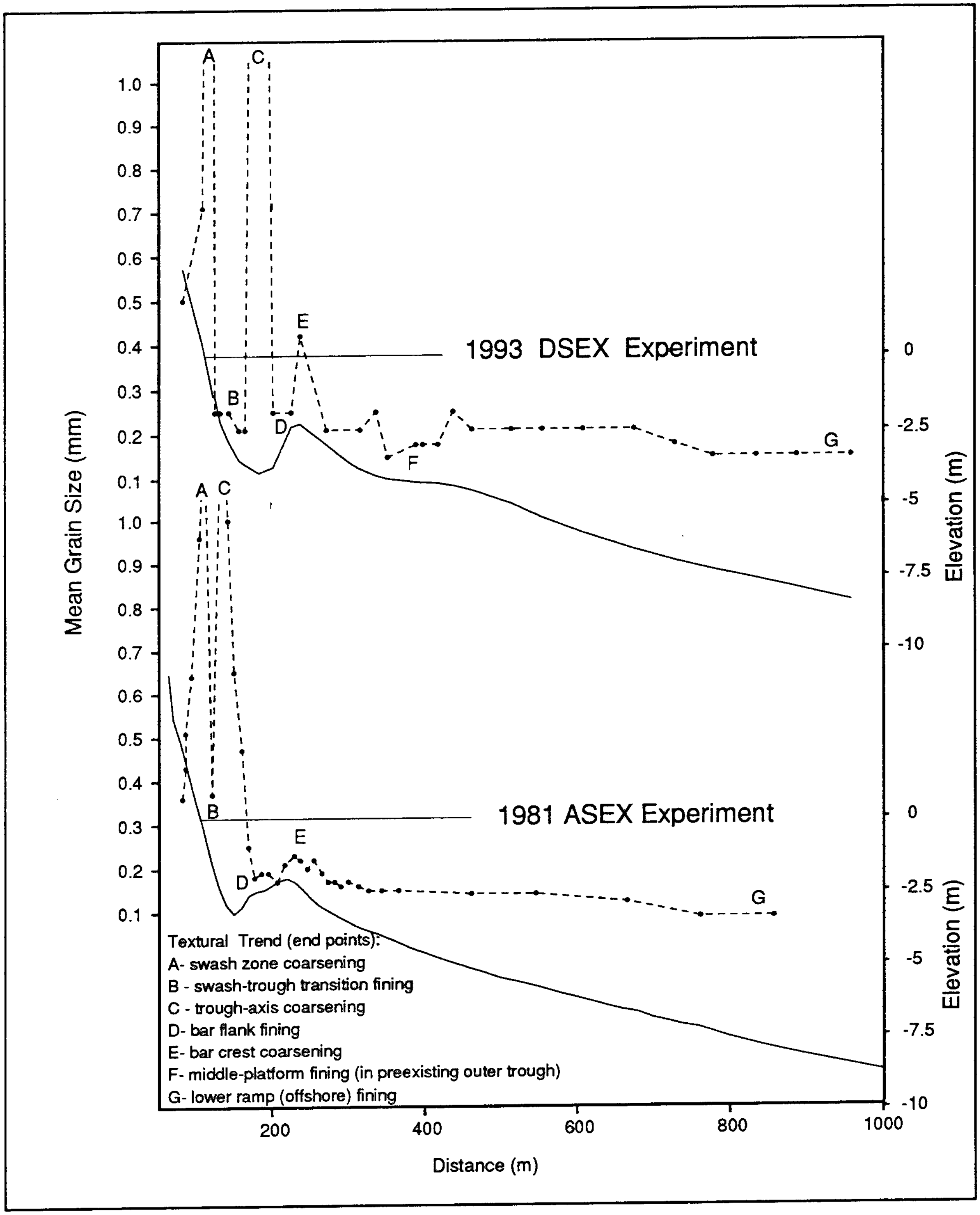

Figure 8. Profile shape and sediment texture along the sediment-water interface of line 188 at the time of this study and the 1981 ASEX Experiment (Schwartz 1981b). Textural trends A through D correspond to those depicted in Figures 9 and 10.

Table 5

Diagnostic Second-Order Bed-Sequence Types in Gravel and Relatively Coarse Sand

Grain Size Group	Seq. Type	Sequence Name	Structural Components[1]	Sequence Thickness (cm)	Occurrence and Comments	Sequence Origin
GRAVEL AND COARSER SAND	1	Upward fining low-angle parallel-laminated (swash-zone)	Erosional lower boundary. Stacked normally graded LAPL beds(*1*). (See Figure 7A and 12)	10 - 30	Below active swash zone.	Sequential progradation of seaward-coarsening swash-zone surfaces.
	2	Upward coarsening (swash-trough transition	a) Stacked inversely graded HL or LAPL beds (*3*). (See Figure 7 c, d, and 12) b) Non-graded sandy H beds (*6*) overlain by nongraded gravel beds. (See Figure 12, core 3-20)	8 - 50	Along active swash-trough transition & landward below upward-fining swash-zone sequences. Gravel beds commonly appear structureless in cores.	Seaward progradation of inclined to subhorizontal seaward-fining planar surfaces along margin of inner trough.
	3	Upward-fining cross-stratified (inner trough)	Stacked normally graded LSCS (*4*), LAPL (*2*), and HL (*6*) beds. (See Figures 14 and 15)	5 - 40	Below active inner trough; stratigraphically adjacent below swash zone & swash-trough transition sequences; and, below inner bar in basal part of shoreface prism.	Current-dominated trough setting. Major trough scour event followed by trough infilling and development of coarse planar surfaces and large 3-dimensional ripples.
	4	Upward fining horizontal laminated (inner trough)	a) Stacked normally graded gravelly HL (*6*) beds. b) Normally graded gravelly HL(*6*)-to-normally graded sandy LAPL (*2*) beds. (See Figures 7b and 15)	10 - 20	Below inner bar & trough in lowermost shoreface prism.	Trough setting. Trough scour event followed by aggradation of gravel upon near-horizontal planar surfaces to low-angle sandy surfaces, e.g., lower trough flank.

[1]Numbers in italics refer to bed types in Table 3.

Table 6
Diagnostic Second-Order Bed-Sequence Types in Relatively Fine Sand

Grain Size Group	Seq. Type	Sequence Name	Structural Components[1]	Sequence Thickness (cm)	Occurrence and Comments	Sequence Origin
FINE SAND	5	Upward fining horizontal laminated (upper ramp-middle platform)	Erosional lower boundary. Stacked normally graded or non-graded HL beds (*7*). (See Figures 15 and 16)	6 - 20	Directly below upper ramp & middle platform.	High velocity plane-bed conditions. Major erosional event followed by series of lower energy erosional-depositional events.
	6	Upward fining low-angle parallel-laminated (bar flank)	Erosional lower boundary common. (1) Stacked LAPL beds (*9*). (See Figure 15, core 11-12) (2) LSCS (*10*)-to-LAPL (*9*). (See Figure 15, core 12-39) (3) LAPL (*9*)-to-HL(7). (See Figure 16, core 17-5, Figure 17, core 21-26)	12 - 45	In lower half of shoreface prism below bar, upper ramp, & middle platform.	Episodic erosion and trough development followed by buildup of bar flank surfaces under high velocity plane-bed conditions. Capping horizontal laminae represent final phase of trough infilling & subhorizontal profile development.
	7	Upward-fining cross-stratified (associated trough)	Erosional lower boundary common. (1) Mixed LSCS (*10) & LAPL* (*9*) or HL (*7*) beds. (2) LSCS(*10*)-to-LAPL (*9*). (3) LSCS(*10*)-to-HL(*7*). (See Figures 7, 15, and 17)	10 - 60	In lower half of shoreface prism below bar, upper ramp, & middle platform	Deposition under current-dominated flow conditions in trough or trough-margin setting. Most of the sequence producted by migrating large-scale ripples. Capping horizontal laminae in inner & outer trough settings represent final phase of trough infilling & subhorizontal bed development.

[1]Numbers in italics refer to bed types in Tables 3 and 4.

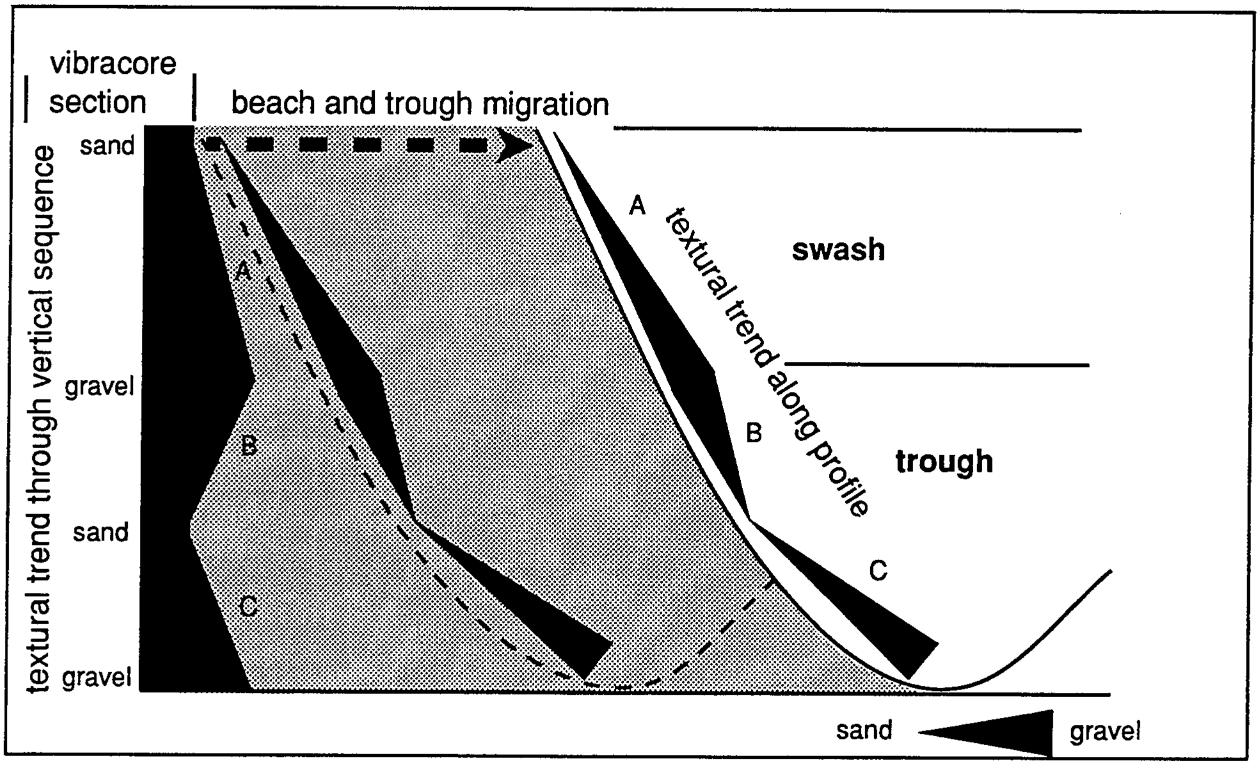

Figure 9. Vertical textural sequences preserved below a prograding beach and the relationship to lateral textural trends across the active beach-and-trough profile (A = upward fining associated with swash zone; B = upward coarsening associated with swash-trough transition; C = upward fining from trough axial zone). A vertical transect through any location in the accreted mass (gray shading) will exhibit the idealized vertical trend shown on the left

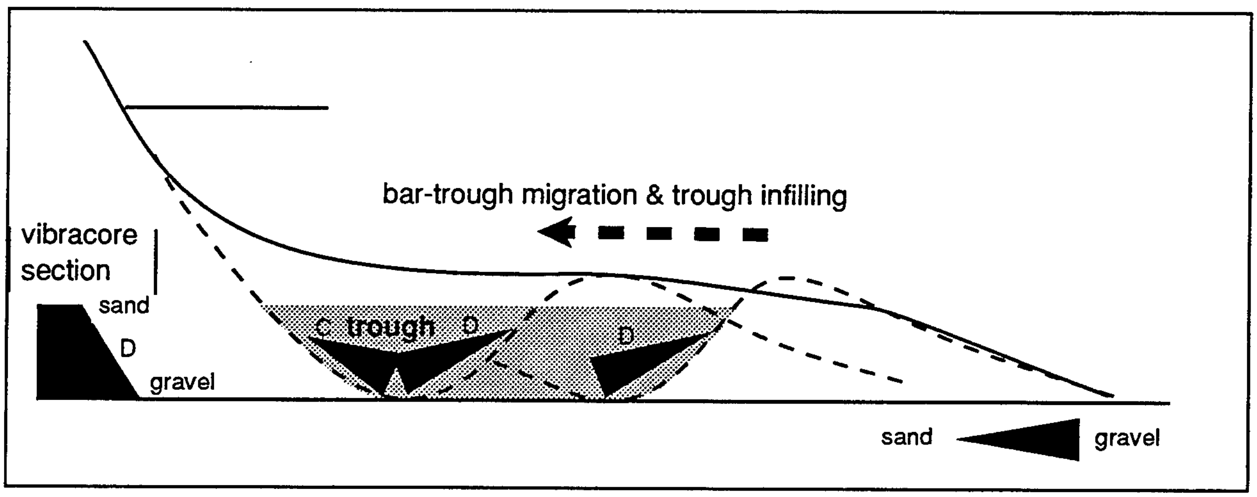

Figure 10. Vertical textural trend in a second-order sequence produced by the shoreward migration and infilling of a coarser-grained trough. A vertical transect through any location in the accreted mass (gray shading) will exhibit the idealized upward fining trend shown on the left. Similarly, normal grading in a single bed may result from aggradation along a downslope-coarsening surface

well-documented in previous trenching and boxcoring experiments at the same site (Schwartz 1981b; Schmittle 1982).

Swash runup and backwash occur across a seaward-sloping planar surface. Flow strength for both phases of the swash process is greater in the downslope direction and, correspondingly, texture coarsens laterally seaward down the surface (Clifton 1969). A single normally graded swash-zone bed represents progressive buildup of the planar surface whereby landward (upslope) finer-grained settings are superposed upon lower (downslope) and coarser-grained swash settings (Figure 9). Bed aggradation under high shear-stress plane-bed conditions accounts for the development of parallel lamination (Clifton 1969).

Normally graded - inner trough associated (Table 3, type 2). Normally graded thin beds (5 - 8 cm), some with poorly developed low-angle parallel-lamination, occurred rarely below the trough axis of profile 188; and, below the bar and upper ramp of both profiles at historical inner-trough depths (Figure 7b).

The low-angle lamination reflects deposition upon a low-angle planar surface within an inner trough setting, perhaps the lower flank of the trough or a gently sloping surface of a large-scale ripple. The normal grading trend most likely results from aggradation whereby finer-grained upslope sediment is stacked upon coarser downslope material (Figures 9 and 10). A similar case is more fully explained in the section on normally graded cross-stratified beds (type 4).

Inversely graded - swash-trough transition associated (Table 3, type 3). Along profile 188, inversely graded gravel and medium- to very coarse-grained beds (Figures 7c and 7d) are relatively common directly below normally graded swash-zone (type 1) beds and, laterally, directly below the upper half of the inner flank of the trough. The beds are relatively thick (10 - 40 cm) and range from structureless and crudely laminated in gravel to distinctly parallel-laminated in sand. Although the laminations appear to be subhorizontal in narrow vibracore sections, the dip is most likely a few degrees, conformable to the actual dip of the bed surface in this region. At the surface, a seaward trend of gravel-to-sand coarsening commonly extends from the seaward margin of the swash zone down onto the upper half the trough flank (Figure 8). A low-tide terrace commonly develops at this location.

The beds are genetically linked to the transitional zone between beach and trough settings. In this innermost surf-zone environment, energy at the bed initially increases upslope as water depth in the trough decreases. Energy then decreases upslope due to dissipation across the low-tide terrace and/or swash zone. Shear stress conditions in this setting are typically high, thus accounting for the development of a plane bed and parallel lamination. Inverse grading within a bed results from the vertical buildup associated with seaward migration, or progradation, of a seaward-fining surface, either that of the low-tide terrace or uppermost trough flank (Figure 9).

Medium- to large-scale cross-stratified. Medium- to large-scale cross-stratified beds occur directly below the sediment-water interface along the trough of profile 188 as well as in historical inner-trough depths along both profiles 188 and 62. Two textural groups occur, normally graded and inversely or inversely-to-normally graded.

Normally graded - inner trough associated (Table 3, type 4). Normally graded cross-stratified sand and gravel beds (Figures 7e, 7f, and 7g), 5 - 20 cm thick, are common at elevations below those for swash and swash-trough transition bedding types. Sand beds typically grade upwards from coarse-to-fine sand. Normally graded gravel beds, two to several centimeters thick, commonly underlie normally graded sand beds (Figure 7e). Although internal structures are not recognizable in many of the beds due to vibracore disruption, better preserved examples document the presence of medium- to large-scale cross-stratification. Internal laminations are typically tangential with the lower set boundary and lower boundaries of cross-stratification sets typically truncate underlying laminations.

The vibracore sections are narrow vertical slices through much wider cross-stratified sets. Based upon the occurrence of variable foreset orientations, evidence for basal scour, and, in some cases, for the presence of slightly concave scour pits, most cross-stratification is interpreted to represent medium- to large-scale trough cross-stratification or the three-dimensional cross-stratification of Rubin (1987). Such cross-stratification is produced by migrating three-dimensional ripple forms or "megaripples." The occurrence of such bedforms, oriented transverse or oblique to mean flow within combined-flow settings of the surf-zone trough, has been documented for other coastal sites (Davidson-Arnott and Greenwood 1976; Greenwood and Mittler 1984), including this site (Schwartz 1981b). A common textural trend across large three-dimensional ripples, in the resultant transport direction, is (a) either textural coarsening down the ripple's lee slope to the base of slope, or (b) coarsening down the lee slope and slightly beyond into the leading ripple-scour pit. The normal grading trends and associated cross-stratification are thus interpreted to represent aggradation at a given location due to lateral migration of relatively coarse-grained large ripples in a current-dominated combined-flow setting.

Inversely graded and inversely-to-normally graded - inner trough associated (Table 3, type 5). Inversely and inverse-to-normally graded cross-stratified beds (Figure 7H), 8 - 25 cm thick, occur rarely in association with the trough-associated normally graded cross-stratified beds described above. Although internal structures are again not recognizable in some beds, better examples document the presence of medium- to large-scale cross-stratification. In addition to occurrence in the modern shoreface prism, this bedding type, as well as normally graded beds, occurs directly below the shoreface prism in coarse tidal-inlet facies (see Appendix A, cores 8-7, 9-14, and 18-8).

Lateral gravel-to-sand fining trends occur across small areas in the inner trough, usually in the direction of net transport from the lee-slope of a large ripple onto a prefrontal surface. Thus, inverse grading and cross-stratification within a bed most likely result from the migration and superposition of a relatively coarse ripple front over a finer-grained downcurrent surface. The reversal from an inverse to normal grading trend represents a sequential phase of fining associated with continued ripple migration. As previously described for normally graded beds (type 4), textural fining up the lee slope onto the stoss side of large ripples is typical. Thus, lateral coarsening trends from the prefrontal region reverse into lateral fining trends up and over the ripple. With bedform migration, the temporal sequence of aggradation at a fixed site would be textural coarsening followed by upward fining. Subsequent partial erosion of full inverse-to-normal sequences can result in removal of normally graded caps and the development of inversely graded remnant beds. The same type of ripples and textural sorting mechanisms occur in channels or troughs of shallow shoreface-associated tidal settings, thus accounting for similar beds in the underlying tidal-inlet facies.

Horizontally laminated normally graded/non-graded - inner trough associated (Table 3, type 6). Normally graded and nongraded horizontal to subhorizontal laminated beds occur rarely in cores from the active trough of profile 188 or at historical inner-trough depths along both profiles 188 and 62 (Figure 7b). The beds are relatively thin (5 - 7 cm) and occur in association with coarse cross-stratified (types 4 and 5) beds.

The internal laminations represent a near-horizontal planar surface or an oblique section through a very low-angle planar surface. An association with type 4 and 5 beds indicates an inner trough setting. The normal grading may represent aggradation associated with diminishing flow and competence conditions in the surf zone, or, aggradation associated with migration of a downflow-coarsening surface.

Finer sand beds

Three types of physical structures are common below, and seaward of, the bar and upper ramp: horizontal to subhorizontal lamination, very low-angle parallel lamination, and medium-to large-scale cross-stratification. The three bedding structures make up more than 95 percent of the shoreface prism below the bar, upper ramp, and middle platform whereas horizontal laminated sand makes up more than 90 percent of the shoreface prism below the lower ramps of both profiles. Less common are scattered occurrences of small-scale trough cross-stratification. As a group, the beds are primarily fine sand with local concentrations of very fine sand, medium sand, and coarser sediment. Similar textural properties, particularly normal grading, may be found in all three of the dominant structural types. Textural properties of the group are initially discussed below so as to facilitate subsequent treatment of the structural types.

Normally graded and nongraded beds are common below the bar, upper ramp, and middle platform sectors of both profiles. In this middle-profile area, fine sand makes up the bulk of the shoreface mass; however, medium to very coarse sand and gravel occur in greater abundance in lower and more landward parts of the prism. The grain size of normally graded beds usually ranges either from granular or very coarse sand up to medium sand (Figures 11a and b), or, from medium sand up to

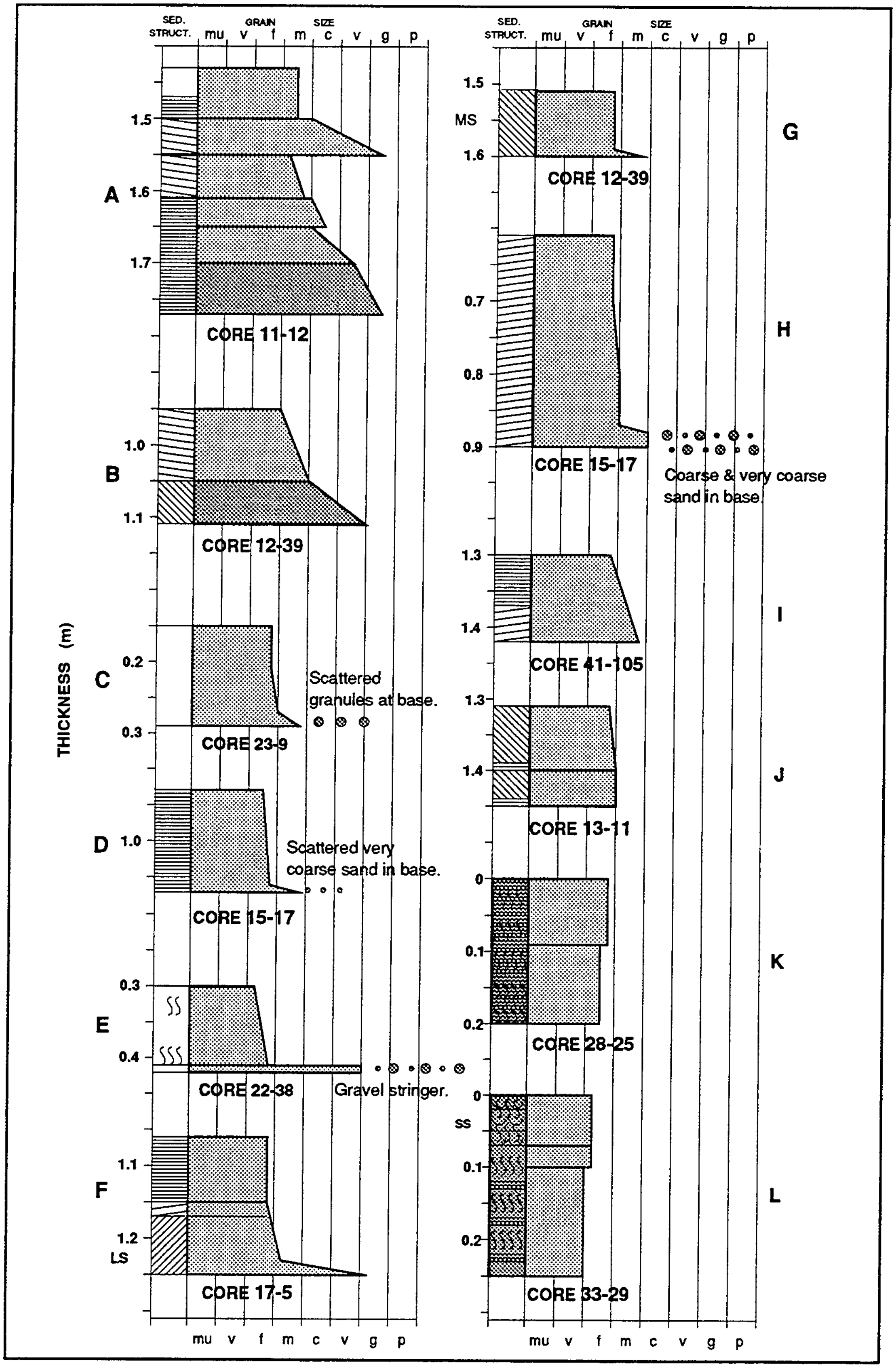

Figure 11. Bedding types below the bar, upper ramp, middle platform, and lower ramp (A = normally graded horizontally laminated (1.62-1.77); B = normally graded cross-stratified and very low-angle laminated; C = normally graded; D, E, and F = normally graded sand above a thin, coarser basal layer; G = nongraded sand above a thin, coarser, normally graded basal layer; H = normally graded very low-angle parallel-laminated; I = low-angle parallel-laminated up to subhorizontal laminated; J = subhorizontal-laminated up to cross-stratified; K = moderate to heavily bioturbated beds with subhorizontal lamination; L = heavily bioturbated beds with physical structures largely obscured (A key to symbols is located in Appendix A)

fine sand with most of the bed consisting of fine sand (Figure 11c). In either case, sand at the base of normally graded units is usually discretely coarser than that of the underlying bed and in many cases rests upon a scour surface. Normal grading is manifested by two basic patterns, (a) progressive grading throughout individual beds (Figure 11b), or (b) an individual bed consisting of one- to several-centimeter-thick relatively coarse basal layer followed either by a relatively thick (decimeter scale) normally graded fine-sand layer (Figures 11d, 11e, 11f) or by a fine-sand layer in which grading is not recognizable and referred to as "nongraded" (Figure 11g). Although textural grading between couplets of thin-coarse and overlying fine beds is not discernable in a number of cases, the close similarity and proximity of such beds to distinctly graded units suggests a similar type of origin.

Below the lower ramp, the group of horizontally laminated beds primarily consist of non-graded fine to very fine sand (Figures 11k and 11l).

Horizontally laminated

Non-bioturbated to slightly bioturbated - bar-, ramp-, and middle platform associated (Table 4, type 7). Subhorizontal- to horizontal-laminated beds of fine sand, collectively referred to as "horizontal laminated," are the dominant structural-bedding type making up the upper half of the shoreface prism between the bar or inner ramp and the seaward edge of the middle platform. Bed thickness ranges between 2 and 30 cm. If a bioturbation fabric is present, such as below in more seaward areas of the middle profile, it is typically slight and does not obscure physical internal structures. Texturally the units are either non-graded (Figure 11f), normally graded with thin coarse basal layers (Figure 11d), or made up of couplets of thin-coarse and thicker-fine nongraded beds. Horizontally laminated fine sand with progressive upward fining throughout the unit occurs locally in the upper prism and locally in lower parts of the prism amid cross-bedded units. Horizontal lamination in coarse sand to gravel occurs rarely and locally in lowermost landward parts of the sediment prism (Figure 11a).

Horizontal, or "planar," parallel lamination in the subsurface may develop in shallow marine sand in two ways (Clifton 1976). It may be generated below an aggrading planar bed surface under sheet flow (high velocity, high shear stress) conditions, equivalent of that of the upper flow regime, or, by much lower velocities associated with the migration of ripple forms and a slow rate of accretion (Newton 1968). During fair-weather wave conditions, the sediment-water interface across the bar, upper ramp, and middle platform sector, that is, the area between about the 2.0- to 4.0-m depth, is usually covered by a planar bedform zone at shallower depths and a wave-rippled zone at greater depths (Schwartz 1981b). During higher energy periods, e.g., wave height >1.2 m and wave periods of 8-11 sec, sheetflow conditions (Clifton and Dingler 1984) extend across the entire middle sector of the profile. Aggradation under high velocity plane-bed conditions, such as > 80 - 100 cm/sec (Komar and Miller 1975; Clifton and Dingler 1984) most reasonably accounts for the development of horizontal lamination in the fine sand beds.

Supporting evidence for plane-bed development of subhorizontal lamination across the middle profile includes the following:

a. A clear relationship between observed plane-bed conditions and parallel-laminated internal structure at shallower depths.

b. Existence of plane-bed conditions across the entire middle profile sector during higher energy events.

c. Textural and heavy mineral evidence for shear sorting (Clifton, 1976).

d. Continuity of horizontal laminated bedding types between the bar-upper ramp and middle platform.

e. Occurrence of small concave-convex shells in a plane-bed (high shear-stress) stable orientation (Clifton 1976).

f. Absence of intermixed wave-ripple cross-stratification structures, including very low-angle climbing ripple foresets, which would reasonably occur in association with ripple-produced parallel lamination over the long term.

The normally graded beds and thin nongraded coarse beds indicate episodes of stronger flow, sometimes associated with scour, followed by lower velocity, but continued, upper-regime flow. Normal grading in horizontally laminated coarse sand to gravel also reflects aggradation on a planar bed coupled with diminishing flow strength, but the planar surface of accumulation may develop either under very weak (very low shear stress) or exceptionally strong flow conditions.

Bioturbated - lower ramp associated (Table 4, type 8). Horizontally laminated sand in this outer region is structurally similar to that at more landward middle-profile locations. However, sand of the lower ramp is finer grained and the physical structures are typically overprinted to various degrees by a bioturbation fabric. Where the degree of bioturbation is slight to moderate, original physical structures remain identifiable (Figure 11k). Where there has been a high degree of bioturbation, bed contacts and internal structures range from partially to totally obscured (Figure 11l). Increased organic content and darker coloration is associated with decreased grain size and increased bioturbation. Bedding thickness ranges from 2 - 20 cm. However, in cases of intense biogenic overprinting, bedding contacts commonly become indiscernible and the sediment appears homogenous.

During fair-weather wave conditions, the sediment-water interface along the lower ramp is covered by active to inactive small-scale, two-dimensional wave ripples (Schwartz 1981b). However, the lower ramp sector becomes part of the surf zone during major storms (Howd and Birkemeier 1987; Lee and Birkemeier 1993) with quantitatively predictable high-velocity sheet-flow conditions along the bed (Clifton and Dingler 1984). Similar to the middle platform, high velocity plane-bed conditions are also interpreted to be responsible for horizontal-laminated bed aggradation in this deeper zone. Minimum velocities of 70 - 80 cm/sec are required for plane-bed development in very fine to fine sand (Harms, Southard, and Walter 1982; Clifton and Dingler 1984). Supporting evidence for a plane-bed interpretation includes:

a. Continuity of horizontal lamination between the middle platform and lower ramp.

b. Predicted existence of plane-bed conditions across the entire middle profile sector during higher energy events.

c. Occurrence of small concave-convex shells in a plane-bed (high shear-stress) stable orientation (Clifton 1976).

d. Absence of intermixed wave-ripple cross-stratification structures.

e. Aggradation in association with high-energy events (discussed later).

In summary, wave-ripple structures, which would serve as a record of accretion under fair-weather conditions, were not present in the vibracores. Conditions for plane-bed and horizontal lamination development occur during periods of elevated bed velocity (e.g., due to an increase in wave and coastal current conditions or an increase in wave conditions to the point that the lower ramp becomes part of a high-energy dissipative surf zone). Subsequent fair weather conditions result in an active wave-rippled bed or inactive biogenically reworked bed. The lower ramp setting is most frequently in a low-energy state compared to shoreward locations, allowing for longer periods of biogenic reworking and consequent overprinting of internal physical structures.

Low-angle parallel-laminated, bar-trough-flank associated (Table 4, type 9). Very low-angle parallel-laminated beds are common below the bar flank in profile 188 and in the lower half of the shoreface prism between the bar crest and the seaward edge of the middle platform (Figure 11h). Landward dipping foresets occur directly under the landward-sloping flank of the bar, whereas dip directions range from landward to seaward in other locations. In some cases, a single bed showed internal progression from low-angle parallel lamination upward into horizontal lamination (Figure 11i). Bedding thickness ranges from 3 - 30 cm. The beds are texturally similar to all varieties described for horizontally laminated beds.

Low-angle parallel lamination represents aggradation upon a very low-angle planar surface, such as upon a bar flank or rip-channel margin. In this case, most occurrences are interpreted to be related to the lateral shifting and upbuilding of bar flanks. Requisite for bar development would be attendant scour or trough "cutting." Although the large-scale surface of accumulation would necessarily be inclined to produce low-angle bedding, the parallel-lamination documents that fluid motion was relatively strong, similar to that for development of plane-bed horizontal lamination. The normally graded beds with erosional bases document high-energy events, which initially resulted in scour and coarser grain deposition.

Medium- to large-scale, cross-stratified, outer-trough-associated (Table 4, type 10). Medium- and large-scale cross-stratified beds are also common in the lower half of the shoreface prism between the bar or upper-ramp and seaward edge of the middle platform. This structure and low-angle parallel lamination together make up about 40 percent of the beds in this part of the subsurface. The medium- and large-scale cross-stratification is usually tangential at the base and exhibits both the landward and seaward components of dip. Some beds show a progressive upward change from horizontal lamination at the base to tangential cross-stratification (see Figure 11j). The grain size of many cross-stratified beds buried below the upper ramp is similar to that of coarser cross-stratified beds (types 3 and 4) below the active trough of profile 188. In the seaward direction, the amount of fine sand making up the beds increases, whereas the amount of gravel and medium sand greatly decreases. Overall, the beds are usually nongraded or normally graded as described above.

The cross-stratified beds represent aggradation associated with medium- to large-scale three-dimensional ripple (megaripple) migration under flow conditions less energetic than that for horizontal and low-angle parallel lamination. Normal grading is partially a product of textural sorting across the bedform, similar to that for the coarser-grained beds (type 3). In cases where a scour surface in fine sand occurs below a much coarser cross-stratified bed, it is most likely that scour and coarsening were also due to current-dominated events which caused larger-scale change rather than just bedform migration alone. The upward change from horizontal lamination to cross-stratification within a single bed records bedform migration and aggradation upon a planar inter-ripple area.

Small-scale trough cross-stratified.

Non-bioturbated, bar-, ramp-, and middle-platform-associated (Table 4, type 11). Small-scale trough cross-stratification, although uncommon, is scattered throughout the middle part of the shoreface prism. It is most common in the stratigraphically lower half of the prism. The structures occur in thin (<5 cm thick) beds of fine to medium sand.

The small-scale trough-shaped structures were produced by the migration of small three-dimensional ripples under relatively low-velocity, current-dominated flow conditions. Infrequent occurrence of this bedding type indicates occasional current-dominated events, such as rip-current or coastal current, which result in local accretion upon middle profile areas.

Bioturbated, lower-ramp-associated (Table 4, type 12). Similar to more landward settings, relatively thin beds (<5 cm) of small-scale trough cross-stratification occur infrequently below the lower ramp (Figure 11l). By contrast, the trough cross-stratified beds are finer-grained and bioturbated, similar to horizontal-laminated beds of the lower ramp.

Small-scale trough cross-stratification in the lower ramp was also produced by the migration of small three-dimensional ripples under relatively low-velocity, current-dominated flow conditions and subsequently bioturbated.

Second-Order Elements - Bed Sequences

A number of upward fining or upward coarsening sequences of beds occur in the shoreface prism in association with particular environmental settings. The sequences are named on the basis of textural trend and dominant bedding structure. Physical properties and interpretations of the sequences are summarized in Tables 5 and 6.

Gravel and coarser sand sequences

Several sequences in the coarse textural group occur below the swash, swash-trough transition, and inner-trough region of the profiles. Gravel dominated, upward fining, and upward coarsening parallel-laminated sequences occur in association with swash and swash-trough transition settings. Gravelly and coarse sand dominated upward-fining sequences of cross-stratified and horizontal-laminated beds occur in association with inner trough settings.

Upward fining low-angle parallel-laminated - swash zone associated (Table 5, type 1). Upward fining gravel-dominated sequences of stacked normally graded low-angle parallel-laminated beds occur below the active swash zone of profile 188 (Figures 7a and 12). The sequences range from 10 to 30 cm thick and are characterized by an erosional lower boundary.

Each sequence represents a temporal trend of net seaward buildup of the swash zone. An example of time-series progradation of the beach face is shown in Figure 13. Individual normally graded beds within a sequence represent a single aggradational event. The succession of beds within a given sequence represents a series of aggradational events separated by minor periods of differing conditions, such as erosion or nondeposition. Upward fining through the sequence records the progressive superposition of landward (upslope) finer-grained settings over preceding lower and coarser-grained swash settings (Figure 9). Superposed second-order sequences (Figure 12) represent periods of net progradation separated by one or more events of relatively major beach erosion.

Upward coarsening - swash-trough transition (Table 5, type 2). Upward coarsening gravel-dominated sequences, 8- to 50-cm-thick, occur below the upward-fining swash-zone sequences and, laterally, below the margin of the inner trough in the swash-to-surf transition zone (Figures 7c, 7d, and 12). The upward coarsening sequences primarily consist of stacked inversely graded and nongraded subhorizontal and low-angle parallel-laminated beds (type 3) as well as mixed normally graded cross-stratified beds (type 4).

Each sequence represents a temporal trend of net seaward progradation of the swash-inner trough transition. In this zone, surficial material commonly fines

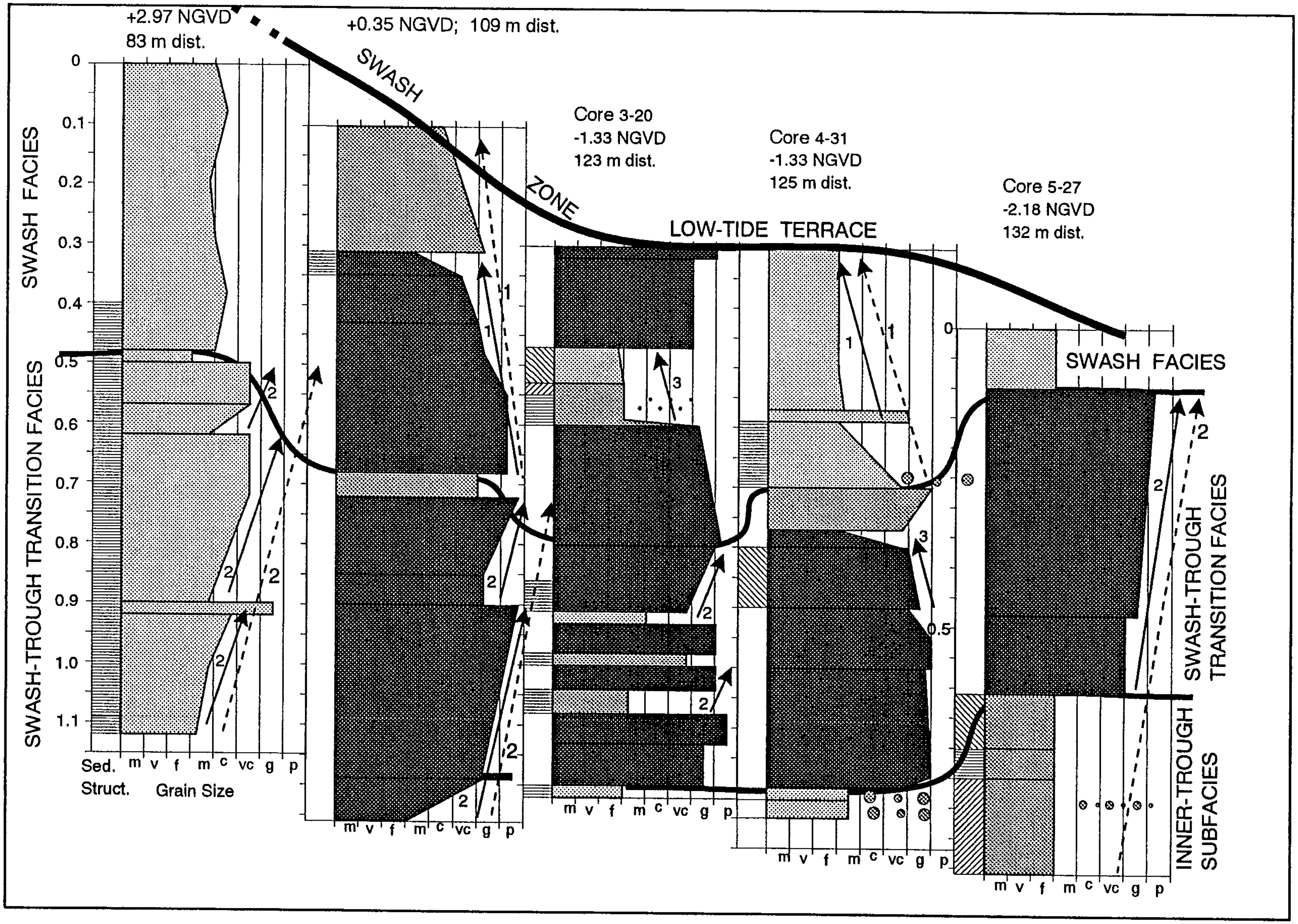

Figure 12. Facies below beach and margin of inner trough along profile 188. Examples of second-order sequence types are indicated by solid arrows and first-order trends through facies by dashed arrows; associated numbers are keyed to Tables 5, 6, and 7. Vibracores are schematically positioned relative to each other with actual NGVD elevations listed at the top of each core; sediment thickness is in centimeters. A key to symbols is located in Appendix A

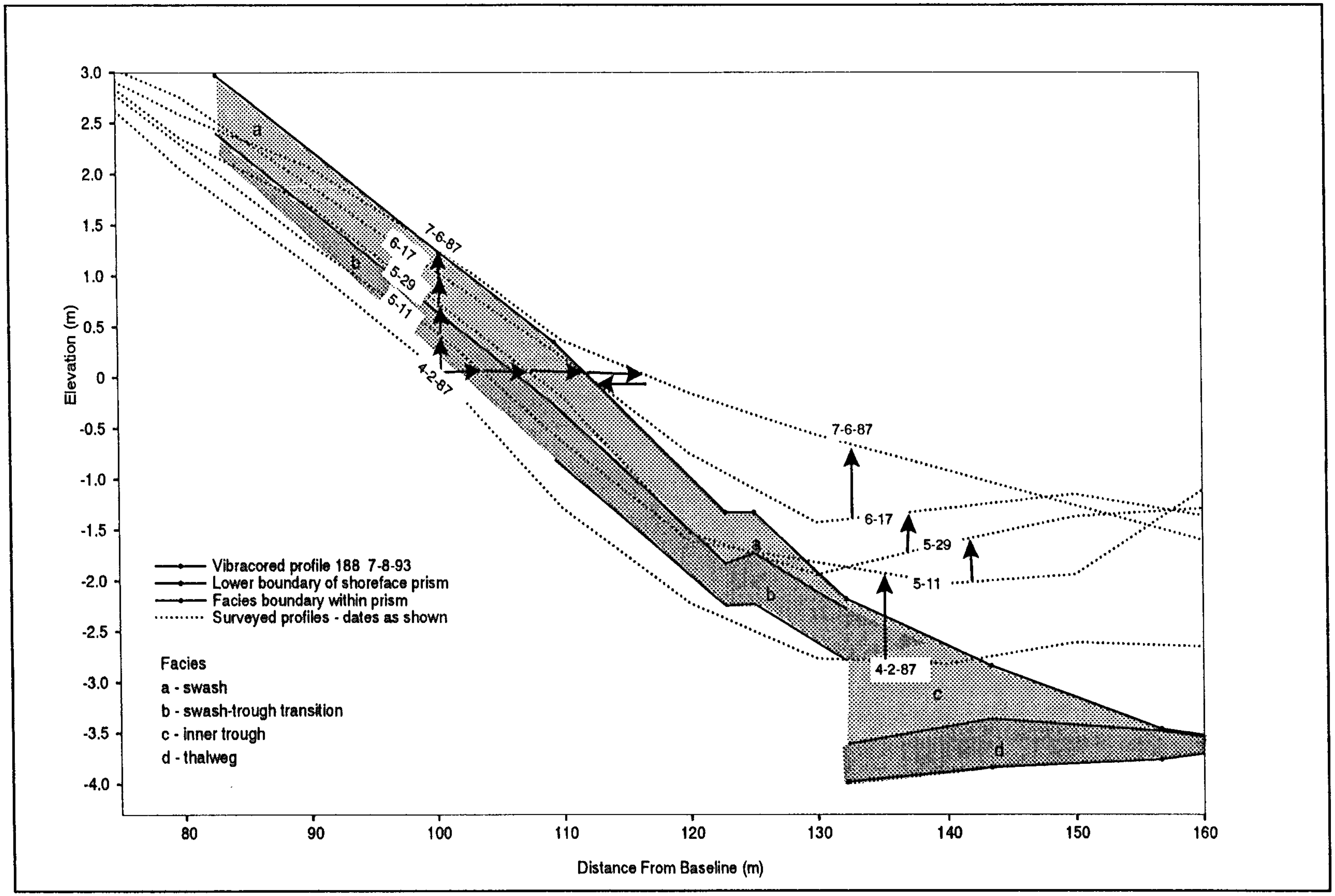

Figure 13. Sequential profile change along profile 188 illustrating progradation of the beach face over a 3-month period. Horizontal arrows indicate lateral migration of the beach and vertical arrows indicate associated vertical accretion which would result in facies pattern a and b. The series of vertical arrows at the far right indicate sequential trough infilling associated with the particular beach progradation event.

Table 7
Summary of First-Order Sedimentologic Elements (Facies and Composite Textural Sequences) and Associated Second- and Third-Order Elements

Facies Name		Grain Size	First-Order Textural Sequences	Second-Order Sequence Types	Third-Order Sequence Types	Facies Thickness (cm)	Occurrence and Origin
1. Swash		Gravel-medium sand	Upward fining. Lateral seaward coarsening.	Upward fining LAPL (1)	LAPL (1) typical; some LSCS (4) in lower part	10 - 60	Located below active foreshore & low-tide terrace. Episodic progradation of seaward coarsening beach (Figure 9)
2. Swash-Trough Transition		Gravel-medium sand	Upward coarsening from uncertying trough sand. Lateral seaward fining onto trough inner flank.	Upward coarsening gravely (2)	Inversely graded HL & LAPL (3); some normally graded LSCS (4) & HL (6).	40 - 60	Located below swash facies; extends seaward to flank of inner trough. Episodic progradation of seaward-fining margin of inner trough (Figure 9)
3. Trough	3A. Thalweg	Gravel-coarse sand	Upward fining from trough facies 3A into 3B or 3C	Upward fining LSCS (3) & HL (4)	Normal and inverse graded LAPL (3), LSCS (4,5) & HL (6); non-graded gravel	≤ 50	In thalweg of inner trough and along base of prism below bar to middle platform. Due to coarse infilling along thalweg of deeply scoured trough
	3B. Inner trough	Coarse to fine sand; minor gravel	Upward fining	Upward fining LSCS (3)	Mixed LSCS (4) & LAPL (2,9) abundant; also HL (7)	≤ 82	3B occurs below beach and upper ramp facies; 3C below upper ramp to middle platform facies. Both due to current-dominated trough scour and infilling
	3C. Outer trough	Coarse to fine sand; minor gravel	Upward fining. Lateral seaward fining	Upward fining LSPL (6) & upward fining LSCS (7)	LSCS (4 & 10) and LAPL (9) abundant; also HL (7)	≤ 150	
	3D. Outer-trough margin - similar to 3C except as noted.				LSCS (1C) and LAPL (9) abundant; also HL (7)	≤ 30	In lower half of prism below outer part of middle platform facies. Due to current-dominated deposition beyond flank of outer trough
4. Bar flank		Fine sand; and granules rare	Weak upward coarsening	----	LAPL (9) mixed with some LSCS (10) and SSTS (11)	≤ 80	Below landward flank of bar. Bar migration with aggradation upon landward flank
5. Upper Ramp - Platform		Fine sand; coarse sand and granules rare	Weak upward coarsening	Upward fining HL (5)	HL (7) dominated	30 - 130	Below upper ramp & middle platform. Buildup under high-energy wave-dominated conditions
6. Lower ramp		Fine sand to very fine sand	Weak upward coarsening	----	(Bioturbated HL (8)	25- - 110	Below lower ramp. Buildup under high-energy wave-dominated storm conditions

seaward from the gravel-rich lower margin of the swash zone or low-tide terrace (Figure 8). Individual horizontal and low-angle parallel-laminated beds represent single aggradational events upon shallow subhorizontal to low-angle surfaces at the inner trough margin. The less common higher-angle cross-stratified beds record the presence of large ripples migrating along the inner flank of the trough under current-dominated flow conditions. Upward coarsening through the sequence records the episodic, but progressive, superposition of previously adjacent (landward upslope) coarser-grained settings of the encroaching swash margin (Figure 9). Superposed upward coarsening sequences represent periods of net progradation separated by one or more periods of relatively major erosion.

Upward fining, cross-stratified, inner-trough-associated (Table 5, type 3). Upward fining gravelly and sand-dominated cross-stratified sequences, 5 - 40 cm thick, occur in several locations: below upward-coarsening swash-trough transition sequences; laterally in the active trough of profile 188; and, in buried historical inner-trough locations of both profiles. The sequences primarily consist of stacked normally graded (type 4) or inverse-to-normally graded medium- to large-scale cross-stratified beds (types 4 and 5) mixed with subhorizontal or low-angle parallel laminated beds (types 2 and 6) (Figures 7e, 7f, 7g, and 14). An erosional surface marks the lower boundary of a sequence.

Each sequence represents eventual trough infilling following a major trough-scour event. The abundance of texturally graded and higher-angle cross-stratified beds reflects the common occurrence and migration of large three-dimensional ripples under current-dominated conditions. Intermixed horizontal and low-angle parallel-laminated beds represent aggradation upon intervening to widespread subhorizontal to low-angle surfaces. Such bedform types are common within active troughs. The textural trend across well-developed troughs is one of textural fining away from the deeper axial region towards the trough flanks (Figure 8). Thus, upward fining through the sequence records the eventual infilling of a trough as increasingly finer-grained settings similar to the trough margin are superposed upon previous trough thalweg settings (Figure 10). Stacked upward fining sequences represent periods of trough infilling separated by one or more periods of scour and trough redevelopment.

Upward fining, horizontal-laminated, inner-trough-associated (Table 5, type 4). Upward fining gravelly parallel-lamination dominant sequences, 10 - 20 cm thick, occur below the active inner trough and below the inner bar at historic inner-trough depths. The sequences consist of stacked normally graded horizontal-laminated beds (type 6) or an upward conversion from horizontal lamination to low-angle parallel lamination (type 2) (Figures 7a, 14, and 15).

The sequence represents scour and partial buildup upon near-horizontal to very low-angle planar surfaces within an inner trough setting. The vertical textural trend through the sequence represents initially coarse conditions associated with thalweg development during the trough-scour phase, followed by eventual buildup of a finer-grained bed (Figure 10).

