

ABSTRACT

Eric D. Sager. HOLOCENE INFILL HISTORY OF ALBEMARLE SOUND, NORTH CAROLINA: AN INTEGRATED SEISMIC, LITHO-, AND CHRONO-STRATIGRAPHIC SYNTHESIS. (Under the direction of Dr. Stanley R. Riggs)
Department of Geology, November 1996.

Valley-fill systems on the U.S. mid-Atlantic margin have been interpreted to represent a continuous Holocene sea-level rise. The lithostratigraphic evaluation of vibracores from Albemarle Sound, North Carolina suggests such a simple infill history resulting from a continuous Holocene transgression. However, coastal lithofacies are diachronous and require the development of an accurate chronology for a more precise interpretation. When the lithostratigraphy is integrated with the high-resolution seismic stratigraphy and radiocarbon chronostratigraphy, the infill record of Albemarle Sound reveals a more complex Holocene sea-level history.

The Holocene section of Albemarle Sound contains three depositional sequences (ASDS-1 to ASDS-3), each consisting of lithologically similar successions of depositional environments. Basal sediments from ASDS-1 were deposited in an open-estuarine environment characterized by tidal channel complexes that occurred between 7.5-7.6 ka and 6.5-6.7 ka. Emplacement of a barrier island system at 6.5-6.7 ka initiated restricted-estuarine conditions that persisted until at least 5.8-5.9 ka. For some interval between 5.8-5.9 ka and 5.5-5.6 ka sea level dropped (< 6 m) producing an extensive erosional surface throughout the middle- and outer-estuarine zone. Deposition resumed as sea level rose to form ASDS-2. Basal sediments of ASDS-2 were deposited in an open-estuarine system between 5.5-5.6 ka and 2.8-3.0 ka, suggesting that the previous barrier island complex was extensively breached. ASDS-2 is capped with closed-estuarine sediments

resulting from the presence of a continuous barrier island complex from 2.8-3.0 ka to 1.4-1.6 ka. Another small drop of sea level, which truncated ASDS-1 and ASDS-2, occurred for some interval between 1.4-1.6 ka and 0.4 ka. This drop was probably between 1 to 2 m based on the absence of basal open-estuarine sediments in the overlying depositional sequence (ASDS-3). This suggests that the barrier island system was preserved and active during the sea-level drop and subsequent transgression. ASDS-3 consists of closed-estuarine sediments that are being deposited during the ongoing marine transgression behind the modern, well developed barrier island system.

A COMPLEX HOLOCENE INFILL HISTORY
OF ALBEMARLE SOUND, NORTH CAROLINA: AN INTEGRATED
SEISMIC, LITHO-, AND CHRONOSTRATIGRAPHIC SYNTHESIS

A Thesis

Presented to

the Faculty of the Department of Geology

East Carolina University

In Partial Fulfillment

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Master of Science in Geology

by

Eric D. Sager

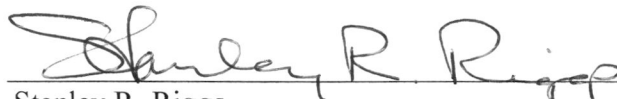
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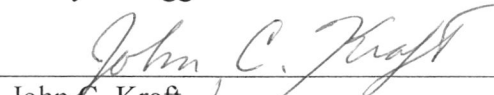
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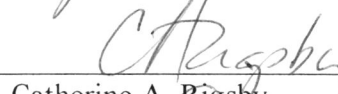
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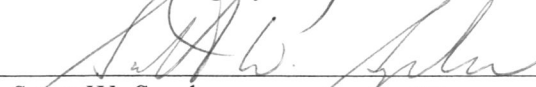
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INTRODUCTION

DEFINITION OF THE PROBLEM

Traditionally, Quaternary formations have been defined utilizing standard litho- and biostratigraphic techniques based on the assumption that deposits are laterally continuous and generally flat lying. The terraced geomorphology of the Coastal Plain (Cooke, 1930; Doering, 1960; Winker and Howard, 1977) demonstrated that major sea-level fluctuations have occurred throughout the Quaternary. Development of oxygen isotope records of deep sea sediments (Shackleton and Opdyke, 1973) suggested that these eustatic sea-level fluctuations reflected episodes of glaciation and deglaciation. Sea-level oscillations caused coastal environments to migrate across the low-sloping continental margin and produced a complex succession of lithologically indistinguishable deposits that have been highly dissected and only partially preserved (Belknap and Kraft, 1981; Hine and Snyder, 1985; Riggs and Belknap, 1988). Therefore, deposits are not laterally continuous, and lithologically correlative units may not define time-stratigraphic units. However, integration of high-resolution seismic stratigraphy and age dating are now aiding in the recognition and interpretation of these complex Quaternary depositional units (Riggs *et al.*, 1992). A seismic stratigraphic section provides a relative chronostratigraphic framework that can be combined with age dating techniques and other geologic data to help ascertain the detailed geologic history for a given region (Vail and Mitchum, 1977).

Recent studies of Holocene coastal evolution have concentrated on coastal marshes (Fletcher *et al.*, 1993a,b) and incised valley systems (Dalrymple *et al.*, 1994). Lithologic studies of coastal marshes suggest a simple and gradual succession of depositional environments resulting from a continuous Holocene sea-level rise (Bloom, 1964; Kraft, 1971; Belknap and Kraft, 1977). Subsequently, DePratter and Howard (1981), Colquhoun and Brooks (1986), and Gayes *et al.* (1992) present data that suggest fluctuations in sea level along the southeast U.S. coast have occurred in the Holocene. These small sea-level events have not been widely recognized in marsh deposits because they are susceptible to compaction, variations in sediment supply, and fresh-water discharge that mask regional sea-level trends (Fletcher, *et al.*, 1993b). Furthermore, the preservation potential of these depositional sequences is low because of subaerial oxidation and weathering during low stands, erosion from migrating tidal channels and inlets, and shore-face retreat (Belknap and Kraft, 1981; Gayes *et al.*, 1992).

Sediments of incised valley systems have a greater chance of containing a detailed geologic record because they have a higher preservation potential (Belknap and Kraft, 1981; Hine and Snyder, 1985; Belknap *et al.*, 1994). Albemarle Sound provides an excellent opportunity to evaluate Holocene sea-level fluctuations because it is a well preserved valley-fill sequence with a detailed database. In addition, the modern depositional systems are analogous to some of the conditions in which the Holocene sediments were deposited.

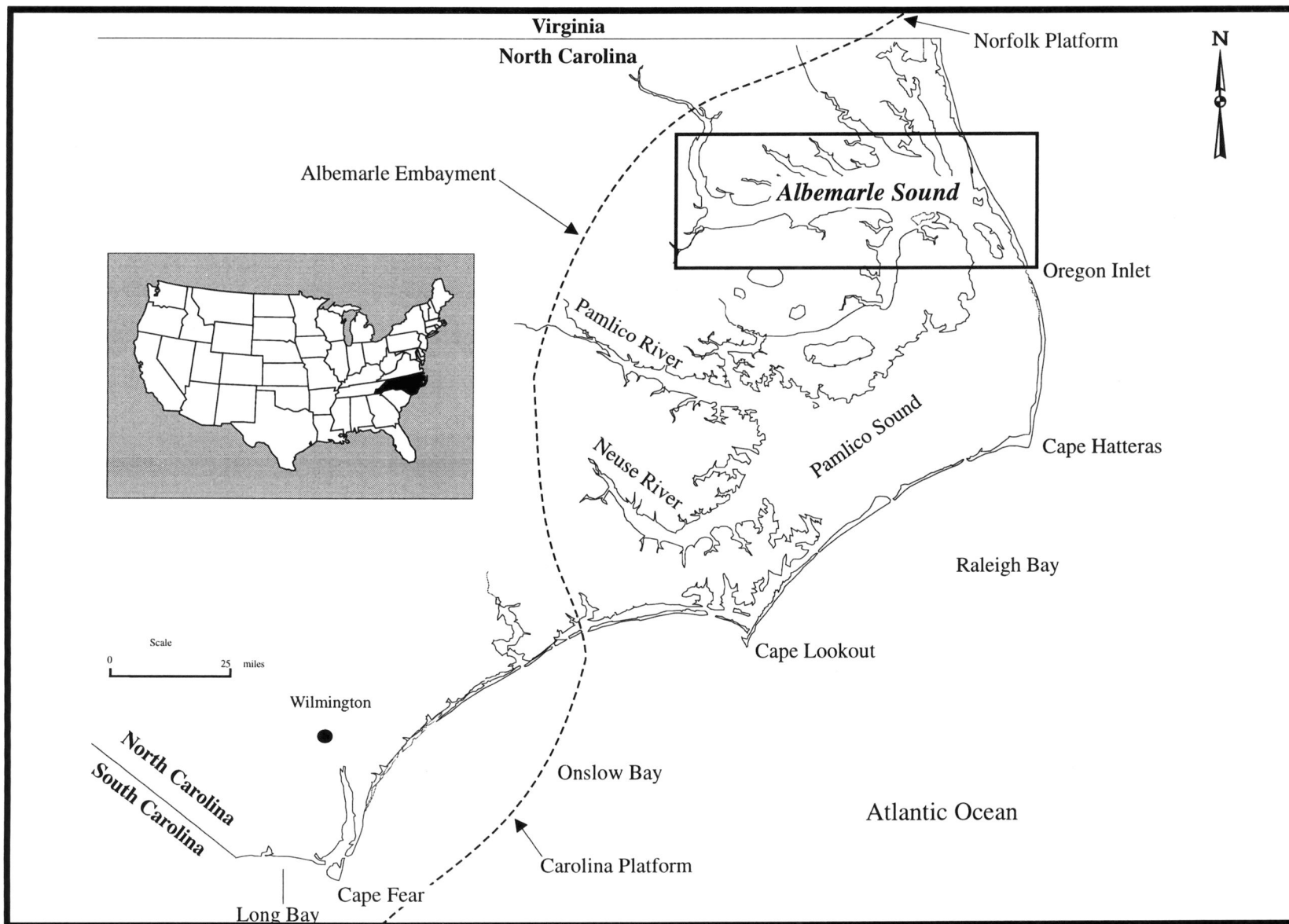
OBJECTIVES

Consequently, the objectives of the present study are to 1) identify the major lithofacies infilling Albemarle Sound and develop a lithostratigraphic model for the Holocene infill history of this region; 2) develop the seismic sequence stratigraphy and chronological framework of the Holocene valley-fill sequence in the Albemarle Sound region; 3) integrate the seismic-, litho-, and chronostratigraphy for development of the Holocene infill history of outer-Albemarle Sound; and 4) compare the lithostratigraphic model with the multi-disciplinary approach that integrates high-resolution seismic stratigraphy and radiocarbon dating with the lithostratigraphy.