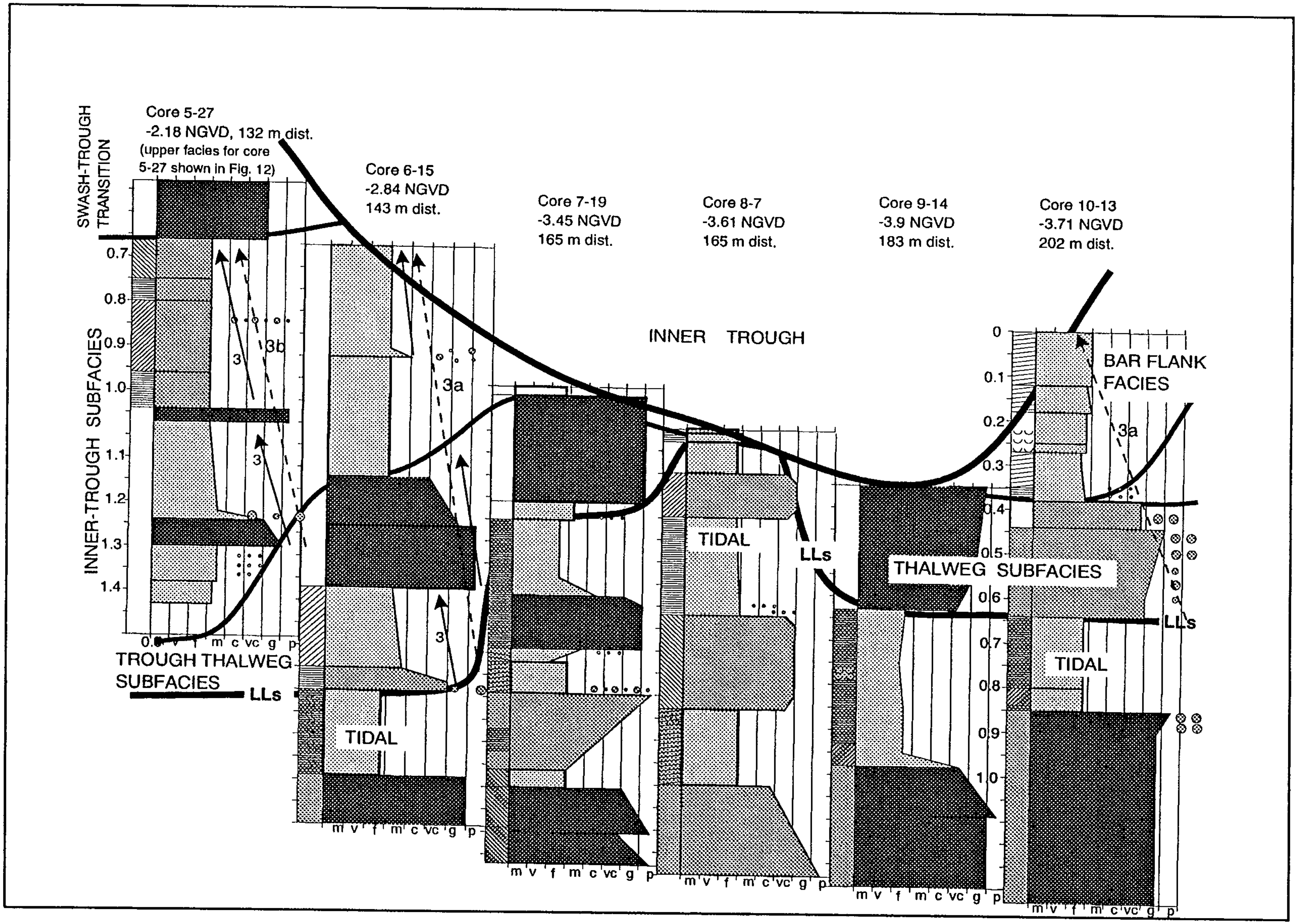

Figure 14. Facies below inner trough of profile 188 (see Figure 12 caption for explanation of symbols, core position, and vertical scale

Finer sand sequences

Distinct sequences in the finer textural group occur directly below the upper ramp and middle platform as well as deeper beneath the same area in association with historical outer-trough and outer-bar locations.

Upward fining horizontal laminated - ramp-platform associated (Table 6, type 5). Upward fining, parallel-lamination dominant sequences, 6 - 20 cm thick, are most common directly below the upper ramp and middle platform and infrequently at underlying positions in historical inner-trough depths (Figures 15 - 17). An erosional lower contact and normally graded and nongraded horizontally laminated beds (type 7) commonly make up a sequence (see Figures 15 and 16).

The lower erosional boundary and overlying horizontal lamination record the occurrence of a significant erosional event followed by deposition under relatively high-velocity conditions. It is possible that the coarser material at the base of the sequence represents winnowing of fine sand as well as the selective transport of coarser sand to the depositional site in association with the initial high-energy event. The upward fining trend may represent trough infilling whereby lateral fining occurs away from a coarser axial zone of downward scour, analogous to that of coarser and well-defined troughs (Figure 10).

Upward fining, low-angle, parallel-laminated, bar-flank-associated (Table 6, type 6). Upward fining, low-angle, lamination-dominated sequences, 12-45 cm thick, occur in the lower half of the shoreface prism below bar, upper ramp, and middle platform locations (Figures 15-17). An erosional lower contact is common, particularly in sequences below the upper ramp. Normally graded and nongraded low-angle parallel laminated beds (type 9) make up a typical sequence. Some sequences consist of medium- to large-scale cross-stratification (type 10) changing upward into low-angle parallel lamination or low-angle parallel lamination changing upward into horizontal lamination (type 7).

In general, all variants of the sequences represent accretion under relatively high-velocity conditions in a bar-and-trough associated setting. The low-angle parallel lamination reflects depositing upon low-angle locally planar surfaces, most likely that of a bar flank. An upward conversion from large-scale cross-stratification into low-angle parallel-laminated beds reflects structures produced by large-scale three-dimensional ripples in trough settings being superposed by bar-flank planar bedding. An upward conversion from low-angle parallel lamination into horizontal lamination reflects further infilling of trough-flank settings and development of a locally subhorizontal bed. The upward fining textural trend represents initial coarsening in zones of trough scour, analogous to the active inner trough of profile 188, followed by infilling from finer adjacent areas (Figure 10).

Upward fining, cross-stratified, outer-trough-associated (Table 6, type 7). Upward-fining, large-scale, cross-stratified sequences, 10 - 60 cm thick, occur in association with low-angle, parallel-laminated sequences in the lower half of the shoreface prism below the upper ramp and middle platform (Figures 15 - 17). An

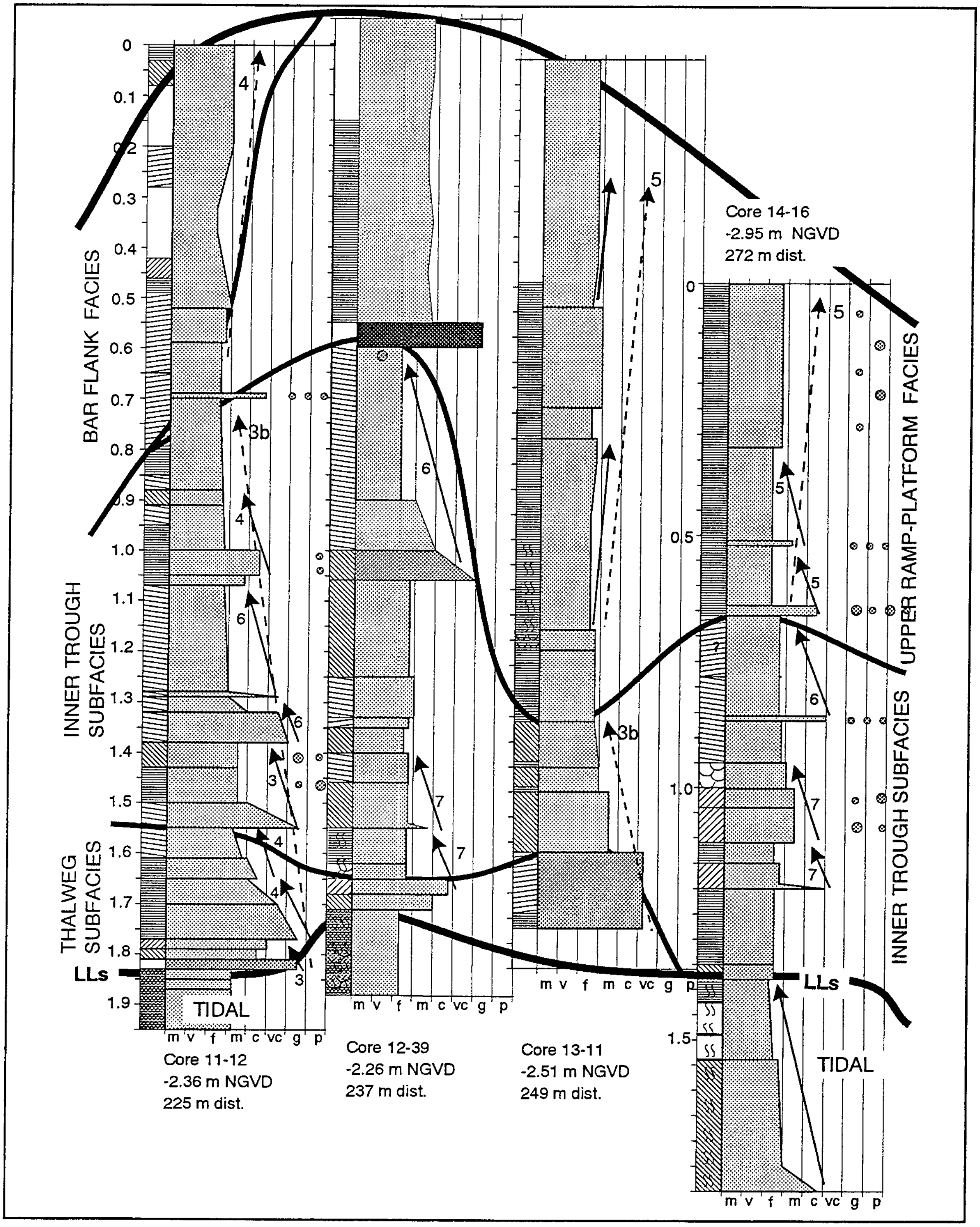

Figure 15. Facies below the active bar and upper ramp of profile 188 (see Figure 12 caption for explanation of symbols, core position, and vertical scale)

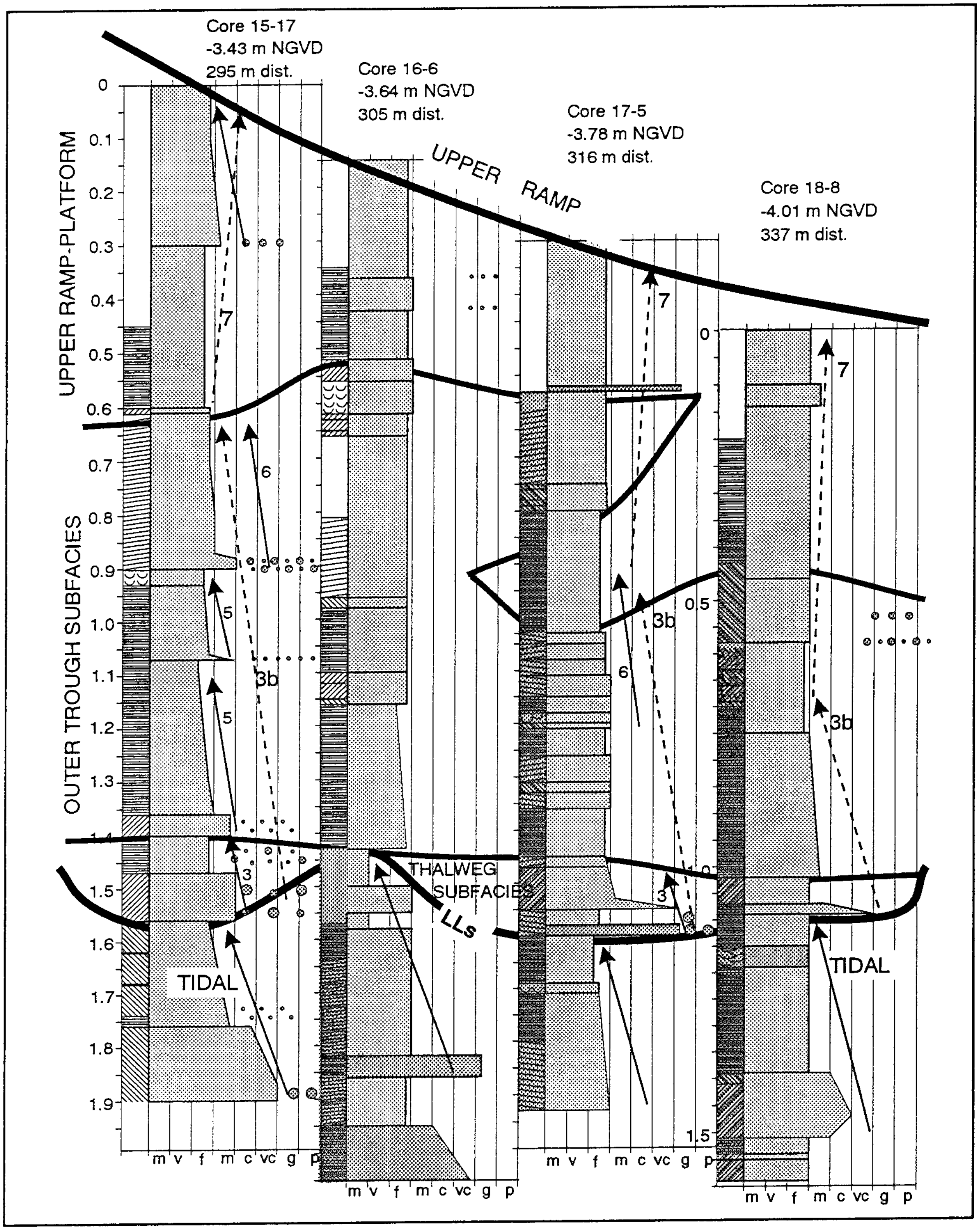

Figure 16. Facies below the upper ramp of profile 188 (see Figure 12 caption for explanation of symbols, core position, and vertical scale)

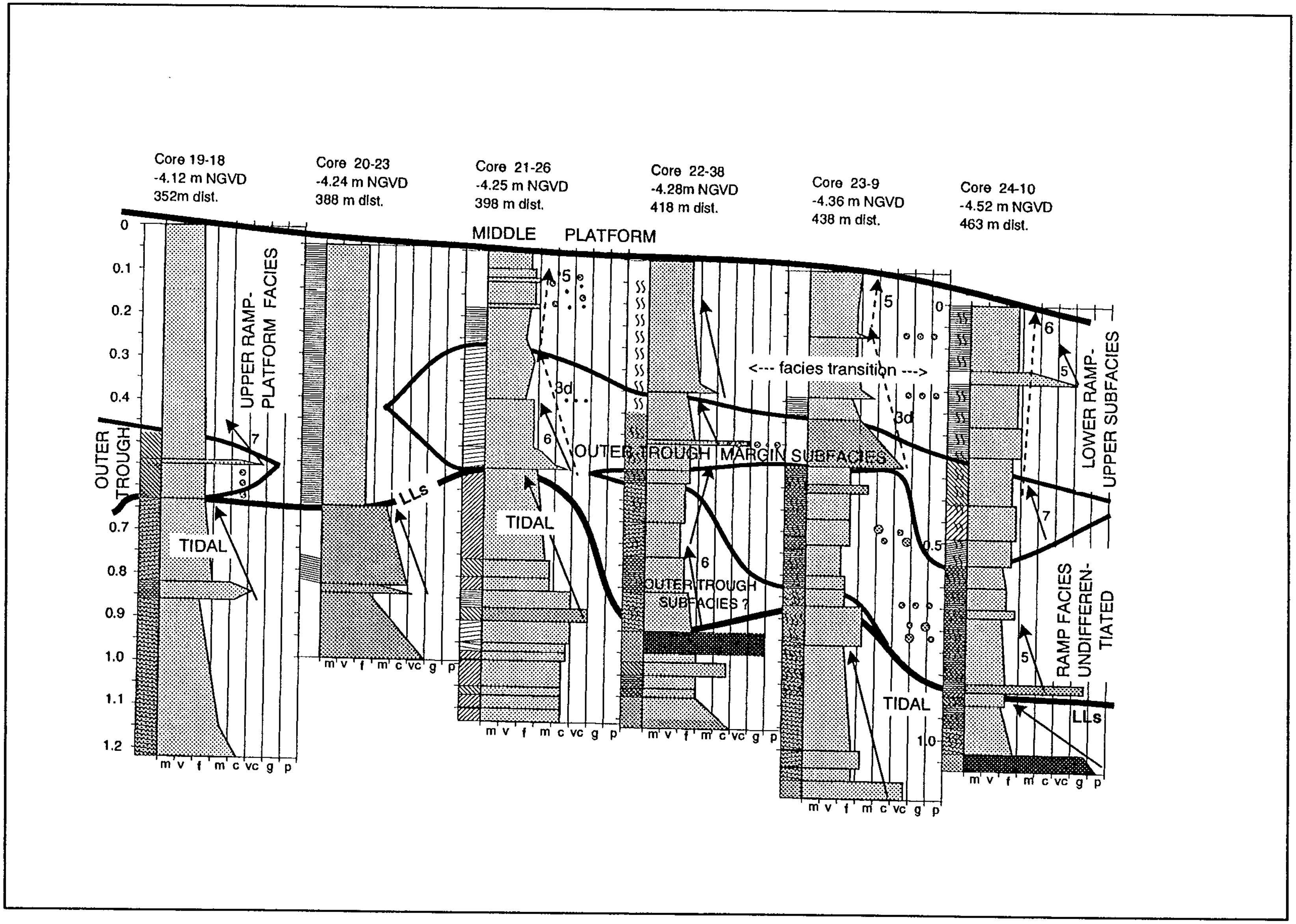

Figure 17. Facies below the middle platform of profile 188 (see Figure 12 caption for explanation of symbols, core position, and vertical scale)

erosional lower contact commonly marks the base of a sequence. Although three-dimensionally cross-stratified beds (type 10) are dominant, the sequences typically contain a mixture of low-angle parallel-laminated beds (type 9) and horizontal-laminated beds (type 7). In some cases, a sequence consists of large-scale cross-stratification changing upward into low-angle parallel lamination or large-scale cross stratification changing upward into horizontal lamination.

All variants of the sequences represent current-dominated settings and are associated, either directly or indirectly, with trough development (later discussed under "Outer Trough Subfacies" and "Outer Trough Margin Subfacies"). The dominance of large-scale cross-stratification reflects the development of large-scale three-dimensional ripples during periods of lower regime current-dominated flow. The mixed low-angle, parallel-laminated and horizontal-laminated beds represent temporal changes whereby sediment accumulated upon low-angle to subhorizontal surfaces during periods of upper regime flow. An upward conversion from large-scale cross-stratification into low-angle parallel-laminated beds represents large-scale, three-dimensional ripples in a trough setting sequentially superposed by a lower-angle surface, perhaps that associated with a large ripple of bar flank. An upward conversion from large-scale cross-stratification into horizontal lamination reflects trough infilling and development of a locally subhorizontal bed. The upward fining textural trend represents initial coarsening associated with trough development, analogous to the active inner trough of profile 188, followed by infilling from finer adjacent areas (Figure 10).

First Order Elements - Facies and Composite Textural Sequences

Six major facies groups were identified within the shoreface prism and named on the basis of their environment of deposition (Figures 18 and 19 and Table 7). The major facies groups include swash, swash-trough transition, trough-associated, bar flank, upper ramp-platform, and lower ramp. Subgroups, or subfacies, were designated for the trough-associated group and the lower ramp group. First-order textural trends occur either between the mapped boundaries of a particular facies or extend from one facies into another.

Swash facies - upward-fining, parallel-laminated sand and gravel

A coarse sand and gravel lens dominated by low-angle, seaward-dipping parallel-laminated bedding directly underlies the lower foreshore and adjacent low-tide terrace of profile 188 (Figure 18). The cored facies is prismatic in shape and ranges from about 60 cm thick in the most landward core to about 10 cm thick at 1.3 m below NGVD. An upward-fining, first-order textural trend extends vertically through the facies (Figure 12). Laterally, the facies coarsens downslope from medium and coarse sand in the uppermost swash region to gravel at the low-tide terrace (about 1.3 m below sea level), then fines seaward into fine and medium sand. The facies contains upward-fining, parallel-laminated, second-order sequences (type 1) and is dominated by normally graded parallel-laminated coarse sand and

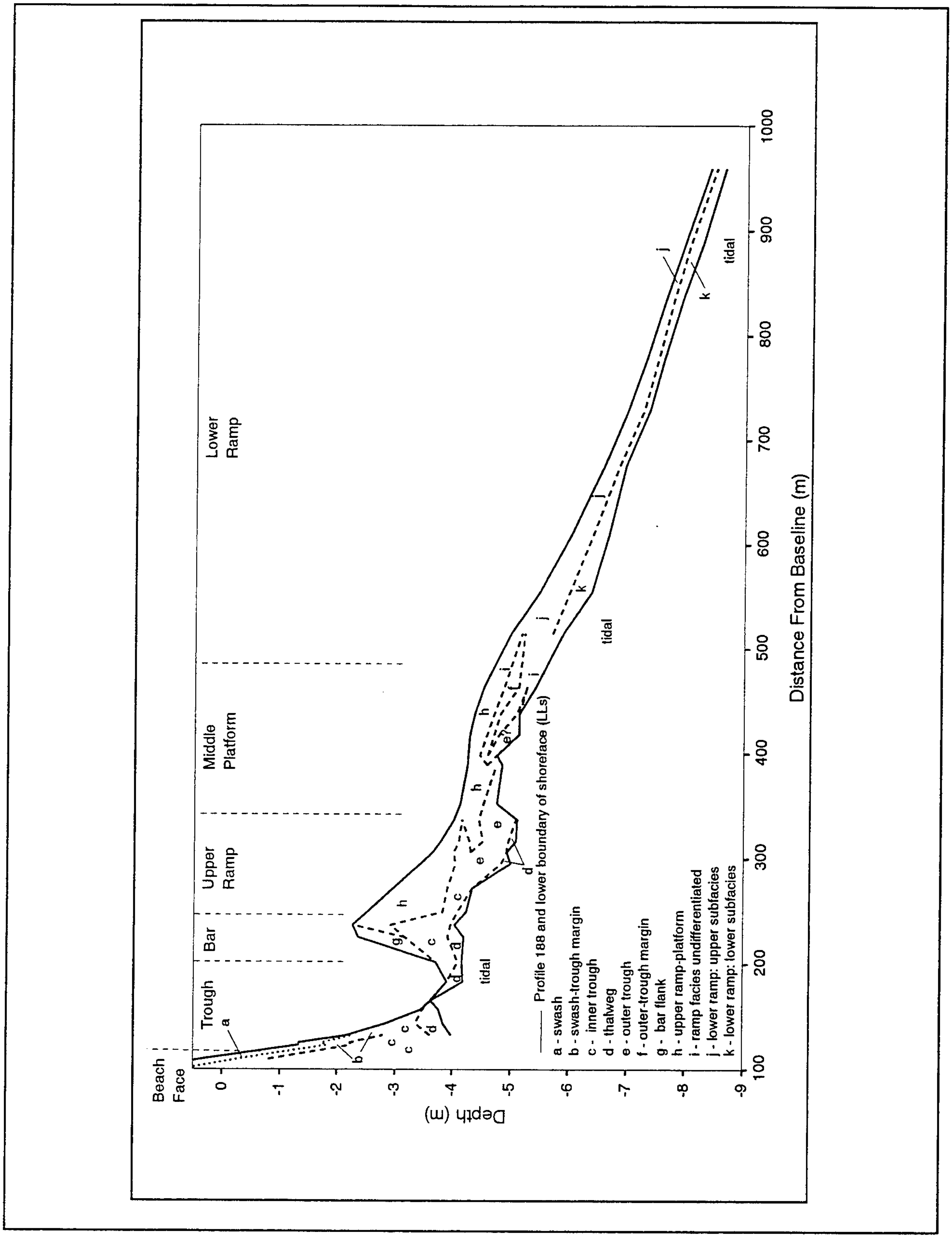

Figure 18. Facies distribution below profile 188

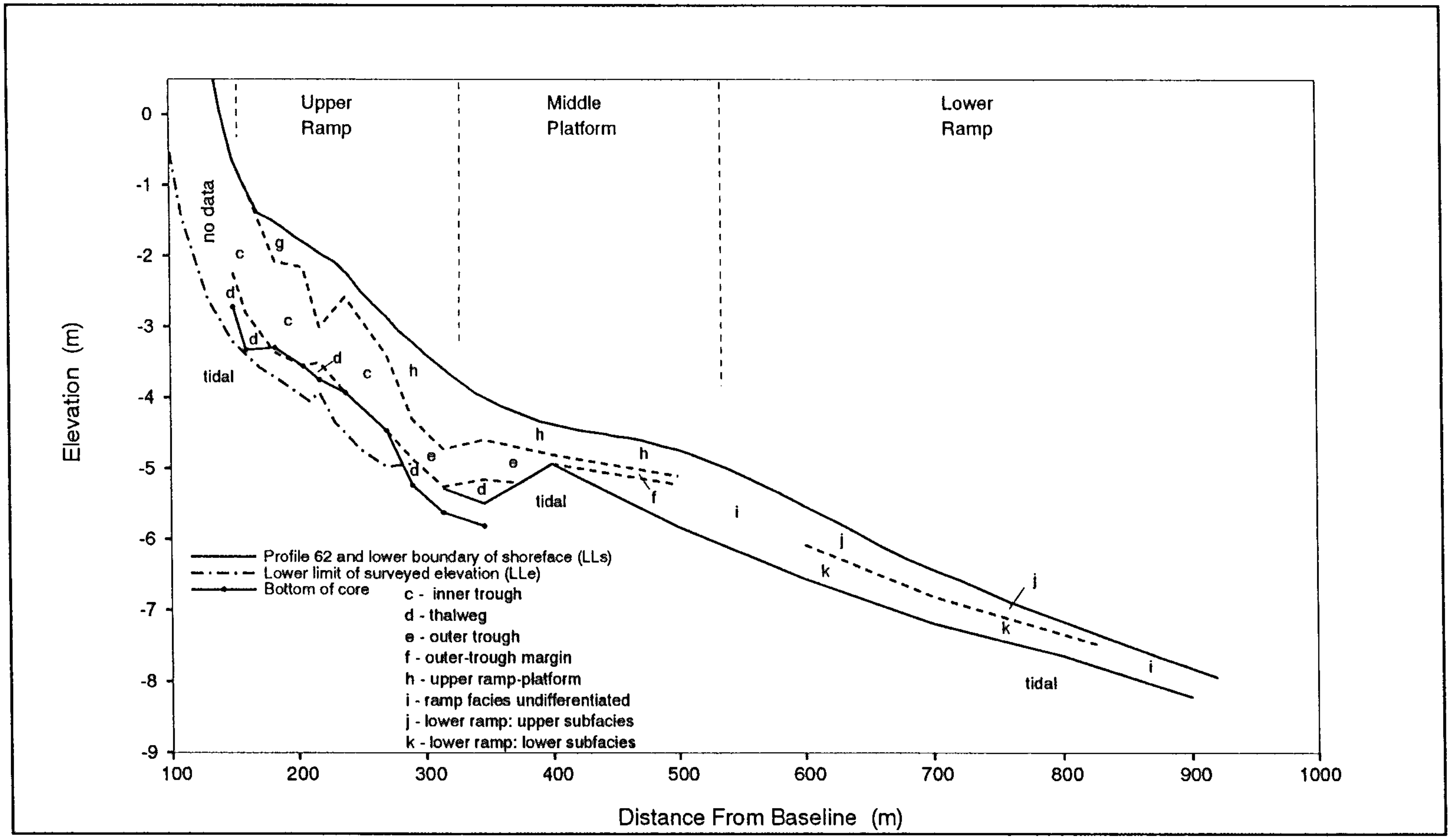

Figure 19. Facies distribution below profile 62

gravel beds (type 1) (Figure 12). However, normally graded, large-scale, cross-stratified sand and gravel beds (type 4) occur in lower and seaward parts of the facies zone.

The facies represents episodic progradation of the swash zone over innermost trough settings (Figure 9). The upward fining trend is not purely progressive, but represents a number of outbuilding and erosional events as recorded by erosional surfaces, stacked normally graded beds, and stacked second-order sequences. An example of time-series progradation of the beach face which would result in such facies development is shown in Figure 13. The occurrence of cross-stratified beds in lower and seaward parts of the facies reflects the presence of large-scale ripples in subaqueous settings downslope from pre-existing planar swash-zone surfaces.

Swash trough transition - upward-coarsening, sand-to-gravel facies

An upward-coarsening, gravel-dominated facies directly underlies the upward-fining swash facies (Figures 12 and 18). The cored unit is tabular shaped, ranging in thickness from 40 - 60 cm, and terminates abruptly between -2.3 and -2.8 m NGVD at, and slightly below (<10 cm), the inner margin of the trough. Vertically, the facies commonly shows strong first-order upward coarsening from an underlying trough sand facies (Figure 12). In the landwardmost location, medium to coarse sand makes up the upper part of the partially cored unit. The facies is dominated by upward coarsening sequences (type 2) and inversely graded low-angle, parallel-laminated beds (type 3). Other bedding types in the facies include normally graded cross-stratified beds (type 4) and horizontally laminated beds (type 6). Overall, the facies makes up the coarsest zone in the shoreface prism.

The facies represents progradation of the swash inner trough margin over deeper portions of the inner trough (Figure 13). The seaward margin is spatially linked to textures and bedforms which occur at the juncture between the swash zone and surf zone along the uppermost margin of the inner trough. Localized gravel with down-flank fining into the trough (Figure 8), planar bed surfaces, and scattered medium-scale to large-scale three-dimensional ripples are commonly observed in that setting at the field site (Schwartz 1981b). Thus, interpreted bedforms and hydrodynamic conditions for the observed parallel-laminated and cross-stratified structures are consistent with the lateral occurrence of corresponding bed conditions along innermost trough settings. The upward coarsening first-order trend represents net progradation of a seaward-fining trough margin setting such as illustrated in Figure 9. Erosional surfaces, stacked beds of alternating sand and gravel, and stacked second-order sequences indicate a number of outbuilding and erosional events during progradation. Inversely graded beds and normally graded beds within the facies are a record of aggradation upon planar surfaces and migrating large ripple forms, respectively.

Trough-associated facies

The lower half of the shoreface prism, between the beach and upper part of the lower ramp, is dominated by trough-associated facies (Figures 18 and 19). Four subfacies were designated: thalweg, inner trough, outer trough, and outer-trough margin. In general, the group manifests first-order upward fining as well as lateral seaward fining. A mixture of large-scale, cross-stratified, horizontally laminated, and low-angle parallel laminated beds are characteristic as well as stacked upward-fining, low-angle, parallel-laminated (type 6) and cross-stratified (types 3 and 7) second-order sequences.

Thalweg subfacies - gravel and coarse sand. A thin (0 - 50 cm) discontinuous, gravel- to coarse-sand-dominated lense extends along the base of the shoreface prism below the active beach and upper ramp(Figures 18 and 19). In most cases, the subfacies rests upon tidal inlet-associated beds of similar texture and composition (Figures 14-16). Most of the subfacies occurs below the lower limit of surveyed elevation change with greatest thicknesses located in concave-based scour zones as defined by the LLs (Figures 18 and 19). Only in the thalweg of the inner trough along line 188 did the subfacies make up the active bed.

Although the subfacies does not show a well-defined internal first-order textural sequence, there is strong first-order upward-fining into overlying sand of the inner-trough subfacies (Figures 14-16). Seaward, the unit becomes thinner and finer grained. Upward-fining, cross-stratified and horizontal-laminated, second-order sequences (types 3 and 4) occur within the subfacies. Dominant bedding types include (a) discontinuous and overlapping normal and inversely graded low-angle parallel-laminated (type 3), (b) large-scale cross-stratified (types 4 and 5), and (c) horizontal laminated (type 6). Although relatively rich in coarse sand and gravel, the thalweg subfacies is texturally and volumetrically subordinate to the swash/trough transition facies.

This basal facies represents initial coarse infilling along the thalweg of deeply scoured troughs in inner profile settings (Figure 20). Most likely, some of the thalweg subfacies was deposited pre-survey (1981) as well as during major storm-trough scour-and-recovery events missed by post-storm surveys. Much of the gravel may be derived from underlying facies of similar texture. However, the presence of internal physical structures and second- and third-order textural trends within the thalweg subfacies clearly indicate a transported bedload, rather than residual lag, and the episodic migration of large-scale ripple forms within the thalweg.

Inner trough subfacies - cross-stratified sand and gravel. A cross-stratified medium-sand dominated and locally gravel-rich unit, 0-82 cm thick, overlies the gravel-rich thalweg subfacies or, in some cases, rests directly upon the erosional lower surface of the shoreface prism (Figures 14-16, 18, and 19). Sand size within the facies usually ranges between upper-fine (avg. ~0.21 mm) to lower-medium (avg. ~0.30 mm). Along profile 188, the unit underlies the coarser-grained swash and swash/trough transition facies and emerges at the active sediment/water interface along the inner flank of the trough (Figures 14 and 18). There, the unit makes up the active bed and thins to negligible thickness over the thalweg subfacies before thickening again and extending below the bar flank. Along profile 62, where an inner trough is absent, the subfacies remains relatively thick below the potential inner trough zone (Figure 19). Along both profiles, the unit thins seaward below the upper ramp and merges laterally with finer-grained sediment of the adjacent finer-grained outer trough subfacies (discussed below).

A vertical transect through the subfacies may show nongraded or weak upward fining. However, a strong first-order upward fining textural sequence extends from within the underlying gravel-rich thalweg subfacies into this sand-rich unit (Figures 14 and 15). Laterally, grain size decreases seaward. The inner trough subfacies is dominated by upward-fining, cross-stratified, second-order sequences (type 3) and by large-scale, cross-stratified (types 4 and 10), and low-angle, parallel-laminated (type 9) beds, many of which show normal grading. Subordinate horizontal laminated beds (type 7) are mixed throughout.

During the period of field investigation, part of this subfacies was active along the sediment-water interface in the inner trough of profile line 188 (Figure 20). Commonly observed bedforms in that setting include scattered medium-scale to large-scale three-dimensional ripples with intervening local to widespread planar surfaces (Schwartz 1981b). Predicted bedform and hydrodynamic conditions for the type of physical structures preserved throughout the subsurface are thus consistent with the occurrence of corresponding bed conditions in sand-rich trough settings. The first-order upward fining trend represents scour and coarser-grained deposition along the base of a deeply incised trough (Figure 8). Stacked upward-fining, second-order sequences represent series of trough scour-and-eventual fill events, whereas smaller scale normally graded beds represent ripple migration and high-to-low energy aggradational events.

Outer trough - cross-stratified, fine-sand-dominant subfacies. A cross-stratified sand and locally gravel-rich zone dominates the lower half of the shoreface prism below the upper ramp and inner part of the middle platform (Figures 15-17, 18, and 19). Maximum measured thicknesses, up to about 1.0 m, occur seaward of the inner-trough subfacies above a concave- or trough-shaped sector of the LLs (Figures 18 and 19). The outer trough subfacies thins seaward, terminating below the middle of the middle platform atop a convex-shaped sector of the LLs. The facies zone consists of discrete partially connected lenses, such as under profile 188 (Figure 18), and composite bodies, such as under the inner part of profile 62 (Figure 19). Individual lenses under profile 188 are characterized by planar tops and an erosional concave-shaped base. Laterally coalesced and vertically stacked lenses make up an irregular composite geometry. Along both profile lines, the combined outer trough and thalweg subfacies extend downward to the erosional base of the shoreface prism.

Grain size of the subfacies ranges from gravelly medium sand to fine sand (Figures 15 - 17). The landwardmost deposits contain abundant medium sand, whereas the seaward deposits are dominantly fine sand. In addition to lateral seaward fining, first-order upward fining through the subfacies is also characteristic. Gravelly and coarse sand beds are common at the base of the subfacies in landwardmost locations, whereas fine sand or very thin beds of coarser sand or scattered gravel are characteristic of basal beds in more seaward locations. At any

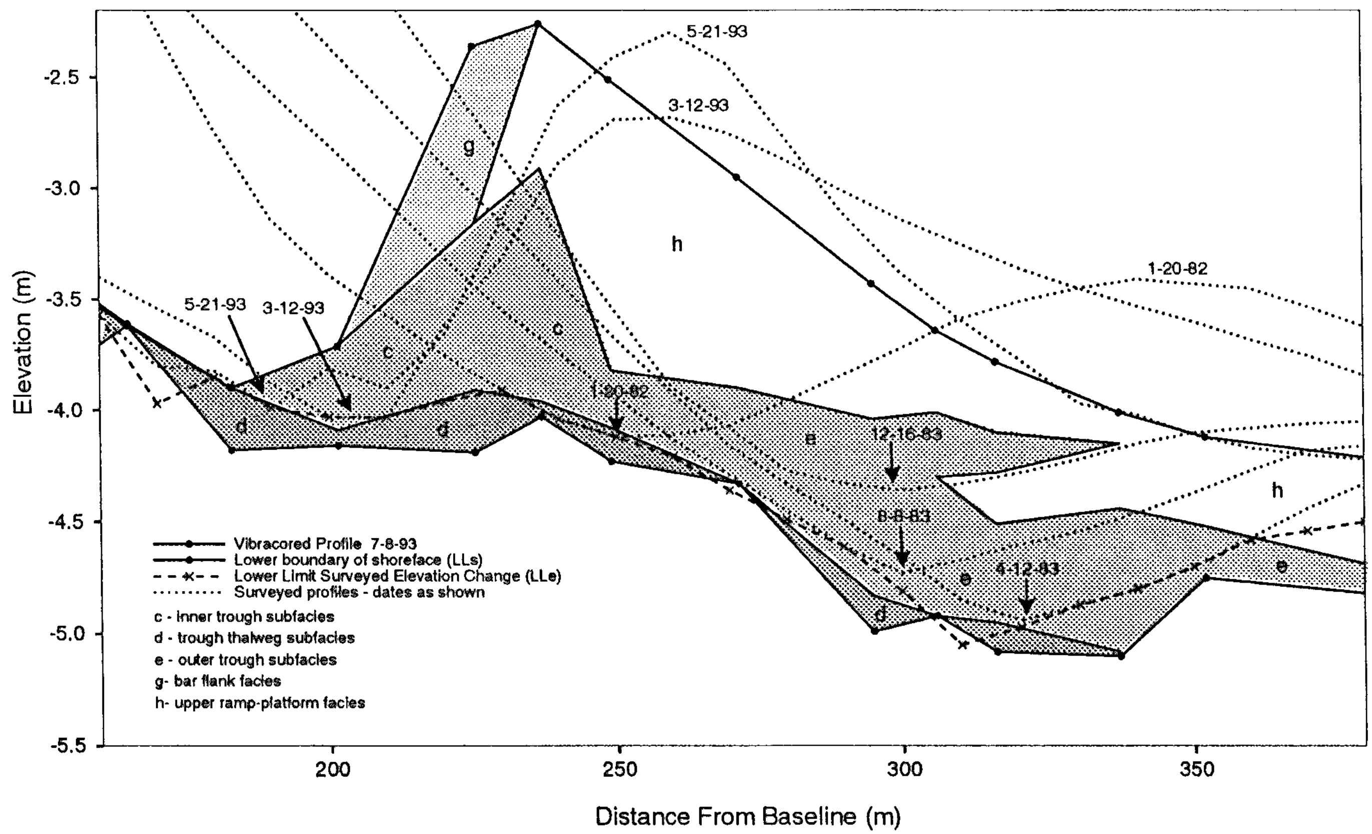

Figure 20. Comparison of trough facies distribution below the bar and upper ramp with surveyed trough occurrence at selected locales. Arrows mark the thalweg of troughs at the indicated times. Note that downward scour and the base of the trough facies occur at two levels, about -4.0 to -4.2 m and -4.7 to -5.0 m

given location, average grain size for the cross-stratified facies is usually slightly to appreciably coarser than that of adjacent horizontal laminated facies. Second-order sequences include upward-fining large-scale, cross-stratified sequences (type 7) and low-angle, parallel-laminated sequences (type 6) (Figures 15 and 16). Dominant bedding types include medium- to large-scale, cross-stratified types (types 4 and 10) and low-angle, parallel-laminated types (type 9) with landward- and seaward-dipping foresets (Figures 15-17). Subhorizontal-laminated (type 7) and small-scale trough cross-stratified beds (type 11) occur less commonly throughout the facies. Normally graded beds are abundant.

Similar to the inner trough subfacies, this subfacies primarily represents medium- to large-scale three-dimensional ripple, bar flank, and plane-bed development in the troughs of past profiles (Figure 20). Although a given storm may cut a single well-defined outer trough, the presence of multiple outer-trough subfacies zones with concave-shaped lower boundaries, numerous internal scour surfaces, stacked upward-fining sequences, and laterally and vertically stacked sand bodies indicates a composite of many cut-and-fill events. Zones of exceptional coarsening at deeper levels within the facies are related to coarsening along the axial zones past troughs, similar to that of profile 188 in this study and as documented by other profile shape-texture studies (Stauble 1992). The concentration of coarsest material in more landward and basal parts of the facies and fine sand in seaward parts of the facies serves to document that long-term, shore-normal size sorting does occur within the zone of long-term trough development. Moreover, given that outer troughs are cut during more extreme coastal events, the shore-normal grain size distribution documents that the greatest amount of coarser material, i.e., medium sand to gravel, tends to remain in the innermost part of the nearshore system in beach and inner trough settings. The first-order upward fining trend represents long-term infilling along a zone in which outer troughs tend to develop and deeply incise. Stacked second-order, upward-fining sequences represent repeated shallower-level trough scour events followed by eventual filling. Cross-stratified and normally graded beds represent ripple migration under current-dominated flow conditions and high-to-low energy aggradational events.

Outer trough margin, cross-stratified, fine-sand-dominant subfacies. Sand deposits with physical attributes similar to that of the outer trough subfacies occur adjacent to the outer trough subfacies and extend seaward to the juncture with the lower ramp (Figures 18 and 19). By contrast, this marginal subfacies is thinner and does not fully rest upon a well-defined trough-shaped scour base to the shoreface prism. Rather, seaward from its juncture with the outer trough subfacies, the marginal subfacies is "detached" from the seaward-dipping erosional base of the shoreface prism and extends as a thin lens into the middle of parallel-laminated, platform- and lower-ramp-associated facies.

Physical properties of this subfacies also represent deposition in a current dominated setting. Because of its physical similarity to, and lateral association with, the outer trough subfacies, it is most likely that this marginal subfacies also represents deposition related to widespread surf and longshore current occurrence. However, in contrast with the conditions for outer trough subfacies development are profile morphology and timing of current-dominated deposition along the marginal zone. In the outer trough zone, storm-caused trough scour precedes eventual current-dominated infilling, or recovery, of the trough. By contrast, Figure 21 illustrates that, as an outer trough sequentially developed in response to successive northeaster storms in February and March of 1989, excavated sand was simultaneously displaced seaward onto flanking areas. Illustrated in Figure 22 is the time-series history of surveyed elevation change within the marginal zone. The profile changes illustrated in Figure 21 occurred between erosional maximum E2 and accretion maximum A2 on Figure 22. The nature of profile change is representative of that associated with all other labeled accretion trends (E-to-A series). Prior to major accretion in the marginal zone, that part of the nearshore profile is typically in an erosional state as documented in Figure 22. Also demonstrated in Figure 22 is the linkage between cored subfacies and the E2-A2 time series of outer trough scour and marginal buildup. The pre-storm erosional maximum, E2, correlates with the base of an upward-fining current-associated sequence. The depositional sequence was subsequently truncated by the next erosional maximum, E3. Thus, the combined data sets indicate two facets of nearshore processes. First, while the nearshore profile undergoes scour in the outer trough zone, sand is displaced seaward onto adjacent parts of the middle platform or lower ramp. Secondly, for water depth-distance combinations associated with the cross-stratified marginal subfacies, that is, out to about 5.2 m (Figures 18 and 19), current-dominated longshore flow is capable of transporting and depositing landward-derived material.

Erosional base and geometry of trough-associated facies group. The composite distribution of trough-associated facies documents the occurrence of a relatively wide, somewhat irregular, but concave-shaped zone in which flow can be longshore-current dominated. Maximum thickness of the belt occurs below the bar or upper ramp and ranges between 1.0 and 1.5 m. For both profile lines, the seaward limit of trough-associated facies extends to near the middle platform-lower ramp break-in-slope, about 500 m from baseline (Figures 18 and 19). Although core coverage was insufficient to document a landward limit, cored inner trough subfacies extend beneath the swash and swash-trough transition facies, to about 150 m from baseline. Assuming a minimum depth of 0 to -1.0 m NGVD for inner trough development, profile survey data indicate a landward limit about 100 to 112 m from baseline during the last 12 years (Figures 5 and 6). Thus, approximate dimensions of the trough-associated facies belt is about 400 m.

The base of the trough-scour zone , marked by the thalweg, inner trough, and outer trough subfacies, shows a seaward decrease in elevation from about -3.7 to -4.0 m NGVD (~150 m from baseline) to about -5.1 m NGVD (~340 m from baseline). Within this zone, data from profile 188 show a rough stepwise decrease in maximum erosion consisting of two levels (Figure 9). An upper level occurs at an average depth about -4.2 m NGVD below the swash zone and bar (~150 to 280 m from baseline). An outer and lower level occurs at an average depth of about -5.0 m NGVD below the upper ramp and middle platform (~300 to 340 m from baseline). Within each level, concave-shaped sectors of the erosional lower boundary indicate a localized zone of maximum downward scour, one below the active trough and inner bar flank (~180 to 230 m from baseline) and one below the

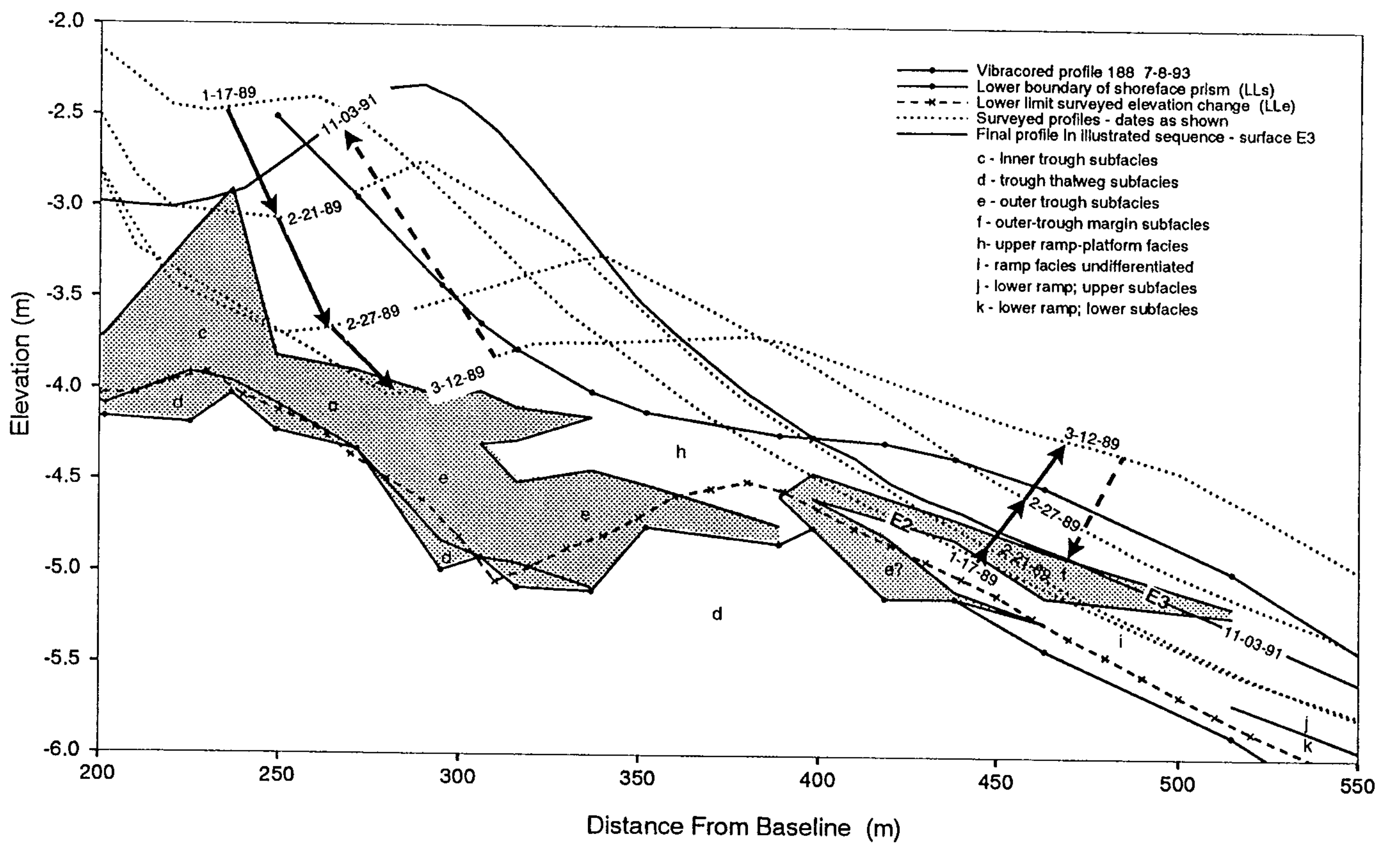

Figure 21. Profile change illustrating outer-trough scour and corresponding buildup in the middle platform to lower ramp sector followed by trough infilling and platform-ramp subelevation. The arrows near 450 m from baseline indicate the succession of profile shapes associated with the time-series sequence E2-A2-E3 in Figure 22. Most of the outer-trough margin subfacies (f) near 450 m was deposited upon erosional profile surface E2 (represented by 1-17-89) and truncated by erosional profile surface E3 (represented by 11-03-91)

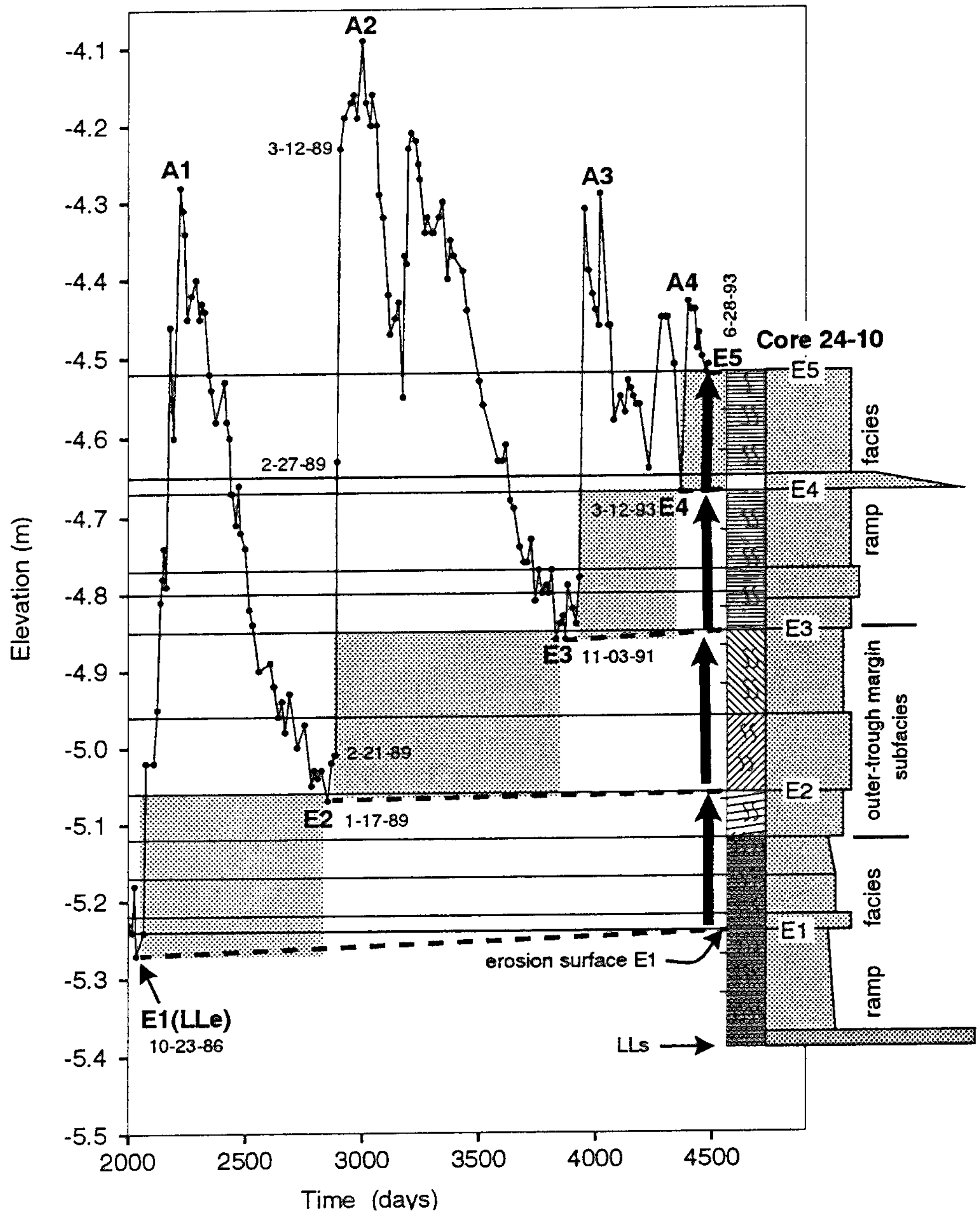

Figure 22. Time-series elevation change at 463 m from baseline related to the cored sequence from the same location. Accretion trends following the date of maximum erosion (10-23-86) are indicated by E-to-A elevation series and erosion trends by A-to-E elevation series. Bold letters E1 through E5 designate erosional maxima following a preceding accretion trend. The profile surfaces corresponding to erosional maxima are likely to be recorded as contacts at the top of truncated accretion sequences in the cores. Gray shaded areas between the various E levels designate the expected amount of remaining accretion in the cores. Correlations between erosional surfaces, expected accretion amounts, and core stratigraphy are indicated by the dashed lines and bold arrows. Dates shown along the E2-A2-E3 elevation sequence correspond to profile shapes illustrated in Figure 21

upper ramp-middle platform transition (290 to 350 m). Seaward of the outer concave-shaped scour zone, the erosional base to the shoreface prism rises in elevation to form a locally convex sector prior to undergoing essentially planiform decrease in the seaward direction. As discussed, in this seawardmost area, the base of the outer trough margin subfacies rises above the base of the shoreface prism, maintaining a depth of about 5.1 to 5.2 m. A comparison cannot be made with the innermost part of profile 62 due to insufficient core penetration; however, the facies and erosional-base data for line 62 are consistent for the outer and lower level where cores penetrated the entire shoreface prism (Figure 19).

Overall, the composite concave-shaped facies belt represents a zone in which individual troughs develop, migrate, and fill. Bars, associated with the troughs, are represented by remnant low-angle, parallel-laminated sequences within the trough facies. During extreme events, breaker zone widths can exceed 1,000 m.[1] However, along the outer margin of the facies belt, where an existent profile declines below 5.2 m, water depth apparently exceeds that for effective longshore-current scour. There the longshore current simply results in current-dominated accretion upon the profile. The seaward terminus of the outer trough margin subfacies serves as an estimate for the minimum offshore distance of longshore current effectiveness associated with major outer-trough scour events. The two stepwise levels of erosion and localized zones of maximum downward scour within each level indicate a statistical loci for profile downcutting along an inner and outer zone over long periods of time.

Bar flank facies - landward-dipping parallel-laminated sand

A thin lens of fine sand characterized by landward-dipping parallel lamination mantles the landward flank of the bar along profile 188 (Figures 14, 15, and 18). The lens is inclined subparallel to the frontal profile of the bar form and thins from 40-80 cm thick in cored locations to 0 cm thick near the base of the slope and bar crest. The lens laps downward onto underlying trough facies and lies adjacent to very low-angle, seaward-dipping parallel lamination of the upper ramp.

The bar flank facies consists almost entirely of fine sand with scattered occurrences of coarse to very coarse sand and granule stringers (Figures 14 and 15). A slight first-order upward coarsening trend extends through the facies. Textural data from the sediment-water interface show that slight upslope coarsening within the fine-sand range occurs along the sediment/water interface of the bar flank (Figure 8). The dominant structural type is low-angle landward-dipping parallel lamination (type 9). Other structures include local occurrences of medium- to large-scale cross-stratification (type 10), small-scale trough cross-stratification (Figure 11), and, near the bar crest, subhorizontal lamination (type 7). Normal grading is well-developed in beds low on the bar-trough flank, analogous to beds buried at similar depths in more seaward locations below the upper ramp and middle platform (discussed later).

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[1] Personal Communication, November 1996, William Birkemeier.

The bar-flank facies is a product of net accretion associated with landward migration of the bar (Figure 23). Lens geometry and landward-dipping internal lamination both represent form-parallel accretion upon the frontal (landward) profile of the bar during high-velocity, plane-bed conditions. Upward coarsening through the facies represents the vertical stacking of up-flank settings upon down-flank settings. The cross-stratified beds document the ephemeral occurrence of small-scale to medium-scale three-dimensional current-dominated ripples on an inclined, but predominantly planar, surface. The coexistent assemblage of trough, overlying bar flank, and adjacent ramp facies in the active upper part of the shoreface prism serves as an analogue to partial assemblages buried at deeper positions within the shoreface prism.

Upper-ramp-platform, subhorizontal-laminated, sand facies

An elongated, predominantly subhorizontal-laminated, fine-sand facies made up the upper half of the shoreface prism below the bar crest, upper ramp, and middle platform (Figures 18 and 19). The active sediment-water interface served as the upper boundary to the facies. The lower boundary is irregular shaped and may either locally extend downward into the underlying mass of coalesced trough-associated facies or surround partially isolated lenses of trough-associated facies. Thus, the stratigraphic sequence may either consist of trough facies overlain by ramp-platform facies or interlayered ramp-platform and trough facies capped by ramp-platform facies. The upper ramp-platform facies merges laterally seaward with structurally similar deposits of the lower ramp (Figures 17 and 24). Maximum thicknesses, up to about 1.3 m, occur below the upper ramp or inner part of the middle platform. Seaward, the facies thins to about 30 - 40 cm near the juncture with the lower ramp. Horizontal (type 7) to indistinguishable very low-angle parallel lamination dominates the facies. Although bedding along the upper ramp is dipping seaward at several degrees across a relatively wide area, internal parallel laminations appear as subhorizontal to horizontal in the several-centimeter-wide cores; identical to laminations below horizontal sectors of the middle platform (type 7). Medium-scale, cross-stratified (type 10); small-scale, trough-cross-stratified (type 12); and low-angle, parallel-laminated (type 9) beds are locally intermixed within lower parts of the facies. Very thin, nongraded coarse sand and granular beds (<1 cm thick); normally graded, fine-sand beds (type 7); and upward-fining, second-order sequences are ubiquitous (type 5). A first-order textural trend of weak upward coarsening characterizes the facies in many locations (Figures 15-17). Elsewhere, the facies sequence is usually nongraded. However, along both profiles 188 and 62, a first-order, upward-fining trend occurs near the landward margin of the middle platform. In all cases, the first-order trends overlie slightly to significantly coarser trough facies.

The upper boundary of the facies is a zone across which wave shoaling or dissipative surf occurs. During high-shear-stress conditions, the fine sand bed is typically planar (see section on horizontal-laminated sand beds (type 7), (Schwartz 1981b)). Subhorizontally laminated beds, making the bulk of the facies, represent plane-bed conditions in very low-angle bar-flank, upper ramp, or platform settings where slope angle was a few degrees or less. The similarity, but progressive change,

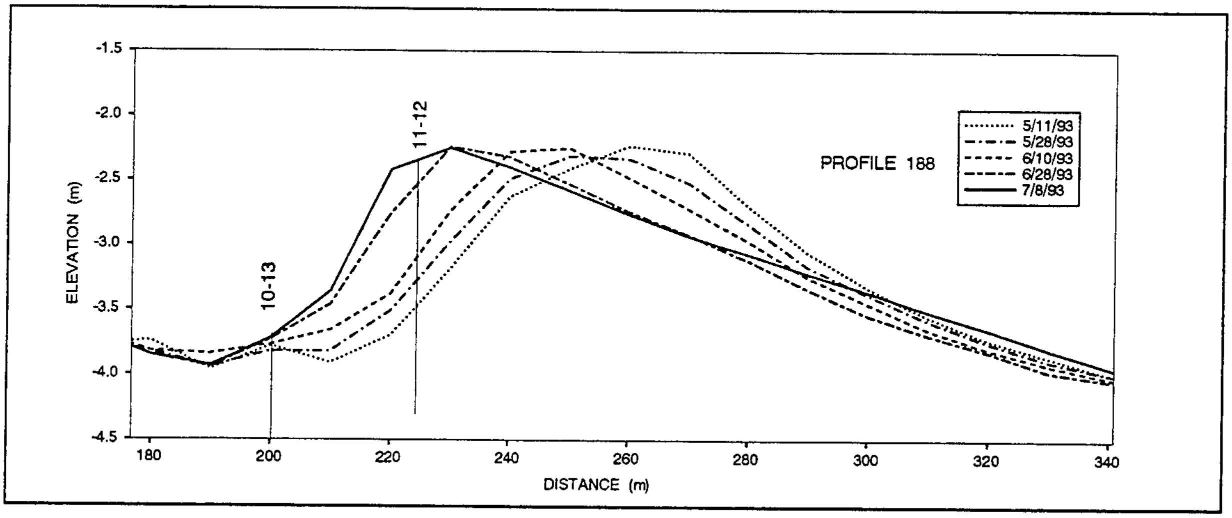

Figure 23. Landward migration of bar on profile line 188 during the 2 months prior to vibracoring. Bar flank facies are preserved in the upper parts of cores 10-13 and 11-12

between the texture and structures in this facies and those of the lower ramp attests to a continuum of processes between the two zones. The shape of the lower boundary to the facies and intermixture with trough-associated structures reflects middle platform buildup upon areas of outer trough scour. Arrays of medium-scale to large-scale three-dimensional ripples, or "megaripples," have been documented to occur intermittently in this sector of the profile under some oceanographic conditions. The occurrence of cross-stratified beds at deeper stratigraphic levels in the facies indicates that the ripples, responsible for such cross-stratification, usually develop in association with erosion along upper ramp to middle-profile locations, exhumation of slightly coarser bed material, and current-dominated flow.

Widespread low-angle geomorphic surfaces in this sector of the shoreface prism are associated with profile buildup. Buildup most commonly occurs by means of onshore migration of an outer storm bar or by simple infilling of a middle-profile trough without significant migration of bar forms. The common occurrence of subtle first-order upward coarsening trends is a result of decreasing water depth and energy increase associated with bed buildup. The depth-energy-grain size association is reflected by slight landward coarsening towards the bar crest (Schwartz 1981b). The localized occurrence of first-order upward fining may possibly be related to middle profile scour and infilling as presented in the trough facies section. High-energy episodes of strong flow and scour, followed by lower velocity, but continued, upper-regime conditions are represented by the punctuated occurrence of thin coarse beds, normally graded beds, and upward-fining sequences.

Lower ramp facies - bioturbated subhorizontally laminated sand

Fine to very fine sand consisting almost entirely of bioturbated subhorizontally laminated beds (type 8) underlies the lower ramp of both profiles (Figures 18 and

19). The facies is prismatic in shape, ranging from 1.1 m thick at the landward margin of the ramp to 0.25 m thick at about the 8.4-m depth. Bedding structures are the same as, and continuous with, those of the subhorizontal laminated facies in the middle-profile region. Depending upon the degree of bioturbation, individual bed boundaries range from distinct to indistinct or nonrecognizable.

The ramp facies consists of two subfacies, a yellow to light gray, moderately bioturbated, upper sand and a usually darker, finer-grained, and more heavily bioturbated underlying sand (Figure 24). At the contact between the subfacies there is usually a very slight improvement in sorting, with sand becoming slightly cleaner due to decreased clay or organic content. Both of the subfacies extend across the entire lower ramp and have prismatic geometries, which are subparallel to each other and to the active profile (Figures 18 and 19). The superposed subfacies make up an upward-coarsening first-order sequence (Figure 24). In more landward-located cores, sediment color lightens and the degree of bioturbation decreases upward through both subfacies.

Moderately bioturbated upper subfacies. At the landward margin, the upper subfacies extends both above and below the lens of outer-trough margin subfacies (Figures 18 and 19). Above the lens, beds of the upper subfacies become less bioturbated in the landward direction and merge with those of the middle platform. Several stringers of biodisrupted granules and small pebbles occur within fine sand near the landward margin at levels adjacent to the trough-associated facies (see core 25-33 in Figure 24 and core 45-106 in Appendix A). In the seaward direction, the upper subfacies fines both along the sediment-water interface and internally from upper-fine sand (~0.21 mm) to lower-fine sand (~0.149 mm) (Figures 8 and 24). In addition, sediment color darkens seaward from yellow to various shades of gray as the amount of disseminated organic material increases. Correspondingly, the degree of bioturbation increases seaward from slight to moderate or high. Internally, the subfacies is vertically uniform or subtly coarsens upward. Thin interbeds (<5 cm) of small-scale trough cross-stratification (type 12) occur in the two outermost cores along profile 188 (Appendix A cores 32-30 and 33-29). Also, in the most seaward cores, sediment texture, color, and degree of bioturbation become nearly identical to those of the underlying subfacies.

Lower heavily bioturbated subfacies. The lower subfacies predominantly consists of gray, very fine (0.088 - 0.125 mm) to middle-fine (~ 0.177 mm) sand with abundant reduced organic matter (Figure 24). Scattered gravel clasts occur rarely in shallower water deposits at the landward margin of the subfacies. Similar to the upper subfacies, sediment texture fines and degree of bioturbation increase in the seaward direction. Vertically, the subfacies coarsens upward in landward locales and is uniform in seaward locales. Most of the subfacies is heavily bioturbated with the beds largely to completely overprinted by bioturbation fabric. Scattered small, delicate, grayish-white whole and broken bivalve remains occur at various locales within the subfacies. Although cross-stratification is rare, a 4-cm-thick bed of stacked, seaward-oriented, small-scale cross-stratified sets occurred at the seaward end of the subfacies along profile 188 (Appendix A: core 31-35). In general, sediment texture and the degree of bioturbation at a particular NGVD level within

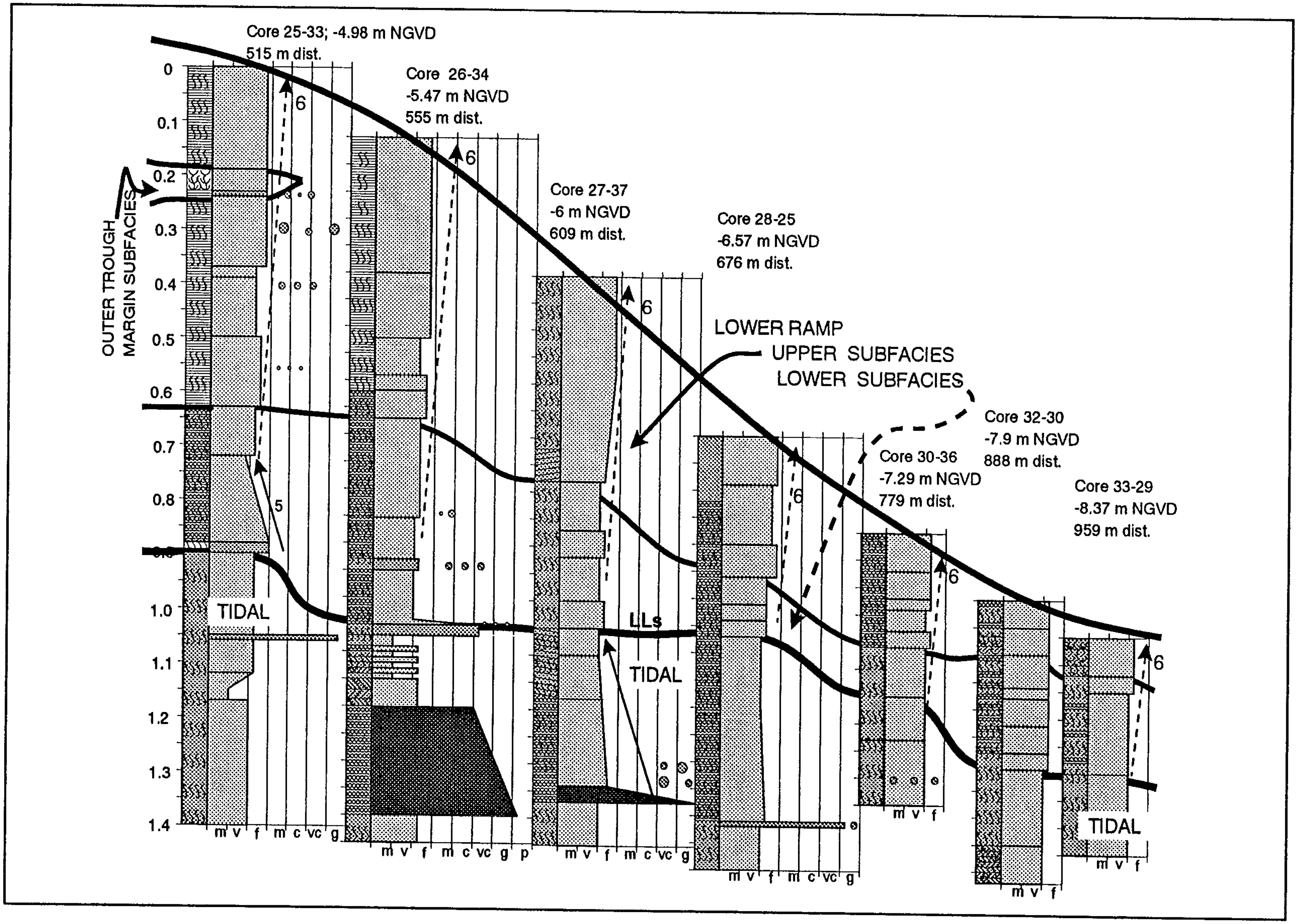

Figure 24. Facies below the lower ramp of profile 188 (see Figure 12 caption for explanation of symbols, core position, and vertical scale). Not shown are cores 29-24 and 31-35 (Appendix A) which exhibit patterns similar to adjacent cores

the lower subfacies are similar to those of sand at laterally equivalent NGVD levels in the upper subfacies and at laterally equivalent water depths along the active sediment/water interface. That is, a textural-structural match occurs between deposits along similar elevation levels through the lower ramp facies.

Interpretation for combined subfacies. Plane-bed conditions with velocities greater than 80 cm/sec result in the development of subhorizontal lamination in the lower ramp facies(see section titled "Third-Order Elements-Beds"). Because the lower ramp facies consists almost entirely of stacked subhorizontally laminated beds, it is concluded that high velocities associated with storm events are primarily responsible for buildup in this otherwise low-energy zone. However, fair-weather wave conditions and associated small-scale wave ripples temporally dominate the lower ramp region. Nonetheless, wave-ripple cross-stratification produced by accretion upon wave ripple bedforms was not present in the cores. Therefore, the dominant wave-transport process during most fair-weather periods must be sediment removal with resultant subelevation of the ramp. The association between storm-associated buildup and fair-weather subelevation of the lower ramp is supported by the profile survey data. The profile changes illustrated in Figure 25 occurred between erosional maximum E1, accretion maximum A1, and erosional maximum E2 on Figures 22 and 26. Figure 25 illustrates that, during the E1-A1 accretion trend, an outer trough sequentially developed in response to major storms (Lee and Birkemeier 1993) and excavated sand was displaced seaward onto the lower ramp. Conversely, during the subsequent A1-E2 erosion trend, the ramp underwent long-term subelevation as the middle platform and upper ramp accreted. The nature of profile change during the E1-A1-E2 trend is representative of that associated with all other accretion-erosion trends for the lower ramp region (for example, see Figure 21). Also demonstrated in Figure 25 is the form-parallel nature of profile change along the lower ramp and sub-parallelism to geometry of the subfacies. Both buildup and erosion tend to occur in a form-concordant manner along the lower ramp compared to the middle profile region where the fill represents a complicated composite of various profile shapes.

The lateral seaward trends of decreasing grain size, increasing bioturbation, and increasing organic content within each of the lower ramp subfacies reflect a seaward increase in water depth and corresponding decrease in energy along the sediment-water interface of past profiles. Upward coarsening through the facies group and the upward decrease in bioturbation reflect net energy increase as the ramp prograded and shallower lower ramp settings were superposed upon deeper and lower-energy ramp settings. A comparison of the cored stratigraphy with surveyed elevation data provides further detail concerning the history and morphodynamics of lower ramp sedimentation. The occurrence of ramp-wide erosion following long-term (e.g., 500- to 1,000-day) erosion trends is clearly documented by time-series elevation data for the lower ramp (Figure 27). Labeled E1 through E5 in Figure 27 are lines approximating a series of successively shallowing erosional maxima along line 188. E1 marks the deepest measured erosion level to occur during the 12+ year survey period. An E "timeline," although not truly synchronous, represents a widespread erosional surface which developed following a preceding accretion and

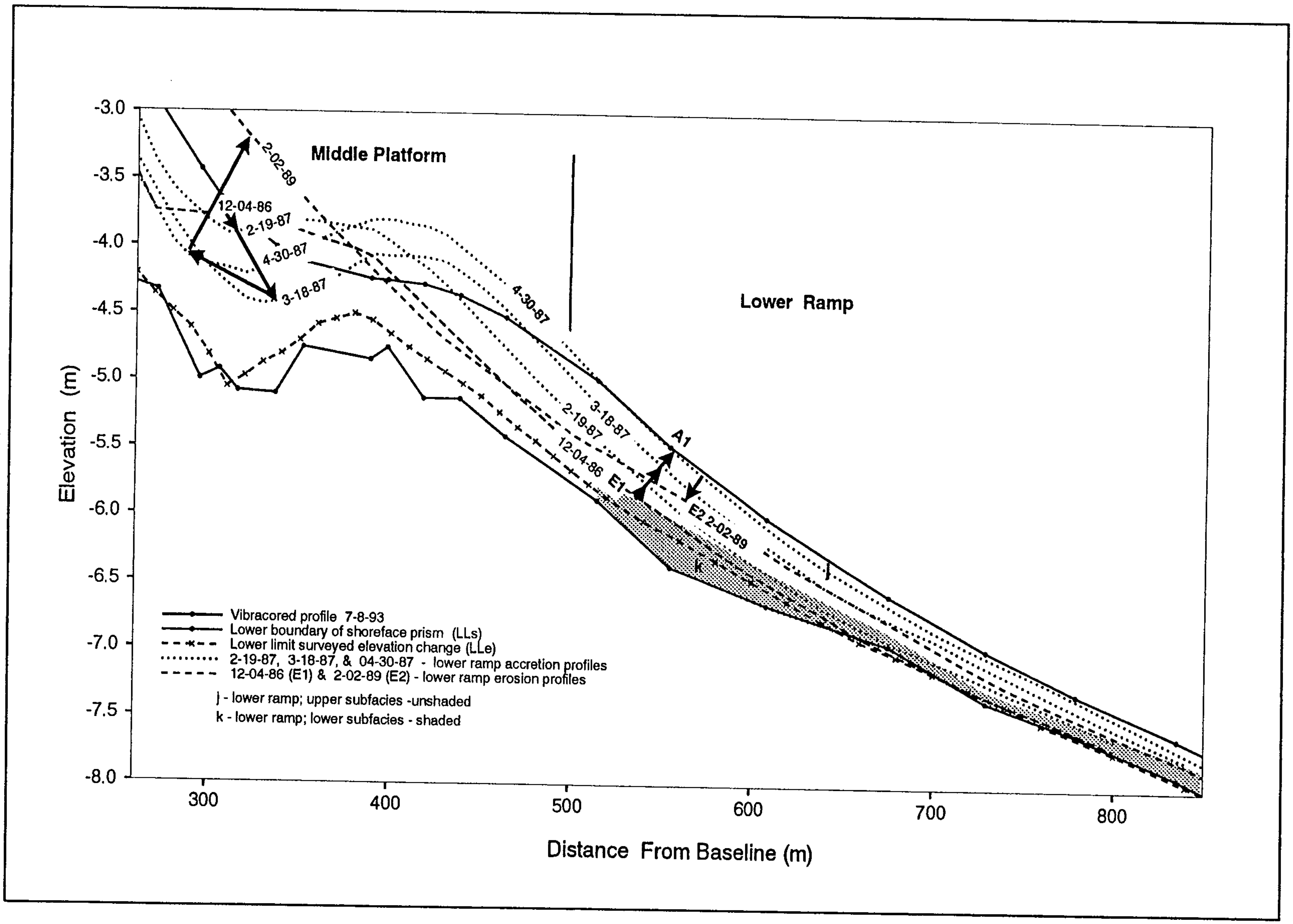

Figure 25. Profile change illustrating some outer storm trough scour events and corresponding buildup along the lower ramp. Arrows below the lower ramp indicate profile shapes associated with the time-series sequence E1-A1-E2 in Figure 26. Arrows below the middle platform indicate corresponding changes for the adjacent landward sector.

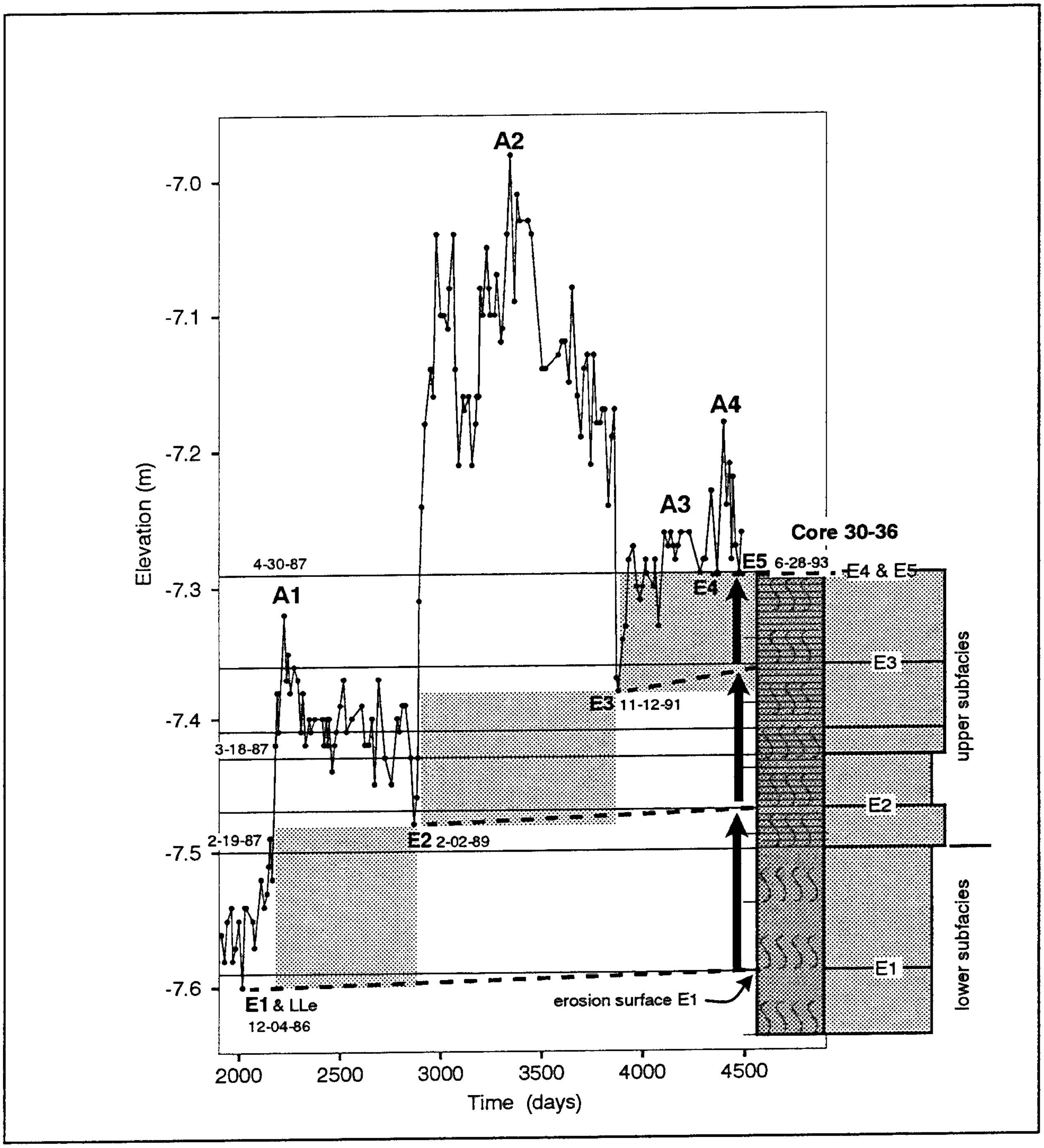

Figure 26. Time-series elevation change at 779 m from baseline related to the cored sequence from the same location. Accretion trends are indicated by E-to-A elevation series and erosion trends by A-to-E elevation series. Bold letters E1 through E5 designate erosional maxima following a preceding accretion trend. The profile surfaces corresponding to erosional maxima are likely to be recorded as contacts at the top of truncated accretion sequences in the cores. Gray shaded areas between the various E levels designate the expected amount of remaining accretion in the cores. Correlations between erosional surfaces, expected accretion amounts, and core stratigraphy are indicated by the dashed lines and bold arrows. Dates shown along the E1-A1-E2 elevation sequence correspond to profile shapes illustrated in Figure 25

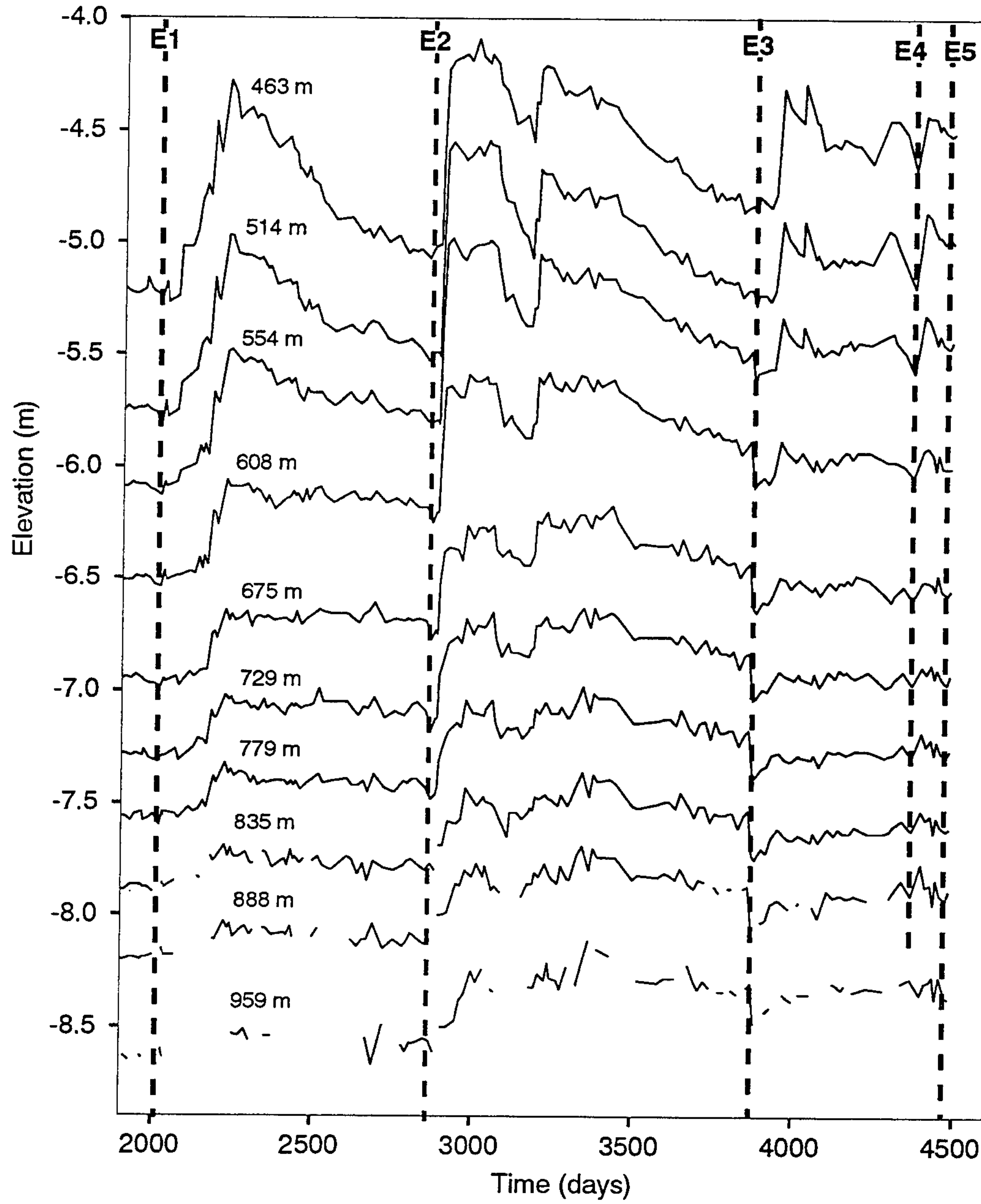

Figure 27. Time-series elevation change at vibracore locations along lower ramp following establishment of the LLe; that is, about time E1, along the lower ramp sector. Bold letters E1 through E5 mark timelines for selected erosional maxima following accretion trends. In most cases, elevations at the timeline intercepts along each elevation series are such that E1<E3<E4<E5. The profile surfaces corresponding to E times are likely to be recorded as erosional bed contacts in the cored depositional sequences. Seaward of 729 m from baseline, erosion maxima for E5 became similar to, then exceeded, E4, as illustrated in Figure 28

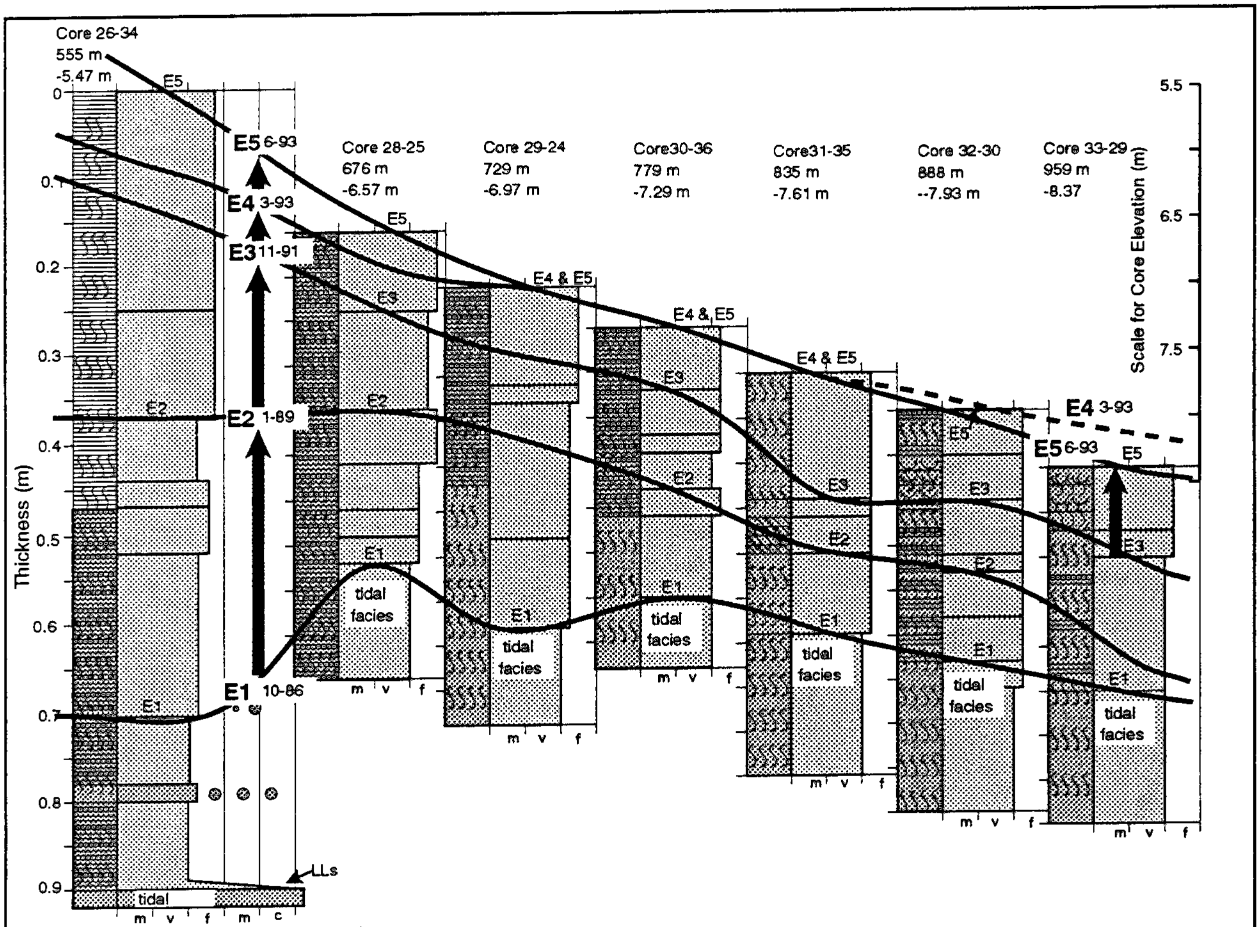

Figure 28. Correlation between erosion-surface timelines and bedding contacts in cores. Bold lines (E1-E5) represent the approximate time and elevation of maximum erosion along the lower ramp (see Figure 27). Smaller sized E's mark data points where surveyed bed elevation and measured contact depth correlate. Bold arrows indicate E-to-A accretion trends (Figures 22 and 26) which were subsequently truncated by erosion surfaces at the labeled times. Timeline E1 represents the lower limit of surveyed erosion along the lower ramp (LLe) and is correlated with the lower boundary of the shoreface (LLs) seaward of core 26-34

erosion trend and was associated with erosional profile shapes such as those illustrated in Figures 21 and 25. Successively shallower erosional surfaces, E2 through E5, cut downward into previously accreted lower ramp sequences with the potential of being preserved as bedding contacts in the stratigraphic sections. Figures 26 and 28 show the correlation between the depicted erosion-surface timelines and lower-ramp stratigraphy. Over the survey period, most of the lower ramp underwent four phases of storm-related accretion since fall 1986 (E1) for which there is a sedimentary record. Although other significant accretion-erosion trends occurred, such as between E2 and day 3200 (Figure 27), only sediment between the E1 - E5 erosion levels was preserved. Near the middle of the lower ramp, erosional surface E5 cut below surface E4, resulting in the preservation of only three accretion sequences in cores seaward of core 28-25 (Figure 28). The relationship between upward coarsening and shallowing is demonstrated on two different scales in Figure 26. Net coarsening throughout the core corresponds to net elevation decrease over the survey period. In addition, upward coarsening trends occur between the E1-E2 and E2-E3 bedding contacts. Thus, stacked upward coarsening sequences, although not evident in all cores, serve as a record of individual long-term accretion events. In Figure 28, the occurrence of lower ramp facies below E1 in core 26-34 is related to events predating the survey period.

The scattered delicate grayish-white bivalve clasts in the lower subfacies are transported debris, most likely reworked from similar faunal remains observed in fine grained tidal-related deposits below the shoreface boundary. The restriction of rare scattered gravel and coarse sand in the landward part of the facies, adjacent to the seaward margin of trough facies, indicate a minor seaward displacement of coarser material beyond trough-margin settings during some high-energy events. The scattered gravel and coarse sand in the lower ramp may have been originally derived from coarse tidal deposits at various locations below the shoreface boundary (see Figure 17, core 22-38; Figure 24, core 26-34; and, Appendix A cores 42-114, 45-106, and 47-108). Exhumation most likely occurred in locales of trough downcutting during high-energy events. Alternatively, some of the coarse material may have been originally exhumed during erosional conditions at, or seaward of, the lower ramp and subsequently moved landward by wave-induced transport. The rare occurrence of small-scale trough cross-stratification documents the ephemeral occurrence of current-dominated mean flows. Seaward orientation of the stacked small-scale foresets documents that some of the flows are offshore directed, consistent with findings by Wright *et al.* (1991).

7 Comparison of Surveyed Lower Limit (LLe) and Sedimentologic Lower Limit (LLs) of the Shoreface Prism

The lower limit of surveyed elevation change, hereafter referred to as the LLe, is a plot of distance and minimum elevation pairs representing maximum erosion over 12 years of biweekly surveys (Birkemeier 1985; Lee and Birkemeier 1993). Similarly, the sedimentologically determined lower limit to the shoreface (LLs) represents maximum downward erosion on the geologic time scale. In the following section, cross-sectional profiles for LLe and LLs data from both survey lines are compared.

Profile Line 188

The shape and position of the LLs profile is similar to that of the LLe profile (Figure 29). In both cases, there is a landward trend of decreasing depth of erosion. An exception occurs locally under the upper ramp, between about 300 m and 380 m, where both the LLs and LLe are concave shaped and significantly deeper than in other areas. As expected, LLs values are similar to, or below, LLe values across the entire profile line. The difference between LLs and LLe values becomes greater in the landward direction.

Significant patterns of lower-limit differences occur in zones along the shoreface. The shape of the LLs profile below the lower ramp is very slightly concave and similar in shape to the LLe profile and to active lower ramp profiles (Figure 29). Along the outer half of the lower ramp, LLs values are nearly coincident with LLe values. Along the inner half of the lower ramp, the LLs profile drops slightly below

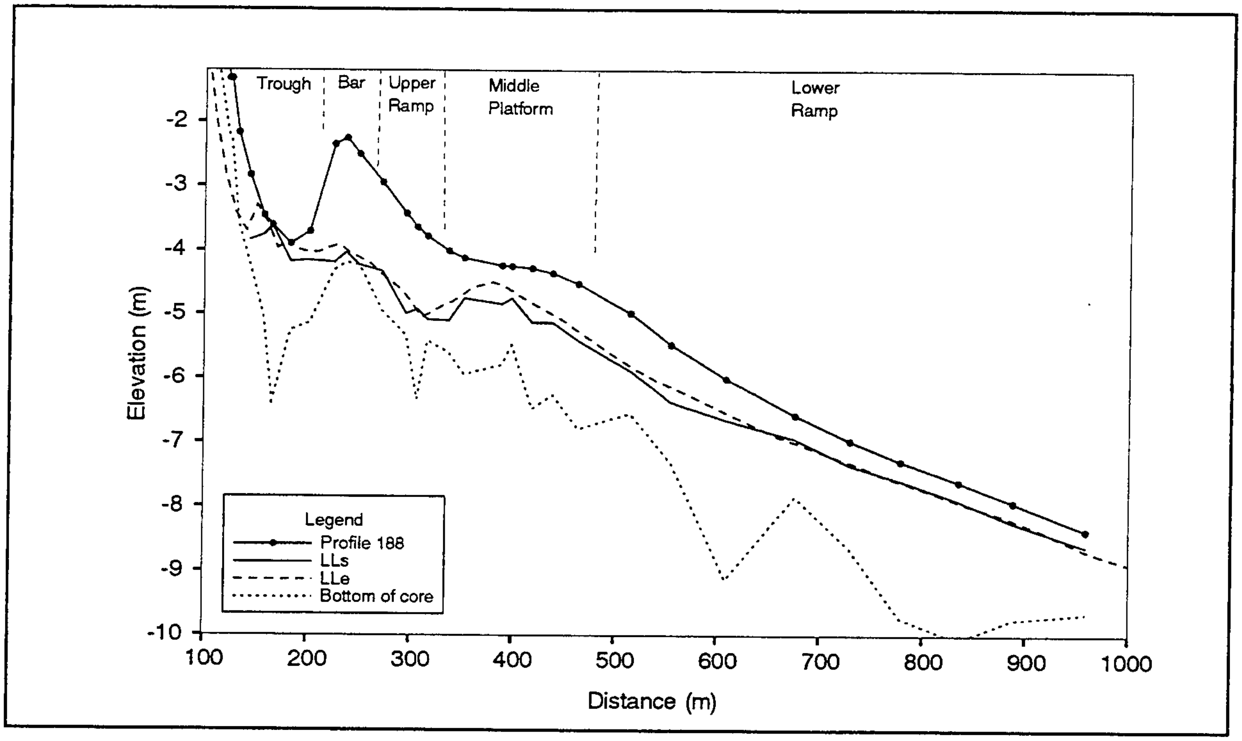

Figure 29. Comparison of lower limit of surveyed elevation change (LLe) and the sedimentologic lower limit (LLs) of the shoreface along profile line 188. The absence of a solid line indicates locations where vibracore penetration was insufficient to document the LLs

the LLe profile, with an average difference of about 14 cm. The range in lower-limit differences across the entire lower ramp is from 0 - 24 cm, with an average difference of about 8 cm.

Under the remainder of line 188, the LLs profile becomes more irregular and undergoes even greater departure from the LLe profile. The difference between LLs and LLe for this inner section ranges from 0 - 50 cm. In addition, maximum differences between LLs and LLe values occur locally in discrete zones. Under the middle platform, an irregular convex-shaped LLs profile segment occurs below a convex-, or bar-shaped, LLe segment (Figure 29, between 380 and 440 m). The range in lower-limit differences for this segment is 12 - 29 cm with an average difference of 22 cm. Adjacent, a well-developed concave- or trough-shaped LLs segment occurs directly below a well-developed trough-shaped LLe segment (between 270 and 350 m). The range in lower-limit differences for this zone is 12 - 32 cm, with an average difference of 24 cm. Similarly, a trough-shaped LLs segment occurs below a trough-shaped LLe segment both of which are below the trough thalweg and bar inner flank (between 180 and 225 m). Here the range in lower-limit differences is 15 - 26 cm, with an average difference of 22 cm. Adjacent, under the landward side of the trough (between 143 and 157 m), an LLs segment again dips below a narrow trough-shaped LLe zone. The range in lower-limit differences here is 29 - 50 cm, with an average difference of 40 cm.

Profile Line 62

The shape of the LLe profile along line 62 is basically similar to that of line 188 (Figure 30). A notable difference is the single relatively large trough-shaped LLe segment which occurs below the upper ramp of line 62 (Figure 30, between 180 m and 330 m), in the same zone which includes two of the narrower trough-shaped LLe-LLs segments along line 188 (between 165 and 350 m). Because of insufficient vibracore penetration landward of the middle platform on line 62, only a partial comparison between LLe and LLs values can be made. However, similar to line 188, a trough-shaped deflection in the LLs occurs below the outer part of the trough-shaped LLe. Between 300 and 400 m, the LLs sharply descends below the LLe with a range of 65 - 100 cm in lower-limit differences and an average difference of 83 cm.

Below the lower ramp, the shape of the LLs profile is again similar to the LLe profile. Along the outer half of the lower ramp, LLs values are nearly coincident with LLe values. Along the inner half of the lower ramp, the LLs profile extends slightly below the LLe profile, with a range in lower-limit differences of 12 - 32 cm and an average difference of 23 cm. Under the middle platform, the LLs and LLe profiles continue to be slightly convex- or bar-shaped and subparallel up to about 400 m from baseline.

Discussion of Lower-Limit Data

The LLe profile represents a time-composite surface of maximum downward erosion along the survey line. In other words, it consists of various sized segments of "instantaneous" nearshore profiles. Similarly, the LLs profile is a sedimentologically defined profile representing a composite of erosional surfaces, most of which occurred over a longer time scale. Local sectors of the LLe and LLs profiles may have been caused by a single erosional surface or represent the coalescence of erosional surfaces. The LLe is constrained by duration of the survey program (~12 years), frequency of surveys, and survey accuracy (Howd and Birkemeier 1987; Lee and Birkemeier 1993). The LLs is constrained by the geologic history of shoreface erosion, core spacing, and accuracy of contact delineation.

Overall, the LLe profile serves as an excellent approximation to the shape of the LLs and a good approximation to the elevation of the LLs, particularly seaward of the middle platform. Average deviation in the middle of the platform is about 24 cm, averaging about 14 cm along the landward part of the lower ramp and essentially 0 cm along the outer part of the ramp. Deviation in the landward direction is both more irregular and larger, ranging from 0 - 100 cm.

The shape of the LLe profile below the lower ramp of each survey line is similar to the active profiles surveyed along each line. The indication is that, although the

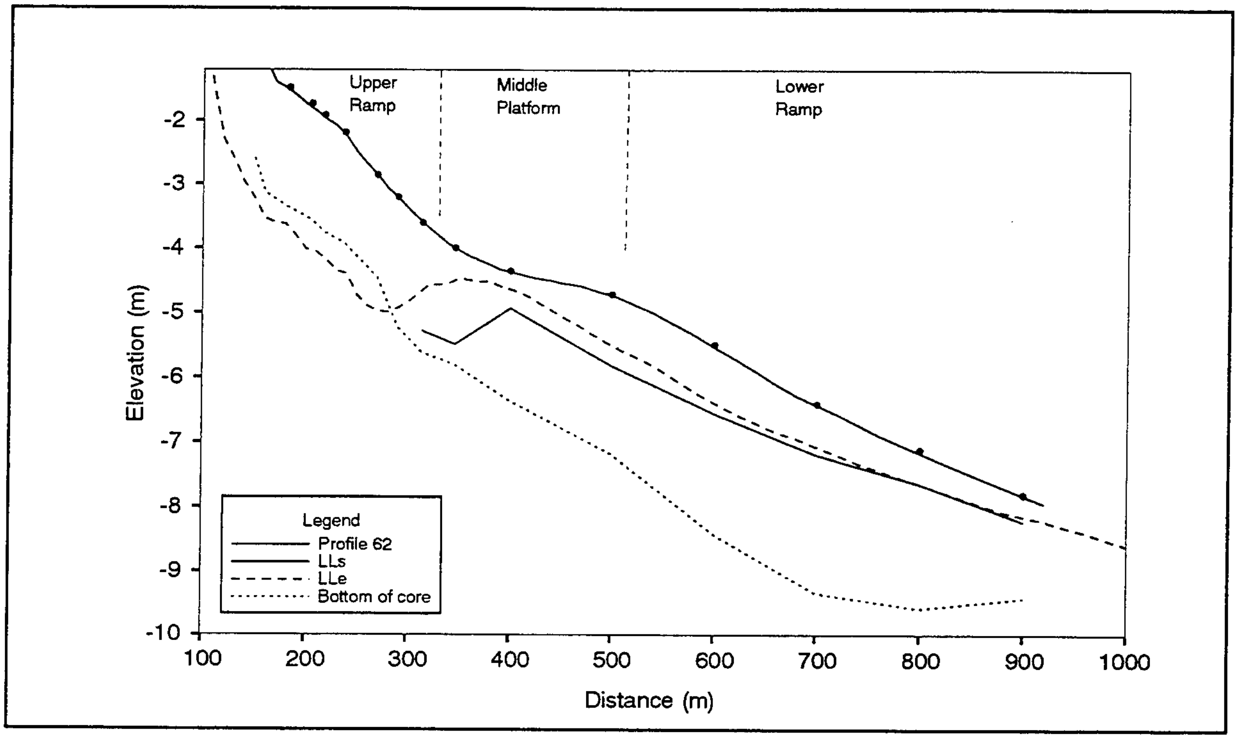

Figure 30. Comparison of lower limit of surveyed elevation change (LLe) and the sedimentologic lower limit (LLs) of the shoreface along profile line 62. The absence of a solid line indicates locations where vibracore penetration was insufficient to document the LLs

nearshore-wide LLe is a composite profile representing segments of many profile shapes, much of the LLe surface below the lower ramp can be produced by a single type of profile shape, such as the 12-04-86 profile in Figure 25.