REGIONAL GEOLOGIC SETTING

Albemarle Sound is a large, drowned-river estuarine system occupying the paleo-Roanoke River valley, which is situated entirely within the Coastal Plain province of northeastern North Carolina (Riggs *et al.*, 1993; Riggs, 1996) (Figure 1). Coastal Plain deposits consist of an eastward thickening wedge of Cretaceous and Cenozoic sediments that rest upon crystalline basement rocks. Albemarle Sound occupies a portion of the Albemarle Embayment (Figure 1), a major depositional center that existed throughout the Plio-Pleistocene and resulted from structural downwarping possibly caused by the reactivation of older faults (Ward *et al.*, 1991). Albemarle Embayment occurs on the northern flank of the Carolina Platform High (Cape Fear Region) and is bounded to the north by the Norfolk Platform (Cape Henry Region) (Ward *et al.*, 1991). Plio-Pleistocene sediments crop out along the perimeter of Albemarle Sound and form the framework for the Holocene infill. The Plio-Pleistocene units were deposited during previous glacial

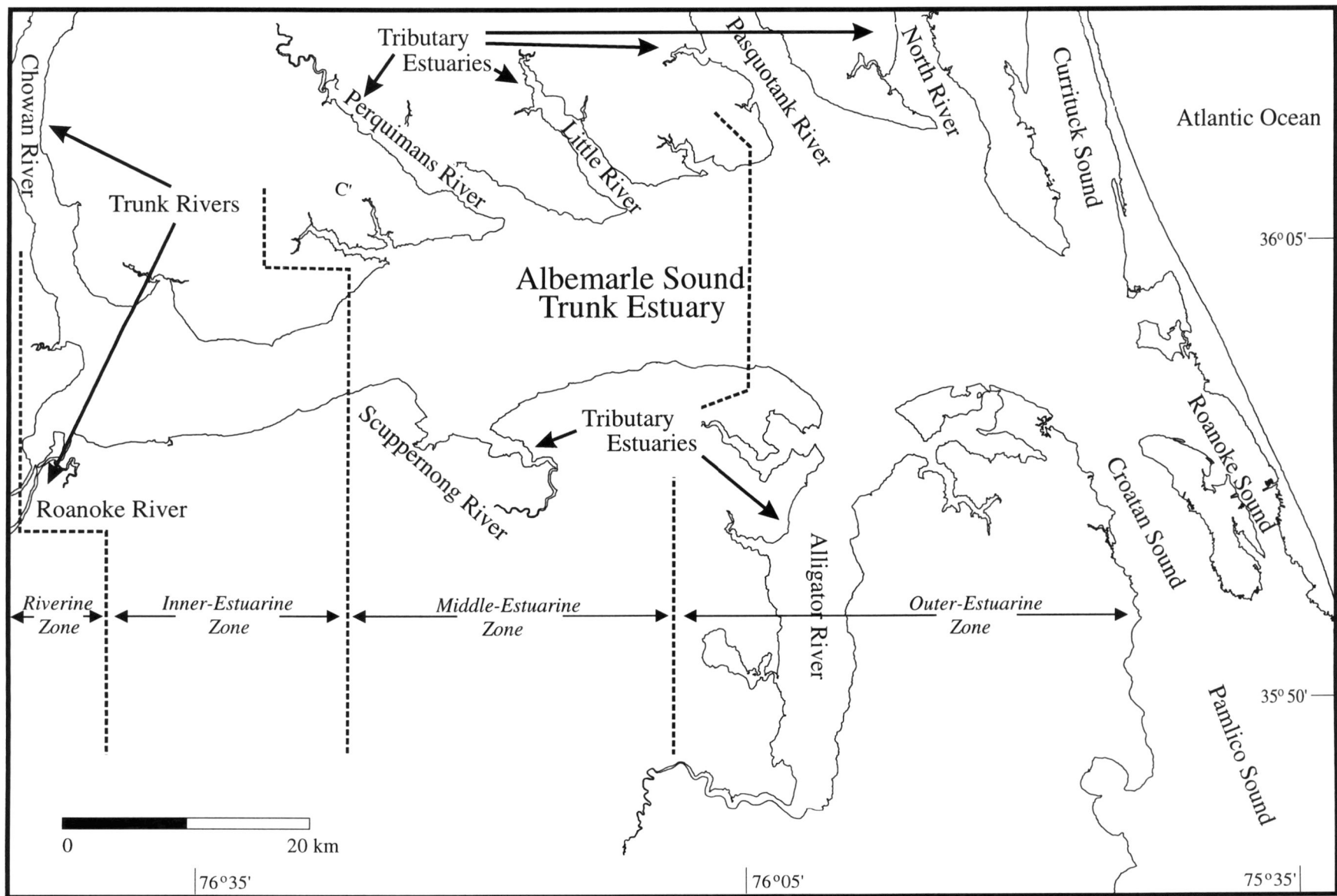
Figure 1: Regional location map depicting North Carolina's position along the Atlantic continental margin and the position of Albemarle Sound within northeastern North Carolina. The dashed line depicts the structural features for this region.



and interglacial periods (Blackwelder, 1981; Riggs and Belknap, 1988; Ward *et al.*, 1991) and contain fluvial, estuarine, barrier island, and continental shelf sediments that directly control the morphology of the Albemarle estuarine system (Riggs *et al.*, 1993; Riggs, 1996).

The Albemarle estuarine system encompasses approximately 2000 square kilometers of water and consists of two trunk rivers, two trunk estuaries, and six major tributary estuaries (Figure 2). This network forms the largest drainage system in North Carolina (Riggs *et al.*, 1993). The tributary estuaries are the drowned segments of small, black-water streams that drain the swamp forests and pocosins of the sandy Coastal Plain. The riverine zone of the Roanoke and Chowan trunk rivers is bounded by extensive swamp-forest floodplains and extends into the Piedmont province of North Carolina and Virginia. The riverine zone passes into a transitional zone characterized by eroding swamp-forest floodplains as the rivers are drowned by the ongoing rise in sea level. The trunk estuaries are the drowned portions of the Roanoke and Chowan Rivers that increase in width and depth seaward from the transitional zone. The Albemarle trunk estuary is further subdivided into the inner-, middle-, and outer-estuarine zones (Figure 2). The estuarine zones are characterized by eroding sediment banks resulting from irregular storm tides and high wave energy associated with the increased fetch. The bottom morphology within the estuaries is analogous to a shallow dish. A narrow perimeter platform, composed of Pleistocene sediments with minor amounts of modern surficial sand on top, slopes gently from the shoreline to water depths of 1.5-2.0 meters. At the edge of the perimeter platform, the slope increases abruptly down to a broad,

Figure 2: Location map of Albemarle Sound depicting the two trunk rivers, two trunk estuaries, and six major tributary estuaries of the Albemarle estuarine system.



relatively flat organic-rich mud floor of the central basin that is 4.5-6.5 meters below the water surface (Riggs *et al.*, 1993).

METHODOLOGY

SEISMIC STRATIGRAPHY

Data Collection

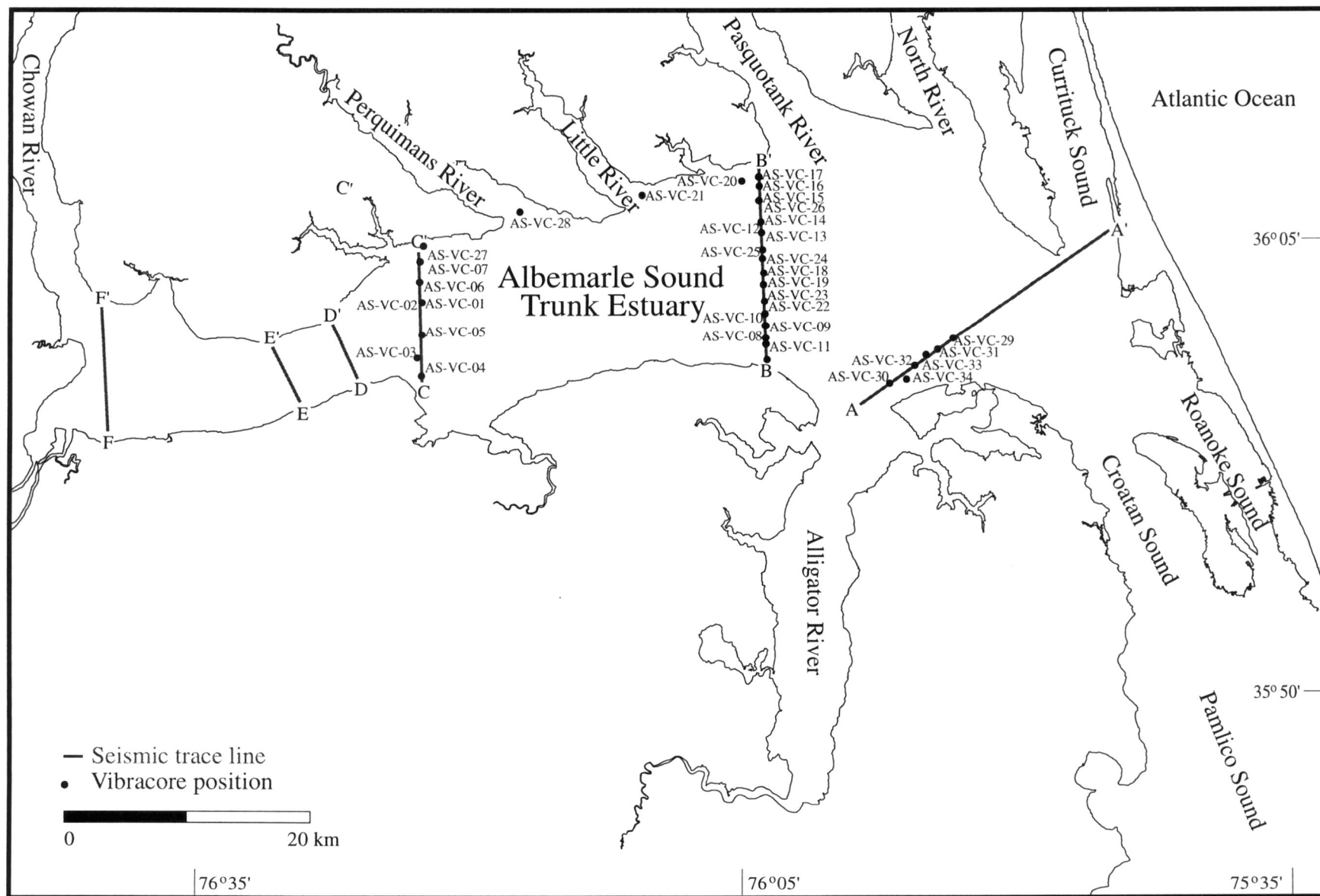
A single-channel, high-resolution seismic reflection system consisting of an EG&G UNIBOOM and Hunttec SeaOtter tow sled were utilized to collect seismic data along six cross-sectional transects (Figure 3). The research vessel, R/V *Nitro*, was used to collect the data while navigation was monitored via Global Positioning Satellites (GPS) with a Trimble NavTrac XL. The UNIBOOM system employs a broad band, high frequency (400 Hz to 14 kHz) wave spectrum that delivers enhanced vertical and horizontal resolution in the shallow subsurface, but sacrifices depth of penetration (Snyder, 1994). Subsurface penetration was less than 0.1 second (85 m) 2-way travel time, with the highest resolution obtained in the upper 20 milliseconds (17 m).

Data Reduction

The incoming signal was received on an 8 element hydrophone and graphically recorded. Each seismic line produced roughly 3-5 meters of raw data due to the rapid firing rate and detailed horizontal resolution. In order to manage this information, the raw seismic data was photocopied, interpreted, and reduced to line drawings following the procedures outlined by Snyder (1994).

Subbottom reflectors were interpreted to be either real or multiple reflectors. Bottom and peg-leg multiples were the most common multiples in the Albemarle data.

Figure 3: Location of the 97 kilometers of seismic track line and the 34 vibracores collected in Albemarle Sound.

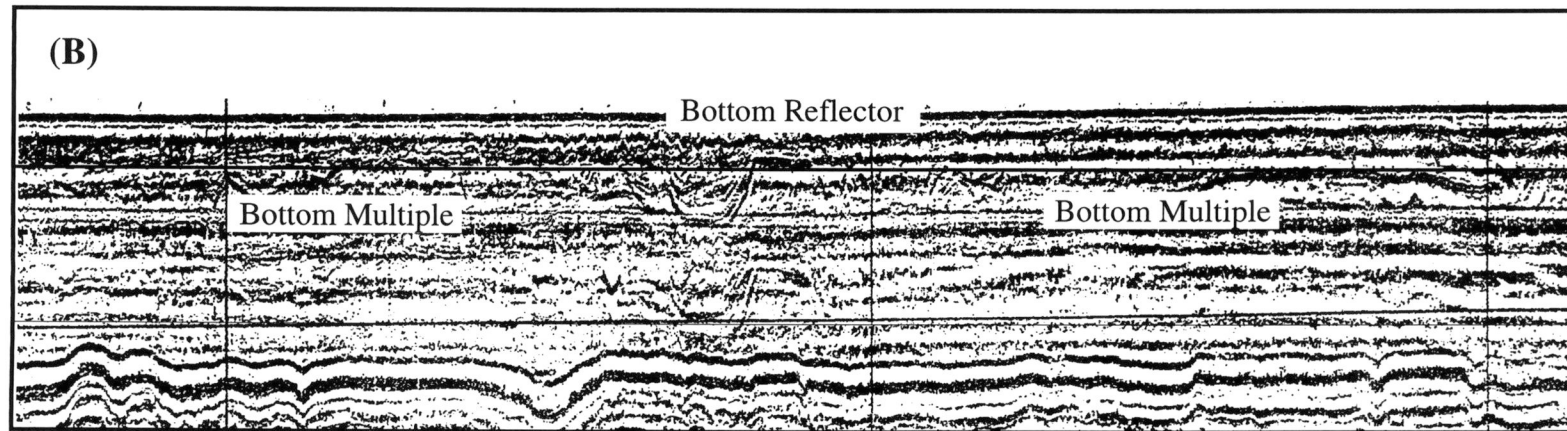
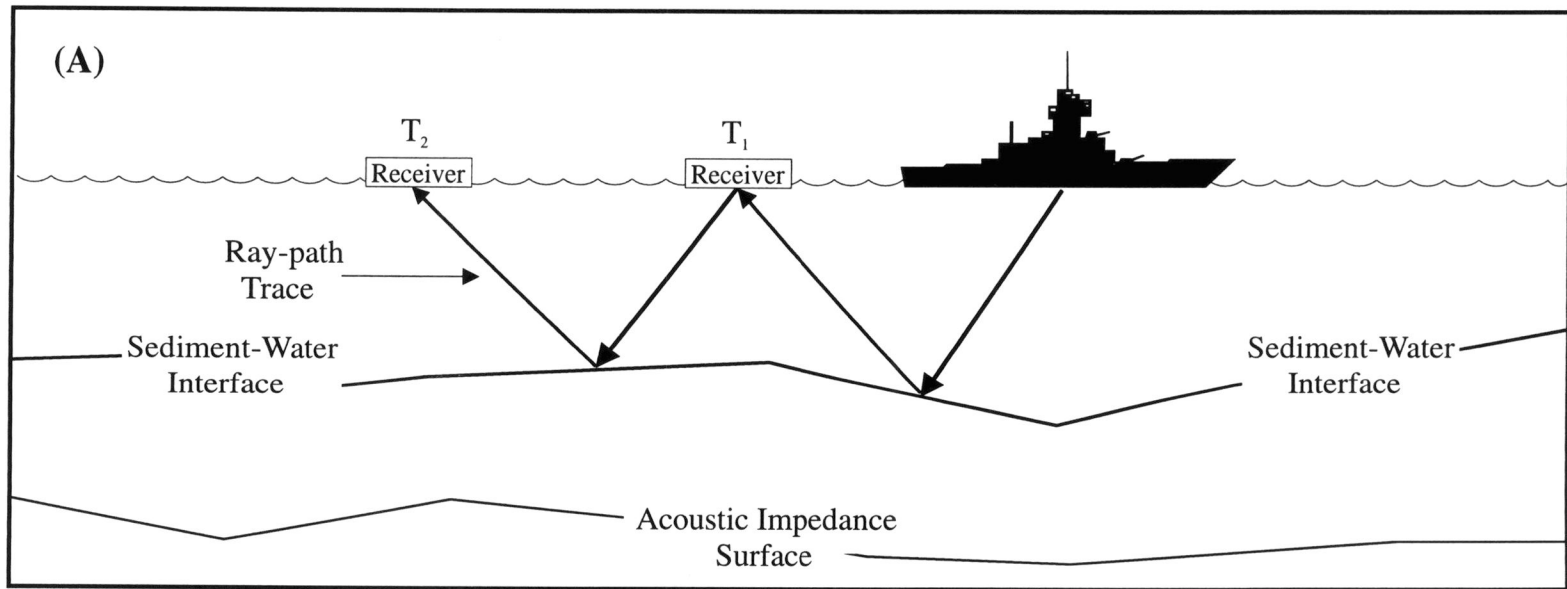


Bottom multiples result from reverberation of the seismic signal ray-path between the sediment-water interface and water-air interface. Bottom multiples mimic the sediment-water interface and are recorded at a water depth travel time below the real bottom reflector (Figure 4). Peg-leg multiples, a combination of real reflection travel time and water depth travel time, are produced by reverberation of a reflected seismic wave through the water column. Peg-leg multiples mimic real internal reflectors and are recorded at a water depth travel time below the acoustic impedance surface that produced the reflection event (Figure 5).

Real seismic reflectors were distinguished from multiple reflection events by comparing travel time of subbottom reflectors with travel time of all possible multiples. Real seismic reflectors were highlighted using a four color scheme, with the bottom reflector used as a reference for all reflection events. Reflections with comparable amplitudes were labeled as strong reflectors, while reflectors with slightly weaker amplitudes were labeled moderate, and so forth. Following this procedure, the color scheme consisted of reflection events that are 1) very strong (yellow), 2) strong (red), 3) moderate (blue), and 4) weak (green). Changes in the amplitude of continuous reflectors were marked by changes in the color scheme.

The interpreted seismic data were reduced to line drawings of manageable size and scale utilizing a digitizing program and computer work station developed by Dr. Stephen Snyder, North Carolina State University. The horizontal scale was developed from latitude and longitude positions recorded by GPS during data acquisition. The vertical scale was produced by converting two-way travel time to depth below the

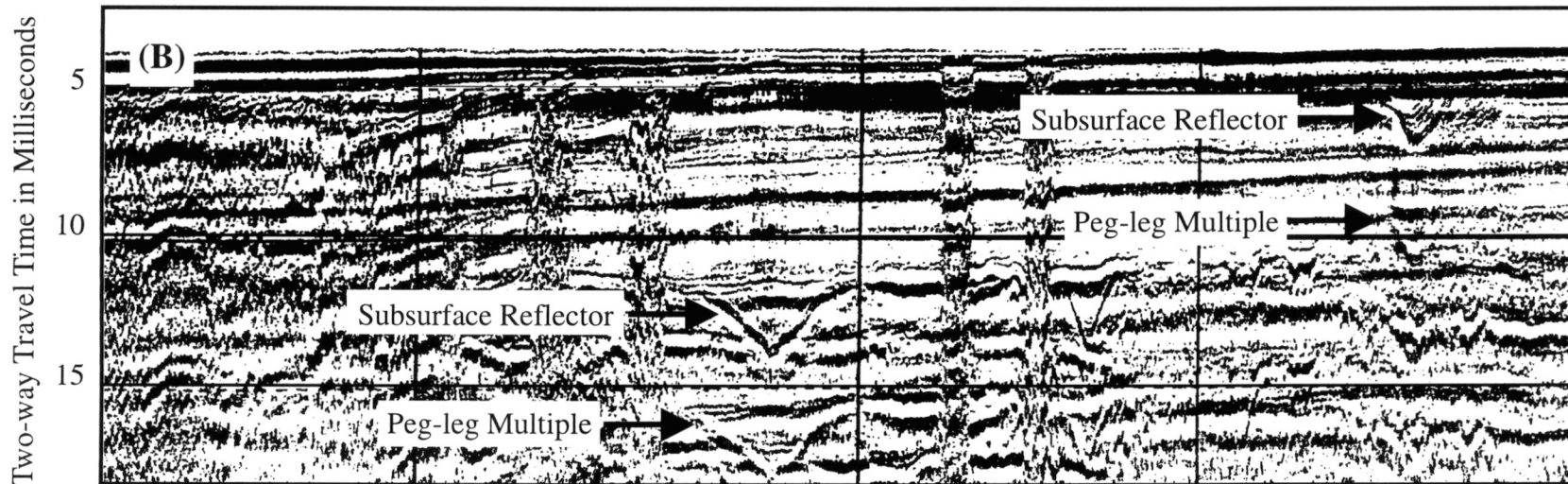
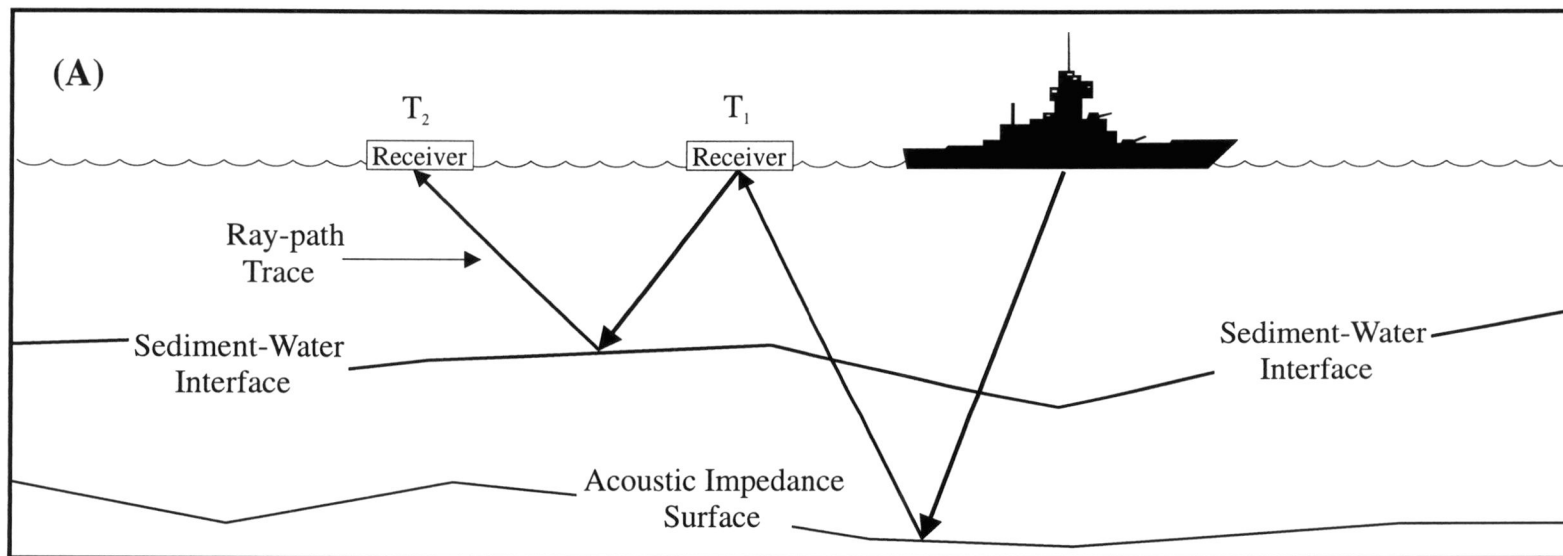
Figure 4: (A) Hypothetical ray-path trace of a seismic signal that produces a bottom multiple. T_1 represents the two-way travel time and ray-path trace of a seismic signal that reflects off the sediment-water interface and is recorded by the seismic receiver to produce a bottom reflector. T_2 represents the two-way travel time and ray-path trace of a seismic signal that reflects off the sediment-water interface, air-water interface, and sediment-water interface again, before being recorded by the seismic receiver to produce a bottom multiple. (B) Raw seismic data collected in Albemarle Sound that depicts the bottom reflector corresponding to T_1 above, and a bottom multiple corresponding to T_2 above.