As presented earlier, the time-series data document that maximum erosion occurred along the lower ramp between October and December 1986 (Figure 27). Thus, erosion surface E1 accounts for the position and shape of the LLe along the lower ramp (Figure 28). Because of the overlap, or merger, in shape and position of the LLs and LLe seaward of 600 m on line 188, it is concluded that erosional surface E1 accounts for development of the LLs along that sector. Although similar, temporal and spatial correspondence are less clear for line 62. The downward shift of the LLs away from the LLe below the middle platform and landward part of the lower ramp along both surveys (Figures 29 and 30) indicates the occurrence of pre-survey profiles which cut more deeply into underlying tidal facies. Because lower ramp surfaces tend to subelevate in response to fair-weather processes over much longer periods than they elevate or aggrade in response to storm events, it is unlikely that LLs development below the LLe was simply missed by the surveys. Thus, maximum erosion along the inner sector of the lower ramp, as well as some progradation, occurred prior to the survey period. This pre-survey phase of deposition was followed by net lower ramp erosion between 1981 and late 1986 (data not shown) and again by net lower ramp progradation between late 1986 and 1993 (Figure 28).

Shoreward of the lower ramp, both the LLe and LLs are spatially and genetically associated with trough facies. The LLs serves as the base of the trough facies, whereas the LLe generally intersects trough facies at a shallower stratigraphic level. The shape of LLs profile segments, and sometimes LLe profile segments, provide supporting evidence that troughs are formed by "shore-parallel" scour along landward portions of the nearshore profile. The concave shapes are similar to that of surveyed inner fair-weather troughs and more seaward storm troughs (Figure 20; Birkemeier 1984). Discrete locales of concave LLs and LLe development, such as along line 188, indicate loci of trough thalweg occurrence and maximum down-cutting (Figure 20). However, overplots of all surveys for profile lines 62 and 188 (Lee and Birkemeier 1993) document that, given sufficient time, troughs can shift in the shore-normal direction to all positions from the beach through middle platform. Because of this, a composite and much wider trough-shaped LLs or LLe zone could result in the long-term, such as the wider concave zone under profile line 62. Although most of the significant LLs departure below the LLe may be pre-survey, there is a higher likelihood that a maximum downward scour event could be missed by post-storm surveys due to the higher rate of recovery in the shallower high-energy zones. For example, rapid scour and fill are most likely in inner trough locations, such as landward of 200 m on profile line 188 (Figure 18).

8 Summary and Discussion

Vibracore data documenting the internal makeup of the modern shoreface prism and its relationship to profile dynamics are presented in this report. The combined vibracore and profile data sets are unique in that they cover the same shore-normal transects across the most active part of the shoreface zone, from the beach out to about the 8-m-depth, well beyond transitory storm bar-and-trough locations. Detailed hierarchical sedimentologic analysis of closely spaced vibracores enabled high-resolution definition of the textural and structural architecture of the shoreface prism. The spatial distribution of distinctive bedding types (third-order elements), bed-sequences (second-order elements), and facies and composite textural sequences (first-order elements) provide a depositional record of bedform type, profile morphology, and related hydrodynamic conditions. The profile survey data provide a detailed time-series record of profile-shape dynamics, which can be linked to the depositional record. The combined data yield important information concerning the significance of erosional limits of surveyed elevation change, hydrodynamic conditions associated with profile closeout depths, and the effect of storm versus fair-weather processes on cross-shore sediment transport.

Profile Morphology

Depositional and erosional features discussed in this report are genetically related to morphological sectors of contemporaneous and past profiles and to hydrodynamic conditions which occur along those sectors. Profile terminology is based upon the morphology of the sectors and principally includes: beach, trough, bar, upper ramp, middle platform, and lower ramp. At the time of vibracoring, one of the studied profiles (line 188) contained a well-developed inner bar and trough, whereas the other profile (line 62) was non-barred. These profile shapes represent two of several discrete modes of profile-shape occurrence (Birkemeier 1984). Long-term survey data document that more seaward located storm bars and troughs develop below the upper ramp and middle platform of the vibracored profiles, but not in the region of the lower ramp.

Geometry and Stratigraphic Position of Shoreface Prism

The shoreface mass is an irregular-shaped lens, or prism, that rests upon erosionally truncated tidal-inlet associated sediment. The tidal complex formed as part of an earlier, and possibly laterally associated, barrier island system which subsequently underwent inlet filling and transgressive shoreface erosion. The shoreface prism is 3 - 4 m thick below the beach through middle platform sectors. Irregular seaward thinning occurs below the middle platform followed by regular thinning of a concave-shaped lens below the lower ramp. Thicknesses of 30 - 40 cm occur in water depths between 7.5 and 8.5 m.

Facies Distribution and Relationship to Nearshore Processes

Six major facies, or environmentally significant sediment groups, occur within the shoreface prism. Based upon their association with morphologic sectors of profiles, the facies groups are termed swash, swash-trough transition, trough-associated, bar flank, upper ramp-platform, and lower ramp. The relatively coarse sand and gravel-rich swash and swash-trough transition facies are thin, seaward-dipping tabular-shaped bodies that record episodic seaward progradation of beach-to-innermost trough surfaces over finer sand of adjacent trough-flank settings. Parallel laminations within the facies are caused by high shear stress plane-bed conditions typical of the swash and adjacent subaqueous zone.

An active bar-flank sand facies occurs along the landward-facing margin of the longshore trough on line 188. Because the bar-flank facies is spatially and dynamically associated with trough occurrence and because of its mixed occurrence with trough facies in other subsurface locations, bar flank deposits are included within the trough-associated facies group when encountered in buried seaward locations.

Between the beach and seaward margin of the middle platform, facies associated with longshore trough development make up the lower part of the shoreface prism. Four trough subfacies were designated: coarse-sand and gravel-rich thalweg, fine-to-medium sand and gravelly inner trough, fine-sand outer trough, and outer-trough margin. The thalweg subfacies represents coarse axial settings along the base of longshore troughs at inner to middle profile locations. Physical structures and textural properties of the thalweg beds document that the coarsest material is active during high-energy events and that relatively large gravel-rich and coarse-sand bedforms migrate within the trough settings. The finer-grained inner and outer trough subfacies represent trough flank and sand-rich axial settings in longshore troughs along inner to outer profile locations. The subfacies, irrespective of location, are dominated by three-dimensional medium- to large-scale cross-stratification and very low-angle parallel-laminated cross-stratification. The three-dimensional cross-stratification is produced by the migration of relatively large three-dimensional ripples under current-dominated flow conditions and the low-angle parallel-laminated cross-stratification by accretion upon low-angle surfaces, such as bar-and-trough flanks. Relatively thick gravel and very coarse to coarse sand beds make up the base of first-order upward-fining sequences in the inner trough subfacies whereas thinner and finer beds occur at the base of first-order upward-fining sequences in the outer trough and outer-trough margin subfacies. The upward-fining sequences in the inner and outer trough subfacies are a record of progressive long-term infilling following initial storm-related trough scour and coarser deposition along axial zones. The outer-trough margin subfacies represents relatively short-term current-dominated deposition seaward of, but contemporaneous with, outer-trough scour. The outer-trough margin subfacies is deposited upon an adjacent fair-weather-related erosional surface of the adjacent lower ramp.

The combined sedimentologic and profile data sets clearly establish a causal relationship among longshore currents, longshore trough development, and the occurrence of cross-stratified "trough" facies. Because the trough-associated facies are deposited upon low-level erosional surfaces, the preservation potential is higher than all facies other than those of the lower ramp. The mapped lower and seaward boundaries of the trough-associated facies group thus indicate the limits of longshore current-dominated flow along the bed. The erosional lower boundary of the thalweg, inner-trough, and outer-trough subfacies group marks the downward limit of longshore-current scour. Two stepwise levels for the erosional base, about -4.2 m NGVD along the inner-trough region and about -5.0 m along the outer-trough region, indicate a statistical loci for profile downcutting along those zones over long periods of time. The estimated width for significant trough-associated scour in the study area is about 250 to 300 m (limits at about 350 to 400 m from baseline). The seaward limit of about 500 m from baseline for outer-trough margin deposits serves as an estimate for the maximum offshore distance of longshore current-dominated deposition. The corresponding longshore current width, between the beach and the 500-m limit, is about 400 m. The 500-m facies limit also corresponds to the break-in-slope between the middle platform and lower ramp, thus indicating a dependency between profile morphology and longshore-current-associated processes. It is most likely that longshore currents extend beyond the platform-ramp break, such as, out to 1,000 m from baseline, during extreme events.[1] However, results from this study suggest that water depths greater than about 5 m at distances beyond 500 m from baseline exceeds those for effective longshore-current-dominated scour and deposition. At such depths, orbital flow most likely dominates that of potential longshore components.

A subhorizontal-laminated fine-sand facies directly underlies the upper ramp and middle platform of each profile. The subhorizontal lamination is a product of accretion under high-velocity (>80 - 100 cm/sec) plane-bed conditions. Such conditions are common to this zone, both during storm and more energetic

[1]Personal Communication, 1996, William Birkemeier.

fair-weather conditions. The vertical sequence of finer-grained upper ramp-platform facies overlying coarser-grained trough facies is as a record of storm-trough development followed by fair-weather modification and buildup of the middle profile region.

A bioturbated finer-grained subhorizontal-laminated facies underlies the lower ramp sector of the profiles. The facies is subdivided into two subfacies, an upper fine-grained moderately bioturbated subfacies and an underlying finer-grained and more heavily bioturbated subfacies. In the seaward direction, the facies becomes finer grained and increasingly bioturbated.

A comparison of facies geometry and profile surveys shows that the ramp tends to both erode and build up in form-parallel fashion, contrary to the bar-ramp-middle profile sector, which is characterized by more localized cut-and-fill events. Profile survey data also show that the lower ramp typically builds up in association with storm-trough development and sediment removal from the bar, upper ramp, or middle-platform sectors. The stratigraphic record of lower-ramp accretion consists almost entirely of subhorizontal lamination, again a product of high-velocity bed conditions (e.g., >80 cm/sec). Such high-energy conditions are consistent with the observation of middle profile erosion and contribution of sediment to the lower ramp during storm events. Similar findings for profile change and bedding structure were documented for the Topsail Island shoreface study (Schwartz et al. 1981). Thus, an event-driven relationship exists between morphodynamics, facies development, and net transport between the lower ramp and inner profile region.

The subhorizontally laminated beds are not a product of the most frequently occurring conditions along the lower-ramp sediment-water interface. A low-energy wave-rippled to physically inactive bed is temporally predominant. Profile survey data show that the lower ramp typically undergoes slow subelevation during long fairweather-dominated periods. Thus, the absence, or unobserved rarity, of wave-ripple structures in the vibracores is consistent with wave-ripple occurrence during fairweather erosional states and subhorizontal lamination development with plane-bed conditions during high-energy accretional states.

The lateral seaward trends of decreasing grain size, increasing bioturbation, and increasing organic content within the lower ramp facies reflect a seaward increase in water depth and corresponding decrease in energy along the sediment-water interface of profiles. Upward coarsening through the facies group and the upward decrease in bioturbation reflect net energy increase as the ramp prograded and shallower lower ramp settings were superposed upon deeper and lower-energy ramp settings. A comparison of the cored stratigraphy with surveyed elevation data provides greater detail concerning the history and morphodynamics of lower ramp sedimentation. Time-series elevation data document the occurrence of the ramp-wide maximum-erosion surfaces that develop over relatively long periods, e.g., 500 - 1,000 days. Following an erosion-surface maxima in the fall of 1986, the lower ramp underwent four phases of accretion for which there is a sedimentary record. The accretion phases were related to major storm activity in early spring

1987, winter-spring 1989, late fall-winter 1991, and spring 1993. Although other accretion and erosion trends occurred during the survey period, erosional maxima immediately preceding each of the above dates resulted in preservation of sediment for the four phases.

Sedimentologic and Surveyed Limits of Erosion

The lower sedimentologic boundary of the shoreface prism is the lower limit of downward erosion (LLs) for the modern marine system. The shape and location of the surveyed lower limit of erosion (LLe) is similar to that of the LLs profile. More than 80 percent of the shoreface prism lies within the envelope of surveyed profile change. Increasing amounts of departure occur between the LLe and LLs in more landward sectors of the nearshore zone.

The LLs profile is nearly coincident with the LLe profile in the outer part of the lower ramp and drops below the LLe in the landward direction. The range in measured deviation of the LLs below the LLe along the inner half of the lower ramp is 7-24 cm along profile 188 and 12-16 cm along profile 62. The range in measured deviation of the LLe below the LLs landward of the middle platform is 0-50 cm along profile 188 and 65-100 cm along profile 62.

In the lower ramp sector, the LLs and LLe are similar in shape to that of most surveyed active profiles and can be attributed to relatively wide erosional profile surfaces. In the outer part of the lower ramp, where the LLs and LLe merge, maximum downward erosion occurred between fall 1986 and early winter 1986. Along the inner part of the lower ramp, where the LLs descends below the LLe, maximum erosion occurred along lower-ramp surfaces prior to the survey period. Shapes of some LLs and LLe segments landward of the lower ramp are concave and similar to trough concavities as documented by survey data. Landward of the lower ramp, downward deviation of the LLs below the LLe represents erosion associated with trough scour which occurred either prior to, or between, surveys.

Depth of Profile Closure and Coastal Processes

Data from this study provide further information regarding the closeout concept and dynamics along a zone of profile closure. Closeout depth is a geometry-based concept originally defined as the minimum water depth at which no measurable change in bottom elevation occurs for pre- and post-storm inner shelf profiles (Bruun 1962). Bruun considered depth of closure to be the point on an equilibrium profile beyond which there is no significant net offshore transport of sand. For some time, profile closeout was considered to mark the boundary between a zone of active cross-shore sediment transport and a deeper zone of negligible sand transport.

With the high-resolution survey data collected at the FRF, it became apparent that true closeout does not occur within survey range, especially in the longterm.

Surveys document that although negligible elevation change can occur in depths of about 4 - 6 m over the short term (e.g., one to several weeks) (Birkemeier 1985), short-term changes on the decimeter to tens-of-decimeter scale also occur at those depths (see Figure 27). At the profiling limit, about 1,000 m from baseline at a 9-m water depth, periods of no measurable elevation change are longer and short-term elevation differences on the several centimeter scale occur during extreme storm events.[1] Overall, closure periods of varying duration and elevation changes of varying magnitude occur along the outer profile, e.g., between 4 m and 10+ m in depth. Reversing changes in bed elevation decrease in asymptotic fashion from about 70 - 100 cm maximum at about the 4-m water depth to the several centimeter scale at about the 9.0-m water depth. Although including a component of net growth due to deposition along the entire shoreface, the upper and lower limits to surveyed elevation change for the 12+ year survey record demonstrate the asymptotic nature of elevation change, and thus seaward increasing longer-term closure, across this zone (Lee and Birkemeier 1993). As shown in Figures 5 and 6, the upper and lower limits converge at minimum water depths of short-term closeout (about 4 - 5 m), become similar in shape to lower ramp profiles, and show progressive closure across the lower-ramp zone. Thus, a time-dependent zone of measured profile closure coincides with the lower ramp morphologic zone and lower ramp facies of this study.

Also related to the concept of profile closure is the predictive model developed by Hallermeier (1978, 1981a and b) for estimating the seaward limit of wave-caused offshore transport. Hallermeier defined two limits to an area designated as the *shoal zone*. In the shoal zone, surface waves were described as being capable of entraining sand, but causing relatively minor onshore-offshore transport. The landward limit of the shoal zone (d_l) separated the *littoral zone* and the shoal zone. Dominant processes landward of d_l were considered to be longshore transport and significant amounts of onshore-offshore transport as associated with breaking and near-breaking waves. Depth d_l was defined as the depth of annual closure, that is, the minimum water depth at which no measurable or significant change in bottom depth occurs. The seaward limit to the shoal zone (d_i) was defined as the depth limit for entrainment by normal waves beyond which wave-caused onshore-offshore transport was negligible. Based upon data from 11 Atlantic coast sites, including this study area, Hallermeier calculated limits of d_l =-5.7 m and d_i=-22.1 m for the shoal zone. Using field data from just this study area, Birkemeier (1985)[1] evaluated Hallermeier's approach and recalculated site-specific d_l values ranging from -3.7 to -6.1 m, average d_l=-4.8 m, and d_i=-20 m. Similar to the zone of measured profile closure, the calculated shoal zone coincides with, and extends beyond, the vibracored portion of the lower ramp.

Consequently, elevation change across the shoal zone and zone of profile closure out to the 9-m depth is associated with previously discussed form-parallel accretion and erosion along lower ramp surfaces. Data from this study document

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[1]Personal Communication, 1996, William Birkemeier.

that ramp surfaces tend to subelevate slowly in response to fair-weather wave transport and elevate relatively rapidly in association with major storm events. Not only is ramp buildup associated with high-energy events, but high-velocity (e.g., >80 cm/sec) flow conditions occur at these depths with sufficient shear stress to produce a planar bed and horizontal laminations. Although CRAB surveys only extend out to about the 9-m depth, fathometer surveys document that the sightly concave lower ramp continues seaward, becoming asymptotic with the shelf gradient between 10 and 12 m. Recent seismic data indicate that the shoreface prism generally pinches out between the 9- and 12-m depths at the study site (Smith et al., in preparation). Unpublished boxcore data (Fiorina 1993) document the continuation of lower ramp facies throughout those depths and the dominance of horizontal laminated bedding. Based upon the parallelism between lower ramp profile shapes, facies geometry, and the "horizontal" attitude of bedding, it is evident that accretion occurs in a thin blanket-like manner. Because of the direct correspondence between velocity, shear stress, and transported load, the bed must be highly active across the lower ramp during major storm events with significant amounts of sediment in motion. However, net transport is a product of orbital asymmetry and superimposed mean flows, such as those documented by Wright et al. (1991). The rare occurrence of thin, offshore-oriented foreset strata in lower ramp facies attests to at least occasional offshore transport under superimposed current conditions. Overall, even though changes in bed elevation become negligible in the deeper part of the shoal zone and zone of profile closure, sediment is clearly capable of being entrained and transported during storms in the depth zone of 9 - 12 m.

Both calculated d_l and measured short-term closure depths for the study site correspond to the middle platform-lower ramp break of this study. As discussed, the morphologic break marks the seaward limit of trough-associated facies development. Thus, physical evidence documents that the region landward of d_l is episodically dominated by longshore current processes and the redistribution of sediment, both in the seaward and landward directions.

Textural Distribution Within the Shoreface Prism and Cross-shore Sediment Transport

Data from this study provide a substantive base for information concerning sediment transport in the nearshore zone. The shore-normal orientation and depth of the sedimentologic cross-section allow two-dimensional cross-shore treatment of the shoreface mass as opposed to one-dimensional surface or near-surface data. Pertinent questions concerning cross-shore transport involve the spatial distribution of sediment size within the shoreface mass, size sorting processes, and net transport direction. The data may be considered on two temporal scales, that of the 12+ year profile survey period and that of the transgressively migrated shoreface mass.

The envelope of profile change shows that essentially all parts of the shoreface prism have been active within a 12-year period. Moreover, the shoreface mass has undergone net landward, or transgressive, displacement over recent geologic time.

Thus, the entire prism can be thought of as a composite of "transported load" as opposed to lag or reworked residuum. Although only small subsets of the sediment mass are active at a single point in time, it is apparent that the cumulative effect has been distinct shore-normal sorting. Fine-grained sand is ubiquitous and makes up the bulk of the sediment mass. 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 inner-trough thalweg zones.

Relatively coarse material does occur at seaward locations, but is almost entirely restricted to trough facies which terminate at the seaward margin of the middle platform. However, the trough facies, which also contains an abundance of fine sand, exhibits textural fining towards its seaward margin. Proportionately minor amounts of finer sized gravel and coarse-to-medium sand occur in trough facies below the bar and upper ramp sectors. Minimal amounts of medium-to-very-coarse sand, in very thin beds, and scattered granular debris occur in trough-associated facies below the middle platform as well as in immediately adjacent subhorizontal-laminated beds.

Overlying the trough facies, subhorizontal-laminated beds of the upper ramp and middle platform facies almost entirely consist of unimodal upper-fine (~0.21-mm) sand. Seaward, and laterally equivalent to both the trough and middle platform facies, lower ramp deposits consist of unimodal seaward-fining fine (~0.21-mm) to very-fine (0.125- to 0.105-mm) sand. Granules and pebbles are quite rare and occur only as scattered grains within the fine-sand laminations. Data from other studies at the FRF study site (Fiorina 1993) show that very fine sand making up subhorizontal-laminated beds continues out to at least 2,000 m from baseline at the 14-m water depth. Wright (1993) reports the conversion of a well-sorted, fine-sand bed to a muddy fine-sand bed, with the fine sand bound in fecal pellets, at about 15 m.

Thus, the net long-term product of both fair-weather and storm transport has been size sorting, with the coarsest of material concentrated at landwardmost locations and well-sorted fine to very fine sand at seawardmost locations. At seaward locations, the subhorizontal-laminated bedding is a product of high-velocity plane-bed flow with sufficient shear stress to entrain and transport relatively coarse material. Based upon laboratory experiments, Simons, Richardson, and Nordin (1965) report that for plane-bed conditions, the size distribution of transported material is equal to the size distribution of the bed material and that appreciable segregation does not occur. Thus, based upon texture of the lower ramp and seaward equivalent beds, all indications are that the transported load across the lower ramp was primarily fine and very fine sand. There is no physical evidence for material coarser than fine sand being lost to the offshore during the 12+-year period, a period which included numerous major storm events. By contrast, the landward concentration of transported coarser material indicates net shoreward transport of any coarse material acted upon by ramp-associated processes. Cores from this study document a local source of coarser material directly below the modern shoreface prism, including below the lower ramp prism. Although coarser particles within beach and inner to outer trough settings are volumetrically concentrated at shorewardmost locations within the prism, evidence does indicate the potential for shore-normal redistribution associated with the development of outer storm troughs. However, the mapped subsurface distribution of seaward-diminishing coarse material documents that medium sand to gravel tends to remain in the inner half of the system even during extreme storm events and the phase of storm-associated ramp buildup.

Beachfill Placement: Synthesis of Closeout Concept and Differential Transport

A brief summary and synthesis of previously discussed information follows, leading to a further discussion of profile closure and the mechanical placement of sediment for beach nourishment purposes. Depth d_l is conventionally used by engineers for estimating closure limits for beach fill projects. Calculated d_l values and the middle platform-lower ramp morphologic break correlate in position along the nearshore profile. Moreover, subsurface facies document that this position is near the boundary between longshore current dominance during extreme storm events and a seaward zone of wave-dominated ramp development. Beginning at the morphologic break, i.e., d_l depths of 4 - 5 m, a time-dependent zone of profile closure occurs across the lower ramp wherein durations of closure increase seaward, and intervening repetitive changes in bed elevation decrease. Maximum short-term elevation change along the studied profiles is about 75 - 125 cm at about the 4-m water depth to several centimeters at about the 9.0-m water depth. The bed along this zone almost entirely consists of well-sorted, fine to very fine sand. Average grain size progressively decreases seaward becoming significantly muddy at about the 15-m depth. The closeout zone, or lower ramp, typically elevates in response to major storm events and subelevates during long fair-weather periods. Bedding structures indicate that, during storms, velocity conditions along the bed are sufficient to entrain and transport sand of all sizes.

The zone of closure is consistent with properties of profile change discussed by Kraus (1992). Kraus considers depth of closure as a seaward limit where waves can no longer produce a measurable change in depth, but not a limit for sediment motion. Moreover, he states that depth of closure is time-dependent (i.e., dependent upon the wave energy associated with discrete events (storms) or oceanographic seasons). Overall, data from this study document that elevation change and sediment motion are partially dependent and that closeout may be thought of as a zone of decreasing seaward transport in which fine to very fine sand is the typical bed-load material, even during highest energy events.

The distribution of grain size throughout the shoreface mass indicates net long-term transport directions and loci of deposition for different-sized material, thus providing guidelines for the placement of fill. Fine-grained sand is ubiquitous throughout much of the shoreface prism and is transported between all sectors of the profile during fair-weather and storm events. However, it is of lowest relative abundance in beach and inner trough settings. During major storm events, fine to very fine sand is selectively transferred seaward onto the lower ramp; during fair-weather periods, the sand slowly undergoes net shoreward transport. During major storm events, medium sand and coarser material may also shift seaward, but remain landward of the lower ramp, in longshore trough settings. However, the abundance of coarser material in shoreward parts of the shoreface mass indicates that such material undergoes net shoreward transport with long-term retention in the innermost parts of the nearshore system. For coastal settings similar to that of this study area, fine sand placed directly upon the beach and adjacent subaqueous bed will largely undergo displacement to bar, middle platform, and lower ramp settings. Medium sand will be retained on the beach for longer periods, but easily undergo seaward displacement during high-energy events with burial throughout the zone of longshore trough development. Disposal in the nearshore zone, at depths landward of d_l, is inherently less efficient than direct placement on the beach. However, compared to potential placement upon the lower ramp, at depths seaward of d_l, sediment entrainment is relatively rapid and subsequent cross-shore transport is provided in a grain-size- dependent manner to nearshore sectors as specified above. Because longshore transport is intrinsic to subaqueous settings landward of d_l, the likelihood of net shore-parallel displacement away from the project site is high.

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Appendix A
Vibracore Logs: Profile Lines 62 and 188

APPENDIX
Vibracore Plots - Profile Lines 188 and 62

The appendix contains plots of the vibracores collected along profile lines 188 and 62. The plots are represented by a number indicating the profile line and the vibracore number. The vibracore number is two-fold; the first part reflects consecutive renumbering in the offshore direction, the second part reflects actual coring sequence. Refer to Figure 1 of the main text for the location of the profile lines and Figures 2 and 3 for the location of individual cores. Distance below the sediment surface is plotted in meters along the vertical axis and grain size is plotted at one-quarter phi intervals along the horizontal axis. A key to symbols is as follows:

KEY FOR SYMBOLS ON CORES

SEDIMENT COLOR

- Yellow, brownish yellow, or grayish yellow.
- Gray or yellowish gray.

SEDIMENT TEXTURE

- Sand
- Gravelly Sand (5-30 % gravel)
- Sandy Gravel (30-90 % gravel)
- Very coarse sand
- Pebbles
- Granules

mu - mud
v - very fine sand
f - fine sand
m - medium sand
c - coarse sand
v - very coarse sand
g - granule
p - pebble

SEDIMENTARY STRUCTURES

- Structureless due to bioturbation or too deformed to decipher structure.
- Tabular cross-stratification - landward dipping (SSCS or LSCS)
- Tabular cross-stratification - seaward dipping (SSCS or LSCS))
- Trough Cross-Stratification (Tr)
- Horizontal to subhorizontal parallel laminae (HL)
- Low-angle parallel laminae - landward dipping (LAPL)
- Low-angle parallel laminae - Low-angle parallel laminae - seaward dipping (LAPL)
- Bioturbation

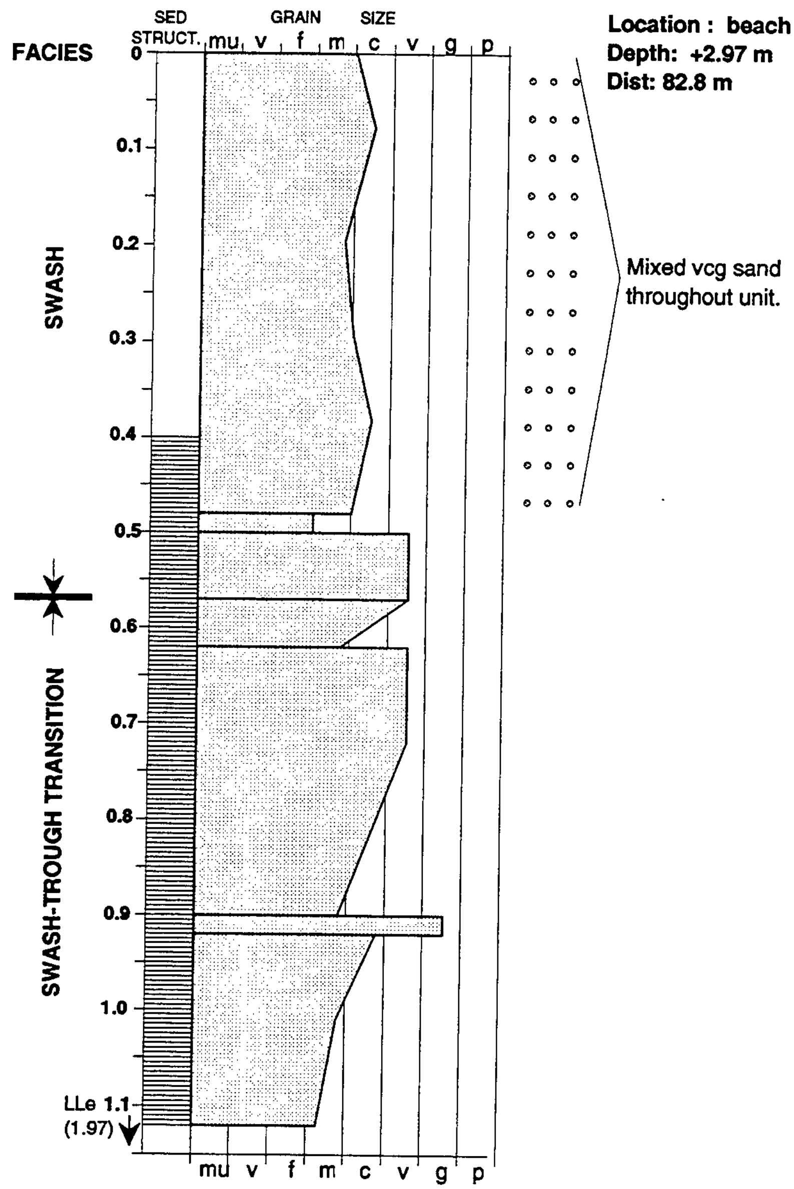
CROSS-STRATIFICATION SET THICKNESS

SS - small-scale - <3 cm
MS - medium-scale - 3-10 cm
LS - large-scale - >10 cm

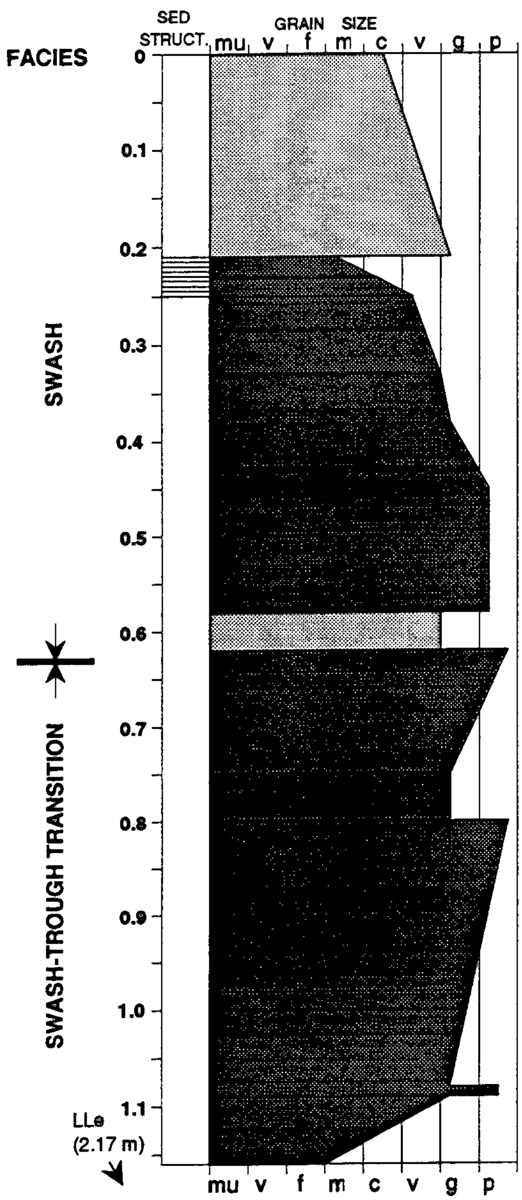
DEGREE OF BIOTURBATION

- low
- moderate
- high

188 VIBRACORE 1-28



188 VIBRACORE 2-32



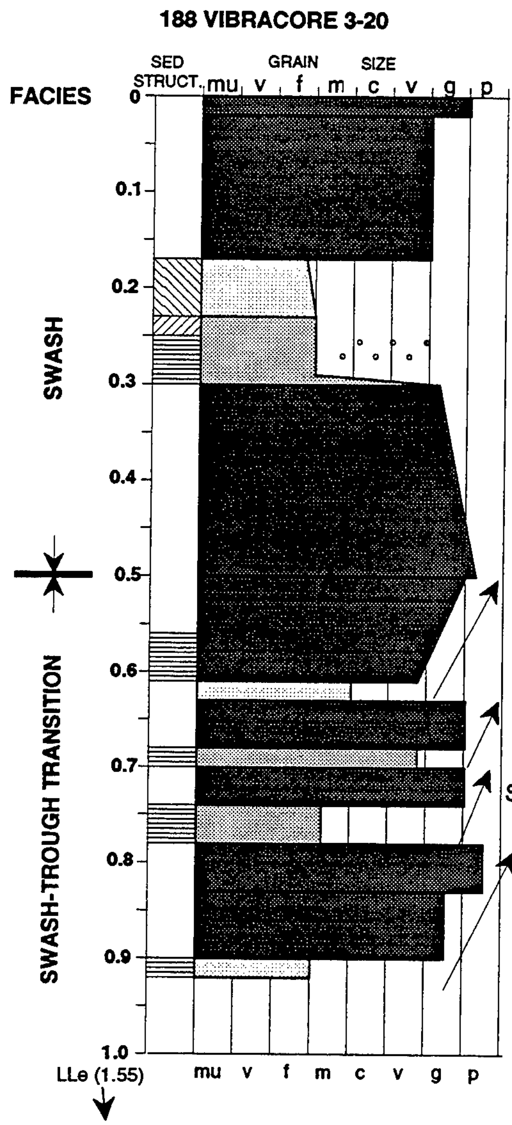
Location : beach
Depth: - 0.35 m
Dist: 109.4 m

All sand & gravel in the core is clean & bright yellow; broken shell fragments are abundant.

Shell alignment in gravel indicates crude HL or LAPL stratification.

Texture of beds throughout the core is typically bimodal with a fg to vcg sand component & a granule to pebble component.

end of core 1.16m



Location : beach face
Depth: -1.33 m
Dist: 122.9 m

All sediment in core is relatively bright yellow.

Mixed fu/ml & vcg sand.

Scattered pebbles up to 3 cm in length.
Crude subhorizontal bedding.

Scattered gravel & pebbles.

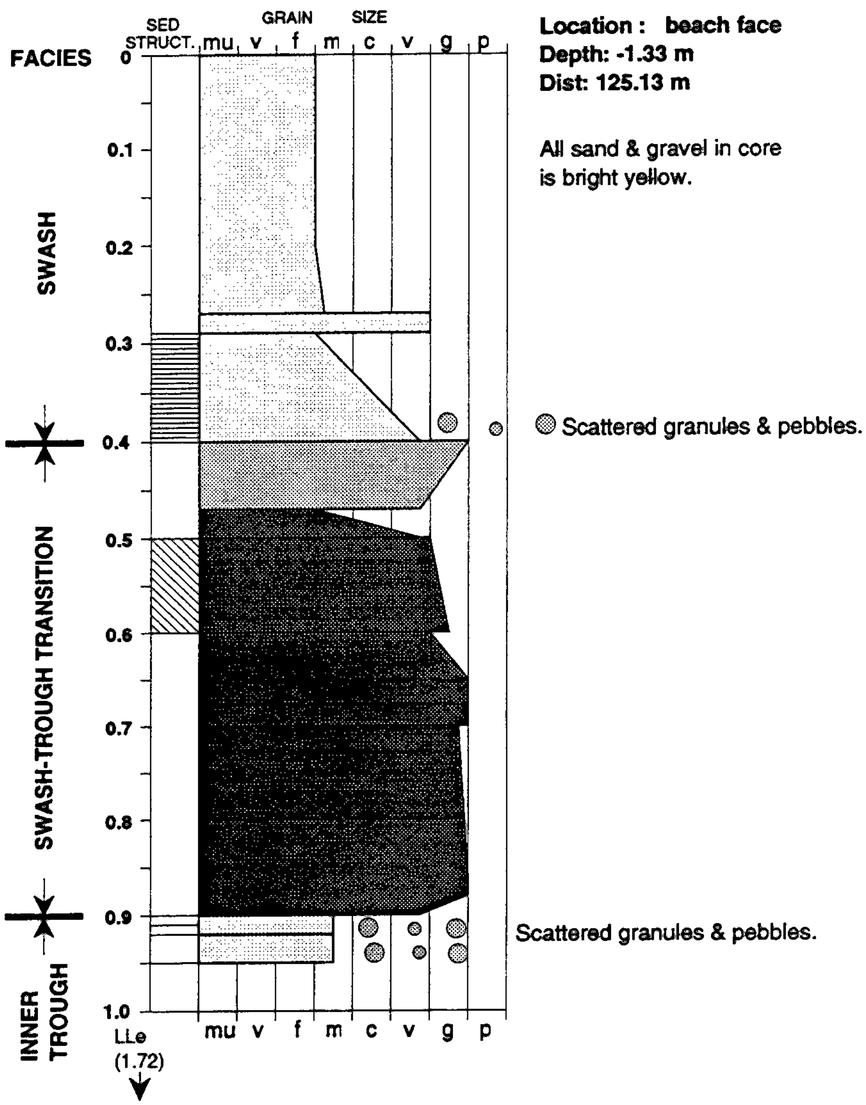
Upward coarsening sequences (arrows): Sharp lower contact with sand on gravel; crude, abruptly transitional upper contacts on beds within sequence.

Mixed mg & vcg sand.

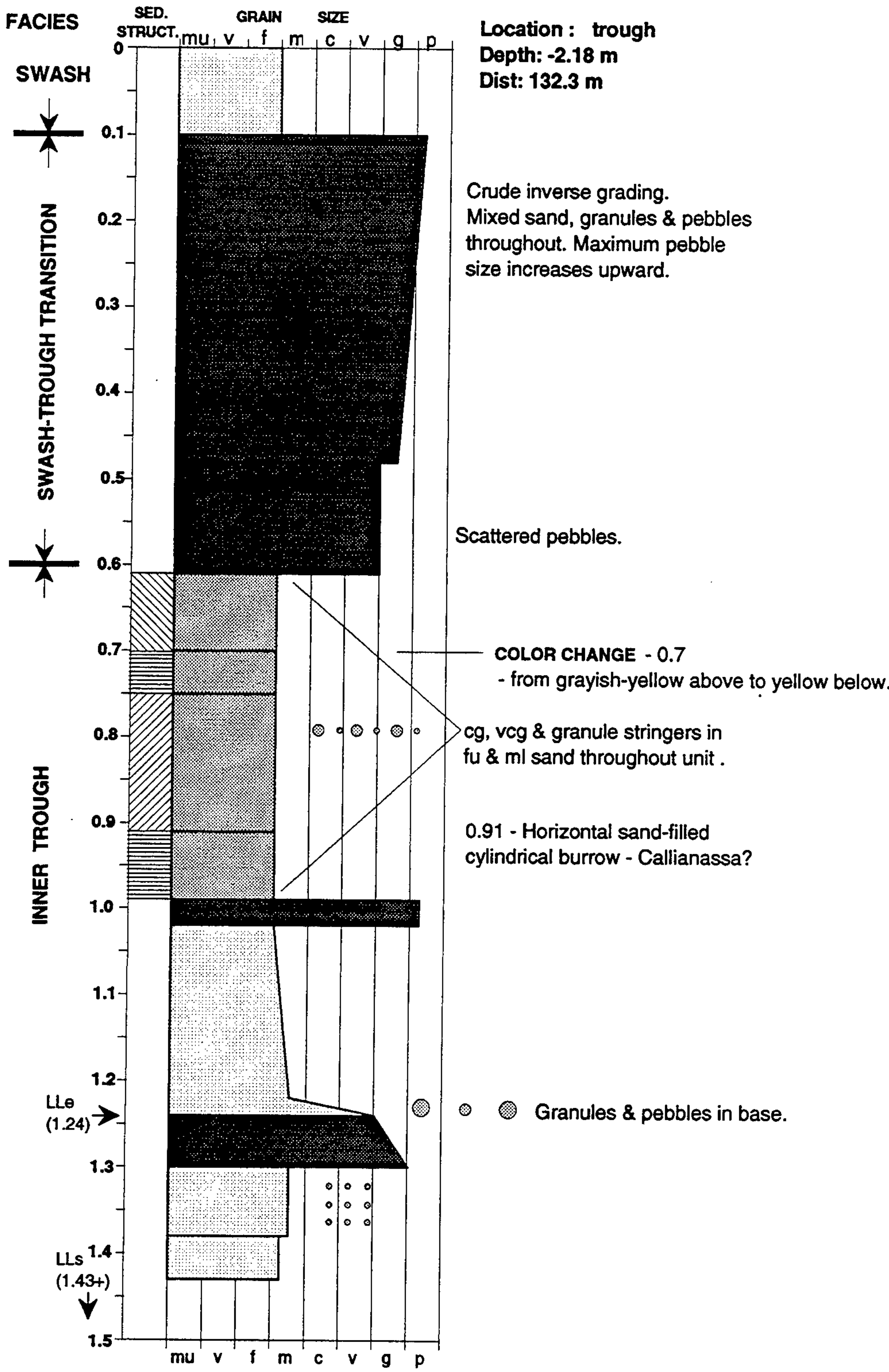
Scattered pebbles.

Mixed pebbles. Amount of sand matrix decreases upwards.