Two-way Travel Time in Milliseconds

Figure 5: (A) Hypothetical ray-path trace of a seismic signal that produces a peg-leg multiple. T_1 represents the two-way travel time and ray-path trace of a seismic signal that reflects off a subsurface reflector and is recorded by the seismic receiver. T_2 represents the two-way travel time and ray-path trace of a seismic signal that reflects off a subsurface reflector, the air-water interface, and the sediment-water interface before being recorded by the seismic receiver to produce a peg-leg multiple.

(B) Raw seismic data collected in Albemarle Sound that depicts subsurface reflectors that correspond to T_1 above, and peg-leg multiples that correspond to T_2 above.



sediment-water interface. The vertical scale was calculated from an assumed subbottom velocity of 1700 meters/second (Snyder, 1994). These data were imported into a standard PC computer graphics program and printed with a vertical exaggeration of 100:1, which reduced the data to a manageable size and still preserved stratigraphic relationships.

LITHOSTRATIGRAPHY

Thirty-four vibracores were positioned (Appendix A) along three seismic lines within the middle- and outer-estuarine zones (Figure 3) to determine the lithostratigraphy of Albemarle Sound. This lithostratigraphic information was integrated with the seismic- and chronostratigraphy to ascertain the infill history of Albemarle Sound.

Vibracoring and Core Processing Procedures

The vibracoring apparatus and procedures utilized in this study are described by Lanesky *et al.* (1979). The vibracore system consists of a concrete vibrator powered by a 5 H.P. engine. The vibrating head is connected to a 7.8-cm diameter aluminum irrigation pipe that is driven into the subsurface utilizing SCUBA divers. After penetration ceases, the diver caps the core pipe to prevent the loss of sediment, and the core is extracted from the subsurface utilizing a set of ship-board winches.

Cores were returned to the ECU sedimentology lab where they were split, photographed, and processed. Detailed sedimentological logs (Appendix B) were generated utilizing a binocular microscope and following the procedures outlined by Folk (1974). Each core was described, photographed, and subsampled for lithologic analysis and radiocarbon dating. The major lithologic units infilling Albemarle Sound were

identified and characterized according to grain size, sedimentary structures, and selected paleontological evidence.

Grain Size Analysis

Grain size analysis was utilized to characterize the major lithofacies and identify differences in the available sediment budget. The sand-dominated fraction of samples from the top, middle, and bottom of the channel complexes and laminated sediments were wet sieved (Folk, 1974) over a nest of screens ranging in size from 2.0 - 4.0 phi, with 1.0 phi increments. If multiple cores penetrated a lithologic unit, samples were taken from the core which displayed the thickest and most complete infill sequence. Sieves larger than 2.0 phi were not used because samples did not contain a significant coarse sand component. The weight fraction of sediments smaller than 4.0 phi was calculated by subtracting the weight sum of each sieve from the total sediment dry weight prior to analysis. The results of the laminated sediments are the work of a directed studies report by Sasha Linsin.

Radiocarbon Analysis

Standard and accelerator-mass-spectrometer (AMS) radiocarbon analyses were performed by Beta Analytic Inc. on calcareous shell, peat, and organic-rich sediment samples from the major lithofacies. The radiocarbon dates were superimposed upon the relative chronostratigraphy constructed from the seismic data to develop an absolute chronological framework for the Albemarle estuarine system.

Radiocarbon results (Table 1) were obtained on the suitable carbon remaining after the necessary pretreatments were performed. Organic sediments and peats were

Table 1: Radiocarbon ages for organic-rich sediments and *in-situ* fauna from vibracores along profiles B-B' and C-C'. See Figure 3 and Appendix A for regional and stratigraphic locations of the samples, respectively. Results are given as calibrated radiocarbon years before present (present = 1950 AD) using the Pretoria Calibration Procedure. Sample numbers (AS-VC-01) are designations for Albemarle Sound vibracore one, Depth (MBSL) refers to the depth in meters below the sea level that each sample was taken, and Location is the position of the sample in latitude and longitude. * Denotes atomic mass spectrometer (AMS) dates

Sample Number	Core Depth (m)	Lithofacies	Dep Seq	Material Dated	Calibrated C-14 Age (1 sigma)	Calibrated C-14 Age (2 sigma)
AS-VC-01	0.75-0.85	LF-6	ASDS-2	Organic-Rich Sed	3365-3480 BP	3330-3595 BP
AS-VC-01	1.05-1.15	LF-3	ASDS-1	Organic-Rich Sed	5770-5810 BP or 5885-5945 BP	5735-6030 BP
AS-VC-01	7.80-7.90	LF-3	ASDS-1	Organic-Rich Sed	6735-6905 BP	6650-7020 BP
AS-VC-03	2.42-2.47	Pre-Holo	Pre-Holo	Peat	N/A	N/A
AS-VC-05	0.50-0.60	LF-6	ASDS-2	Organic-Rich Sed	3360-3475 BP	3265-3580 BP
AS-VC-05	0.70-0.80	LF-3	ASDS-1	Organic-Rich Sed	6875-7170 BP	6755-7215 BP
AS-VC-08	3.98-4.03	LF-2	Pre-Holo	Organic-Rich Sed	N/A	N/A
AS-VC-10	0.15-0.25	LF-6	ASDS-2	Organic-Rich Sed	1945-2140 BP	1865-2315 BP
AS-VC-12	1.53-1.63	LF-3	ASDS-2	Organic-Rich Sed	4540-4835 BP	4435-4860 BP
AS-VC-12	2.82-2.87	LF-5	ASDS-2	Organic-Rich Sed	5920-6290 BP	5730-6420 BP
AS-VC-12	5.80-5.90	LF-5	ASDS-2	Organic-Rich Sed	5080-5115 BP or 5130-5170 BP or 5270-5330 BP or 5395-5445 BP	5020-5480 BP 5530-5565 BP
AS-VC-12	7.53-7.63	LF-3	ASDS-1	Organic-Rich Sed	6280-6420 BP	6185-6500 BP
AS-VC-12	8.45-8.50	LF-3	ASDS-1	<i>Crassostrea</i>	6460-6665 BP	6390-6740 BP
AS-VC-13	0.23-0.33	LF-6	ASDS-2	Organic-Rich Sed	1415-1570 BP	1350-1700 BP
AS-VC-13	1.53-1.63	LF-3	ASDS-2	Organic-Rich Sed	5325-5405 BP or 5440-5590 BP	5300-5635 BP
AS-VC-16	0.22-0.32	LF-6	ASDS-1	Organic-Rich Sed	6210-6240 BP or 6260-6420 BP	6090-6525 BP
AS-VC-16	2.15-2.25	LF-6	ASDS-1	Organic-Rich Sed	7160-7545 BP	6775-7770 BP
AS-VC-16*	4.02	LF-1B	ASDS-1	Wood	6855-6990 BP	6765-7025 BP
AS-VC-16	4.07-4.17	Pre-Holo	Pre-Holo	Organic-Rich Sed	N/A	N/A
AS-VC-18	0.18-0.28	LF-6	ASDS-2	Organic-Rich Sed	2840-2965 BP	2775-3070 BP
AS-VC-18	0.37	LF-5/LF-6	ASDS-2	<i>Crassostrea</i>	2570-2720 BP	2450-2750 BP
AS-VC-18	2.75-2.85	LF-4	ASDS-2	<i>Tegulus</i>	4125-4405 BP	3975-4525 BP
AS-VC-18	8.78-8.88	LF-3	ASDS-1	Organic-Rich Sed	7385-7515 BP	7295-7540 BP
AS-VC-23*	3.38-3.48	LF4	ASDS-2	<i>Cyrtopleura</i>	5485-5525 BP or 5570-5600 BP	5465-5615 BP
AS-VC-23	4.26-4.36	Pre-Holo	Pre-Holo	Organic-Rich Sed	N/A	N/A
AS-VC-25	1.40-1.50	LF-6	ASDS-2	Organic-Rich Sed	5315-5580 BP	5290-5610 BP
AS-VC-25	5.30-5.55	LF-4	ASDS-2	<i>Mercenaria</i>	3955-4095 BP	3885-4165 BP
AS-VC-25	6.95-7.05	LF-4	ASDS-2	<i>Cyrtopleura</i>	4975-5290 BP	4835-5440 BP
AS-VC-25	7.05-7.15	LF-3	ASDS-1	Organic-Rich Sed	7970-8140 BP	7930-8195 BP
AS-VC-25	8.35-8.45	LF-3	ASDS-1	Organic-Rich Sed	7530-7630 BP	7430-7685 BP
AS-VC-27	4.30-4.35	LF-2	ASDS-1	Peat	4950-4805 BP	5055-4750 BP

subjected to acid/alkali/acid washes or acid washes. Acid/alkali/acid washes consist of bathing the sample in hot acid (HCl) to remove carbonates, an alkali wash to eliminate any secondary organic acids, and a second acid wash to neutralize the solution. Samples that contained primary carbon that is soluble in alkali solutions underwent acid washes only. Calcareous shell material underwent HCl acid etches to remove any secondary carbonate material .

Samples measured by the standard radiocarbon technique were analyzed by synthesizing the sample carbon to benzene (92% C), measuring for ^{14}C content in a scintillation spectrometer, and calculating the radiocarbon age. AMS results were calculated by reducing the sample carbon to graphite (100% C), which was sent for ^{14}C measurement in an accelerator-mass-spectrometer. Radiocarbon ages are reported as calibrated ^{14}C years before present (present = 1950 AD) using the Pretoria Calibration Procedure (Vogel *et al.*, 1993). Errors represent 1 standard deviation statistics (68% probability) and are based on combined measurements of the sample, backgrounds, and modern standards.

Paleontological Observations

Paleontological evidence from macro- and microfossils provided information about salinity conditions and the depositional environment of each lithofacies. The macrofossils were identified utilizing Abbott (1974), and the modern habitat of each organism was obtained from Abbott (1974), Wilson (1979), Kirby-Smith (1973), and Stearns *et al.* (1989). Microfossils were identified to generic level by Dr. Scott Snyder, Department of Geology, and Dr. Vincent Bellis, Department of Biology, both from East

Carolina University. Microfossils were prepared for identification by wet sieving samples from the top, middle, and bottom of each channel complex and laminated sediment type through the 0.0 phi and 4.0 phi screens. Sediment retained on the 0.0 phi screen was transferred to a labeled container and retained for subsequent use, while material from the 4.0 phi screen was oven dried overnight at 45°C. The dried sediment sample was slowly emptied into a beaker containing carbon tetrachloride (CCl₄). The detrital sediment settled to the bottom of the beaker, while the hollow-chambered microfossils floated on the dense liquid. The liquid was decanted onto filter paper and the microfossils were recovered and identified.

Sedimentary Structures

Special attention was placed on the description of sedimentary structures within each lithofacies and contacts between depositional units, which were used to determine the processes of deposition and erosion for each lithofacies. Sedimentary structures were described and measured utilizing a binocular microscope and x-radiographs. X-radiographs show the fine detail and microfabrics within the laminated sediments. X-radiographs were provided by Dr. John Wells and Glenn Safrit of the University of North Carolina's Institute of Marine Science in Beaufort, North Carolina. Each sample was x-rayed at 90 kilovolts and 3.0 milliamps for 2.5 minutes.

SEISMIC STRATIGRAPHY

Interpreted, high-resolution seismic sections along A-A', B-B', and C-C' are depicted in Figures 6, 7, and 8. These data were utilized to characterize the numerous channel complexes and non-channelized framework of Albemarle Sound. Emphasis was

Figure 6: Interpreted high-resolution seismic profile along transect A-A'. The shallow subsurface (20 m) is characterized by numerous channel complexes that occur as isolated and multiple, stacked channel structures (See Section on Characterization of Channel Complexes). See Figure 3 for location of profile A-A'.

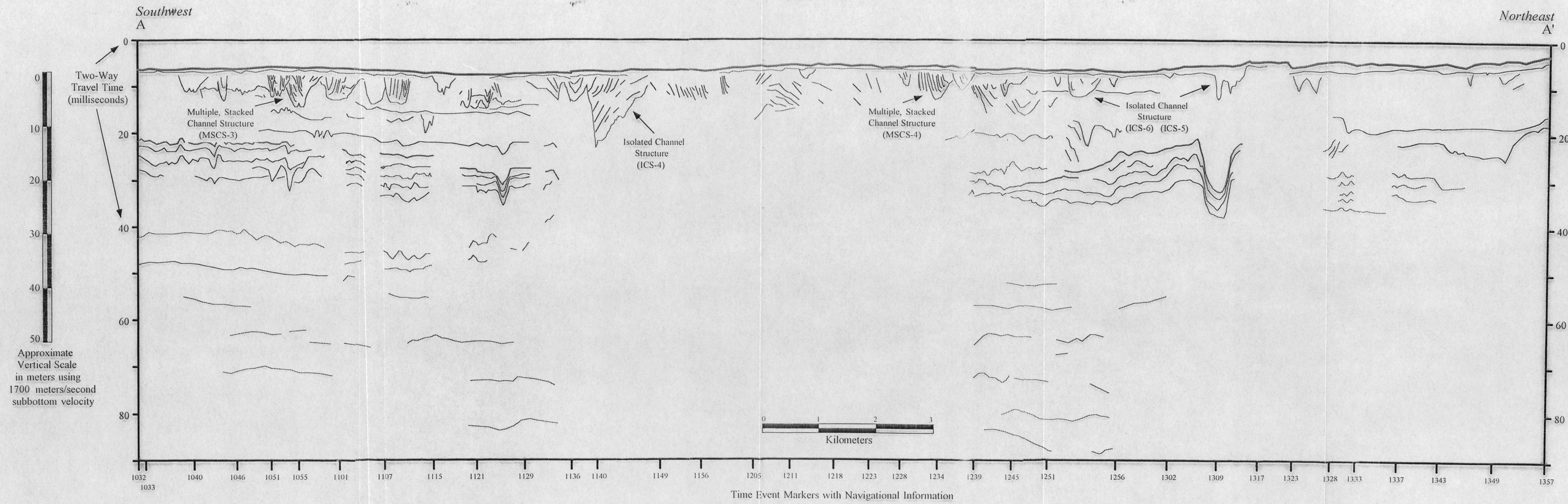


Figure 7: Interpreted high-resolution seismic profile along transect B-B'. The shallow subsurface (20 m) is characterized by numerous channel complexes that occur as isolated and multiple, stacked channel structures (See Section on Characterization of Channel Complexes). See Figure 3 for location of profile B-B'.

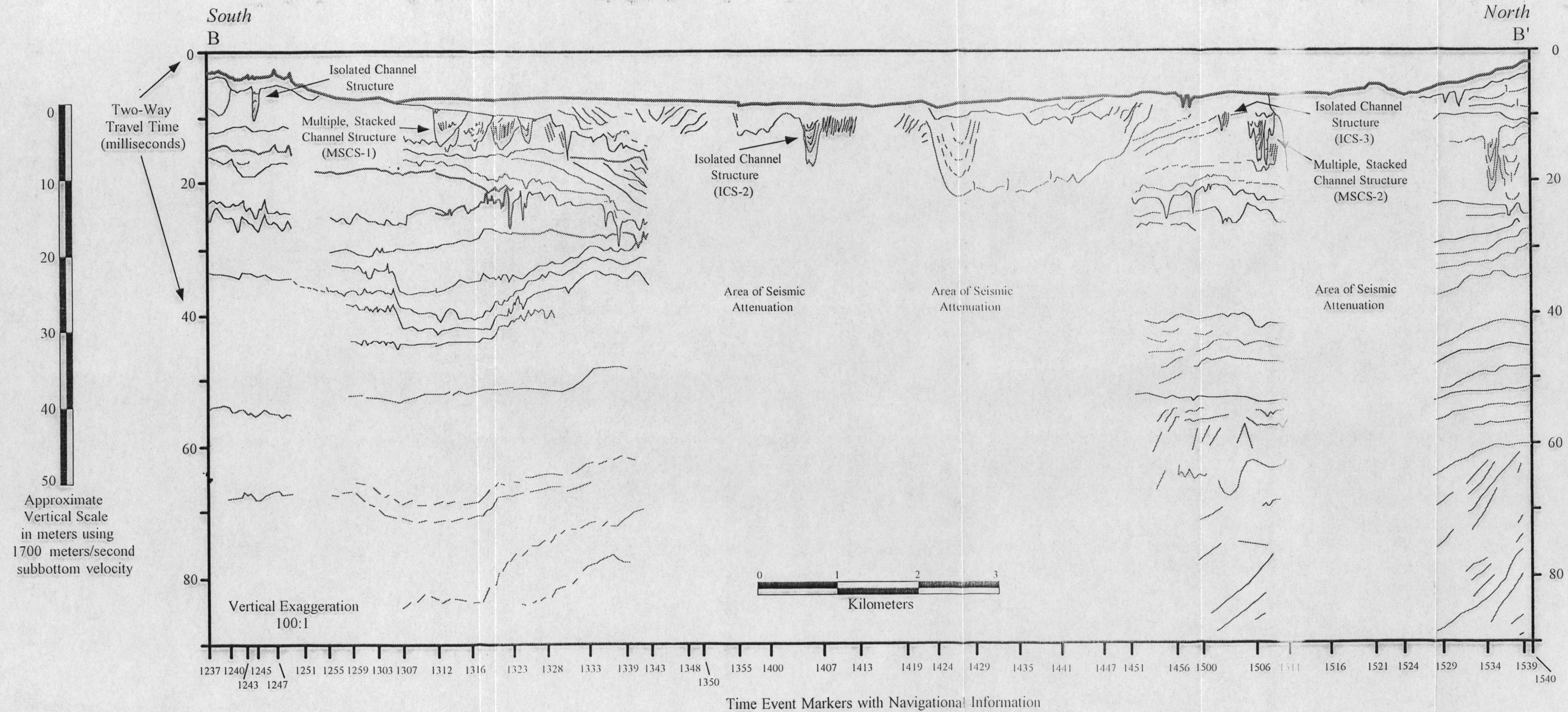
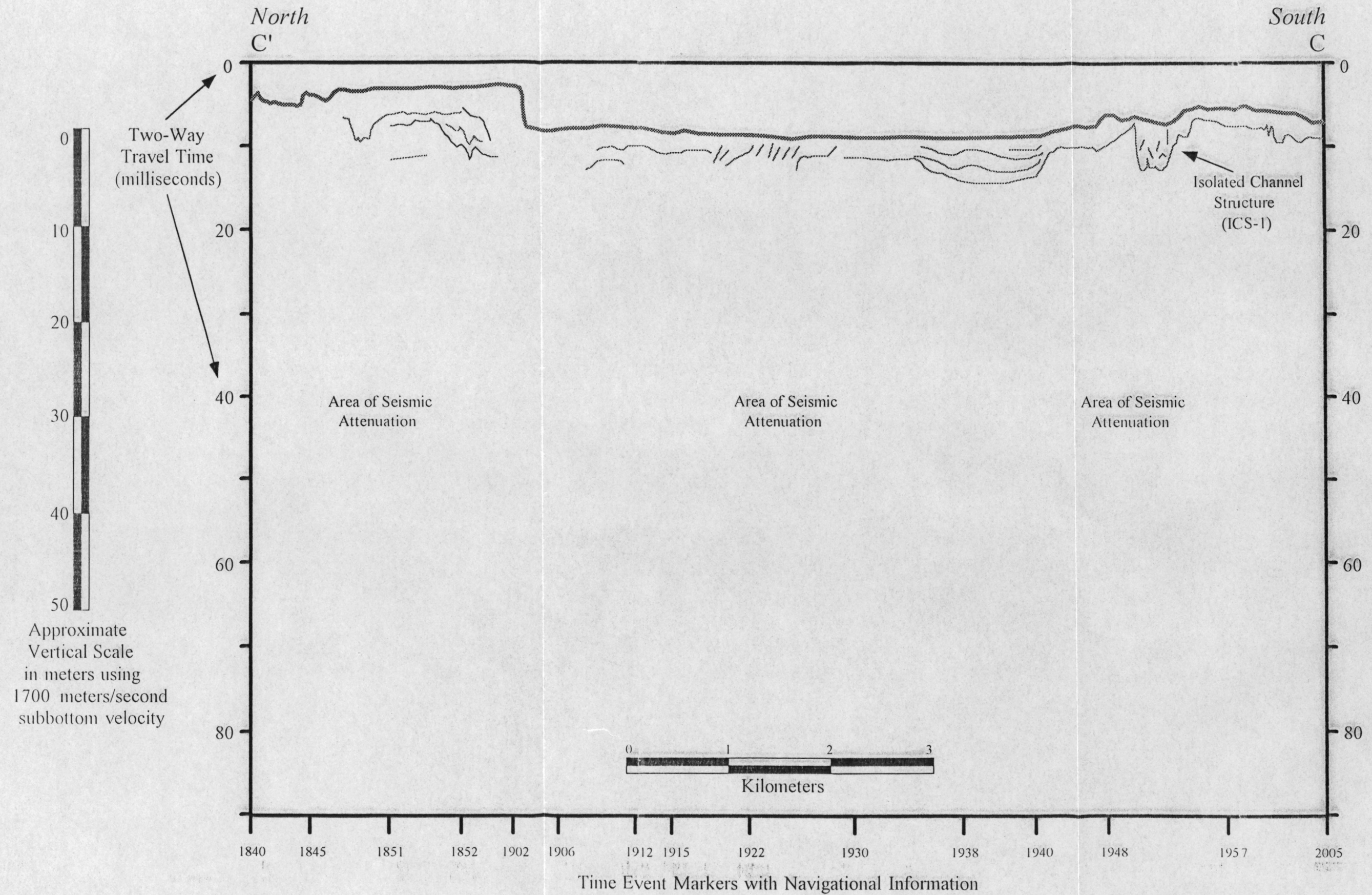