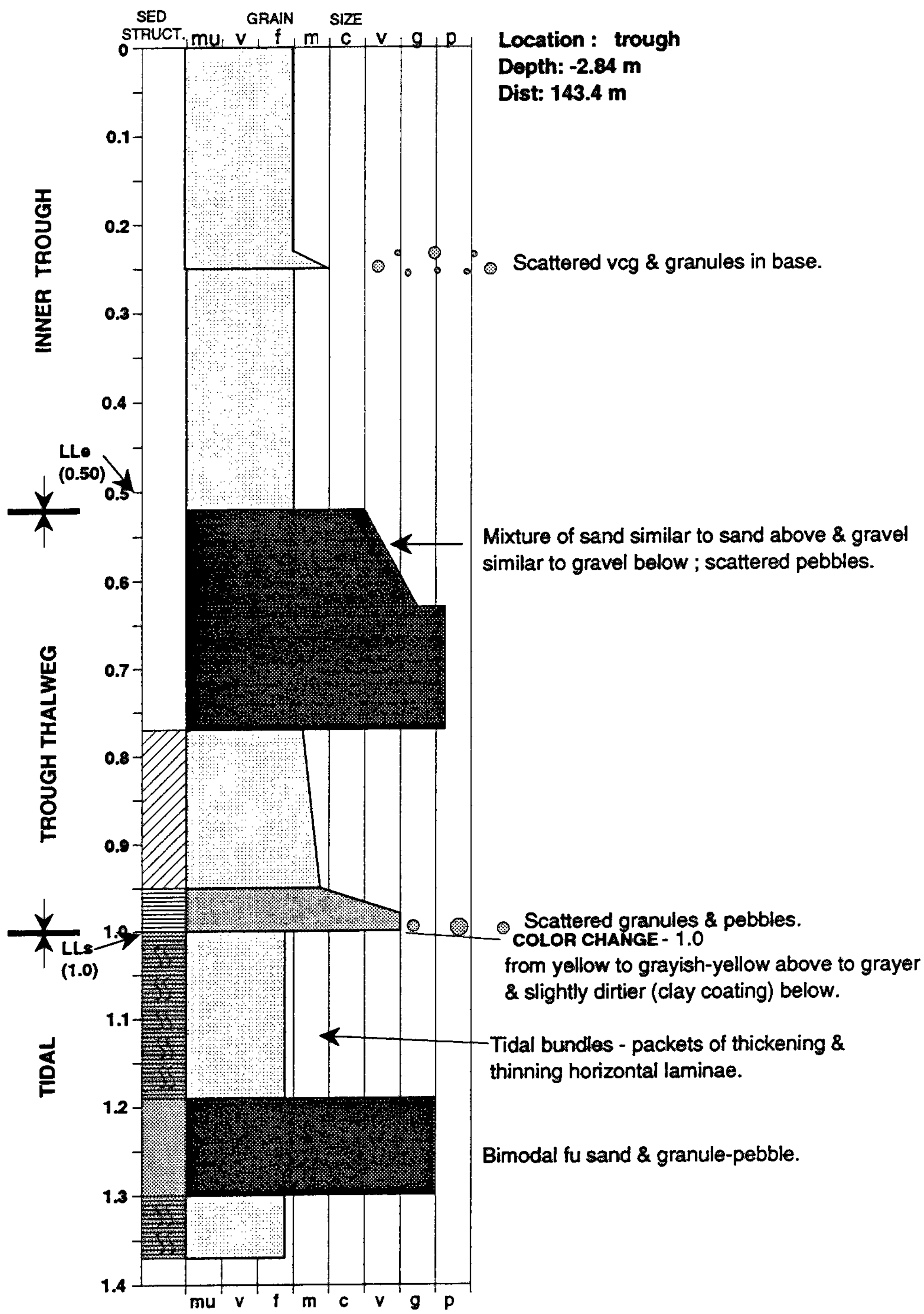
188 VIBRACORE 4-31

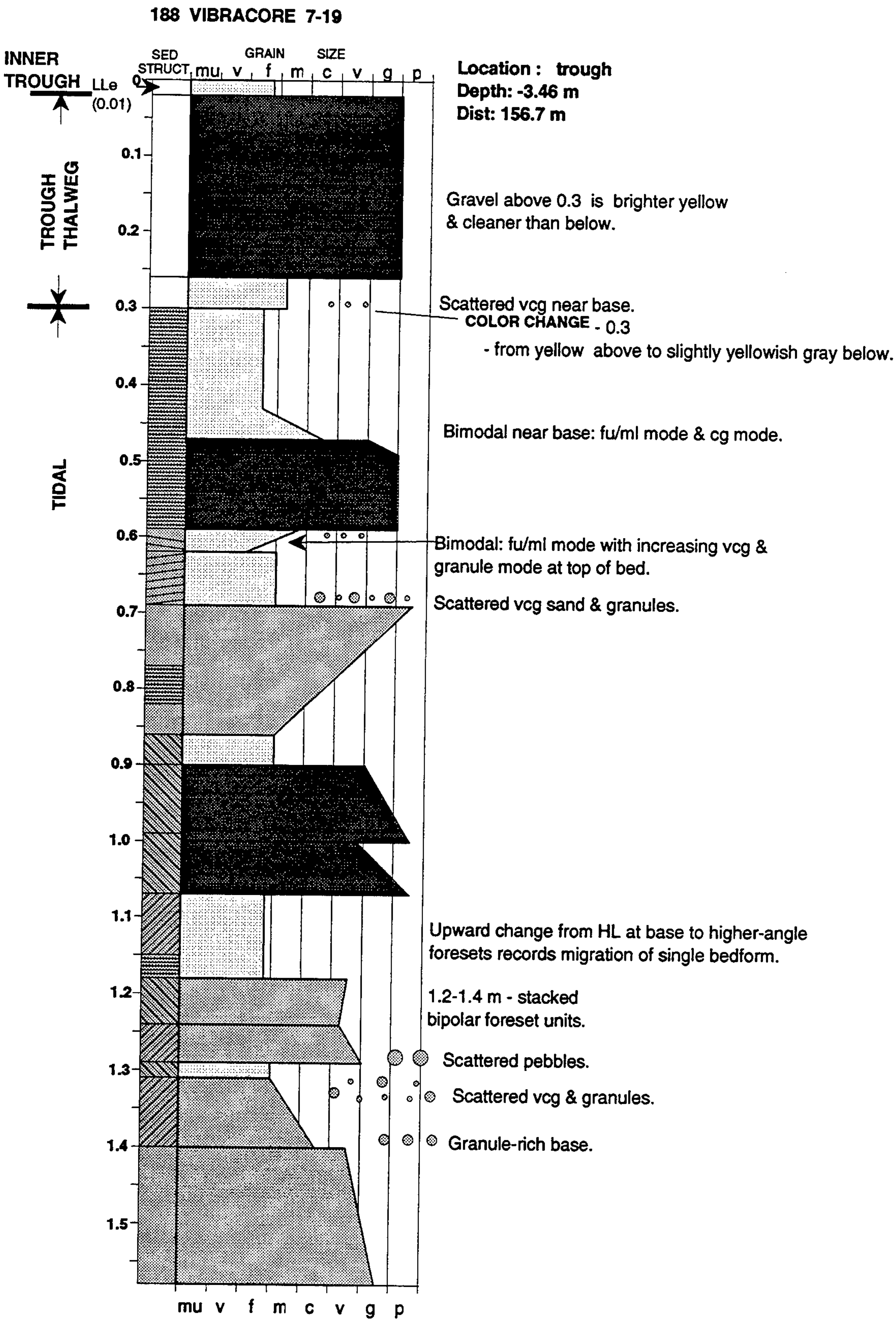


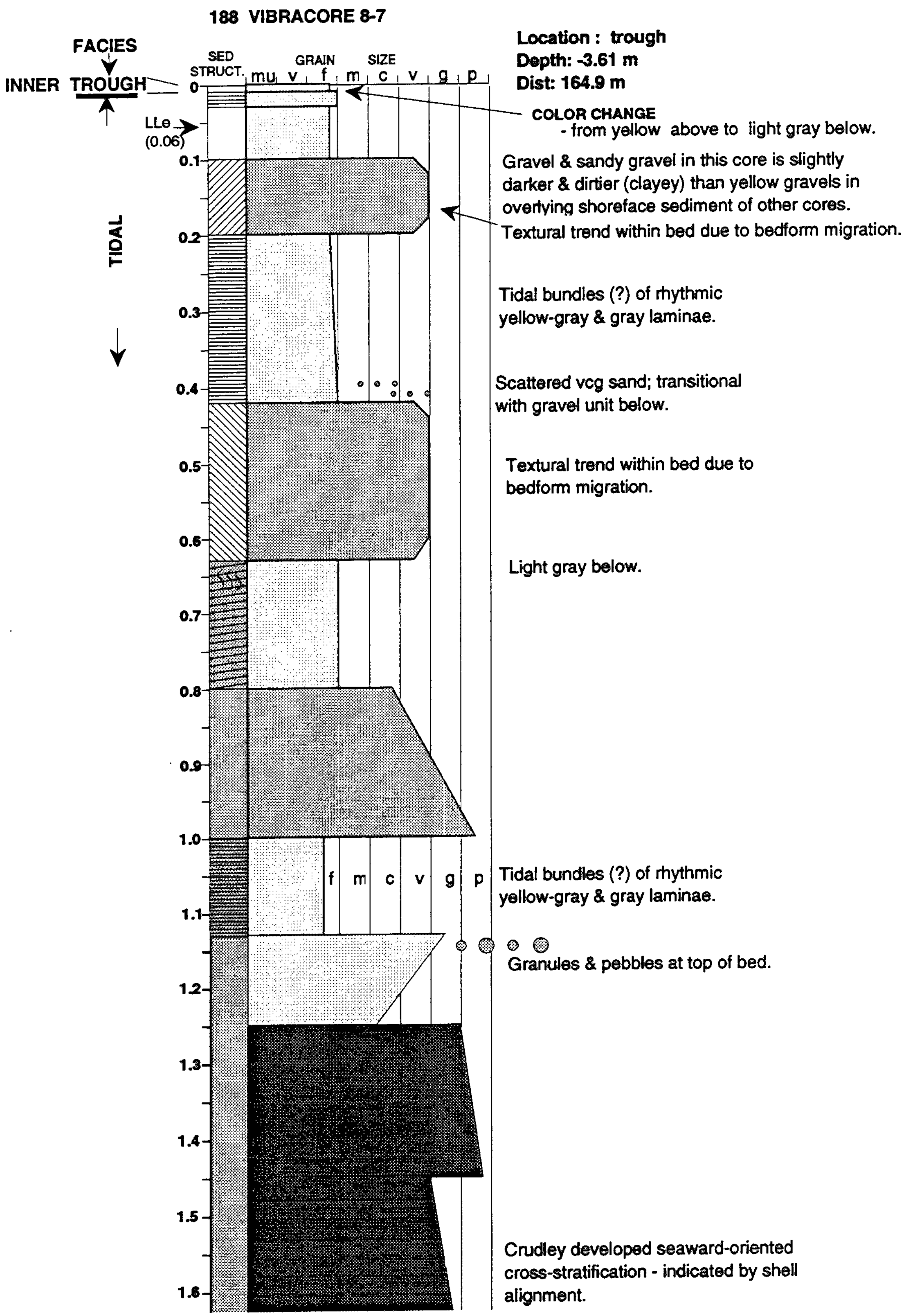
188 VIBRACORE 5-27

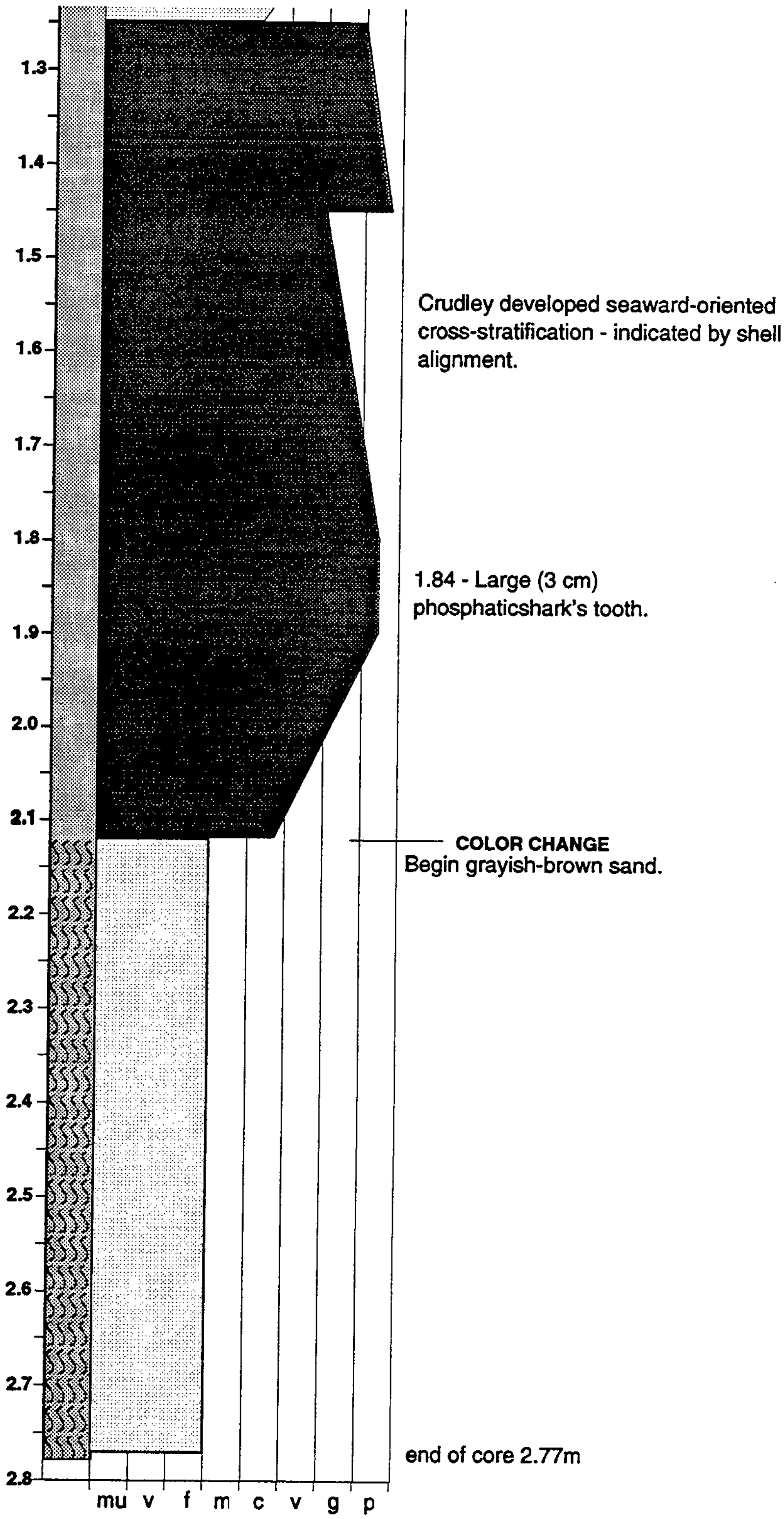


188 VIBRACORE 6-15



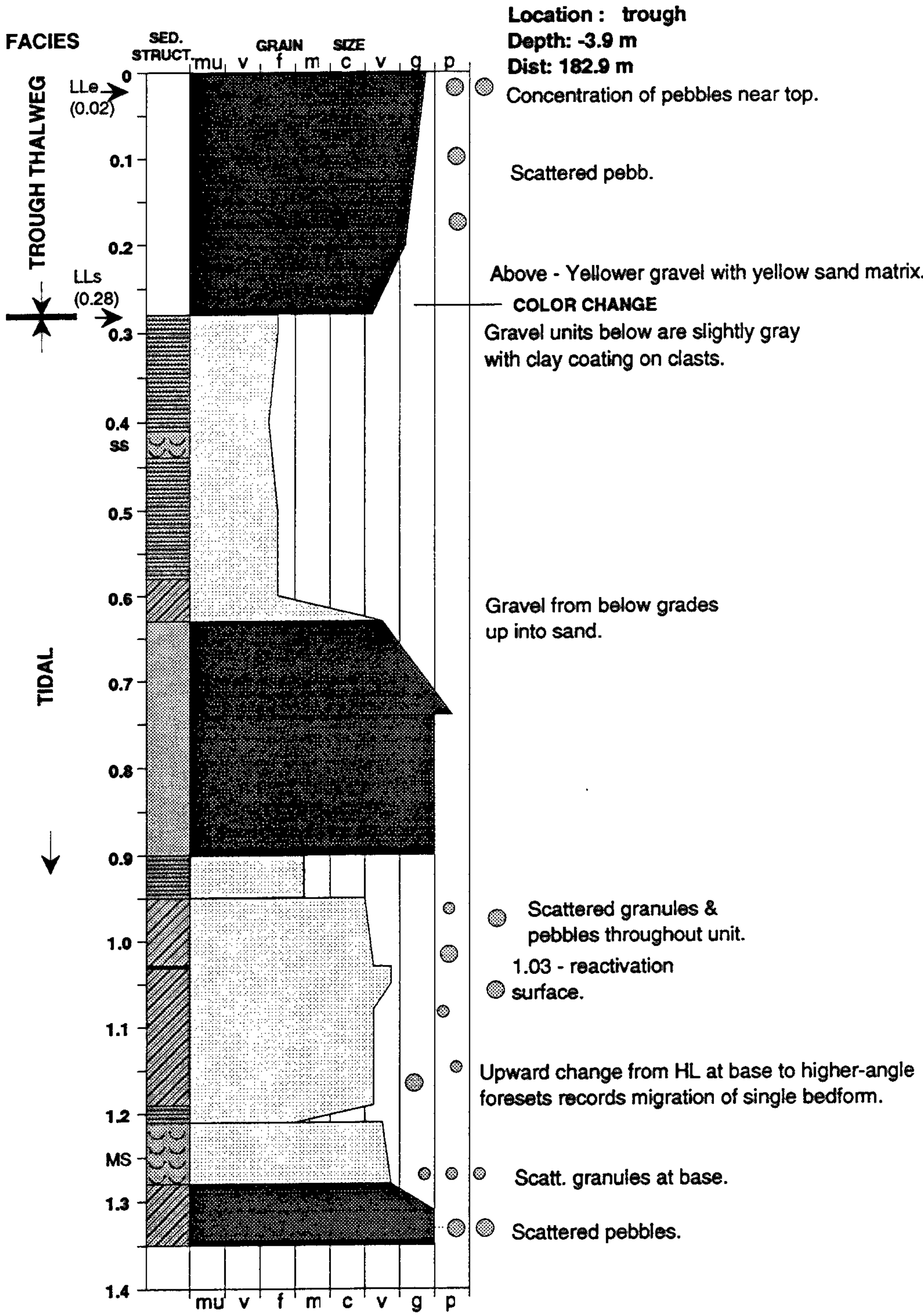

188 VIBRACORE 7-19
INNER TROUGH
LLe
(0.01)
TROUGH THALWEG
TIDAL
SED STRUCT.
GRAIN SIZE
mu v f m c v g p
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Location : trough
Depth: -3.46 m
Dist: 156.7 m
Gravel above 0.3 is brighter yellow & cleaner than below.
Scattered vcg near base.
COLOR CHANGE - 0.3
- from yellow above to slightly yellowish gray below.
Bimodal near base: fu/ml mode & cg mode.
Bimodal: fu/ml mode with increasing vcg & granule mode at top of bed.
Scattered vcg sand & granules.
Upward change from HL at base to higher-angle foresets records migration of single bedform.
1.2-1.4 m - stacked bipolar foreset units.
Scattered pebbles.
Scattered vcg & granules.
Granule-rich base.
mu v f m c v g p

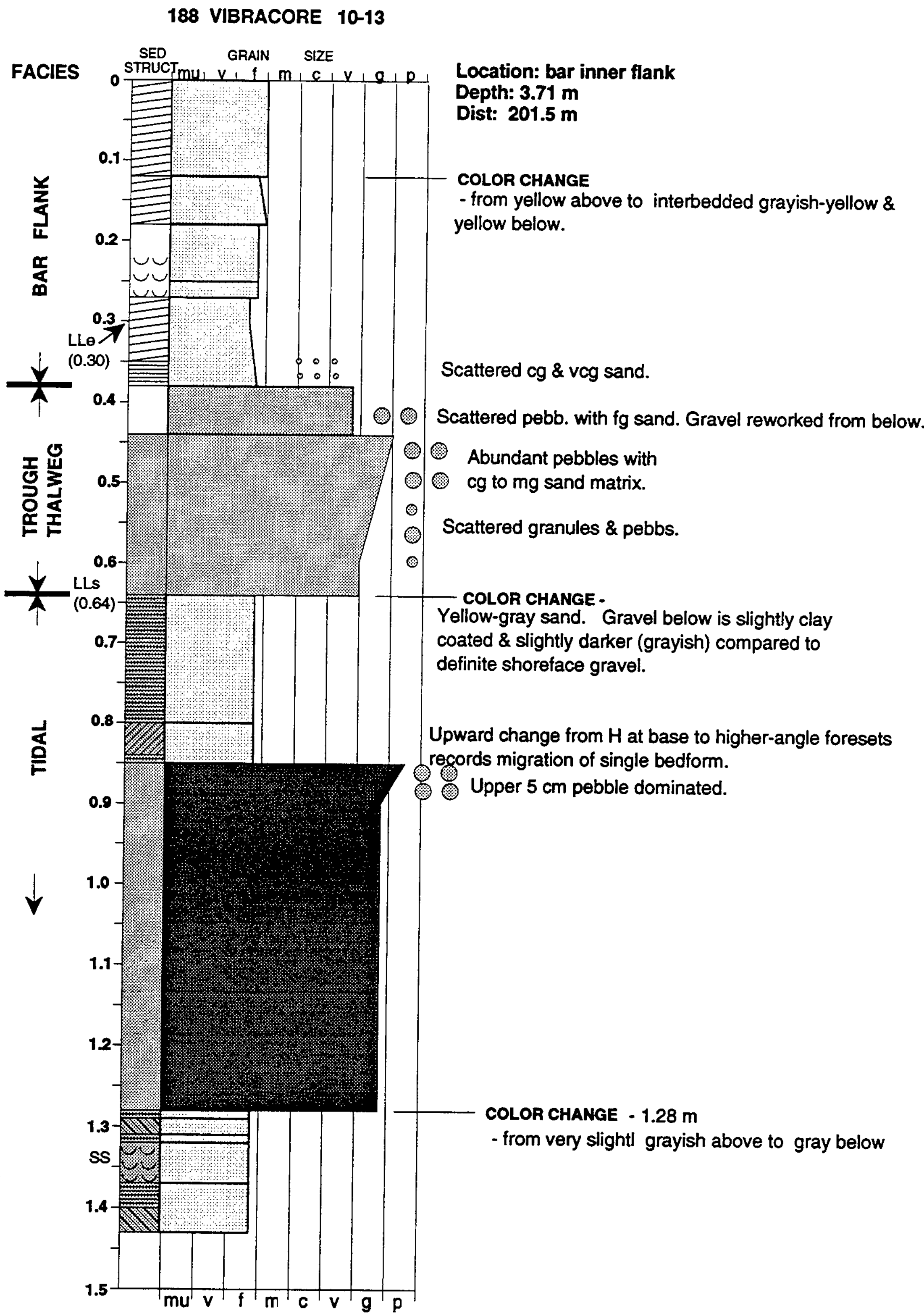

188 VIBRACORE 8-7
FACIES
INNER TROUGH
TIDAL
SED STRUCT.
GRAIN SIZE
mu v f m c v g p
Location : trough
Depth: -3.61 m
Dist: 164.9 m
LLe (0.06)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
COLOR CHANGE
- from yellow above to light gray below.
Gravel & sandy gravel in this core is slightly darker & dirtier (clayey) than yellow gravels in overlying shoreface sediment of other cores.
Textural trend within bed due to bedform migration.
Tidal bundles (?) of rhythmic yellow-gray & gray laminae.
Scattered vcg sand; transitional with gravel unit below.
Textural trend within bed due to bedform migration.
Light gray below.
f m c v g p
Tidal bundles (?) of rhythmic yellow-gray & gray laminae.
Granules & pebbles at top of bed.
Crudley developed seaward-oriented cross-stratification - indicated by shell alignment.

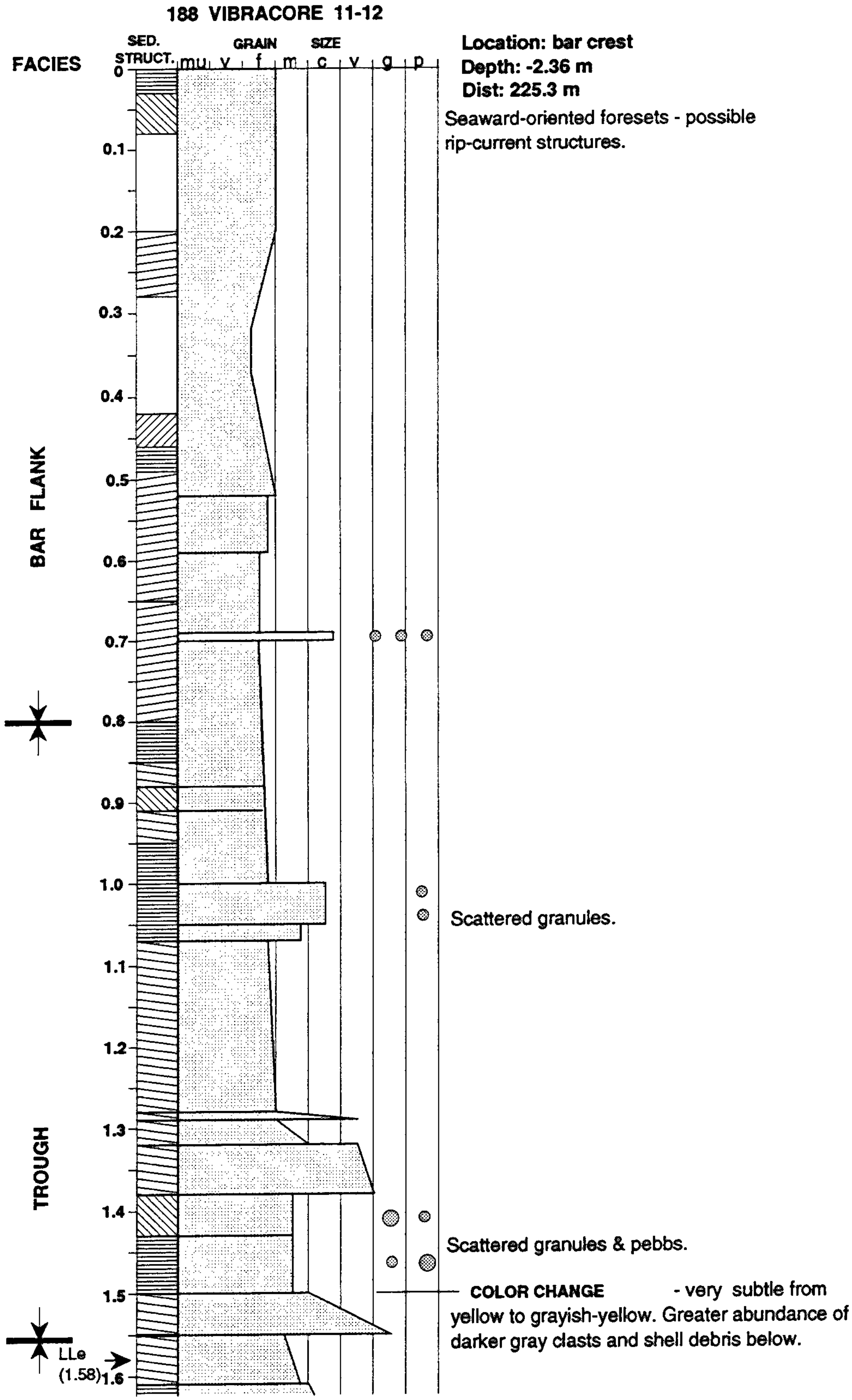


1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
mu v f m c v g p
Crudley developed seaward-oriented cross-stratification - indicated by shell alignment.
1.84 - Large (3 cm) phosphaticshark's tooth.
COLOR CHANGE
Begin grayish-brown sand.
end of core 2.77m

188 VIBRACORE 9-14

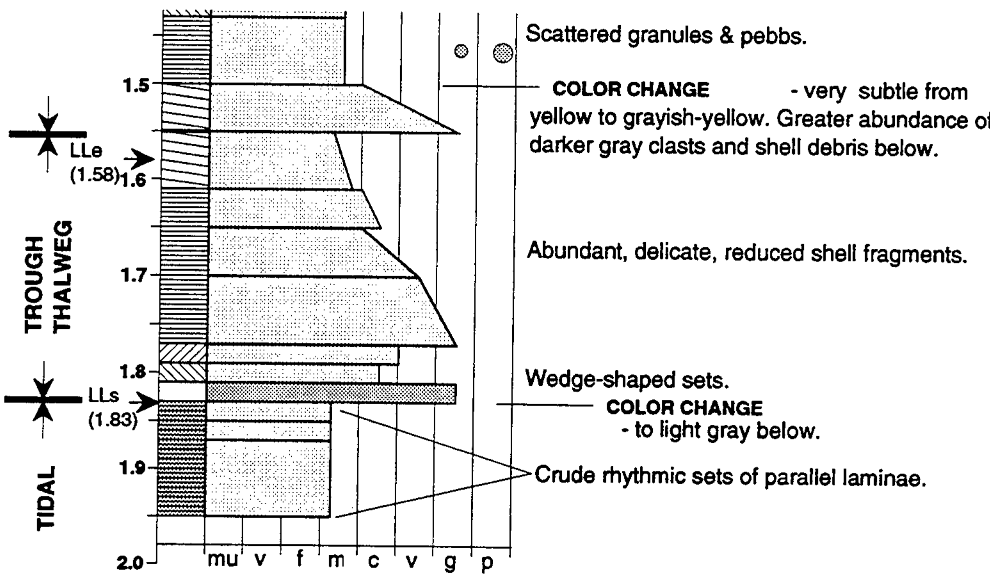



188 VIBRACORE 10-13
FACIES
SED STRUCT
GRAIN SIZE
mu v f m c v g p
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
BAR FLANK
LLe
(0.30)
TROUGH THALWEG
LLs
(0.64)
TIDAL
SS
Location: bar inner flank
Depth: 3.71 m
Dist: 201.5 m
COLOR CHANGE
- from yellow above to interbedded grayish-yellow & yellow below.
Scattered cg & vcg sand.
Scattered pebb. with fg sand. Gravel reworked from below.
Abundant pebbles with cg to mg sand matrix.
Scattered granules & pebbs.
COLOR CHANGE -
Yellow-gray sand. Gravel below is slightly clay coated & slightly darker (grayish) compared to definite shoreface gravel.
Upward change from H at base to higher-angle foresets records migration of single bedform.
Upper 5 cm pebble dominated.
COLOR CHANGE - 1.28 m
- from very slightl grayish above to gray below

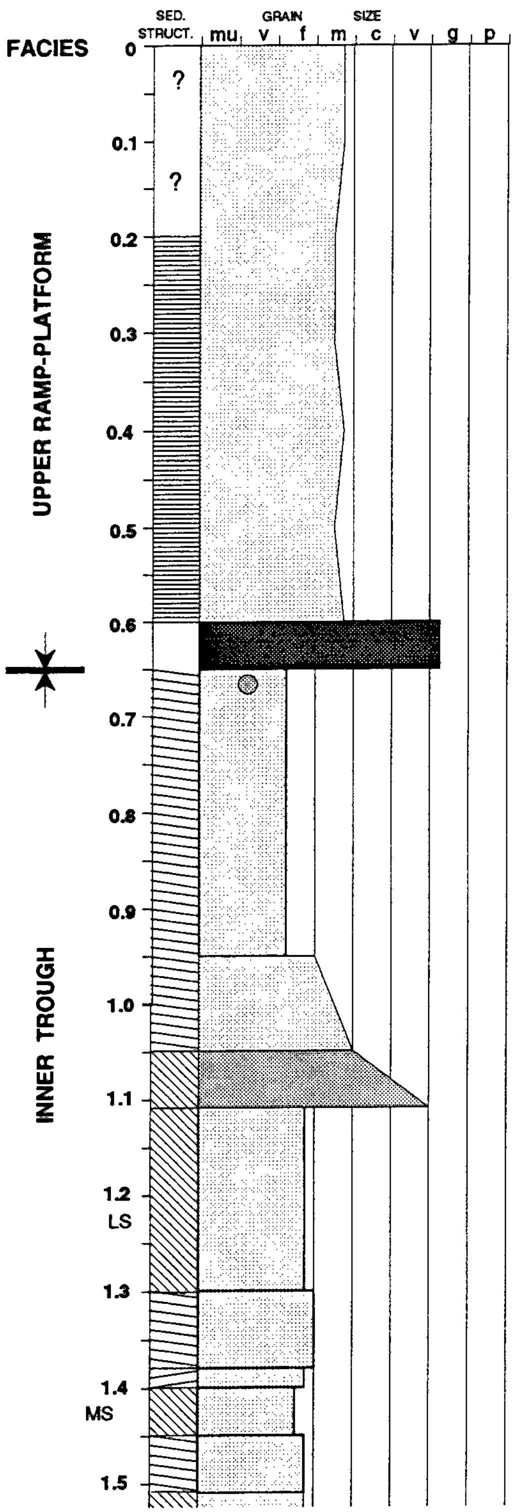


188 VIBRACORE 11-12
FACIES
SED. STRUCT.
GRAIN SIZE
mu v f m c v g p
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
BAR FLANK
TROUGH
LLe (1.58)
Location: bar crest
Depth: -2.36 m
Dist: 225.3 m
Seaward-oriented foresets - possible rip-current structures.
Scattered granules.
Scattered granules & pebbs.
COLOR CHANGE - very subtle from yellow to grayish-yellow. Greater abundance of darker gray clasts and shell debris below.

VIBRACORE 11-12
(continued)



188 VIBRACORE 12-39



Location : bar crest
Depth: -2.26 m
Dist: 236.9 m

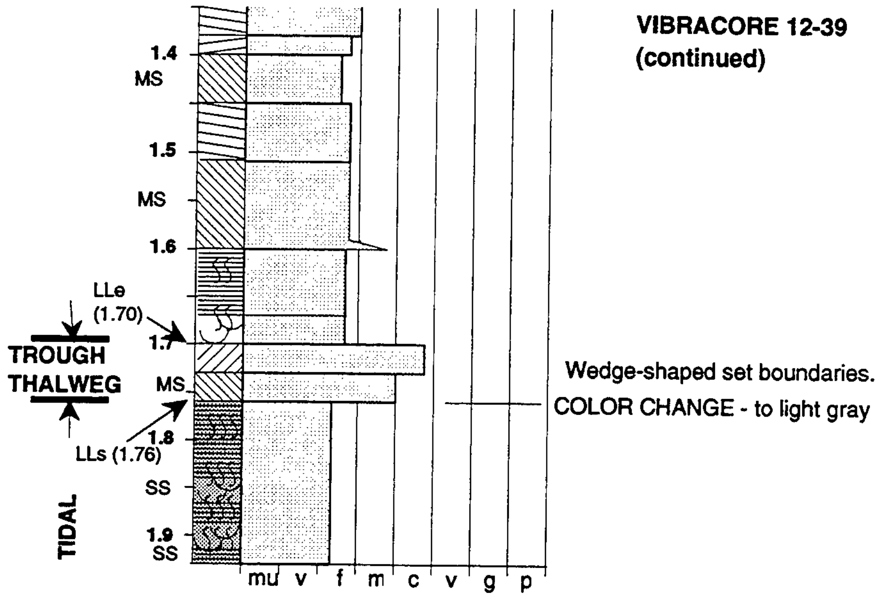
3 cm. long chert pebble at 0.66m.

1.05 to 1.30 - Seaward dipping cross-stratification are not high angle. Instead, a steeper version of LAPL.

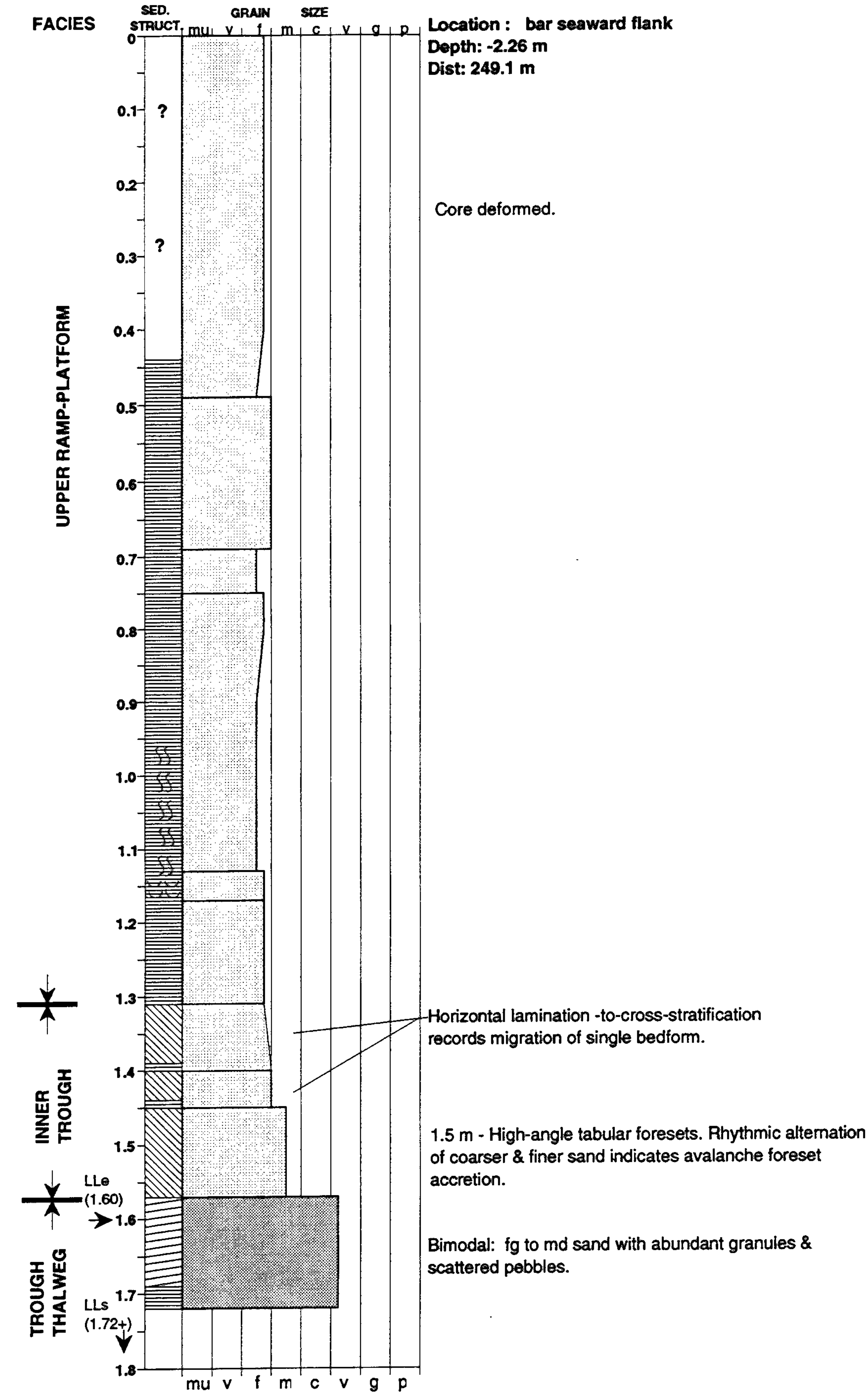
1.05 - 1.11 - Abundant granules & pebbles.

1.11 to 1.60m - Stacked sets with very low-angle to horizontal set boundaries. Seaward migration and aggradation of large-scale bedforms (bars?). Scattered mg sand layers.

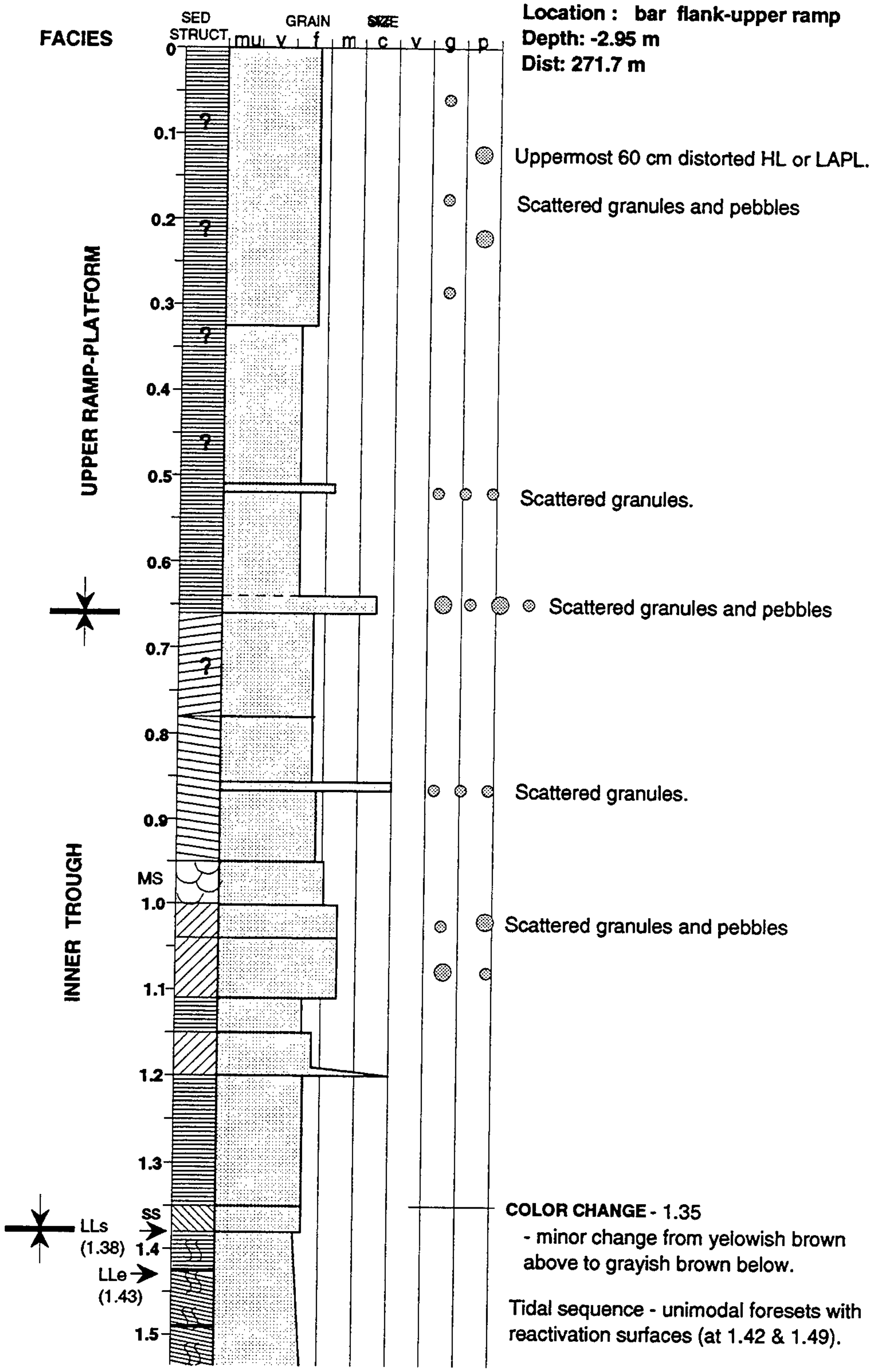
VIBRACORE 12-39 (continued)

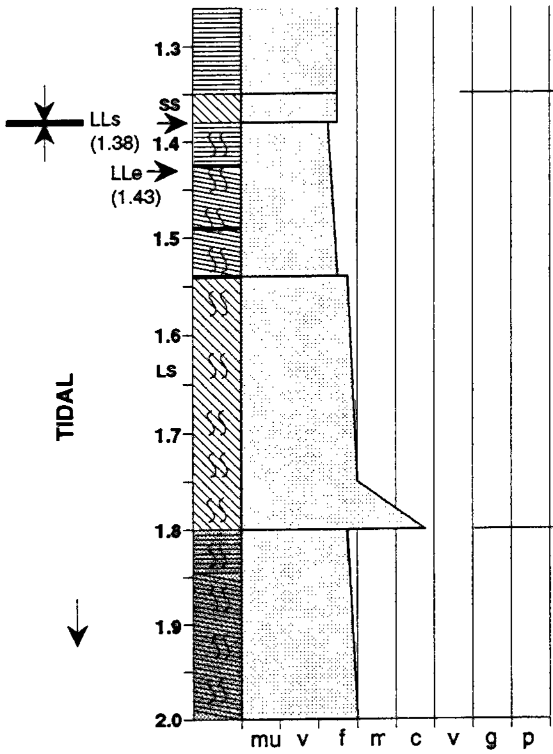


188 VIBRACORE 13 - 11



188 VIBRACORE 14 - 16





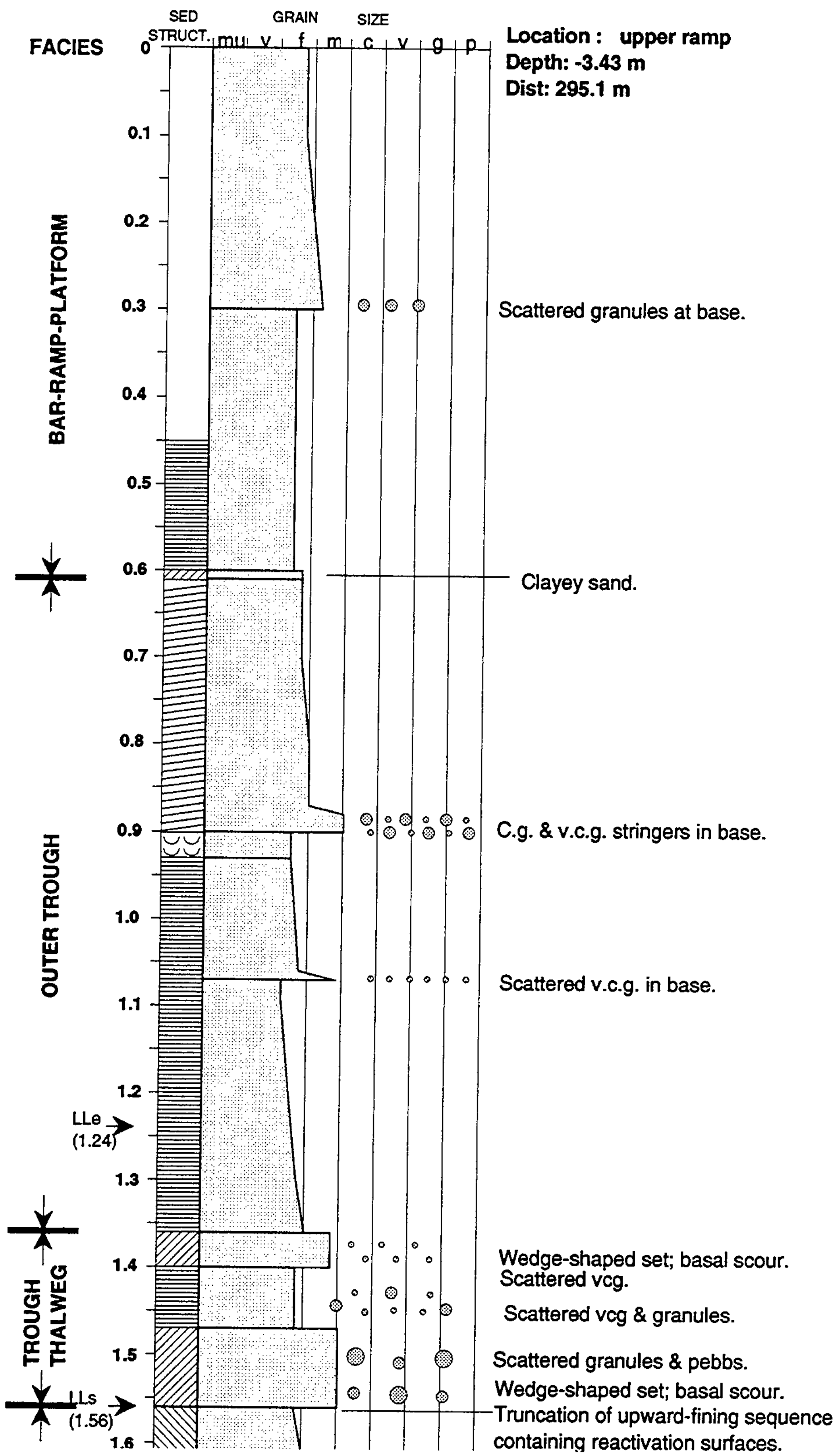
VIBRACORE 14-16
(continued)

COLOR CHANGE - 1.35
- minor change from yelowish brown above to grayish brown below.

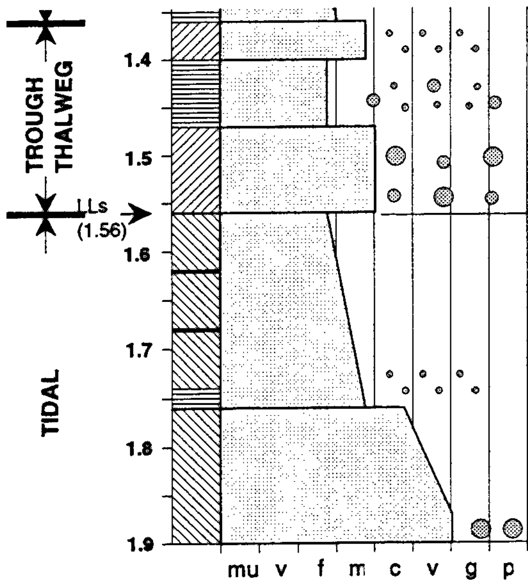
Tidal sequence - unimodal foresets with reactivation surfaces (at 1.42 & 1.49).

COLOR CHANGE - 1.80
- distinct change to brownish gray below.

188 VIBRACORE 15 - 17



188 VIBRACORE 15-17
(continued)



Wedge-shaped set; basal scour.
Scattered vcg.

Scattered vcg & granules.

Scattered granules & pebbs.

Wedge-shaped set; basal scour.

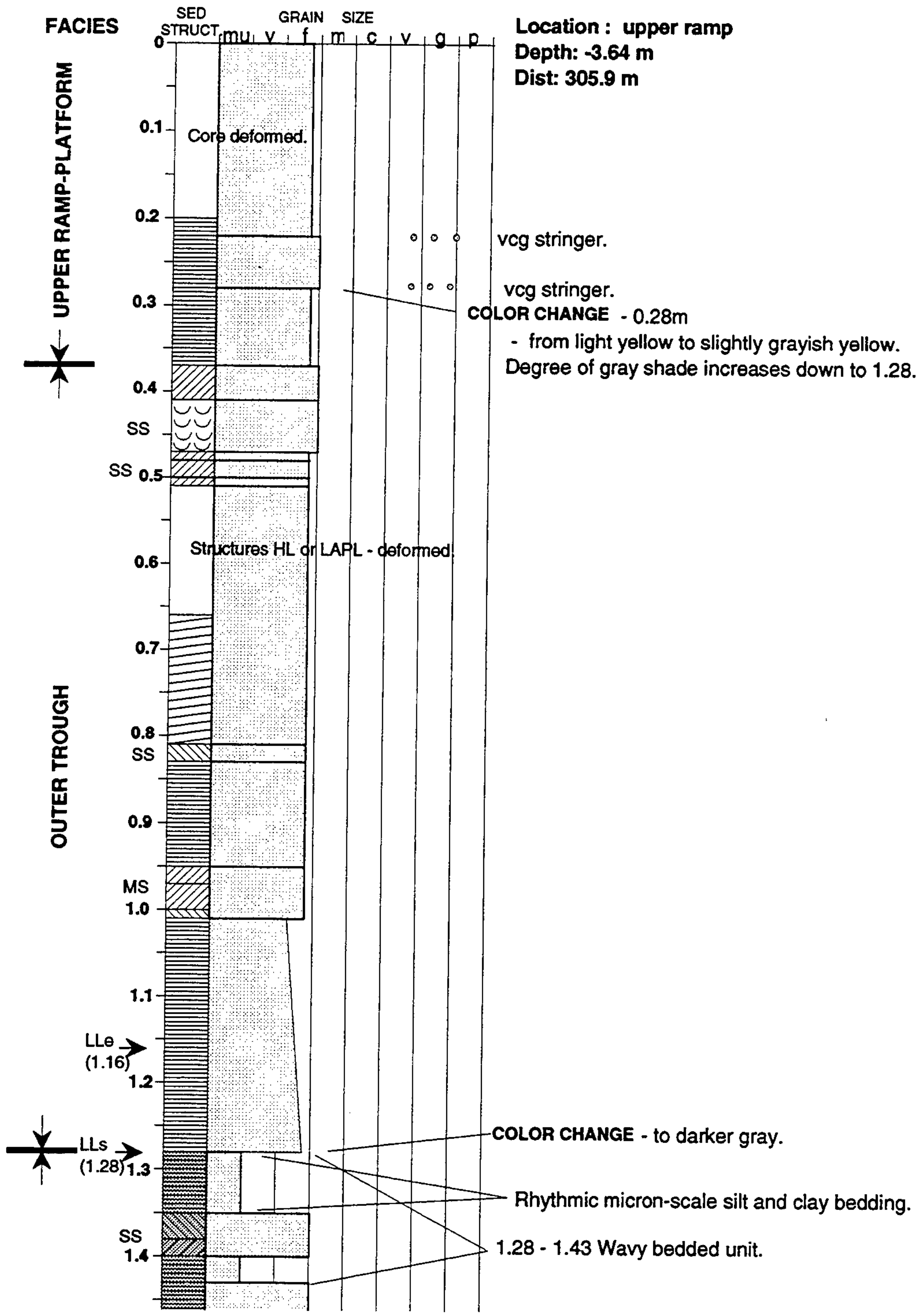
Truncation of upward-fining sequence containing reactivation surfaces.

1.62 - reactivation surface.

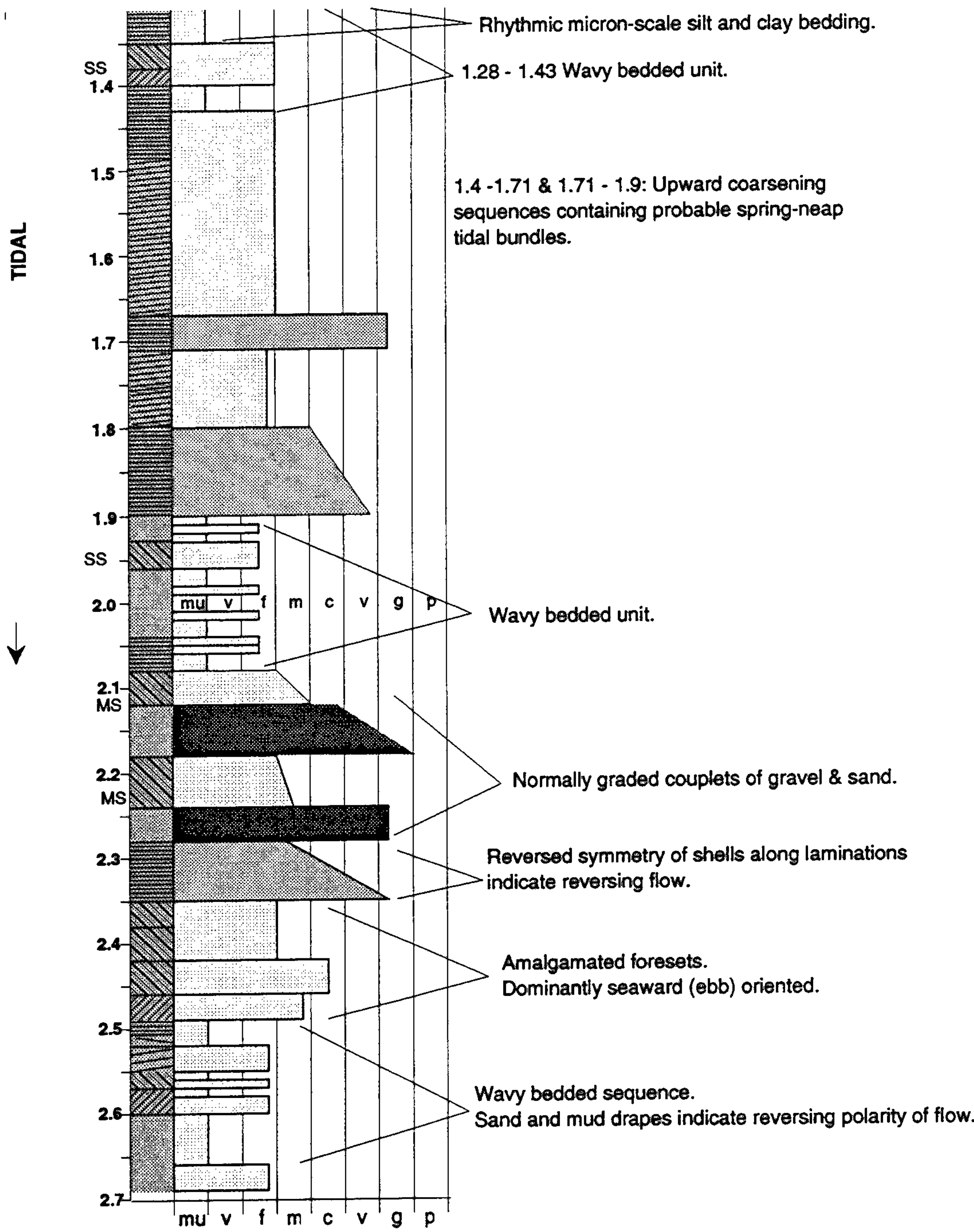
1.68 - reactivation surface.