Figure 8: Interpreted high-resolution seismic profile along transect C-C'. The shallow subsurface (20 m) is characterized by numerous channel complexes that occur as isolated and multiple, stacked channel structures (See Section on Characterization of Channel Complexes). See Figure 3 for location of profile C-C'.



placed on the shallow subsurface (20 ms or 17 m) where the greatest resolution was obtained.

SEISMIC RESOLUTION

The horizontal and vertical resolution of seismic data are controlled by the firing rate of the seismic source, frequency of the seismic source, seismic velocity of the substrate, and boat speed. The resolution of the seismic data is further governed by the penetration of the seismic signal, which is dependent upon energy loss as the seismic signal propagates through the subsurface. In an estuarine setting, energy loss can be high, with the seismic signal being completely absorbed (“gorped out”) by fine-grained sediments. This phenomenon occurred frequently along profiles D-D’, E-E’, and F-F’ where no interpretable data were received; “gorp outs” also characterize most of profile C-C’ and portions of profile B-B’.

Horizontal Resolution

Horizontal resolution (HR) is determined by the firing rate, or number of trigger pulses emitted per second, and boat speed. It is calculated using the following formula:

$$\mathbf{HR = (Boat\ Speed)\ (1863\ m/knt)\ (hr/360\ sec)\ (Shot\ Spacing).}$$

Applying an average boat speed of 4 knots and a firing rate of 3 pulses per second, then the shot spacing of seismic data collected in Albemarle Sound is 0.690 m (Snyder, 1994). Based on the above calculation, the graphical representation of the 97 km of seismic track line is a result of over 140,000 vertical slices of seismic reflection data, which accounts for the detailed horizontal resolution and lateral continuity of data (Snyder, 1994).

Vertical Resolution

The vertical resolution (VR) is dependent upon the peak frequency of the seismic source and the seismic velocity of the substrate. Vertical resolution is calculated using the following equation:

$$VR = 1/4 [(V_p) / (f)]$$

where V_p = average seismic velocity in m/second and f = peak frequency in Hertz (Sheriff, 1977). Assuming an average seismic velocity of 1,700 m/sec for subsurface sediments in Albemarle Sound (Stephen Snyder, personal communication) and using 500 to 800 Hz as the known peak frequency of the EG&G UNIBOOM, then the vertical resolution is approximately 0.53 to 0.85 meters.

CHARACTERIZATION OF CHANNEL COMPLEXES

Interpreted seismic sections (Figures 6-8) reveal that the shallow subsurface of Albemarle Sound is dominated by numerous channel complexes that occupy 36% of the subsurface along A-A', 20 % along B-B', and 7% along C-C'. The channel complexes are incised into and truncate the underlying stratigraphy. Channel complexes are depicted in Figure 9-16 and have been subdivided into two categories: isolated channel structures (ICS; Figures 9-12) and multiple, stacked channel structures (MSCS; Figures 13-16). Each channel structure is characterized according to its morphology and the seismic facies of the infill sequence. Additional channel complexes may exist within the subsurface, but the resolution of the seismic data is not sufficient for further subdivisions.

Isolated Channel Structures (ICS)

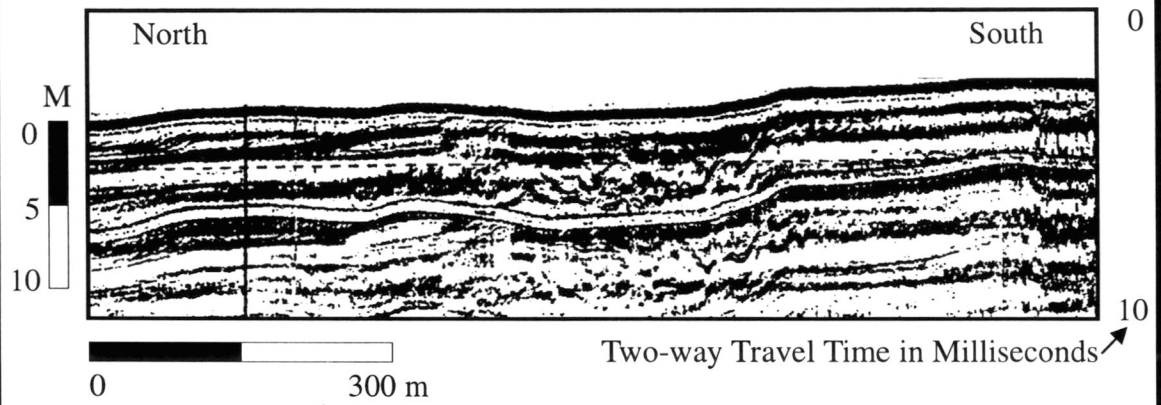
Isolated channel structures (ICS), which occur along each interpreted seismic profile, are characterized in Figures 9-12 and Table 2. These channel structures are commonly symmetrical, with average gradients along the northern and southern flanks of 0.06 m/m and 0.07 m/m, respectively. Most channels are 3-5 meters deep and vary in width from approximately 80 to nearly 850 meters. Seismic facies of the infill sequences are dominated by concave-up reflectors (Figures 10, 12, and 14), with some channels displaying chaotic (Figure 9) and planar inclined (Figure 11) reflectors.

Multiple, Stacked Channel Structures (MSCS)

Multiple, stacked channel structures (MSCS) occur along seismic profiles A-A' and B-B' (Figures 13-16). The morphology and seismic facies of these channel complexes are outlined in Table 3. The MSCS consists of several channels that are superimposed upon one another and display cross-cutting relationships. Channel complexes range from 600 to 1,420 meters in width with individual channels ranging from 160 to > 650 meters in width and 3-8 meters in depth. Individual channels range from broad structures with gently sloping flanks (Figures 13, 15, and 16) to narrow channels with steep slopes (Figure 14), and to channels displaying asymmetrical cross sections (Figure 13, 15, and 16). Seismic facies are variable, but commonly display planar inclined and concave-up reflectors (Figures 14-16). Some channels have seismic facies consisting of chaotic reflectors (Figure 13), while others have no internal reflectors (Figures 15 and 16).

Figure 9: (A) Raw seismic data along C-C'. See Figure 3 for location of profile C-C'.
(B) Interpreted high-resolution seismic section along C-C'. This profile depicts isolated channel structure-1 (ICS-1) which is approximately 600 meters wide and 5 meters deep, with an infill sequence characterized by chaotic seismic facies. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 8 for the location of ICS-1.

(A)



(B)

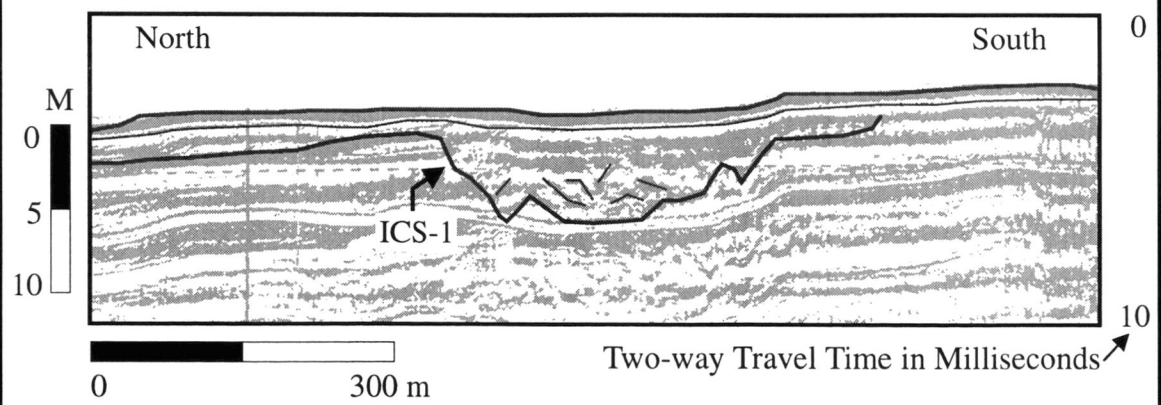


Figure 10: (A) Raw seismic data along B-B'. See Figure 3 for location of profile B-B'.
(B) Interpreted high-resolution seismic section along B-B'. This profile depicts isolated channel structure-2 (ICS-2) which is approximately 400 meters wide and 7 meters deep, with an infill sequence characterized by seismic facies with concave-up reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 7 for the location of ICS-2.