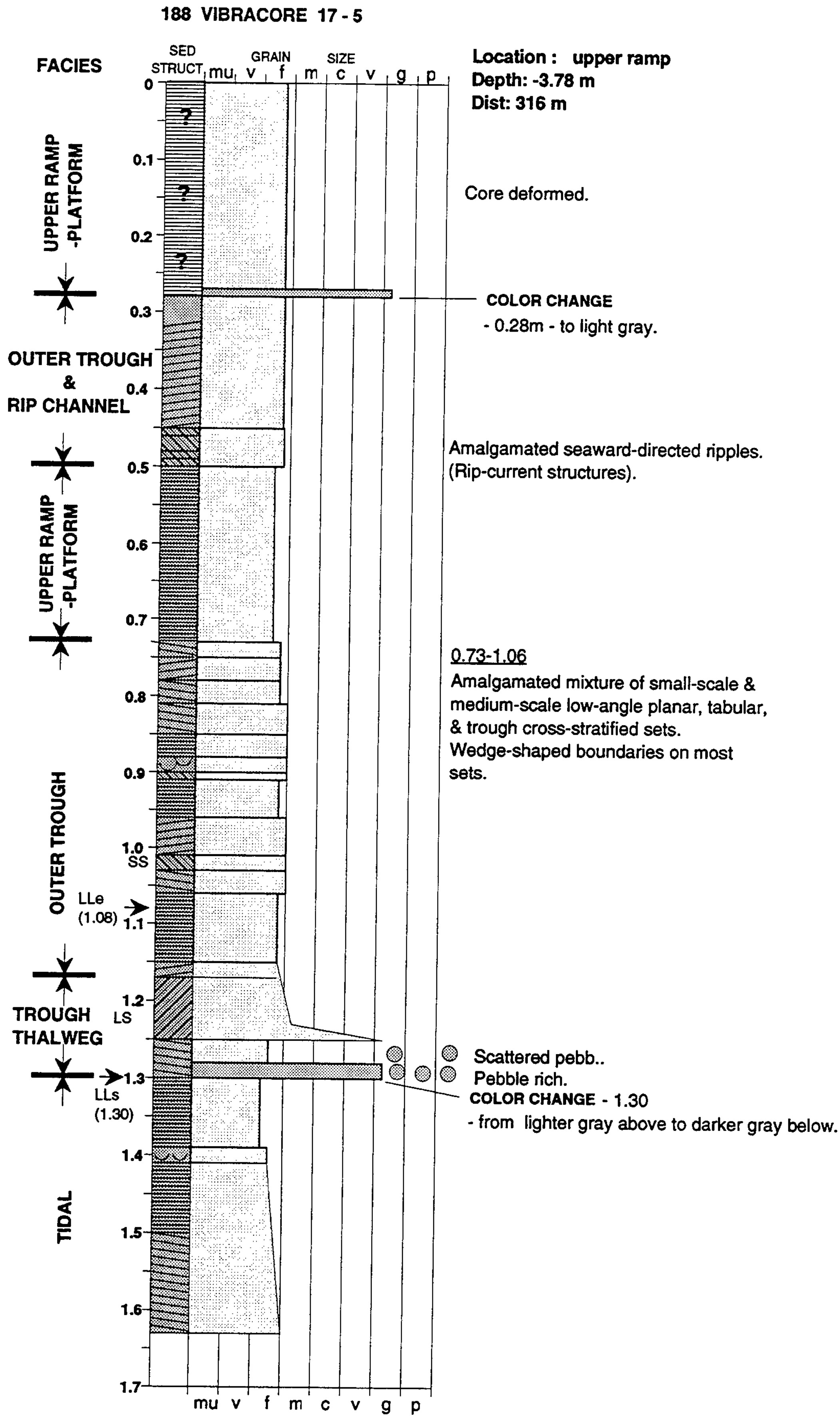
Upward change from HL at base of bed to higher-angle foresets records migration of single bedform.

188 VIBRACORE 16 - 6

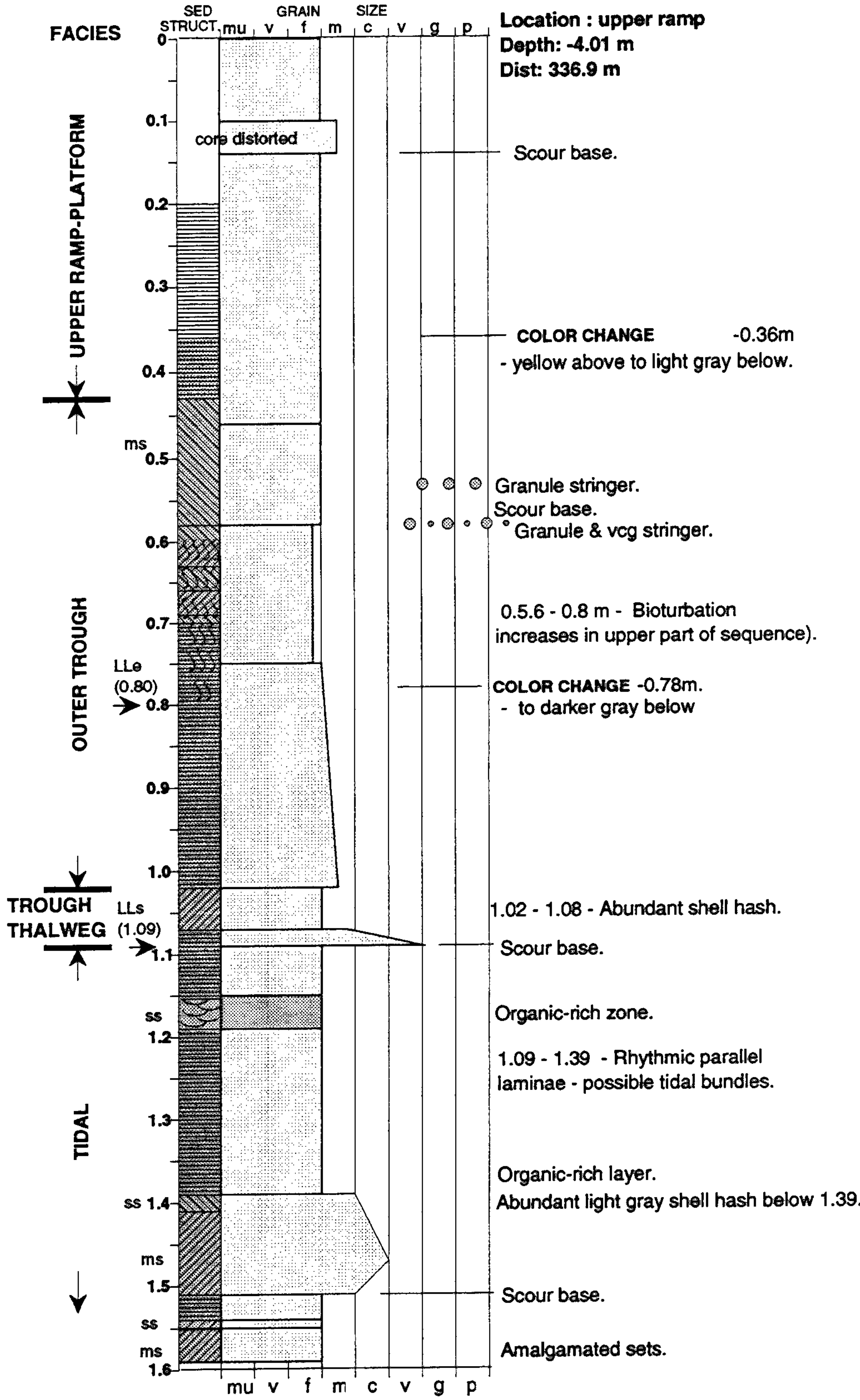


188 VIBRACORE 16-6
(continued)

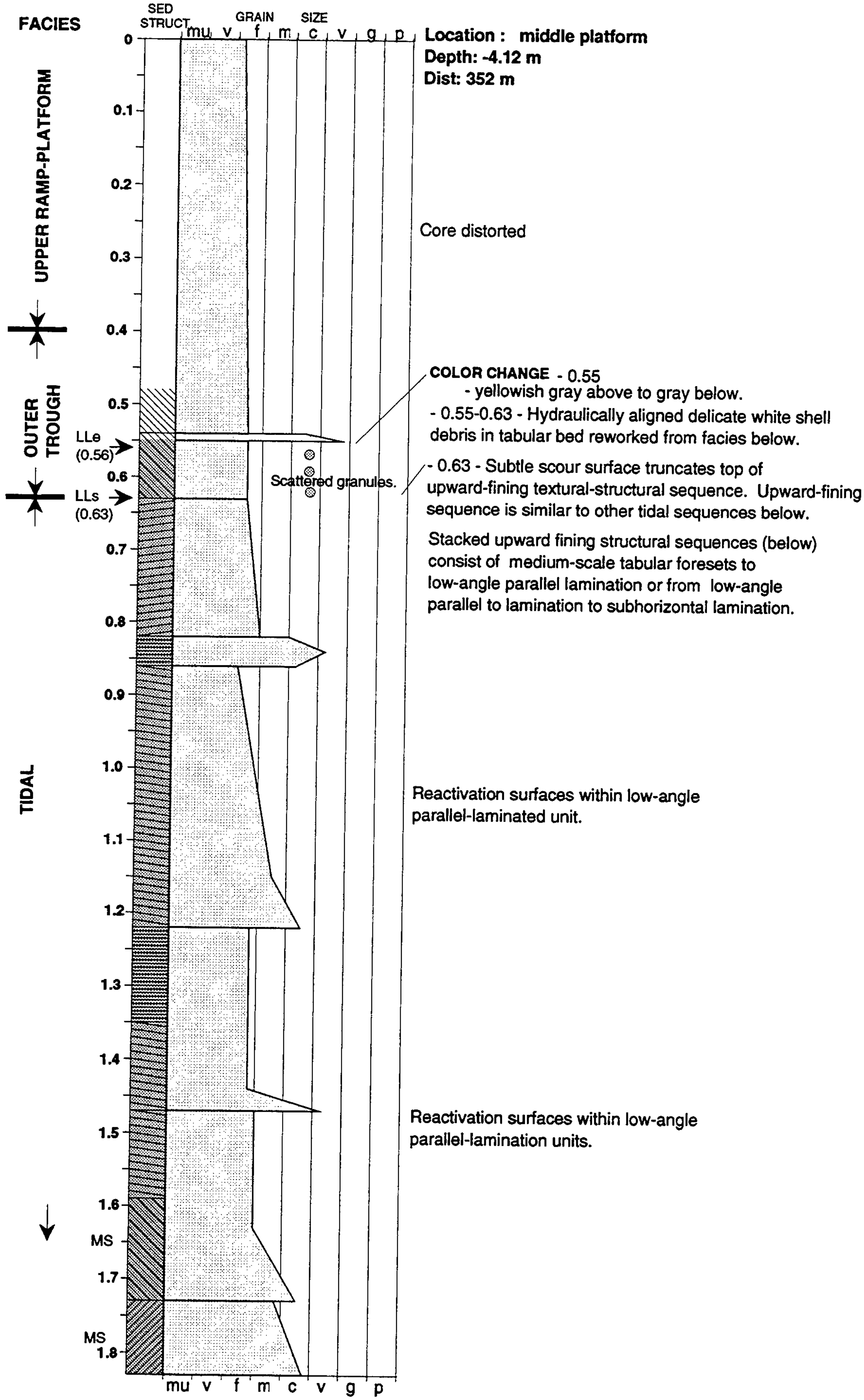



188 VIBRACORE 17 - 5
FACIES
SED STRUCT
GRAIN SIZE
mu v f m c v g p
Location : upper ramp
Depth: -3.78 m
Dist: 316 m
UPPER RAMP -PLATFORM
Core deformed.
COLOR CHANGE
- 0.28m - to light gray.
OUTER TROUGH & RIP CHANNEL
Amalgamated seaward-directed ripples. (Rip-current structures).
UPPER RAMP -PLATFORM
0.73-1.06
Amalgamated mixture of small-scale & medium-scale low-angle planar, tabular, & trough cross-stratified sets. Wedge-shaped boundaries on most sets.
OUTER TROUGH
SS
LLe (1.08)
TROUGH THALWEG
LS
Scattered pebb..
Pebble rich.
COLOR CHANGE - 1.30
- from lighter gray above to darker gray below.
LLs (1.30)
TIDAL
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7

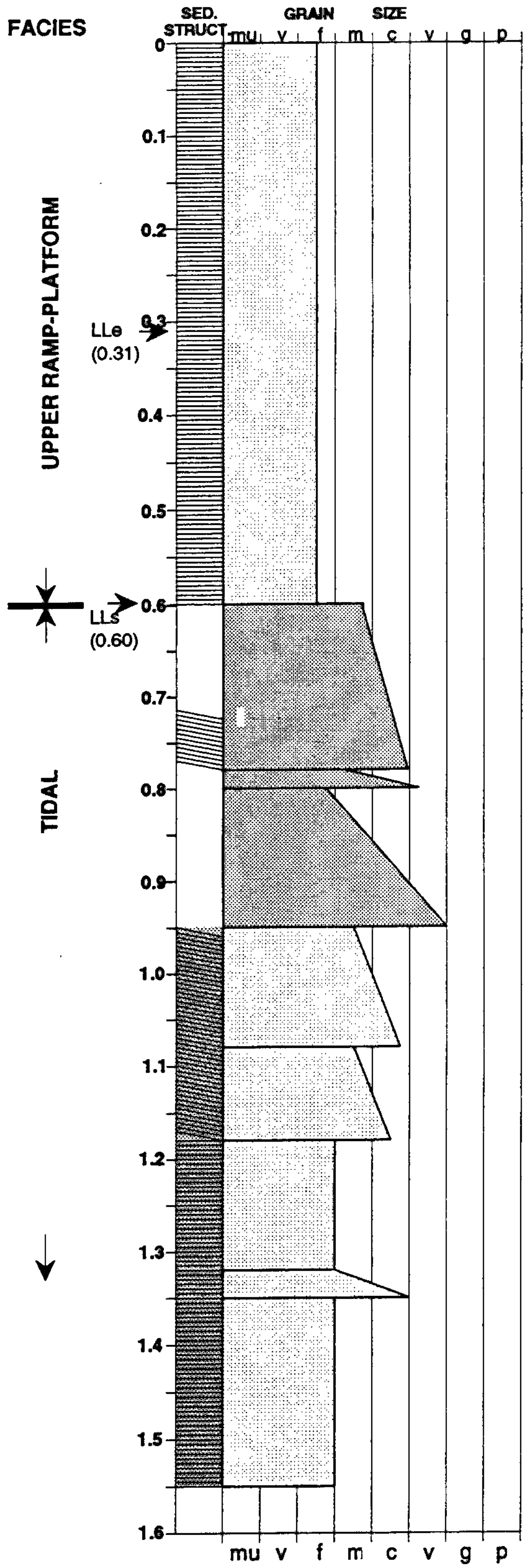
188 VIBRACORE 18 - 8



188 VIBRACORE 19 - 18



188 VIBRACORE 20 - 23

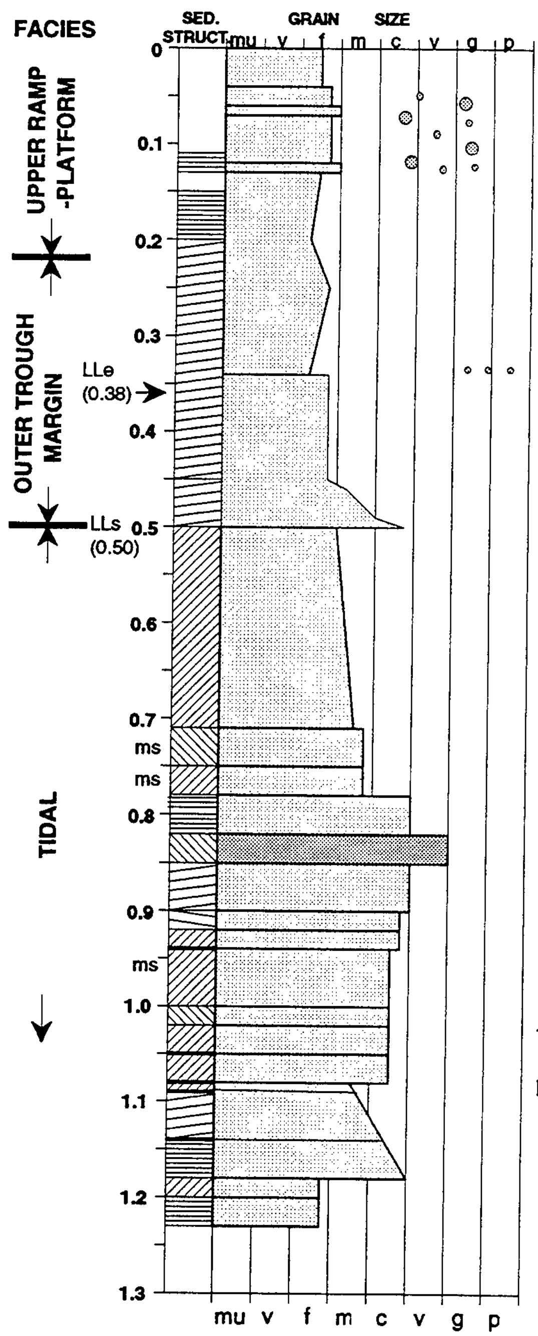


Location : middle platform
Depth: -4.24 m
Dist: 389 m

Below 0.31 - scattered oxidized quartz granules & delicate light-gray shell debris.

0.60 to 0.95 - Upward-fining gravel beds similar to those in cores 10, 18,26,38.

188 VIBRACORE 21 - 26



Location : middle platform
Depth: -4.25 m
Dist: 398 m

Scattered delicate yellow shell debris & vcg to granule clasts.

0.13 - 0.34: Sand is unimodal & much better sorted than below.

Core deformed from 0.2 to 0.5; structures may be HL instead of LAPL.

vcg stringer.

0.34 - 50: Bimodal sand with delicate light gray shell debris aligned parallel to bedding. Modes include some cg sand derived from below & abundant fg sand similar to overlying u

Structures bel ow 0.5 indicate reversing and asymmetric tidal

Below 0.50: Very poorly sorted, bimodal texture - modes include mg, cg & vcg sand; scattered vcg.

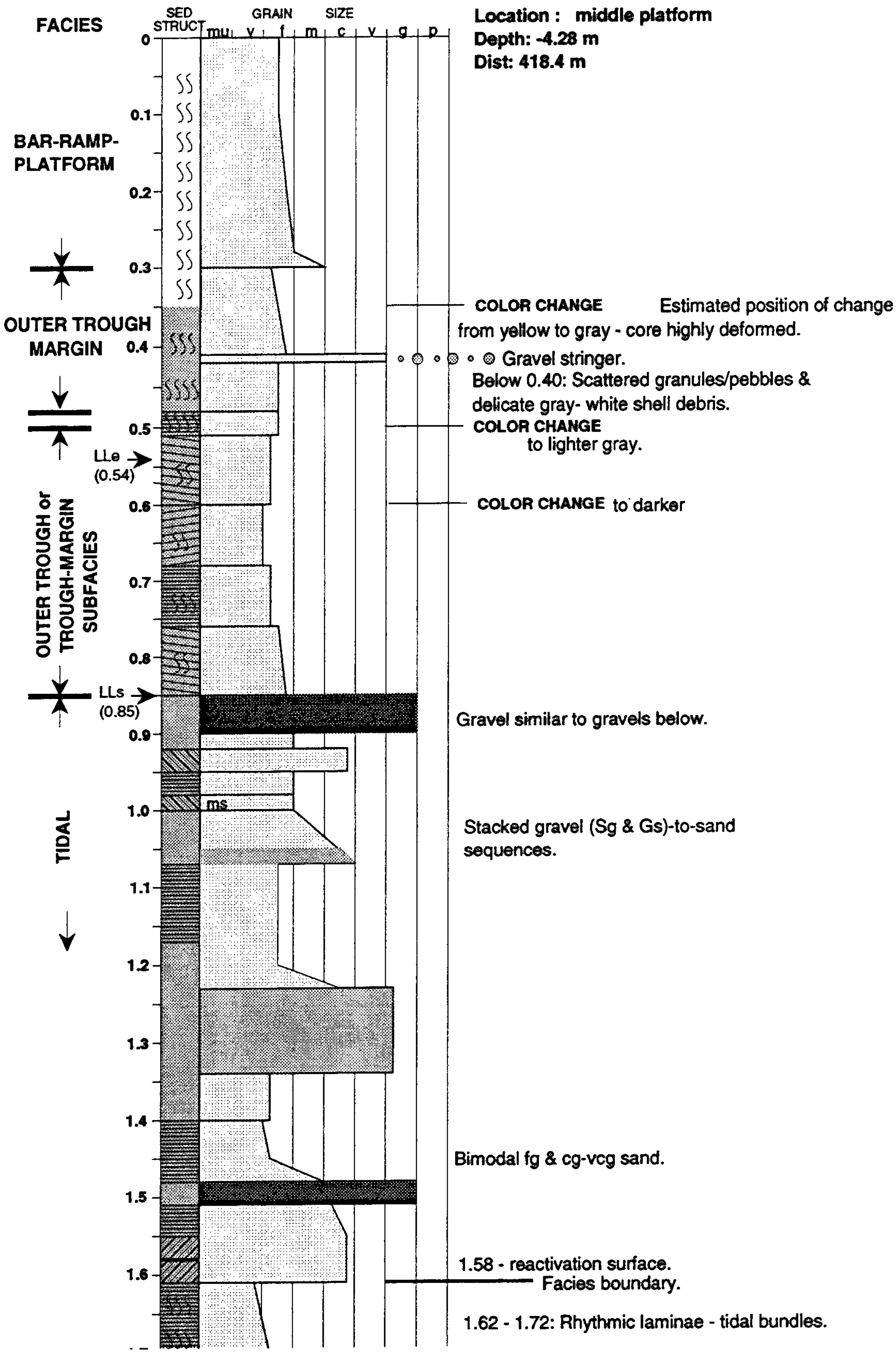
0.5 - 1.05: Stacked foresets with reversed polarity & wedtge-shaped set boundaries.

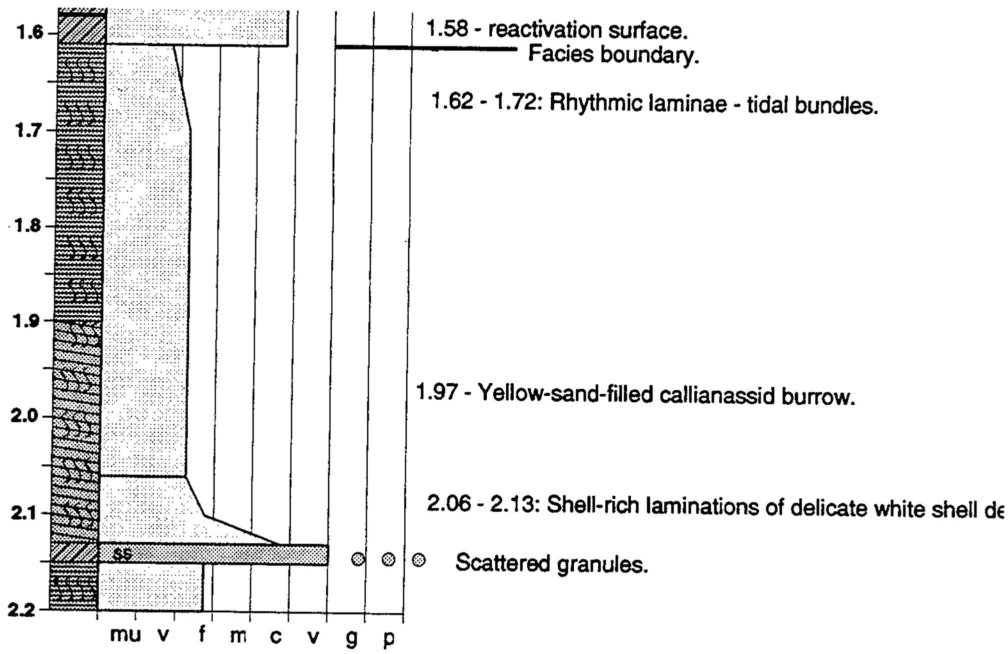
Reactivation surface at 0.94.

1.02 - 1.2 m: Stacked unimodal foresets separated by reacti\

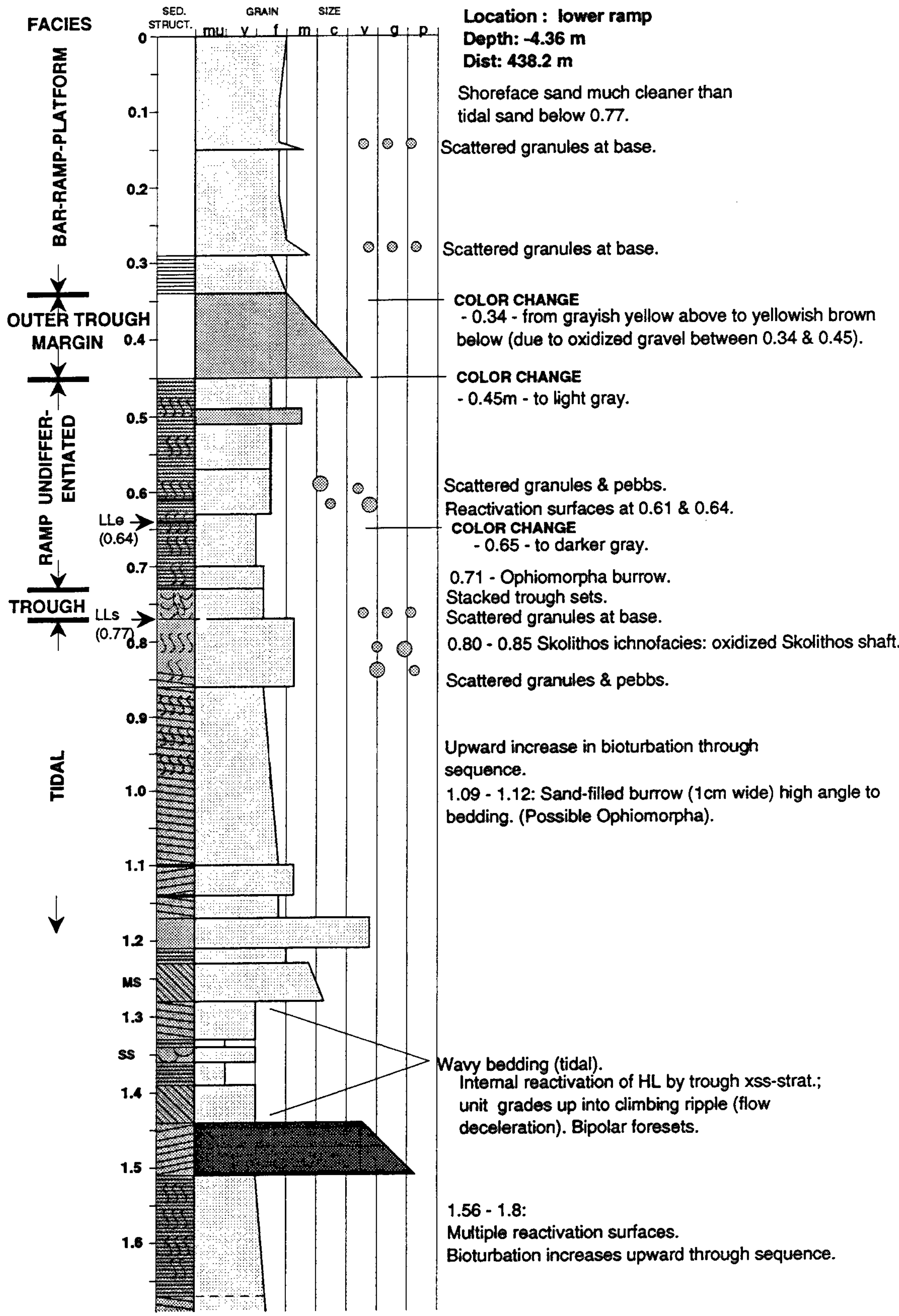
Reactivation surfaces at 1.05, 1.08, 1.09, 1.14.

188 VIBRACORE 22 - 38

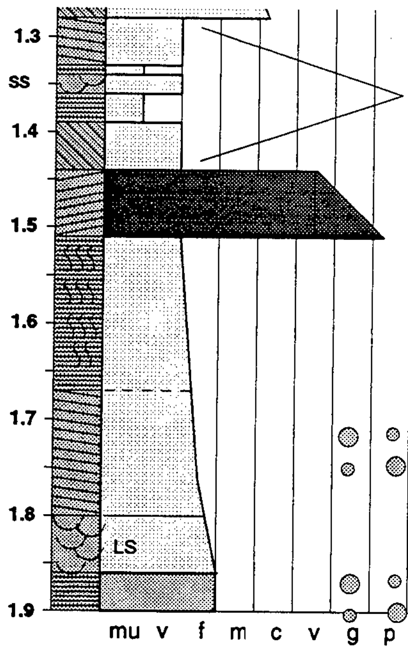



1.6
1.7
1.8
1.9
2.0
2.1
2.2
SS
mu v f m c v g p
1.58 - reactivation surface.
Facies boundary.
1.62 - 1.72: Rhythmic laminae - tidal bundles.
1.97 - Yellow-sand-filled callianassid burrow.
2.06 - 2.13: Shell-rich laminations of delicate white shell de
Scattered granules.

188 VIBRACORE 23 - 9



188 VIBRACORE 23 - 9 (continued)



Wavy bedding (tidal).
Internal reactivation of HL by trough xss-strat.; unit grades up into climbing ripple (flow deceleration). Bipolar foresets.

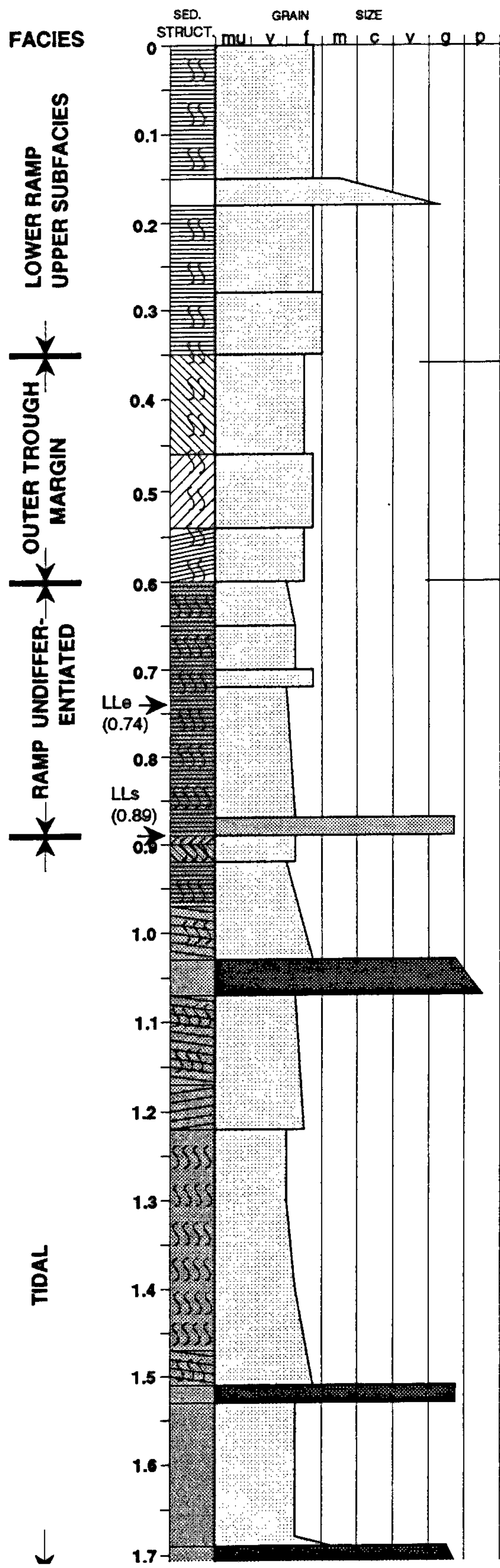
1.56 - 1.8:
Multiple reactivation surfaces.
Bioturbation increases upward through sequence.

Scattered granules & pebbs.

Rhythmic bottom-set beds to overlying LS trough xbd.

Scattered granules & pebbs.

188 VIBRACORE 24 - 10



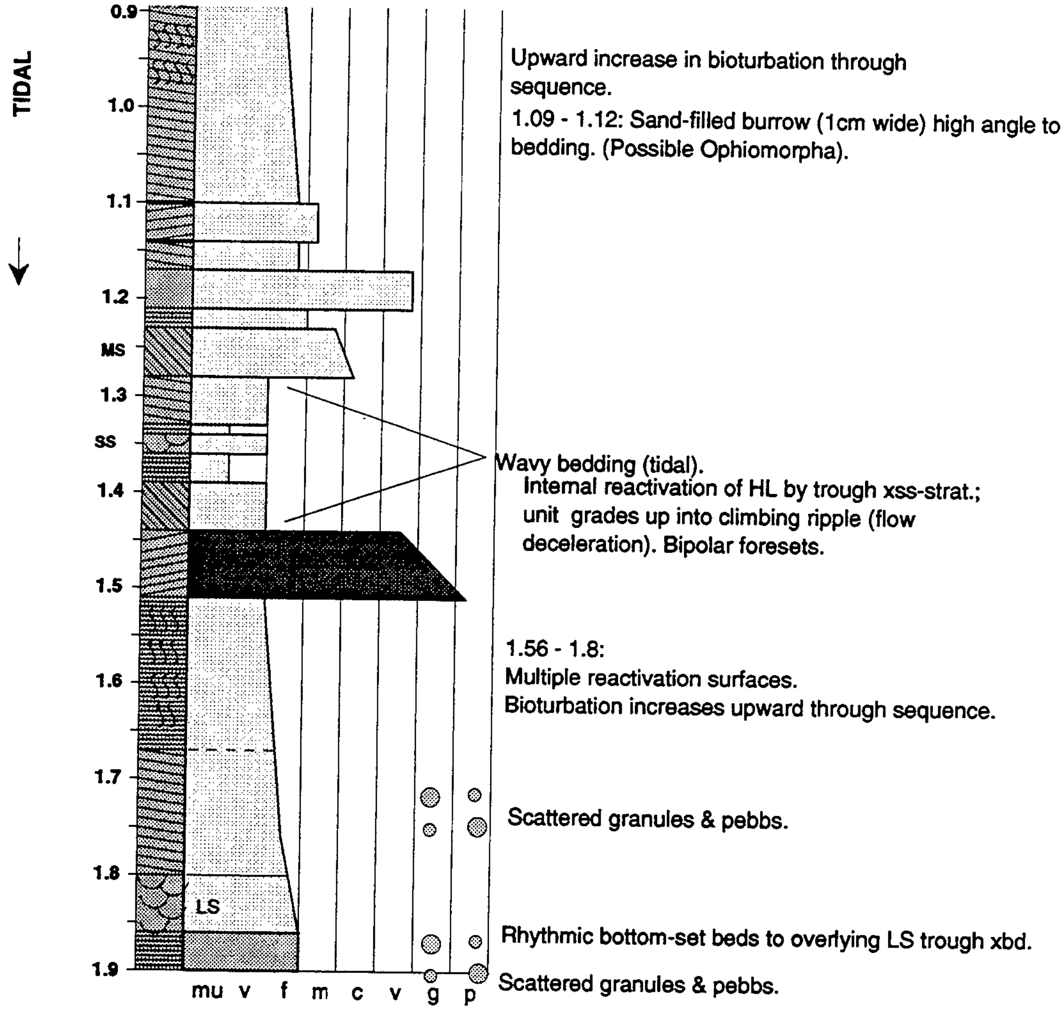
Location : lower ramp
Depth: -4.52 m
Dist: 463.3 m

COLOR CHANGE - 0.35
- from yellow above to grayish-yellow below.

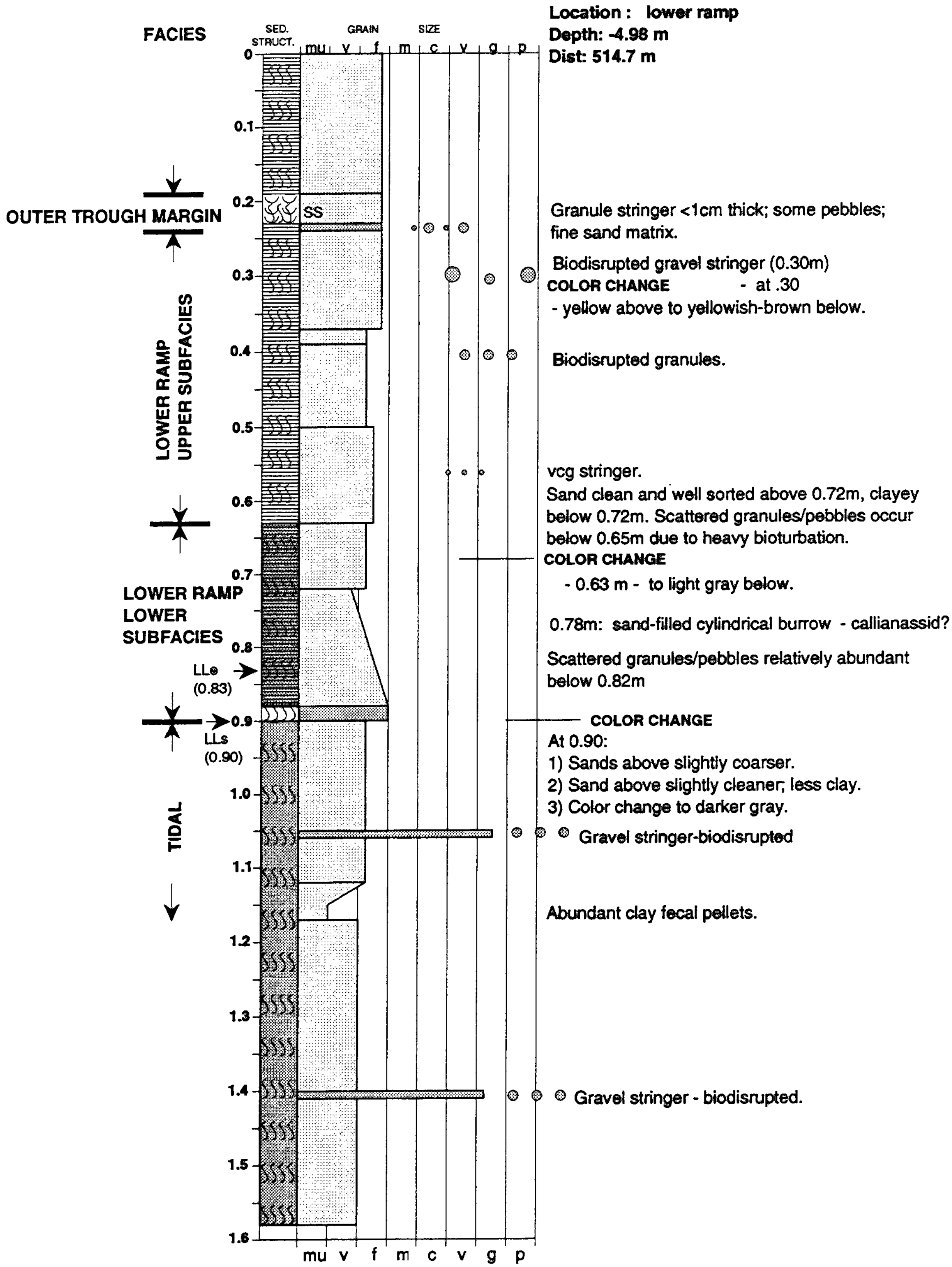
COLOR CHANGE - .60 - to gray below. Scattered gray(clay-coated) granules & delicate gray shell debris below 0.60.

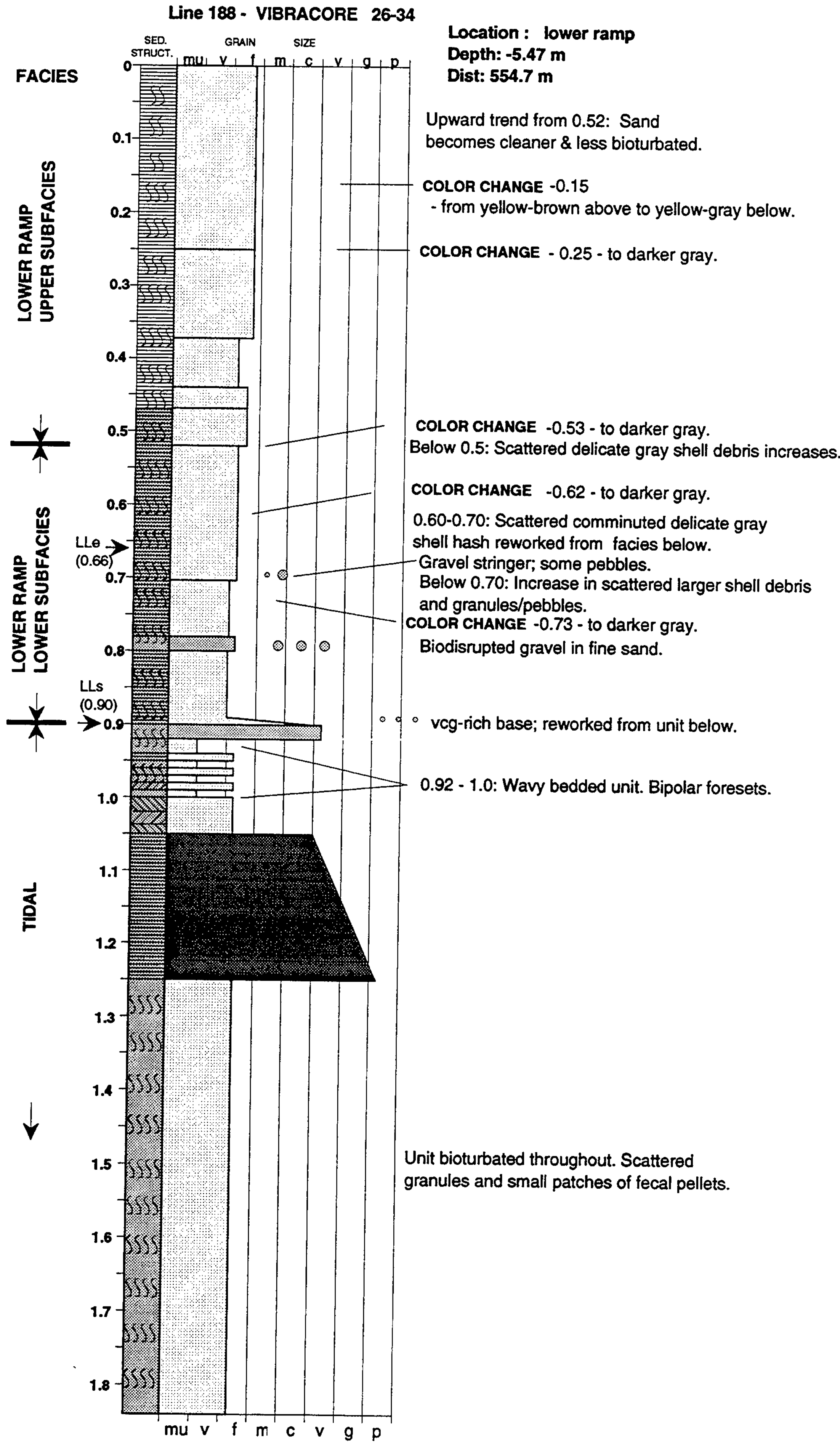
Bipolar foresets.Oblique view of trough cross-stratification with scour bases.

188 VIBRACORE 24-10
(continued)

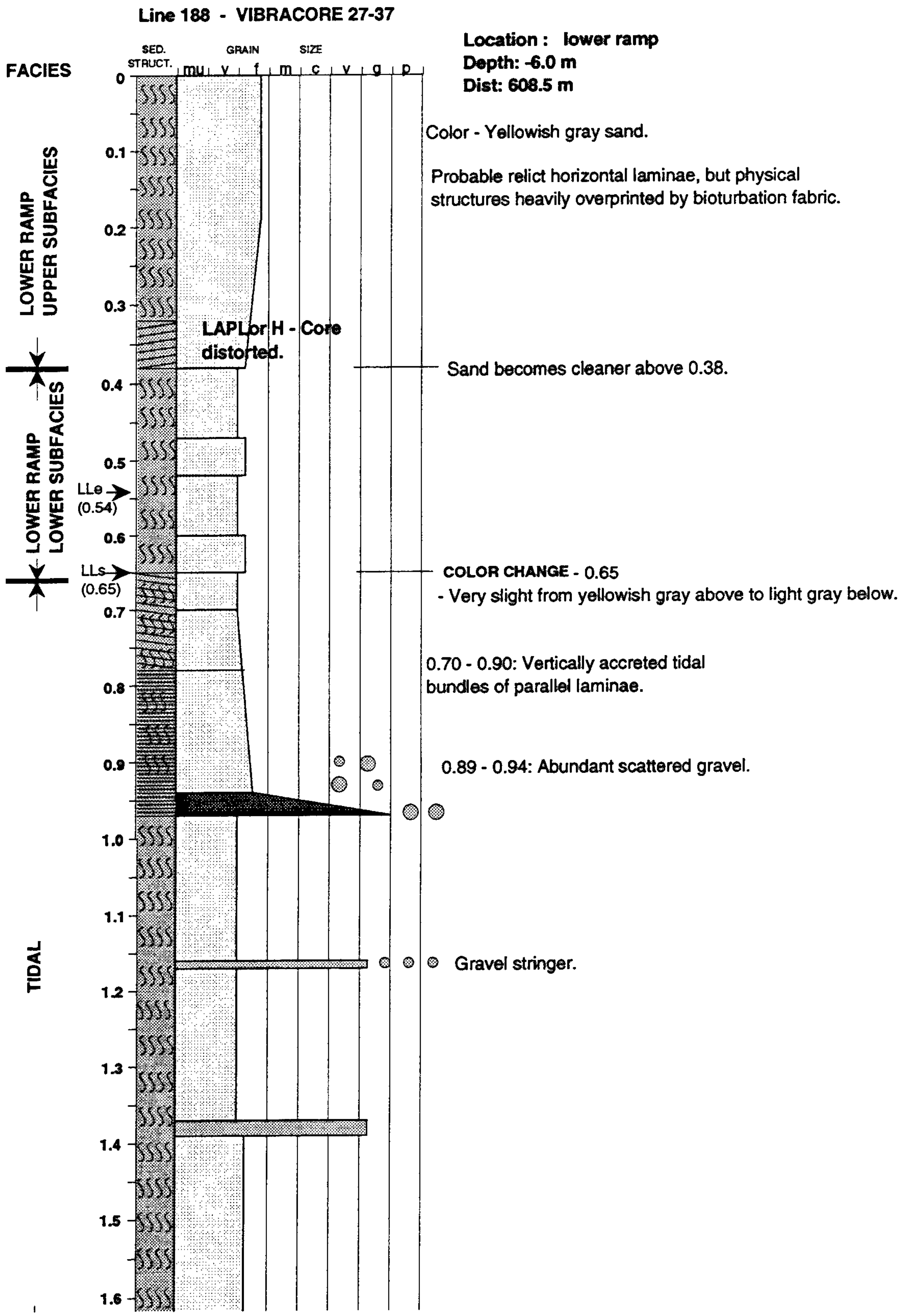


188 VIBRACORE 25 - 33

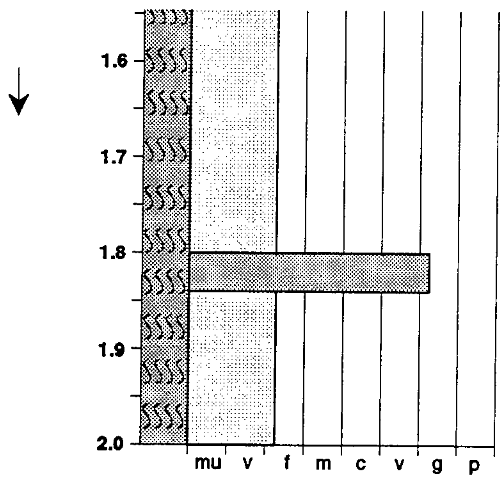




Line 188 - VIBRACORE 26-34
Location : lower ramp
Depth: -5.47 m
Dist: 554.7 m
SED. STRUCT.
GRAIN SIZE
mu v f m c v g p
FACIES
LOWER RAMP UPPER SUBFACIES
LOWER RAMP LOWER SUBFACIES
TIDAL
LLe (0.66)
LLs (0.90)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Upward trend from 0.52: Sand becomes cleaner & less bioturbated.
COLOR CHANGE -0.15 - from yellow-brown above to yellow-gray below.
COLOR CHANGE - 0.25 - to darker gray.
COLOR CHANGE -0.53 - to darker gray.
Below 0.5: Scattered delicate gray shell debris increases.
COLOR CHANGE -0.62 - to darker gray.
0.60-0.70: Scattered comminuted delicate gray shell hash reworked from facies below.
Gravel stringer; some pebbles.
Below 0.70: Increase in scattered larger shell debris and granules/pebbles.
COLOR CHANGE -0.73 - to darker gray.
Biodisrupted gravel in fine sand.
vcg-rich base; reworked from unit below.
0.92 - 1.0: Wavy bedded unit. Bipolar foresets.
Unit bioturbated throughout. Scattered granules and small patches of fecal pellets.
mu v f m c v g p

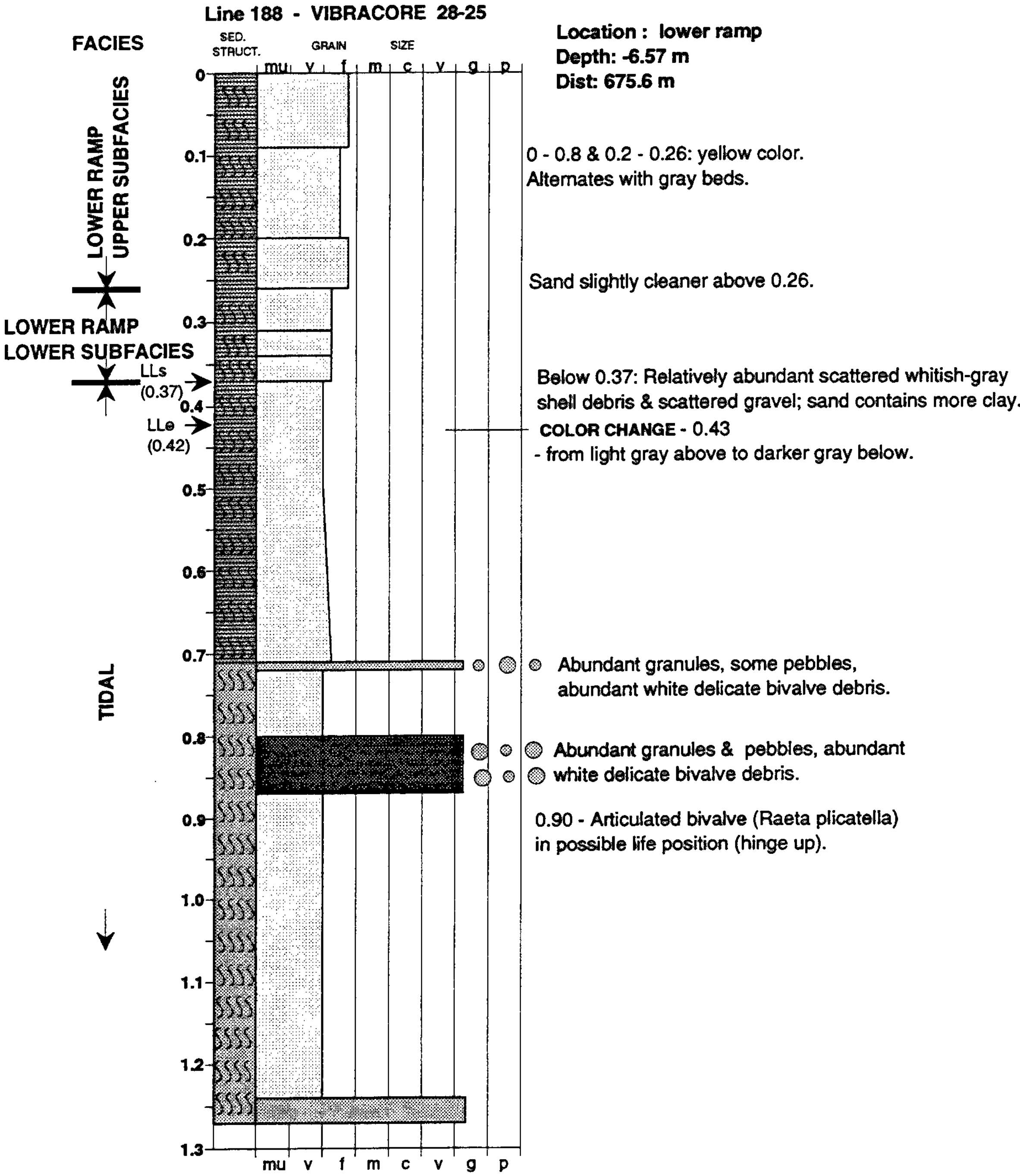

Line 188 - VIBRACORE 27-37
Location : lower ramp
Depth: -6.0 m
Dist: 608.5 m
FACIES
SED. STRUCT.
GRAIN SIZE
mu v f m c v g p
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
LOWER RAMP UPPER SUBFACIES
LOWER RAMP LOWER SUBFACIES
TIDAL
LLe (0.54)
LLs (0.65)
Color - Yellowish gray sand.
Probable relict horizontal laminae, but physical structures heavily overprinted by bioturbation fabric.
LAPL or H - Core distorted.
Sand becomes cleaner above 0.38.
COLOR CHANGE - 0.65
- Very slight from yellowish gray above to light gray below.
0.70 - 0.90: Vertically accreted tidal bundles of parallel laminae.
0.89 - 0.94: Abundant scattered gravel.
Gravel stringer.