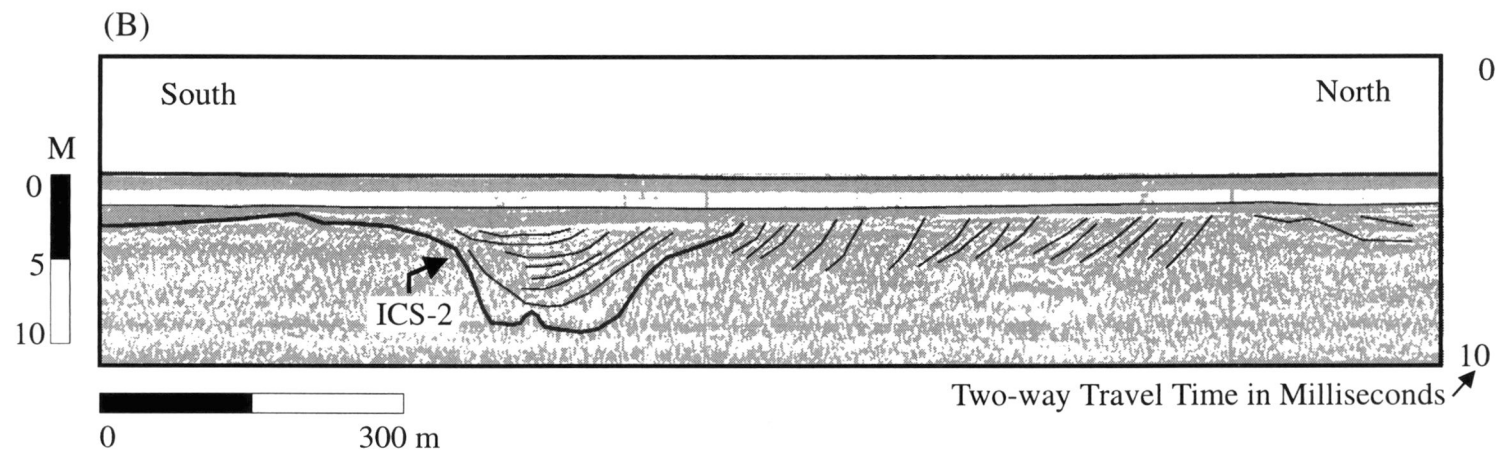
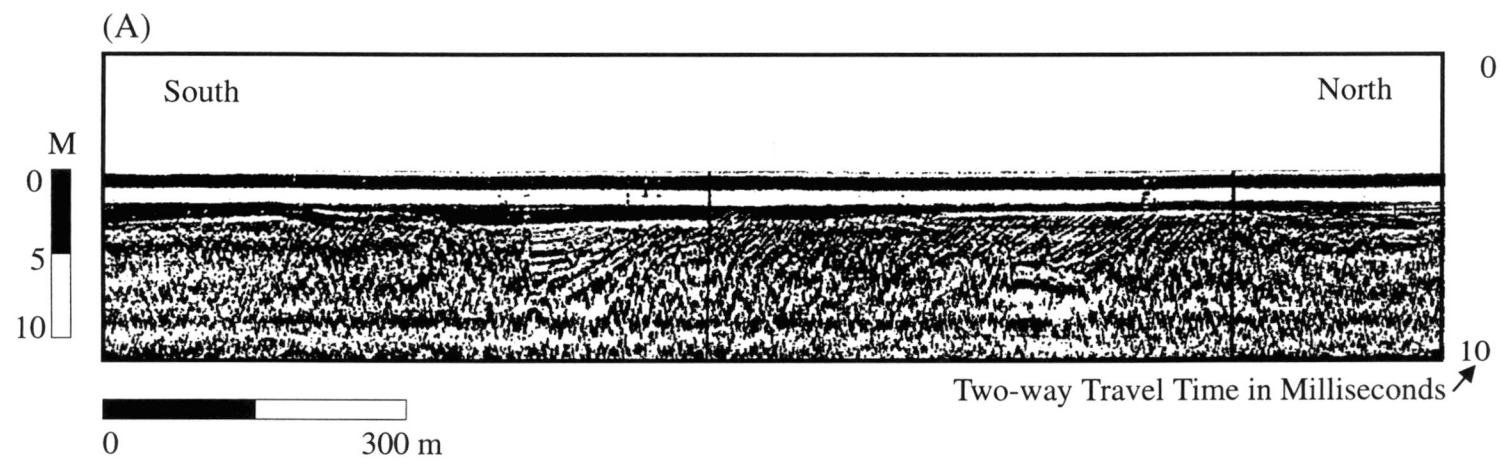


Figure 11: (A) Raw seismic data along A-A'. See Figure 3 for location of profile A-A'.
(B) Interpreted high-resolution seismic section along A-A'. This profile depicts isolated channel structure-4 (ICS-4) which is approximately 850 meters wide and 12 meters deep, with an infill sequence characterized by seismic facies with planar inclined reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 6 for the location of ICS-4.

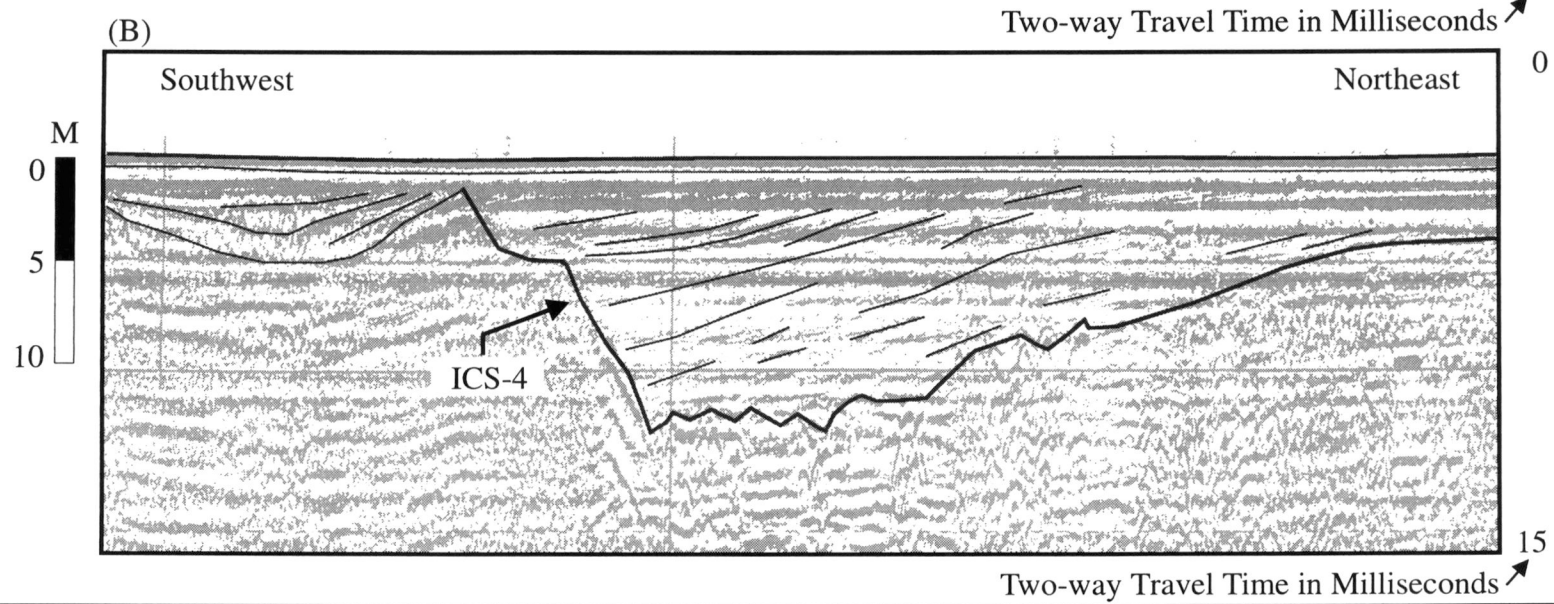
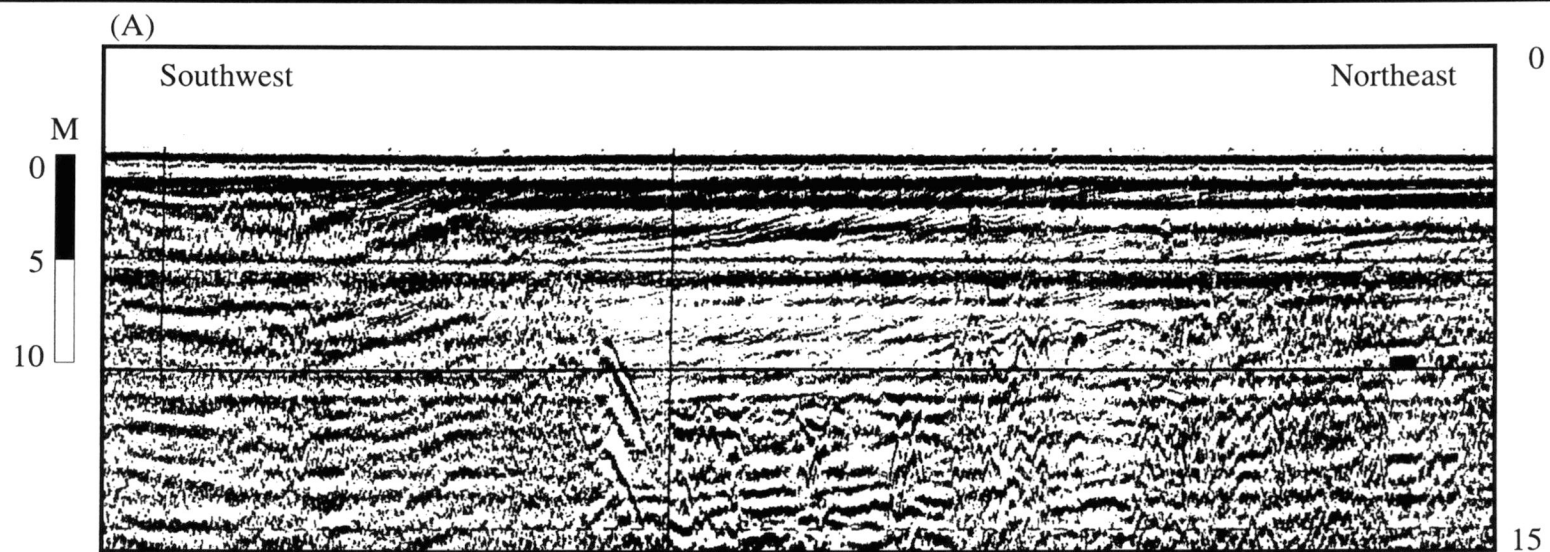
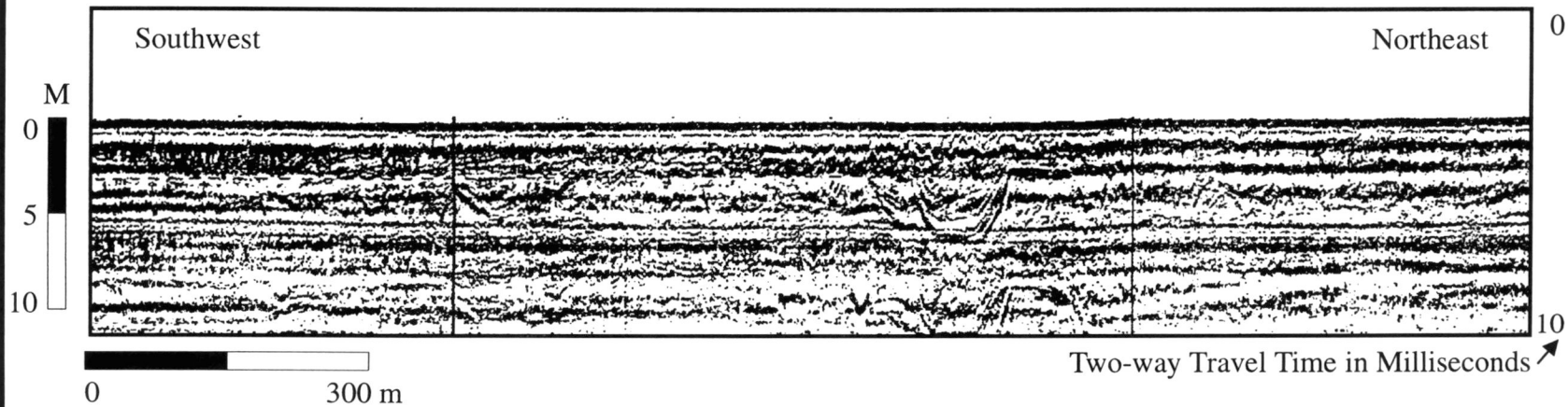