Line188 VIBRACORE 27-37 (continued)

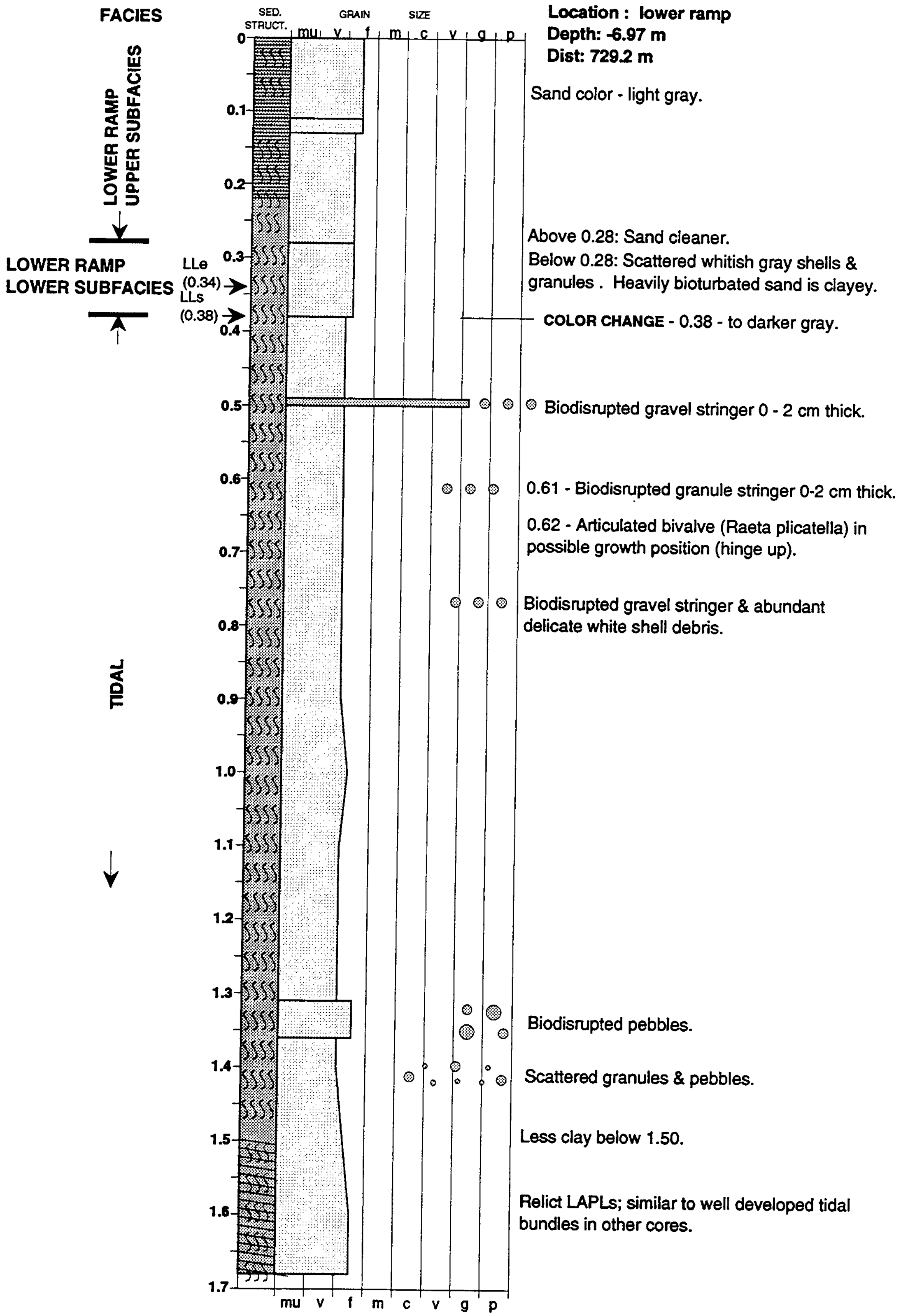


Biodisrupted gravel-rich stringer.

End of core -at 3.13 m; facies similar to above.


Line 188 - VIBRACORE 28-25
FACIES
SED. STRUCT.
GRAIN SIZE
mu v f m c v g p
LOWER RAMP UPPER SUBFACIES
LOWER RAMP LOWER SUBFACIES
LLs (0.37)
LLe (0.42)
TIDAL
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Location : lower ramp
Depth: -6.57 m
Dist: 675.6 m
0 - 0.8 & 0.2 - 0.26: yellow color.
Alternates with gray beds.
Sand slightly cleaner above 0.26.
Below 0.37: Relatively abundant scattered whitish-gray shell debris & scattered gravel; sand contains more clay.
COLOR CHANGE - 0.43
- from light gray above to darker gray below.
Abundant granules, some pebbles, abundant white delicate bivalve debris.
Abundant granules & pebbles, abundant white delicate bivalve debris.
0.90 - Articulated bivalve (Raeta plicatella) in possible life position (hinge up).

Line 188 - VIBRACORE 29-24



Line 188 - VIBRACORE 30-36

Location : lower ramp
Depth: -7.29 m
Dist: 778.8 m

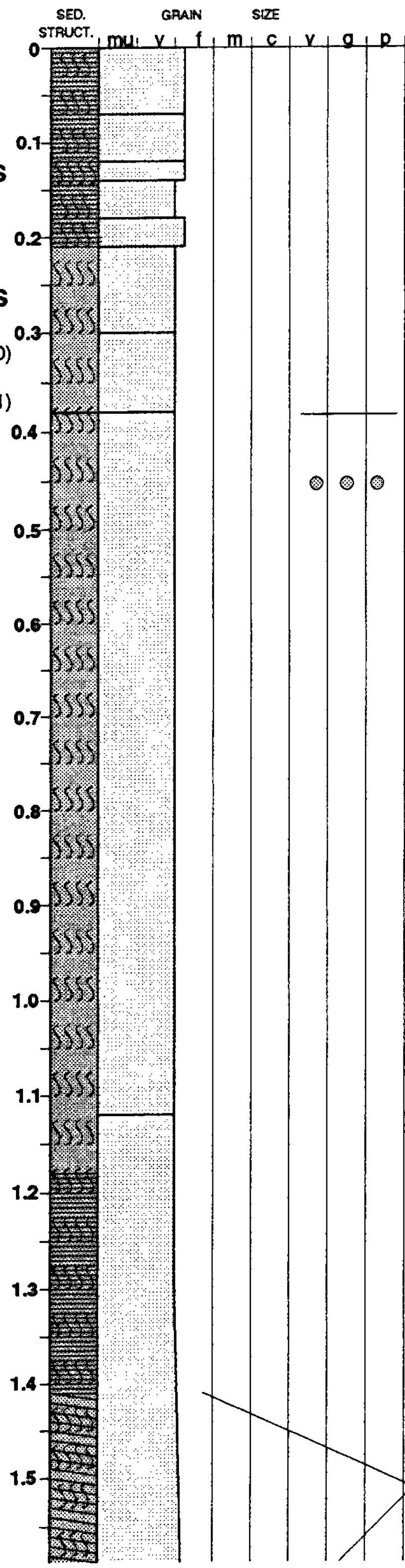
FACIES

LOWER RAMP UPPER SUBFACIES

LOWER RAMP LOWER SUBFACIES

LLs (0.30)
LLe (0.31)

TIDAL



Sand color - yellowish gray.

Above 0.14: Sediment becomes slightly cleaner & physical structures less overprinted.

0.20 - Sand above is slightly cleaner than below.

Below 0.30:
First occurrence of scattered granules.
Scattered delicate whitish bivalve debris & whole valves.

COLOR CHANGE - 0.38
- from yellowish gray to gray.

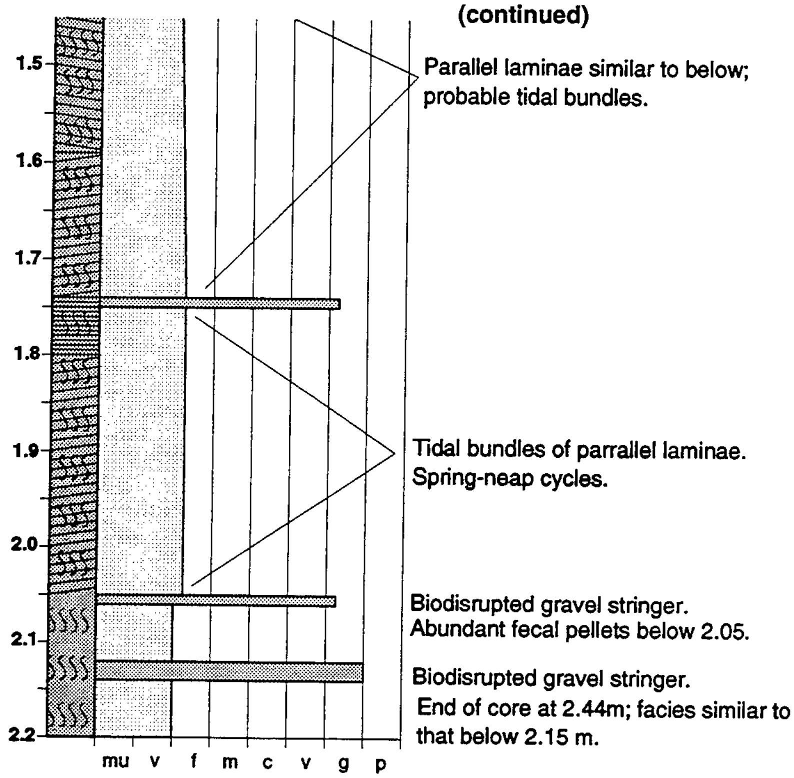
0.45 - Biodisrupted gravel stringer.
0.45 - 0.70:
Scattered biodisrupted gravel.
Scattered delicate white shell debris.

0.75 - Phosphatized bone clast.

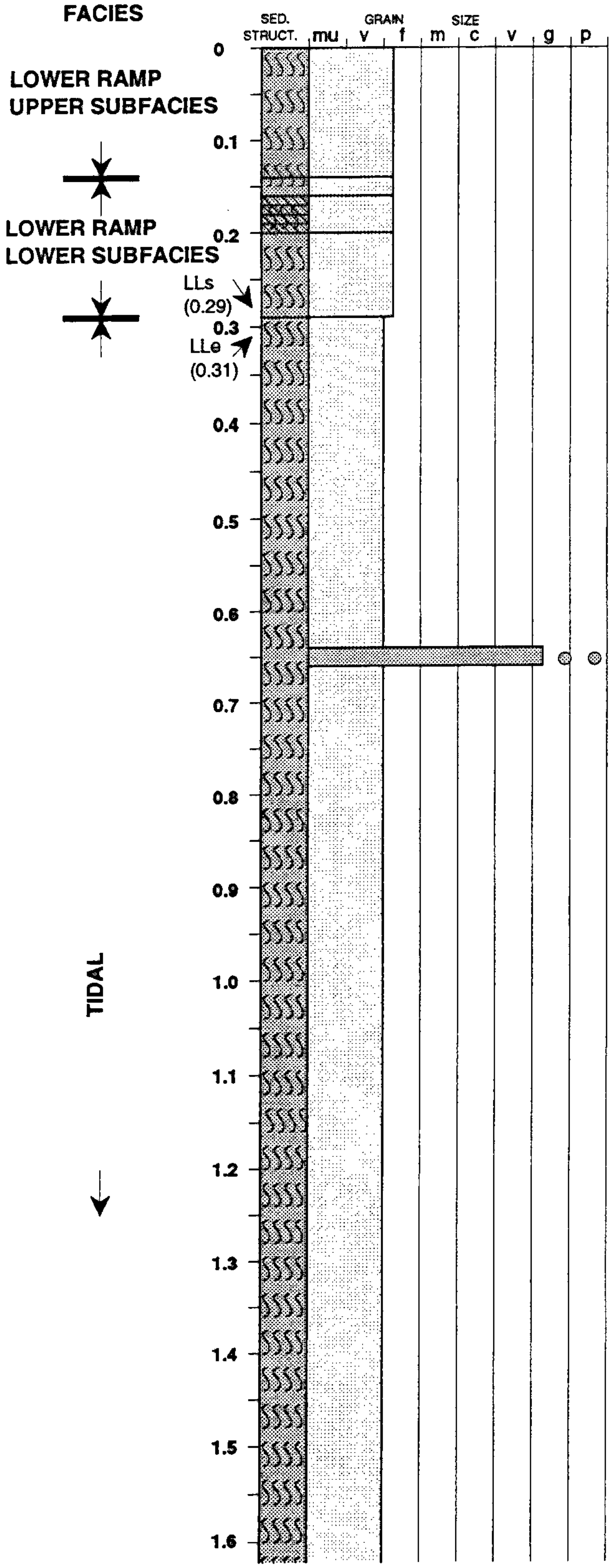
1.0 - 2.05: Bioturbation increases upward.
Bedding progressively destroyed.

Parallel laminae similar to below; probable tidal bundles.

Line188 VIBRACORE 30-36 (continued)



Line 188 - VIBRACORE 31-35



Location : lower ramp
Depth: -7.61 m
Dist: 835.2 m

Sand color - gray throughout core.

0 - 0.20: Sand essentially free of small shell debris & scattered gravel compared to below.

Above 0.14: Sand is slightly cleaner than below.

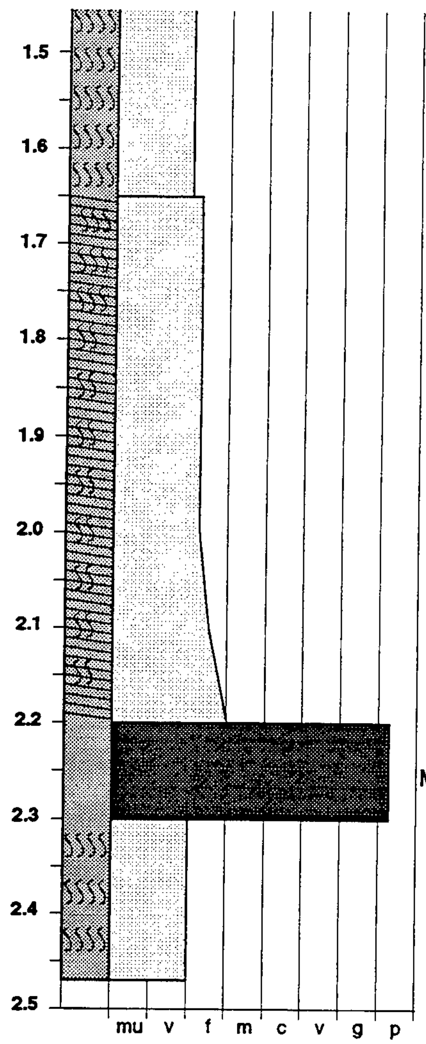
Amalgamated small-scale tangential foresets; seaward oriented.
0.20 - 0.29: Scattered granules & delicate whitish gray shell debris (whole & broken valves).

0.29 - 0.65: Scattered delicate whitish gray shell debris; less common than in unit above.

⊚ Biodisrupted gravel & shells.

0.66 - Articulated bivalve (Raeta plicatella) parallel to bedding.
0.66 - 1.65: Clay matrix increases upward from 1.65.

Line188 VIBRACORE 31-35 (continued)



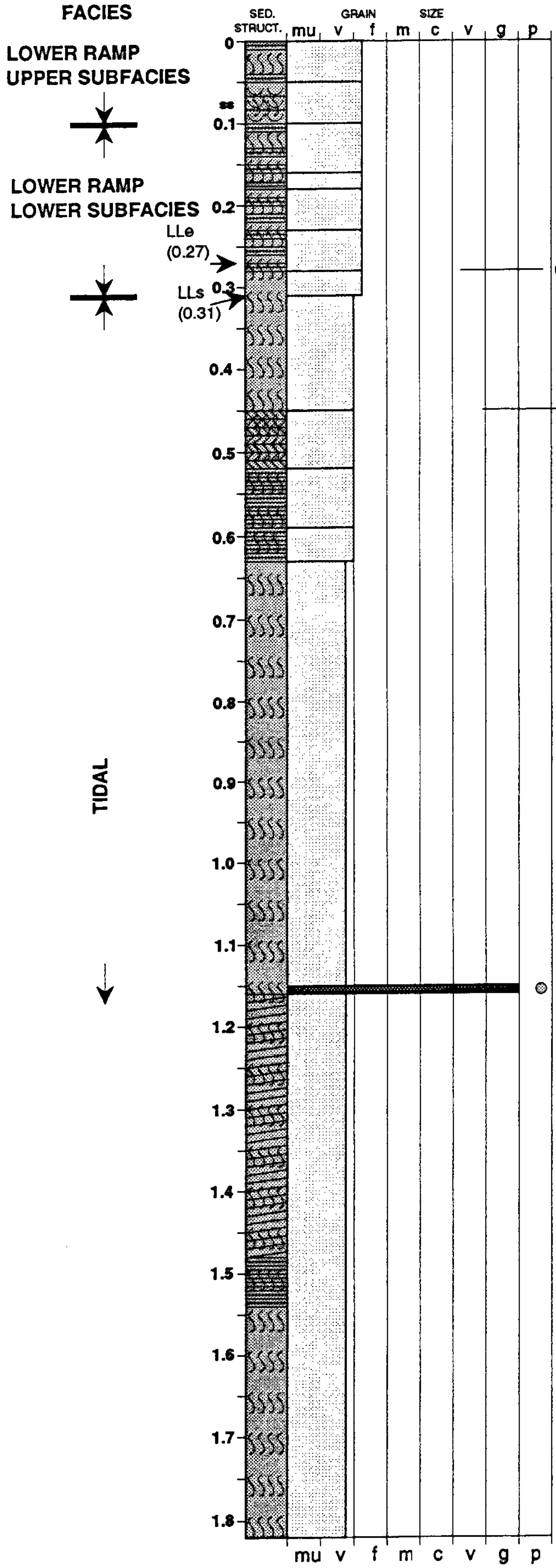
Tidal bundles of parrallel laminae. Couplets indicate tidal asymmetry.

1.9 - Raeta plicatella valve.

Mixed delicate whitish gray shell debris.

Line 188 - VIBRACORE 32- 30

Location : lower ramp
Depth: -7.93 m
Dist: 888.0 m



Sand color - light gray.
Above 0.10: Sand slightly cleaner, better sorted, & less bioturbated. Relict laminae more distinct than below. No pebbles. Relict laminae more distinct than below.
0.10 - 0.23: Rare scattered chert pebbles. Horizontal laminae heavily overprinted by bioturbation fabric.

COLOR CHANGE - 0.28 - to mottled slightly darker gray.

At 0.30:
1) Coarser above.
2) Units above very slightly cleaner (less clay).
3) Color change.

COLOR CHANGE - 0.46 - to darker gray.

0.45 - 0.52: Bipolar ripple sets; largely obscured by bioturbation.

0.62 - 1.20: Scattered small "pods" of fecal-pellet filled burrows.

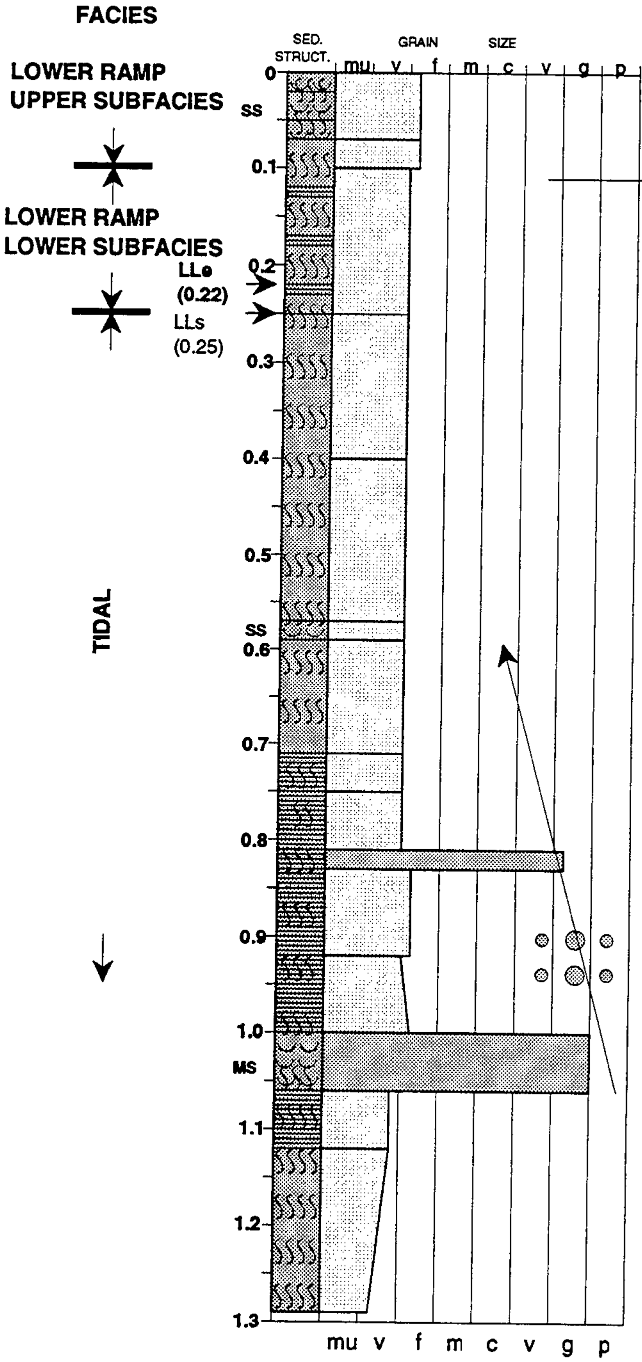
Biodisrupted granule-pebble stringer. Contains coral fragment.

1.16 - 1.50: Tidal bundles of parallel laminae.

1.5 - 1 cm-wide broken sand dollar shell.

Line 188 - VIBRACORE 33 - 29

Location : lower ramp
Depth: -8.37 m
Dist: 958.8 m



Sand color - light gray.
Above 0.10: Sediment slightly cleaner, less bioturbated & physical structures less overprinted.

COLOR CHANGE - 0.10m - to slightly darker gray.
0.10 - 0.25: Above 0.25 sand is slightly better sorted, slightly cleaner (less clay), less bioturbated, and relict horizontal laminae become slightly visible compared to below.

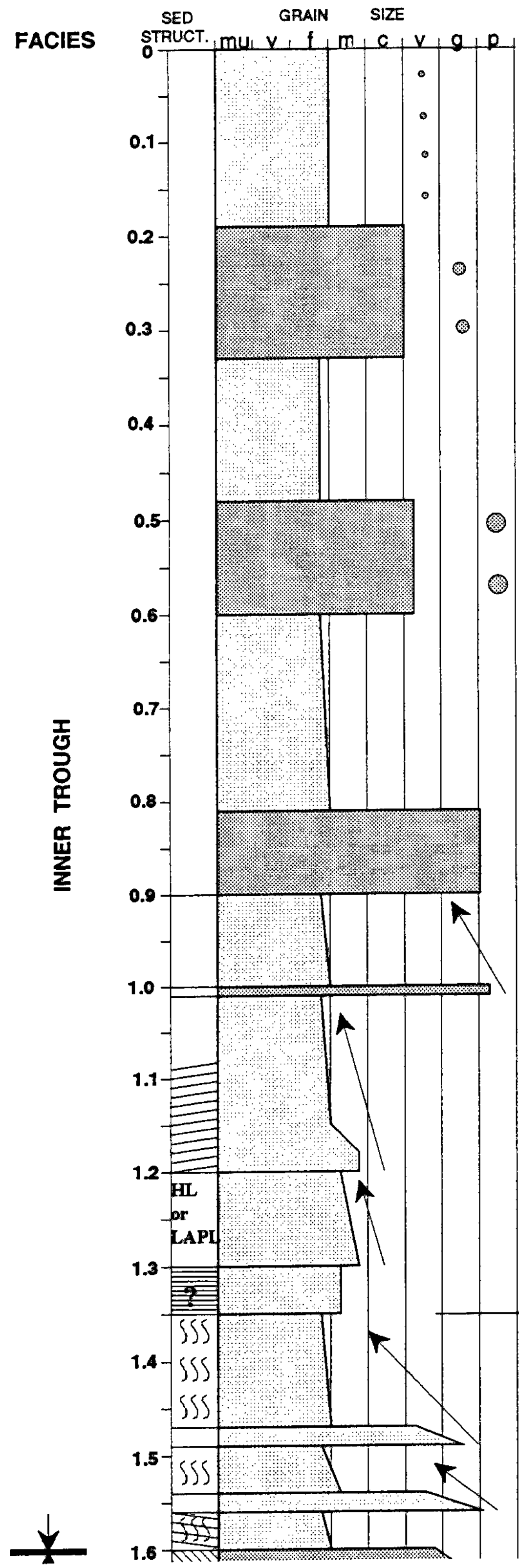
0.59 - 1.07 Genetic sequence:
Upward fining from scour base at 1.07.
Rhythmic bundles of mica-rich parallel laminae between 0.75 & 0.8; tidalbundles.

Biodisrupted gravel.

Biodisrupted gravel stringers.
0.93-1.0: Abundant transported robust shells.

Pellet-filled cylindrical burrows at 1.10.

62 VIBRACORE 34-116



Location : Landward flank of small trough
Depth: -.77 m
Dist: 150.1 m

Core severely deformed above 0.65.

Scattered vcg sand.

Mixed fg sand to granules.

Mixed fg sand to granules & scattered pebbles.

Mixed fg sand to pebbles.

Upward-fining sequences (arrows) are characterized by a basal scour surface, a coarser, bimodal, shell-fragment-rich lower zone & a unimodal, very well sorted top.

Scattered vcg & shell fragments.

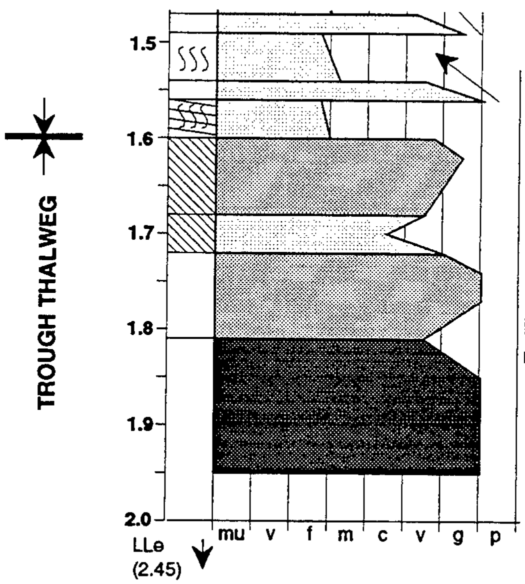
Scattered vcg & shell fragments near base.

COLOR CHANGE - 1.35
- from yellow above to grayish yellow below.

Scattered granules & shell fragments.

Scattered granules & shell fragments.

62 VIBRACORE 34-116 (continued)

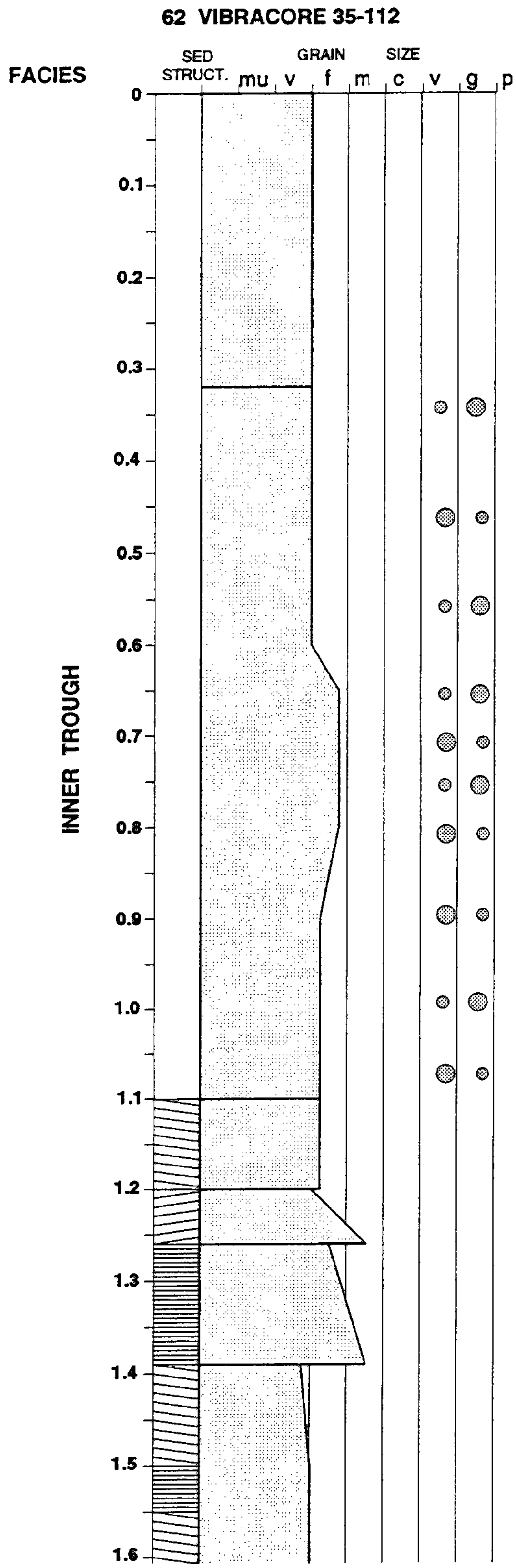


Scattered granules & shell fragments.

Abundant granules; scattered pebbles.

Abundant pebbles.

Inverse textural trend due to bedform migration.

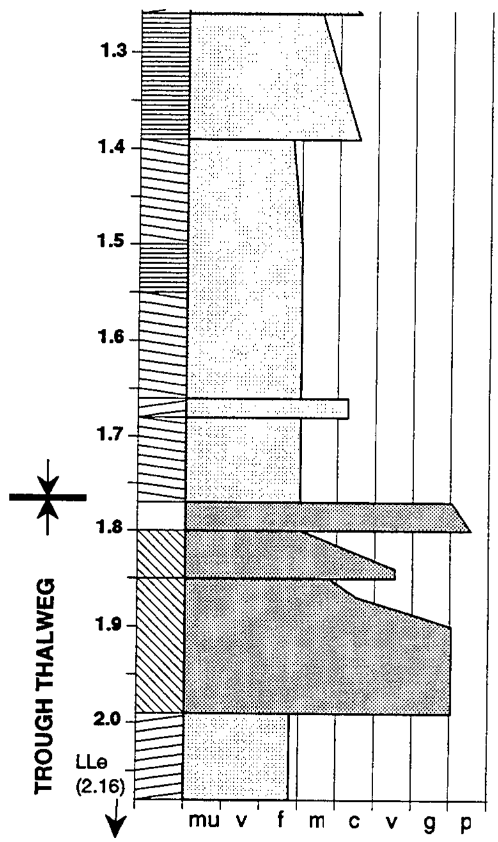


Location : landward flank of small trough
Depth: -1.24 m
Dist: 160.4 m

Core severely deformed above 1.10 m..

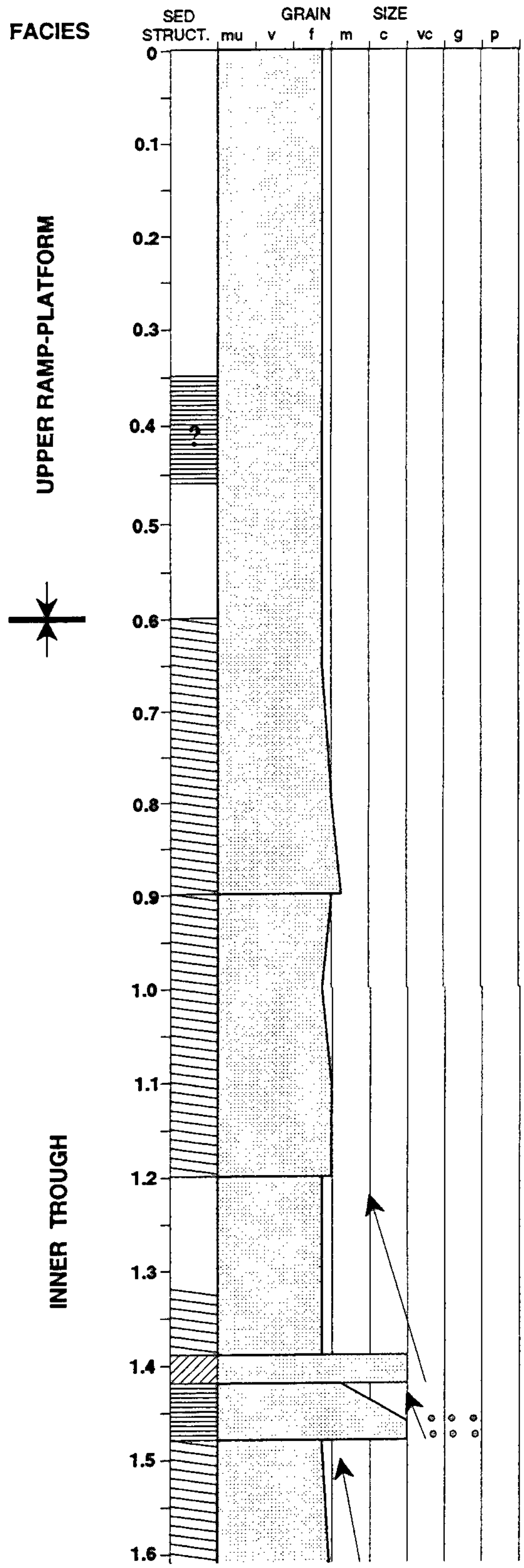
0.32 - 1.10: Abundant scattered granules & pebbles; robust shell fragments common. Gravel concentration between 0.70 & 0.80. Much textural mixing due to vibracoring.

62 VIBRACORE 35-112 (continued)



Mixed fg to vcg sand.

62 VIBRACORE 36-113



Location : upper ramp
Depth: -1.41 m
Dist: 183.2 m

Core severely deformed above 0.90; unable to accurately determine sedimentology.

Color of sediment transitional from yellow at top to yellowish brown at bottom of core.

Deformed HL or LAPL structures.

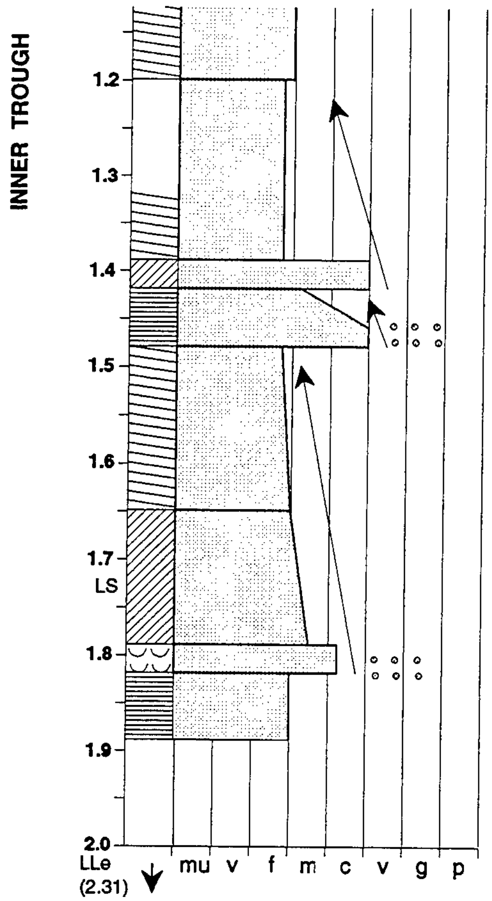
Below 0.60:
Mixed cg & vcg sand, shell fragments & granules.

Scattered cg sand from 1.23 to 1.14.

Upward-fining sequences (arrows) are characterized by a basal scour surface, a coarser, bimodal, shell-fragment-rich lower zone & a unimodal, very well sorted top.

Fg to vcg sand.

62 VIBRACORE 36-113 (continued)

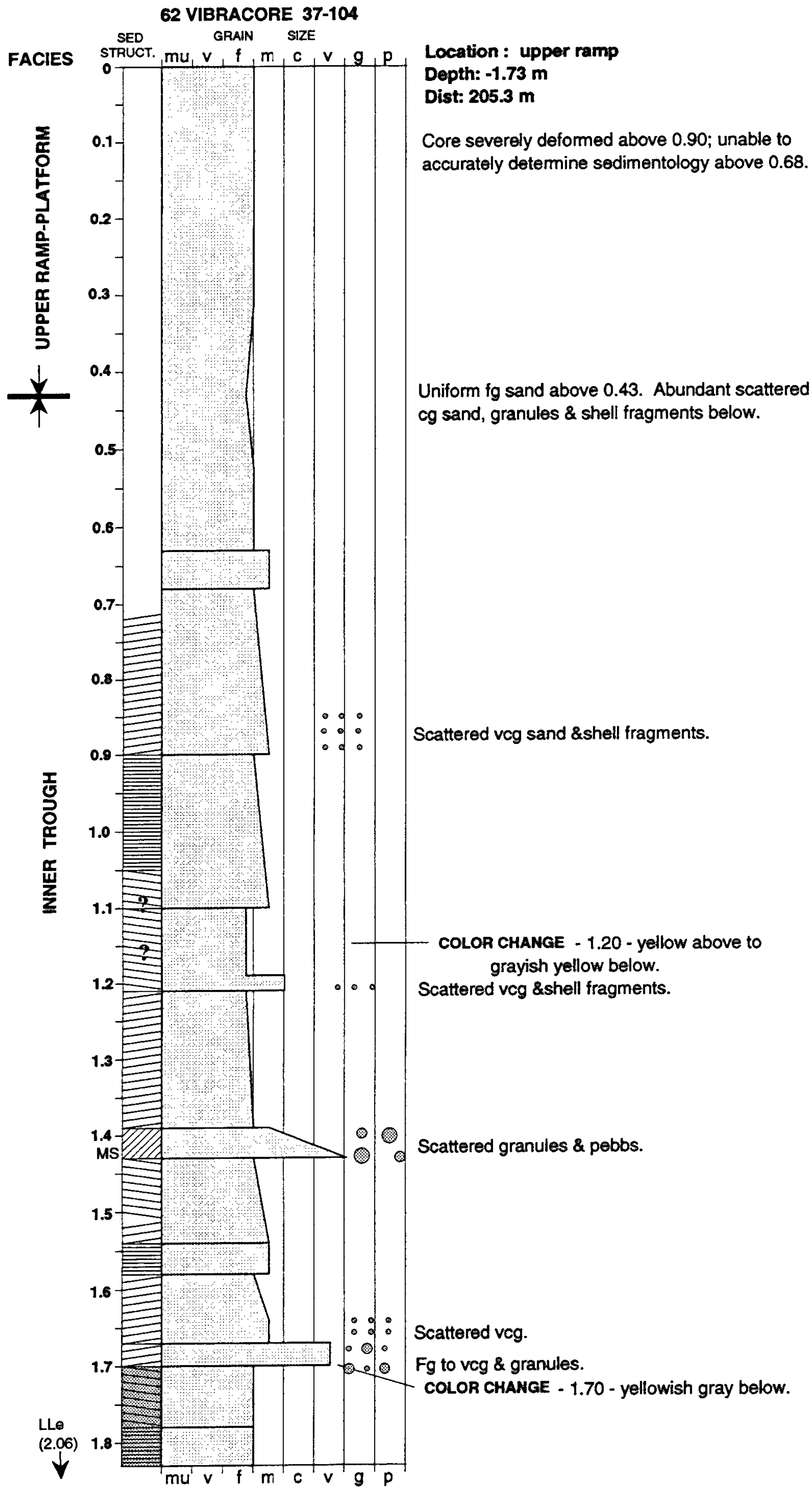


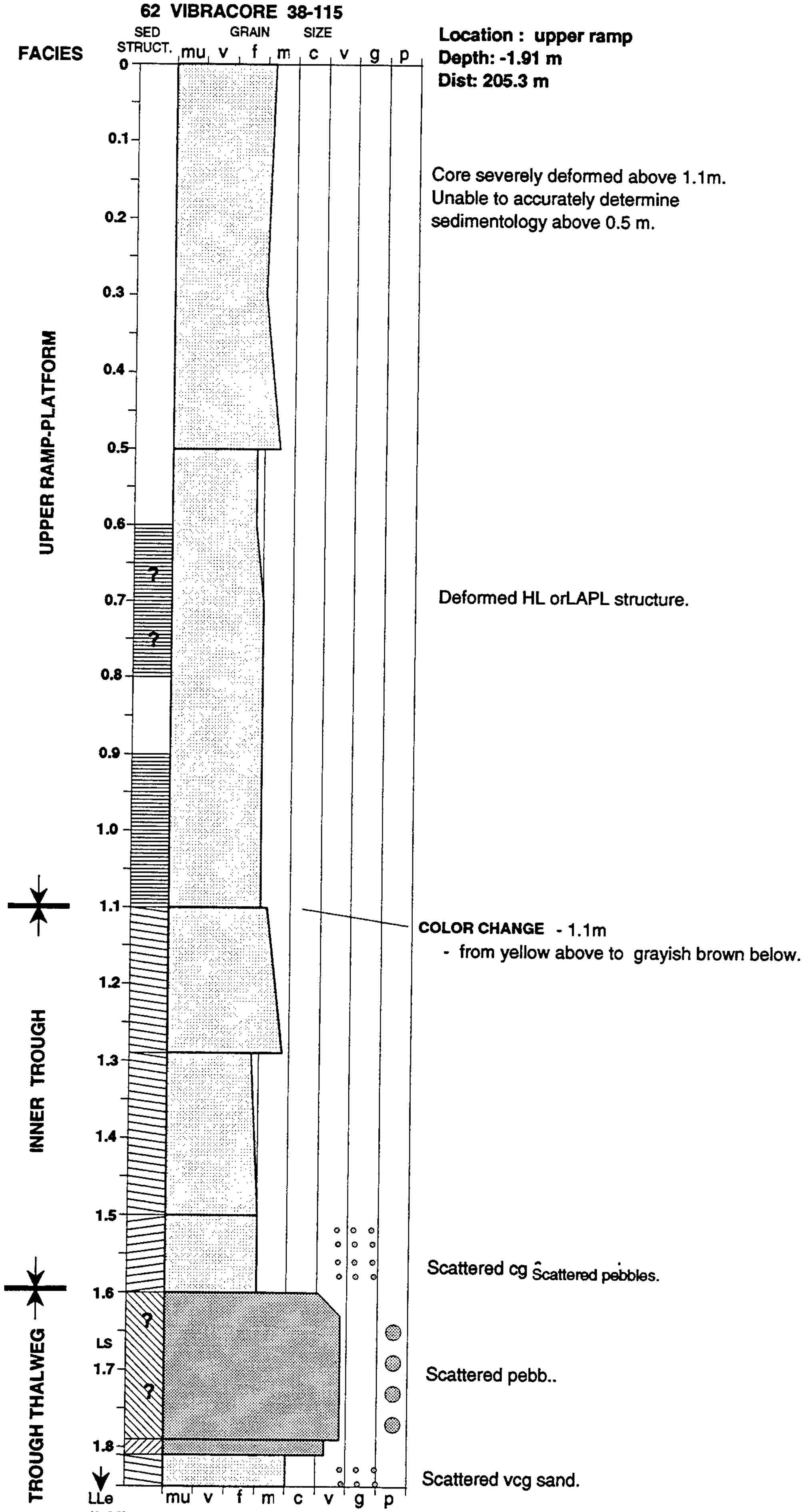
Scattered cg sand from 1.23 to 1.14.

Upward-fining sequences (arrows) are characterized by a basal scour surface, a coarser, bimodal, shell-fragment-rich lower zone & a unimodal, very well sorted top.

Fg to vcg sand.

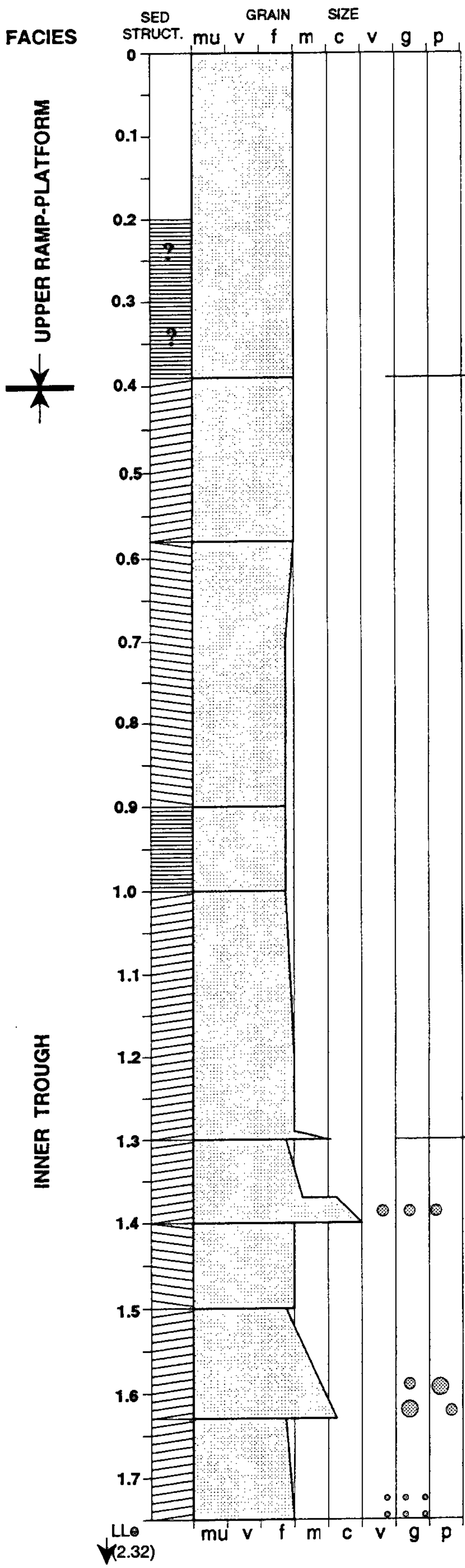
Scattered vcg sand.


62 VIBRACORE 37-104
FACIES
SED STRUCT.
GRAIN SIZE
mu v f m c v g p
UPPER RAMP-PLATFORM
INNER TROUGH
MS
LLe (2.06)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
?
Location : upper ramp
Depth: -1.73 m
Dist: 205.3 m
Core severely deformed above 0.90; unable to accurately determine sedimentology above 0.68.
Uniform fg sand above 0.43. Abundant scattered cg sand, granules & shell fragments below.
Scattered vcg sand &shell fragments.
COLOR CHANGE - 1.20 - yellow above to grayish yellow below.
Scattered vcg &shell fragments.
Scattered granules & pebbs.
Scattered vcg.
Fg to vcg & granules.
COLOR CHANGE - 1.70 - yellowish gray below.



62 VIBRACORE 38-115
FACIES
SED STRUCT.
GRAIN SIZE
mu v f m c v g p
Location : upper ramp
Depth: -1.91 m
Dist: 205.3 m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
LS
1.7
1.8
LLe
(2.26)
UPPER RAMP-PLATFORM
INNER TROUGH
TROUGH THALWEG
Core severely deformed above 1.1m.
Unable to accurately determine
sedimentology above 0.5 m.
Deformed HL orLAPL structure.
COLOR CHANGE - 1.1m
- from yellow above to grayish brown below.
Scattered cg Scattered pebbles.
Scattered pebb..
Scattered vcg sand.

62 VIBRACORE 39-102



Location : upper ramp
Depth: -2.18 m
Dist: 238.1 m

Core severely deformed above 038.

All sand in core is very clean.

Deformed HL or LAPL structure.

COLOR CHANGE - 0.39
- yellow above to brownish yellow below.

1.0 - 1.75 - Upward-fining beds and sequences are characterized by a basal scour surface, a coarser, bimodal, shell-fragment-rich lower zone & a unimodal, very well sorted top.

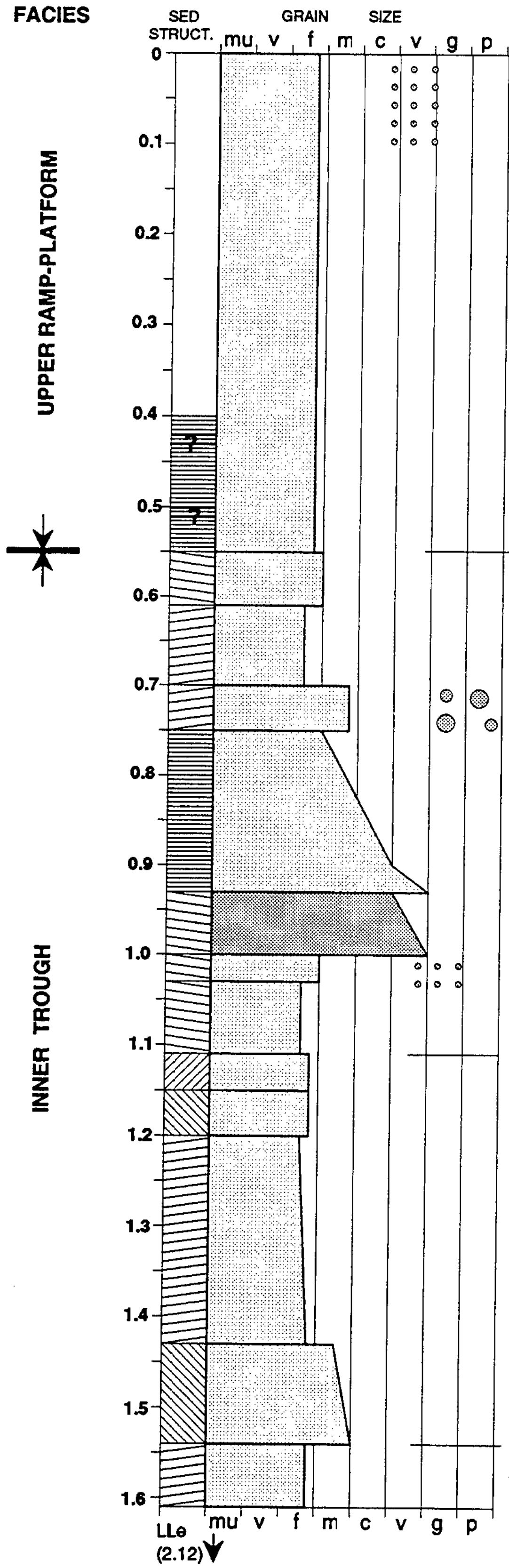
COLOR CHANGE - 1.30
- brownish yellow above to yellowish gray below.

Abundant vcg sand & scattered granules.

Scattered granules & pebbles in lower part.

Scattered vcg in lower part.

62 VIBRACORE 40-103



Location : upper ramp
Depth: -2.85 m
Dist: 270.5 m

Scattered vcg in upper 10 cm.

Core severely deformed above 0.70 m.

Deformed HL or LAPL structure.

COLOR CHANGE - 0.55
- yellow above to brownish yellow & orangish yellow below.

0.7 - 1.0: Relatively abundant scattered shell fragments.
Fg to cg sand with scattered granules & pebbs.

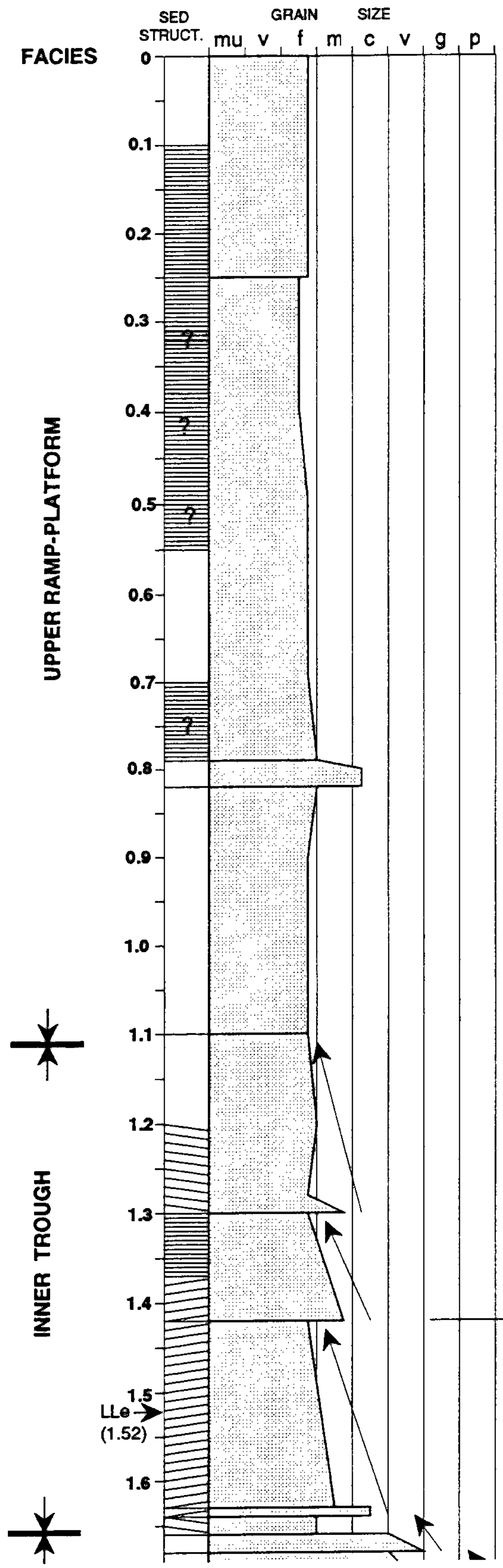
Fg to vcg sand.

Scattered vcg sand.

COLOR CHANGE - 1.1 - to grayish yellow below.

Fg to vcg sand in base of unit.
COLOR CHANGE - 1.54
- grayish yellow above to yellow gray below.

62 VIBRACORE 41-105



Location : upper ramp
Depth: -3.20 m
Dist: 290.0 m

Core severely deformed above 1.30 m.

Deformed HL or LAPL structure.

Deformed HL or LAPL structure.

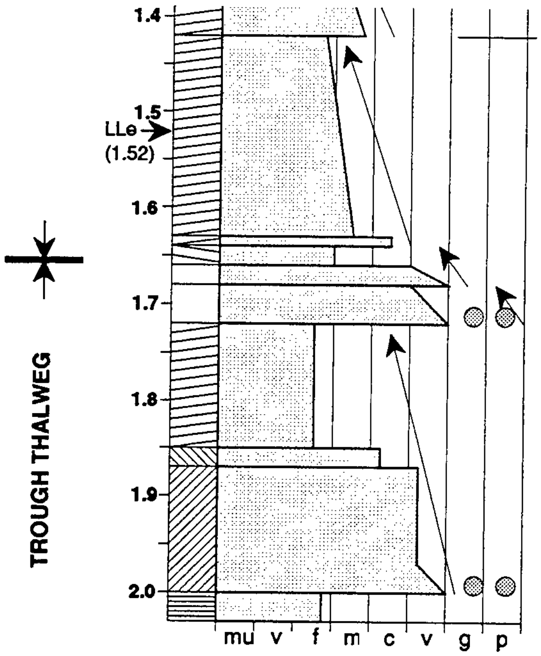
Bimodal fg & cg-vcg sand; abundant shell fragments.

Above 1.1 - sand is typically clean & very well sorted.

Upward-fining sequences (arrows) are characterized by a basal scour surface, a coarser, bimodal, shell-fragment-rich lower zone & a unimodal, very well sorted top.

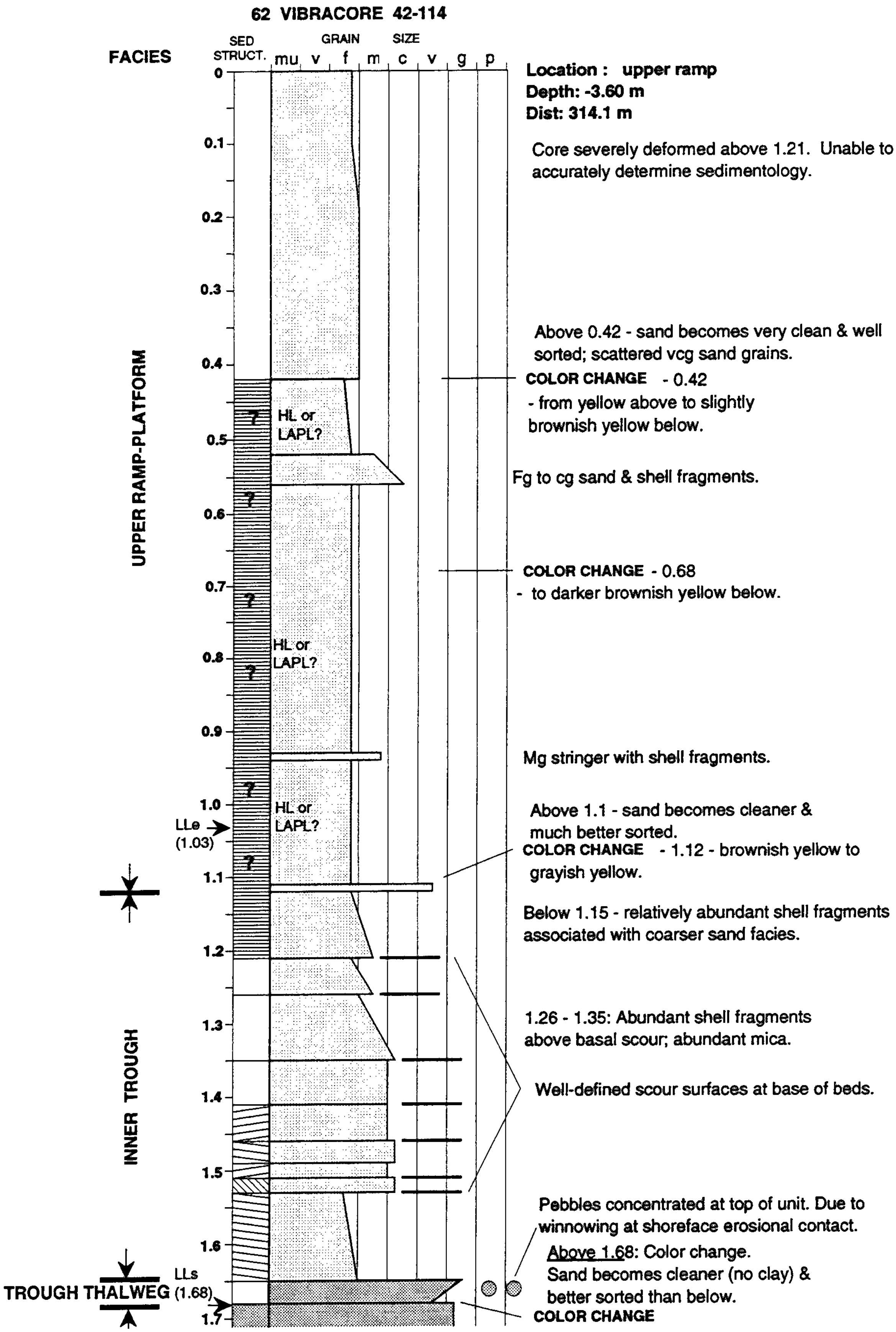
Bimodal fg & mg sand.
COLOR CHANGE 1.42
-brownish yellow above to gray below.

62 VIBRACORE 41-105 (continued)

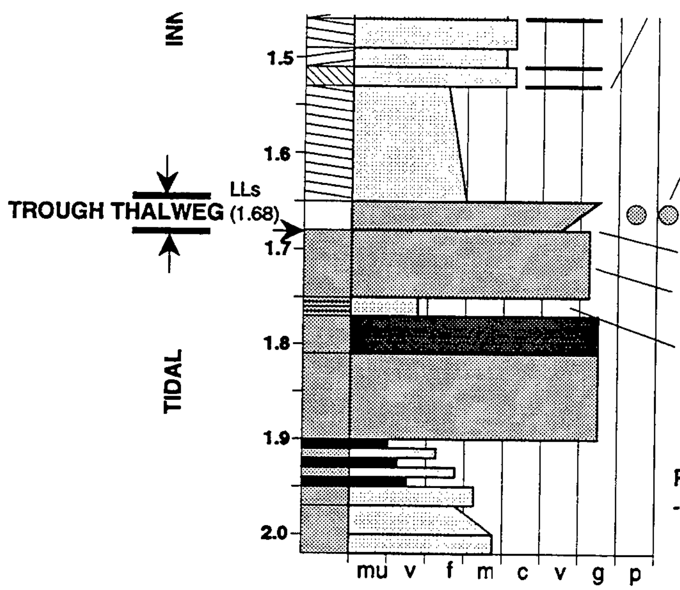


Scattered pebbles at base.

Scattered pebbles at base.


62 VIBRACORE 42-114
FACIES
SED STRUCT.
GRAIN SIZE
mu v f m c v g p
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
UPPER RAMP-PLATFORM
INNER TROUGH
TROUGH THALWEG
LLe (1.03)
LLs (1.68)
HL or LAPL?
HL or LAPL?
HL or LAPL?
Location : upper ramp
Depth: -3.60 m
Dist: 314.1 m
Core severely deformed above 1.21. Unable to accurately determine sedimentology.
Above 0.42 - sand becomes very clean & well sorted; scattered vcg sand grains.
COLOR CHANGE - 0.42
- from yellow above to slightly brownish yellow below.
Fg to cg sand & shell fragments.
COLOR CHANGE - 0.68
- to darker brownish yellow below.
Mg stringer with shell fragments.
Above 1.1 - sand becomes cleaner & much better sorted.
COLOR CHANGE - 1.12 - brownish yellow to grayish yellow.
Below 1.15 - relatively abundant shell fragments associated with coarser sand facies.
1.26 - 1.35: Abundant shell fragments above basal scour; abundant mica.
Well-defined scour surfaces at base of beds.
Pebbles concentrated at top of unit. Due to winnowing at shoreface erosional contact.
Above 1.68: Color change.
Sand becomes cleaner (no clay) & better sorted than below.
COLOR CHANGE

62 VIBRACORE 42-114 (continued)



Pebbles concentrated at top of unit. Due to winnowing at shoreface erosional contact.

Above 1.68: Color change.
Sand becomes cleaner (no clay) & better sorted than below.

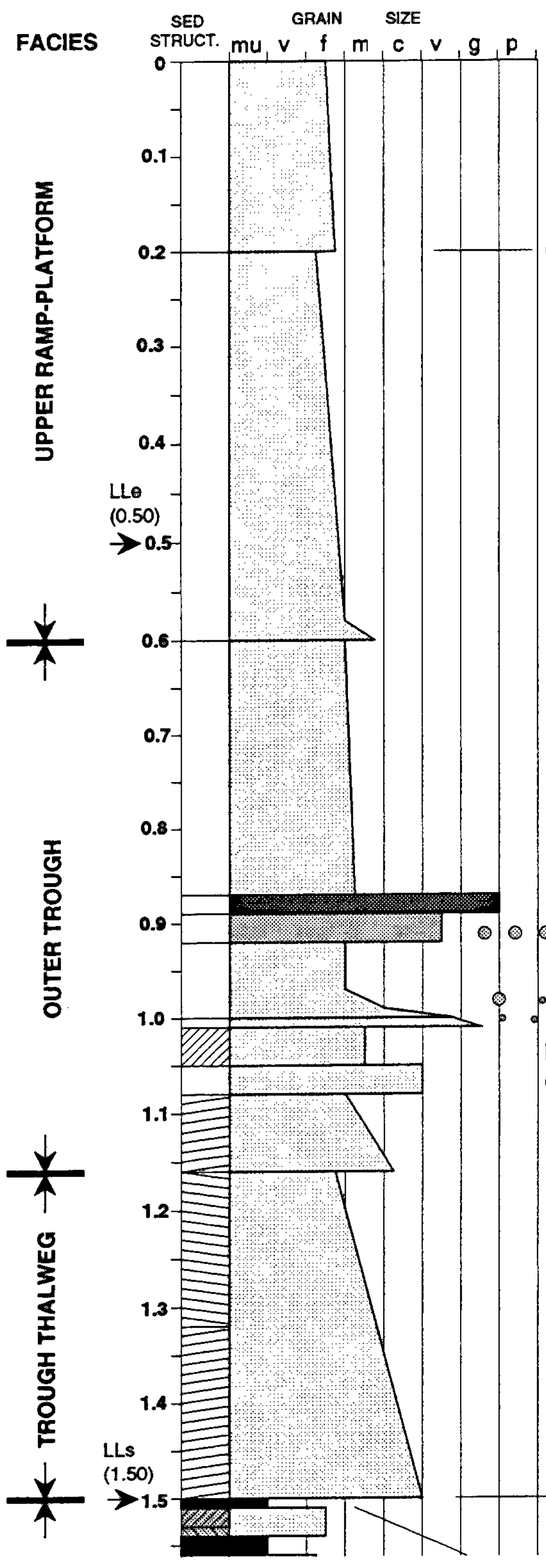
COLOR CHANGE
- 1.68 - from grayish yellow above to gray below.

Clay-covered (grayish white) gravel, relatively abundant shell fragments.

Rhythmic fg sand & silt laminae.

Rhythmic bedding with muddy layers
- tidal wavy bedding.

62 VIBRACORE 43-111



Location : upper ramp-middle platform transition
Depth: -3.99 m
Dist: 346.1 m

Above 0.90 - Core severely deformed. Unable to accurately determine sedimentology.

COLOR CHANGE - 0.20
- yellow above to brownish yellow below.

Facies contact based upon change to uniform fine sand.

Bimodal mg sand & granules.

Scattered vcg & granules in base; gradational from below. Sand matrix is fg to mg.

Bimodal fg & cg-vcg sand

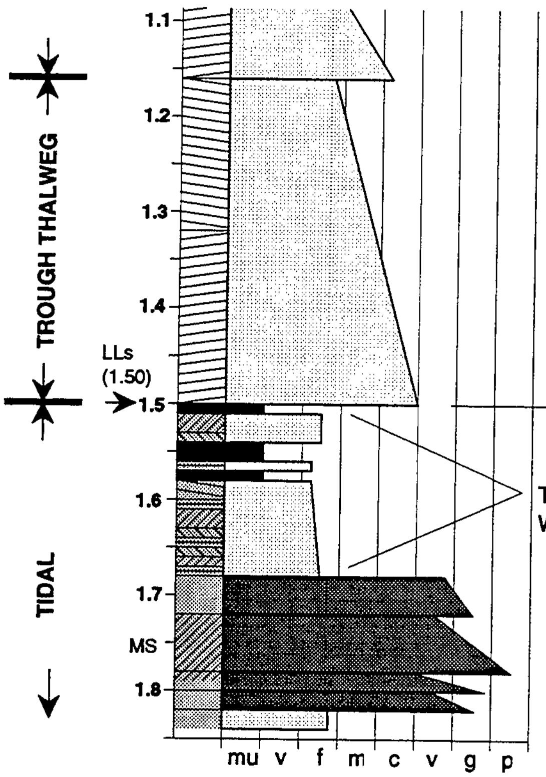
Cg & vcg sand.

Fg to cg sand at base.

1.16 - 1.20: Coarse-sand-filled burrows; filled with sand from above.

<u>Above 1.50</u>:
Very clean sand (vs. clayey sand below).
Cg to fg fairly well sorted sand laminae in base of unit grading up to very well sorted unimodal fg sand.
Abundant delicate white bivalve gragments aligned parallel to bedding probably reworked from facies below.

COLOR CHANGE - 1.5
- from yellowish gray above to dark gray below.



62 VIBRACORE 43-111 (continued)

Fg to cg sand at base.

1.16 - 1.20: Coarse-sand-filled burrows; filled with sand from above.

Above 1.50:

Very clean sand (vs. clayey sand below).
Cg to fg fairly well sorted sand laminae in base of unit grading up to very well sorted unimodal fg sand.
Abundant delicate white bivalve gragments aligned parallel to bedding probably reworked from facies below.

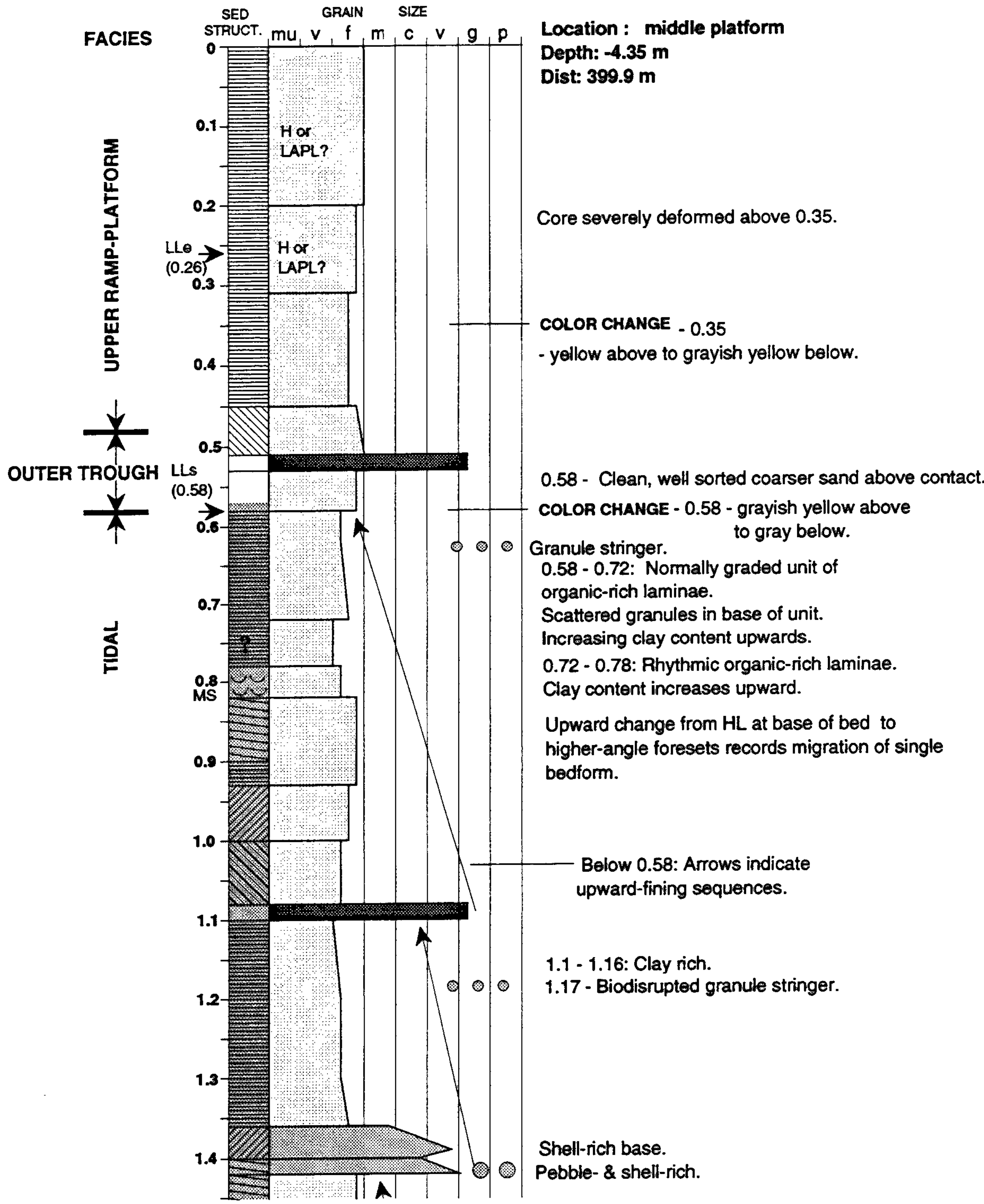
COLOR CHANGE - 1.5
- from yellowish gray above to dark gray below.

Tidal wavy bedding with bipolar foresets.
Wedge-shaped set boundaries

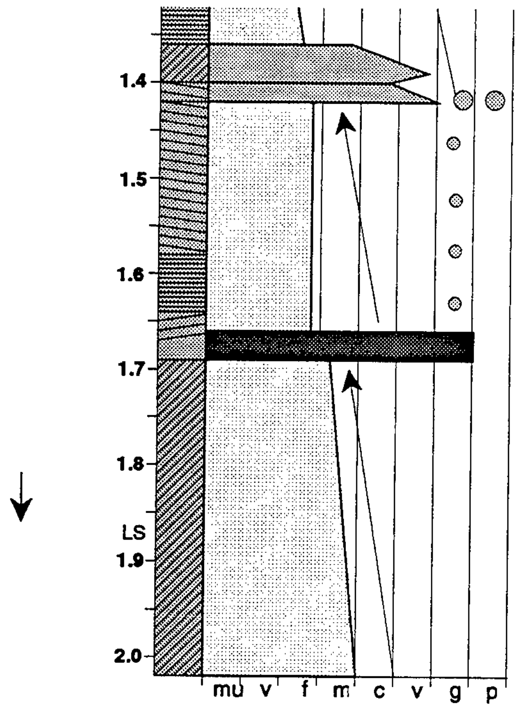
Shell-hash & mica rich.

62 VIBRACORE 44-110

Location : middle platform
Depth: -4.35 m
Dist: 399.9 m



62 VIBRACORE 44-110 (continued)



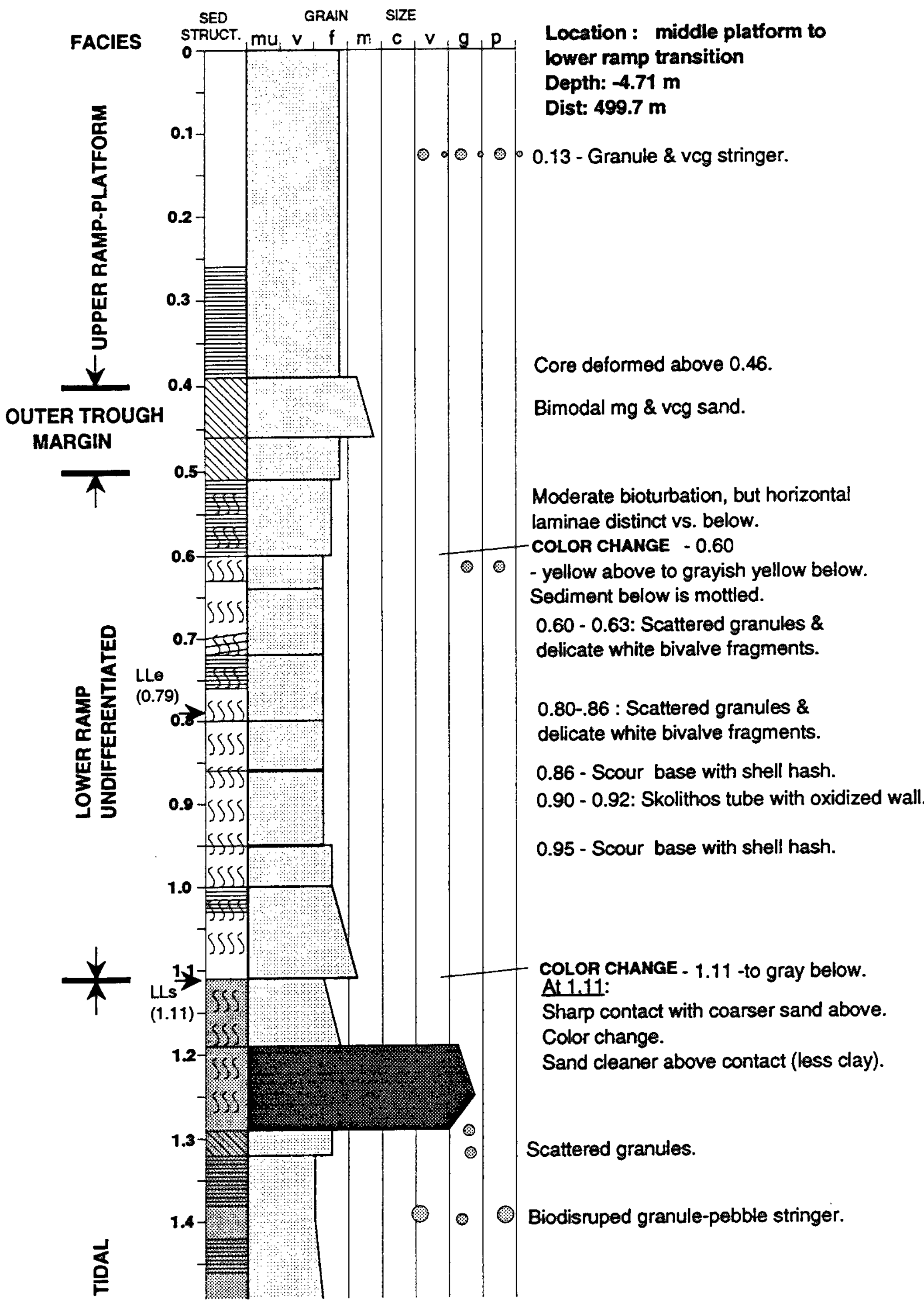
Shell-rich base.
Pebble- & shell-rich.

1.42 - 1.64:
Foreset angle increases upwards through unit due to bedform migration. Reactivation surfaces at 1.55 & 1.60. Scattered granules throughout.

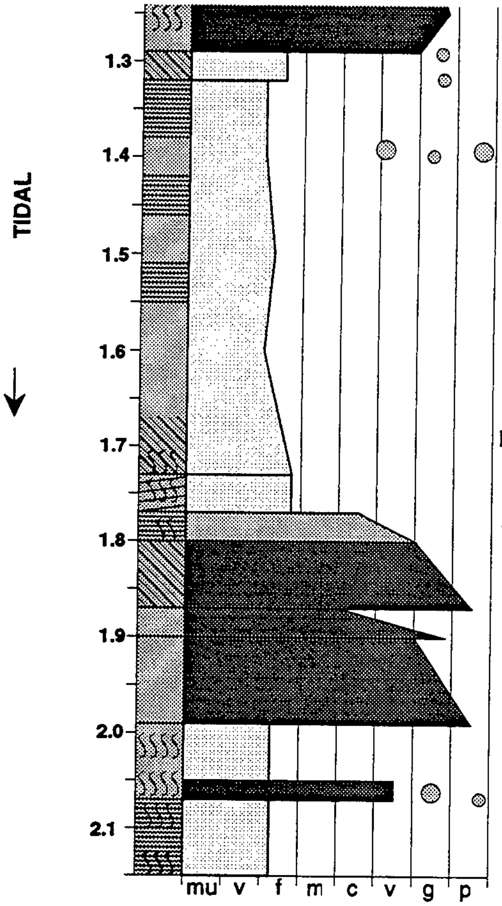
1.69 - 2.02: Reactivation surfaces & rhythmic 2-3 cm-thick normally graded units.

Bimodal fg & cg sand.

62 VIBRACORE 45-106



62 VIBRACORE 45-106 (continued)



Scattered granules.

Biodisruped granule-pebble stringer.

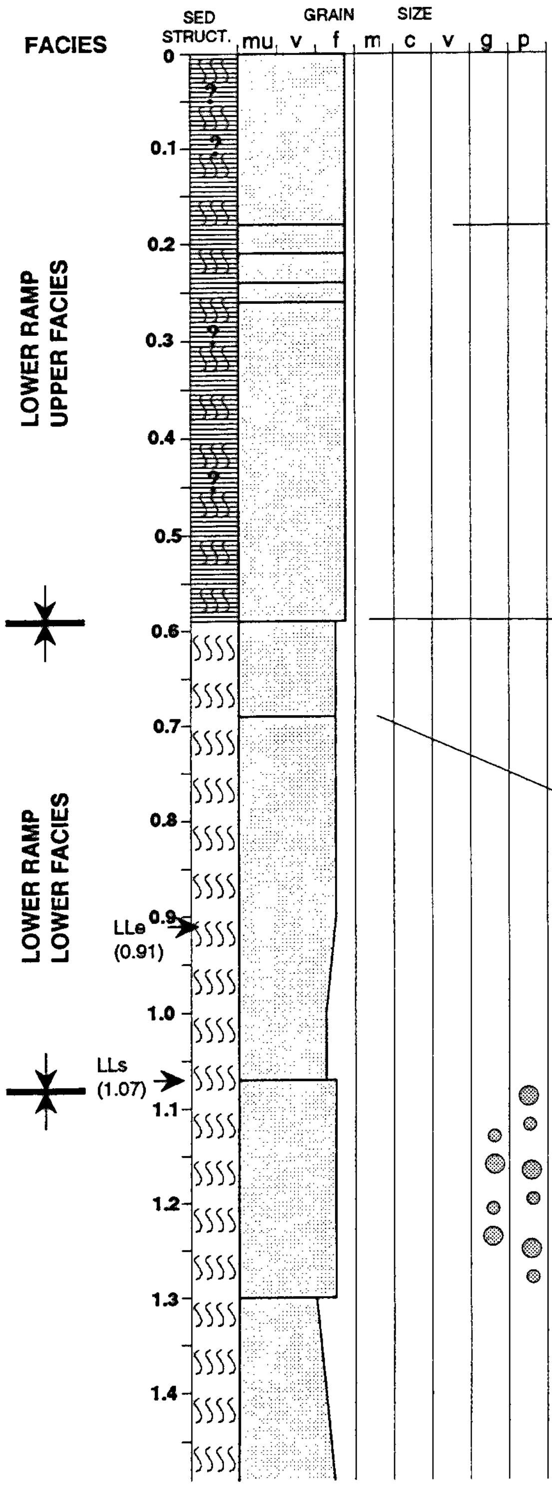
Bioturbation increases up from 1.73.

1.77 - 1.8: Bimodal granules & fg sand.

Biodisrupted granuled & pebbles; concave scour base.

End of core at 2.47 m. Facies similar to 2.1 m.

62 VIBRACORE 46-107



Location : lower ramp
Depth: -5.49 m
Dist: 600.3 m

0-0.10: Deformed H?

COLOR CHANGE - 0.18
- yellow above, brownish yellow below.

0.28-0.45:Deformed H?

Above 0.59: Sand markedly cleaner than below.

COLOR CHANGE - 0.59 - to grayish yellow below.

0.59 - 1.07:
Heavily bioturbated, but less than below.
Mottled fabric distinct on epoxy peel due to partial preservation of bioturbated parallel laminae.

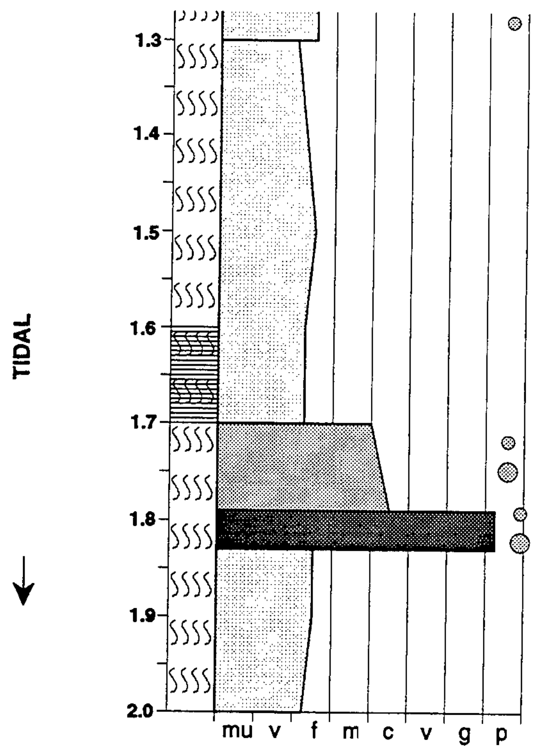
COLOR CHANGE - 0.69
-grayish yellow above to yellowish gray;
becomes progressively grayer downward.

1.07 m:
Truncation of granular unit below.
Sand units clayey below; cleaner above.
Bioturbation heavy, but less above than below.

1.07 - 1.30: Scattered biodisrupted granules, pebbles, & delicate white bivalve debris.

1.07 - 1.79: Heavily bioturbated, but slightly less than deeper in core.

62 VIBRACORE 46-107 (continued)



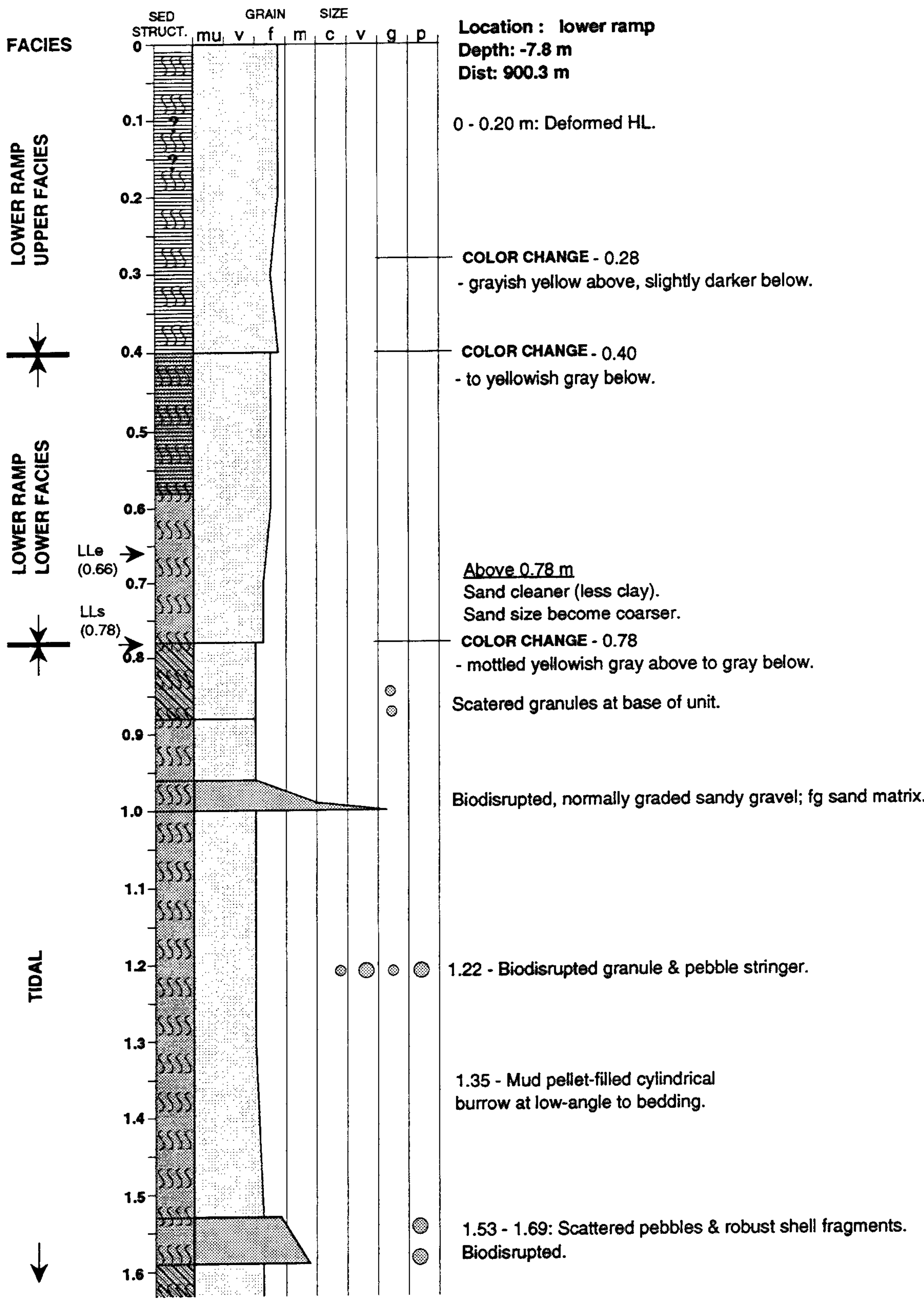
1.6 - 1.7: Abundant large to small, delicate bivalve debris parallel to bedding.

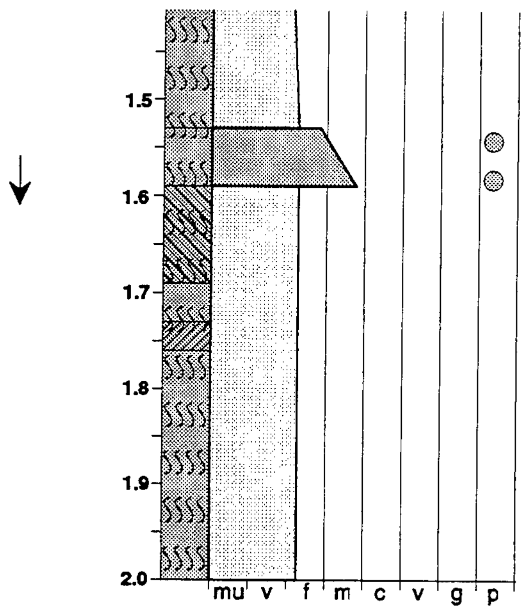
1.7 - 1.79: Scattered granules, pebbles & delicate white bivalve fragments; fg sand matrix.

Biodisrupted granules & pebbles.

1.83 - 2.93: Facies similar to that between1.3 &1.7 m. Bipolar tabular foresets occur near 2.5 m.

62 VIBRACORE 47-108





62 VIBRACORE 47-108
(continued)

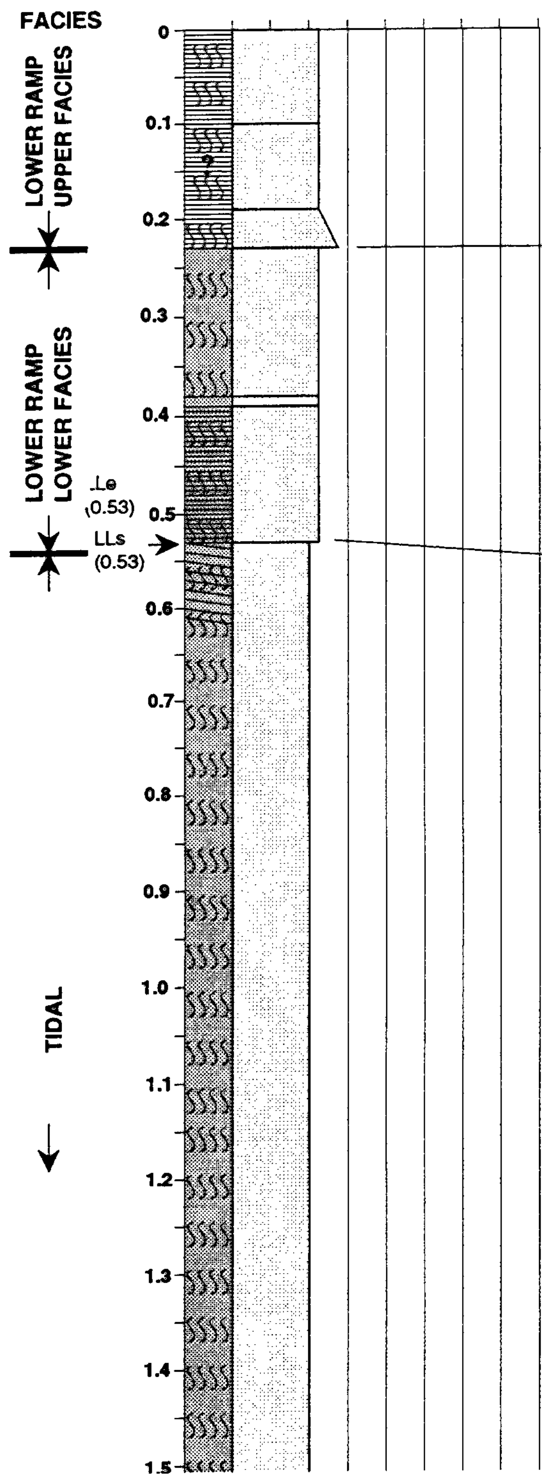
1.53 - 1.69: Scattered pebbles & robust shell fragments. Biodisrupted.

1.73 - 1.76: Abundant razor clam fragments aligned parallel to bedding.

1.80 - 1.88: Mud-lined Callianassa burrow at high angle to bedding.

1.59 - 2.87: Facies characteristics similar through end of core at 2.87m. Includes Raeta fragments & a large clam-type burrow at 2.7m.

62 VIBRACORE 48-109



Location : lower ramp
Depth: -7.11 m
Dist: 800.2 m

0 - 0.10: Very clean & very well sorted.
Core deformed - structures unrecognizable; HL most likely.

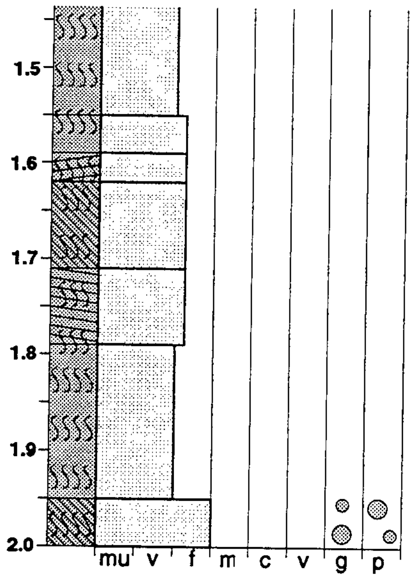
0.10 - 0.19: Deformed HL.

COLOR CHANGE - 0.23
- light grayish yellow above to yellowish gray below.

0.38 - 0.39: Mud-rich layer.
Above 0.53:
Sand cleaner (less clay matrix).
Sand slightly coarser.
Heavily bioturbated, but less than below; relict bedding more distinct than below contact.

COLOR CHANGE - 0.53
yellowish gray above to gray

62 VIBRACORE 48-109
(continued)



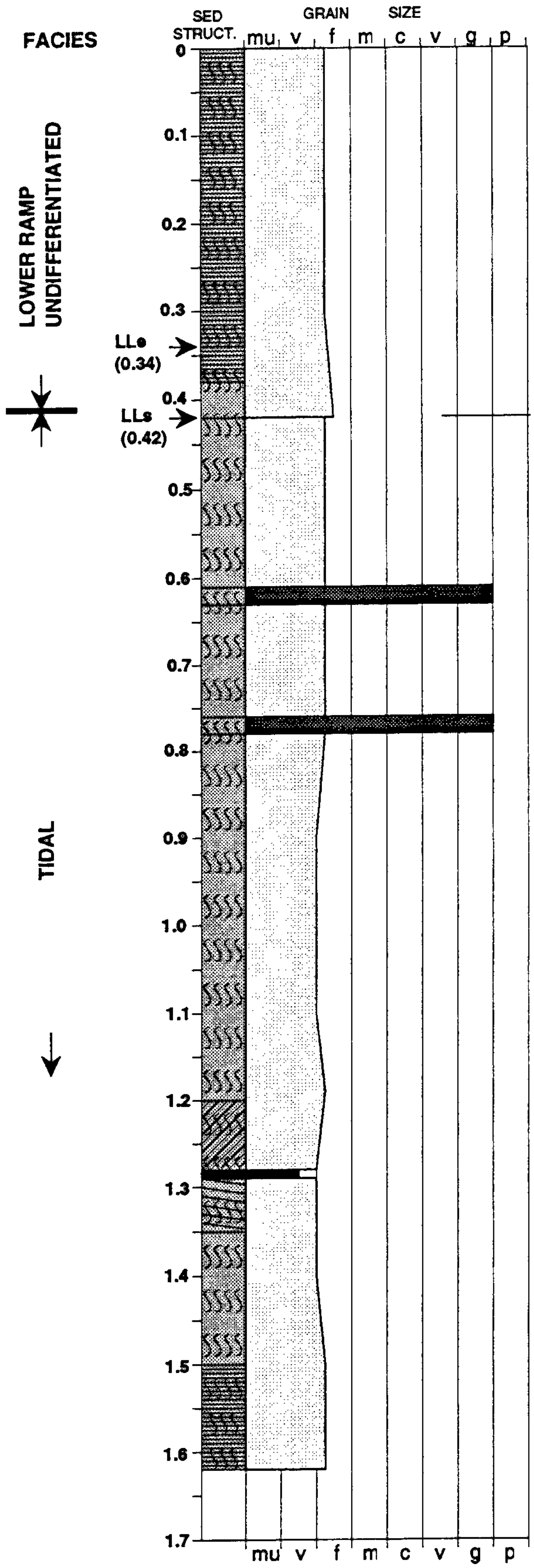
1.55 - 1.59: Shell-rich scour & fill; abundant sand dollar fragments.

1.76 - 1.79: Three cm-thick shell-rich base; delicate bivalve fragments parallel to bedding.

1.95 - 2.1: Biodisrupted granules & pebbles in fg matrix.

End of core at 2.47: Facies characteristics between 2.0 & 2.47 are similar to 1.0 through 2.0.

62 VIBRACORE 49-101



Location : lower ramp
Depth: -7.80 m
Dist: 900.3 m

Core deformed above 0.65
Relict horizontal laminae most likely.

Delicate grayish white bivalve fragments scattered throughout

Above 0.42:
Sand cleaner; less clay matrix.
Relic laminae more visible due to slightly less bioturbation.
Sand slightly coarser at contact.

COLOR CHANGE - 0.42
-yellowish gray above to gray below.

0.43 - 0.48: Thick-walled, mud-lined burrow with sand fill.

Biodisrupted pebbles.

Biodisrupted granules & pebble; Raeta fragment..

1.38 - Fecal-pellet rich layer.

1.37 Fecal-pellet filledburrow; 1-cm diameter.

1.35 - 1.62: Bioturbation fabric increases upward; physical structures overprinted.

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13. ABSTRACT *(Maximum 200 words)*

Forty-nine vibracores were collected along two shore-normal transects extending from the beach out to ~8-m water depth at the Coastal and Hydraulics Laboratory's Field Research Facility at Duck, NC. Close vibracore spacing and detailed hierarchical sedimentologic analysis enabled "high-resolution" definition of the textural and structural architecture of the shoreface prism, which was then compared with biweekly survey data representing a 12+-year period. The shoreface prism erosionally overlies an inlet-associated tidal complex. Maximum shoreface thicknesses of 3-4 m occur below the beach-through-middle profile with seaward thinning down to 30-40 cm between the 7.5- and 8.5-m water depth. The gravel-rich swash zone and swash-trough transition facies record episodic seaward progradation of beach-to-inner trough flank surfaces over cross-stratified finer sand of downflank and trough axis settings. Cross-stratified sand and gravel also occur in the lower half of the shoreface prism below bar, upper ramp, and middle platform sectors of the profile documenting the migration of relatively large three-dimensional ripples and bars in historical current-dominated trough settings. A horizontal-laminated fine-sand facies overlies the trough-associated facies, representing shoal zone buildup under high-velocity plane-bed conditions. A bioturbated, horizontal-laminated, fine-to-very-fine sand facies underlies the lower ramp sector of the profile, also indicating buildup under high-velocity conditions. However, profile data document that the

(Continued)

14. SUBJECT TERMS

Cores	Profile morphodynamics
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Nearshore	Sedimentology
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lower ramp builds up in response to storm events which simultaneously causes erosion and outer-trough development along the landward-adjacent profile. Conversely, the lower ramp undergoes slow subelevation during long fair-weather stretches as the storm-trough sector undergoes buildup.

More than 80 percent of the shoreface prism lies within the envelope of surveyed profile change, with the surveyed lower limit of erosion (LLe) serving as a close approximation to the sedimentologic lower limit of the shoreface (LLs). The LLe is nearly coincident with the LLs below the lower ramp and rises above the LLs in the landward direction where deeper erosion usually predated surveys. Profile data show that the lower ramp tends to erode and build up in form-parallel fashion, contrary to the upper-ramp and middle profile sectors which undergo localized cut and fill. Along the lower ramp, "fair-weather erosion surfaces," similar in shape to the LLe and LLs, cut down into storm-accretion sequences. The LLe and LLs below the lower ramp primarily reflect a maximum erosion surface which developed about 6½ years prior to vibracoring. Lower ramp deposits above the LLe record the occurrence of four accretion trends, each associated with periods of greater-than-unusual storm activity and each truncated by progressively decreasing erosional maxima. Shoreward of the lower ramp, the LLe and LLs represent spatial composites of localized longshore trough-scour events which occurred at various times throughout the 12+-year survey period.

Combined profile and sedimentologic data document that trough-associated scour occurs across a 250- to 300-m-wide zone down to ~-5 m NGVD, resulting in a concave-shaped composite trough fill. The seawardmost location of trough-associated facies corresponds to the break in slope between the middle platform and lower ramp, and serves as an estimate to maximum width for longshore current deposition during extreme events. Textural data indicate that medium sand to gravel tends to remain within the longshore current domain, even during extreme storm events, with no evidence for significant quantities of material coarser than fine sand being lost to the offshore. Short-term closeout depths (e.g. 4–6 m) as well as the calculated depth of annual closure (d_l) coincide with the break-in-slope and facies boundary. Thus, the lower ramp facies coincides with a time-dependent zone of profile closure wherein durations of closure increase in the seaward direction and intervening changes in bed elevation decrease. The zone of closure may be thought of as a zone of decreasing seaward transport in which fine to very fine sand is the typical bedload material, even during high-energy storms. Textural distribution within the entire shoreface mass indicates net long-term transport direction and loci of deposition for different-sized material, thus providing guidelines for project fill and expected retention.