Figure 12: (A) Raw seismic data along A-A'. See Figure 3 for location of profile A-A'.
(B) Interpreted high-resolution seismic section along A-A'. This profile depicts isolated channel structure-5 (ICS-5) and isolated channel structure-6 (ICS-6) which are 350 meters wide and 4 meters deep and 100 meters wide and 5 meters deep, respectively. The infill sequence is characterized by seismic facies with concave-up reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 6 for the location of ICS-4 and ICS-5.

(A)



(B)

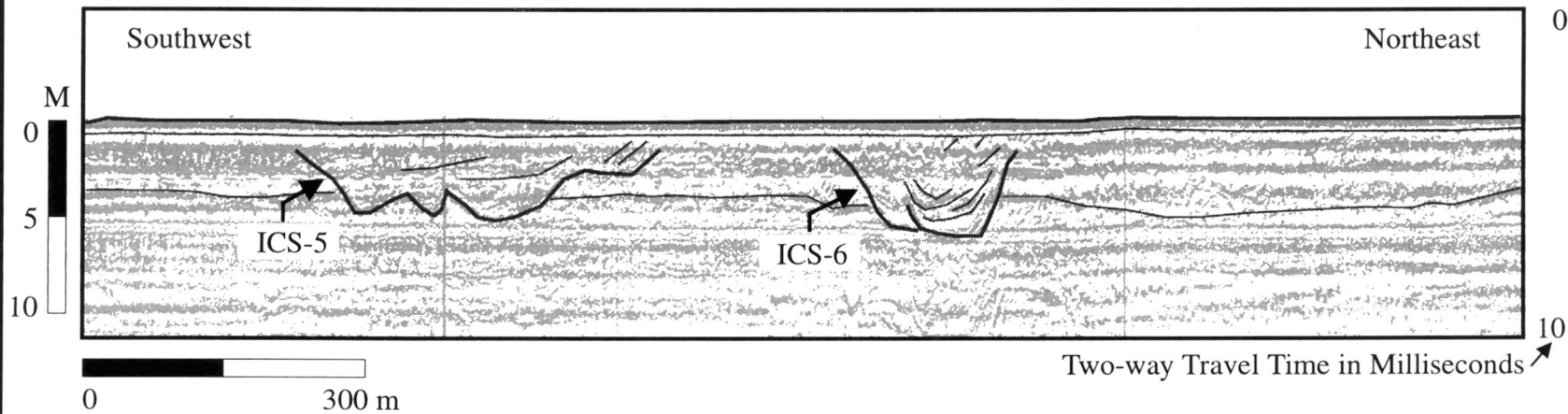


Table 2: Geometry and seismic facies of the isolated channel structures (ICS).

Channel Structure	Channel Width (m)	Channel Depth (m)	Gradient (m/m)		Seismic Facies
			Northern Flank	Southern Flank	
ICS-1	600	5	0.06	0.03	Chaotic Reflectors
ICS-2	400	7	0.07	0.08	Concave-up Reflectors
ICS-3	80	3	0.07	0.09	Concave-up Reflectors
ICS-4	850	12	0.02	0.09	Planar-dipping Reflectors
ICS-5	350	4	0.04	0.06	Concave-up Reflectors
ICS-6	100	5	0.11	0.09	Concave-up Reflectors

Figure 13: (A) Raw seismic data along B-B'. See Figure 3 for location of profile B-B'. (B) Interpreted high-resolution seismic section along B-B'. The profile depicts multiple, stacked channel structure-1 (MSCS-1) which is approximately 1,260 meters wide. MSCS-1A is 420 meters wide and 4 meters deep with no internal reflectors present within the channel, MSCS-1B is roughly 525 meters wide and 4 meters deep with an infill sequence characterized by chaotic seismic facies, and MSCS-1C is nearly 315 meters wide and 4 meters deep with an infill sequence characterized by seismic facies with steeply-dipping reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 7 for the location of MSCS-1.

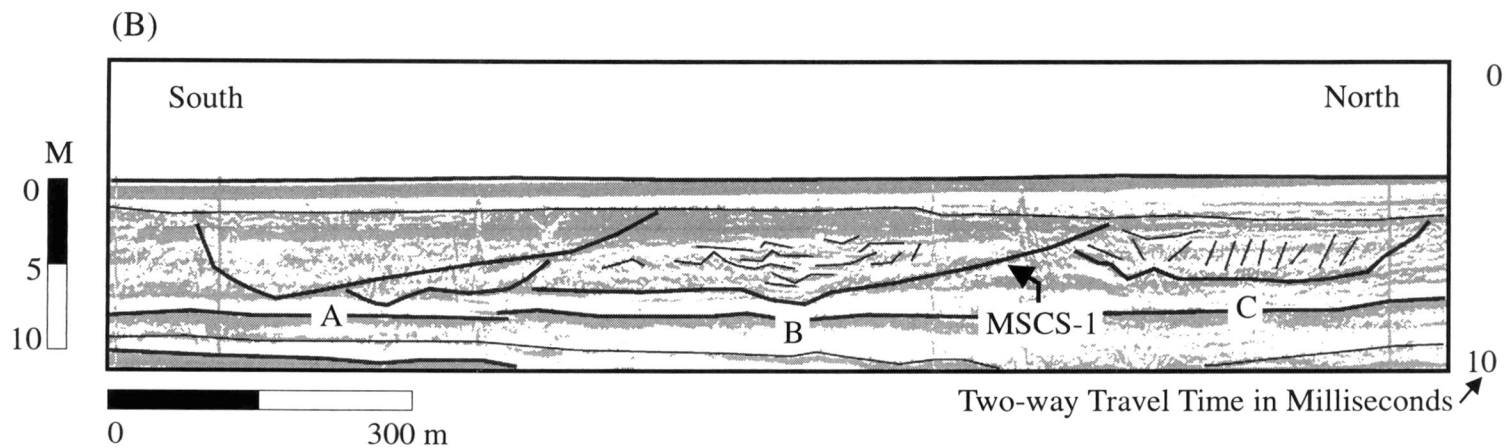
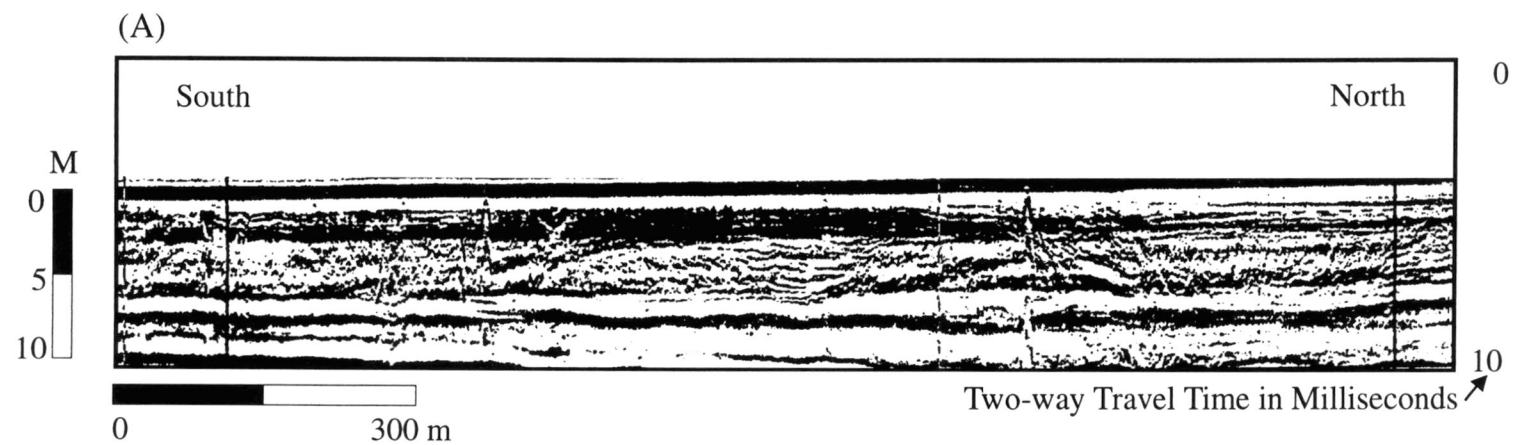


Figure 14: (A) Raw seismic data along B-B'. See Figure 3 for location of profile B-B'. (B) Interpreted high-resolution seismic section along B-B'. This profile depicts isolated channel structure-3 (ICS-3) and multiple, stacked channel structure-2 (MSCS-2). ICS-3 is approximately 80 meters wide and 3 meters deep with an infill sequence characterized by seismic facies with concave-up reflectors. MSCS-2A is 200 meters wide and 6 meters deep with infill sequence characterized by seismic facies with steeply-dipping and concave-up reflectors, MSCS-2B is roughly 160 meters wide and 6 meters deep with an infill sequence characterized by seismic facies with concave-up reflectors, and MSCS-2C is over 240 meters wide and 8 meters deep with no internal reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 7 for the location of ICS-3 and MSCS-2.

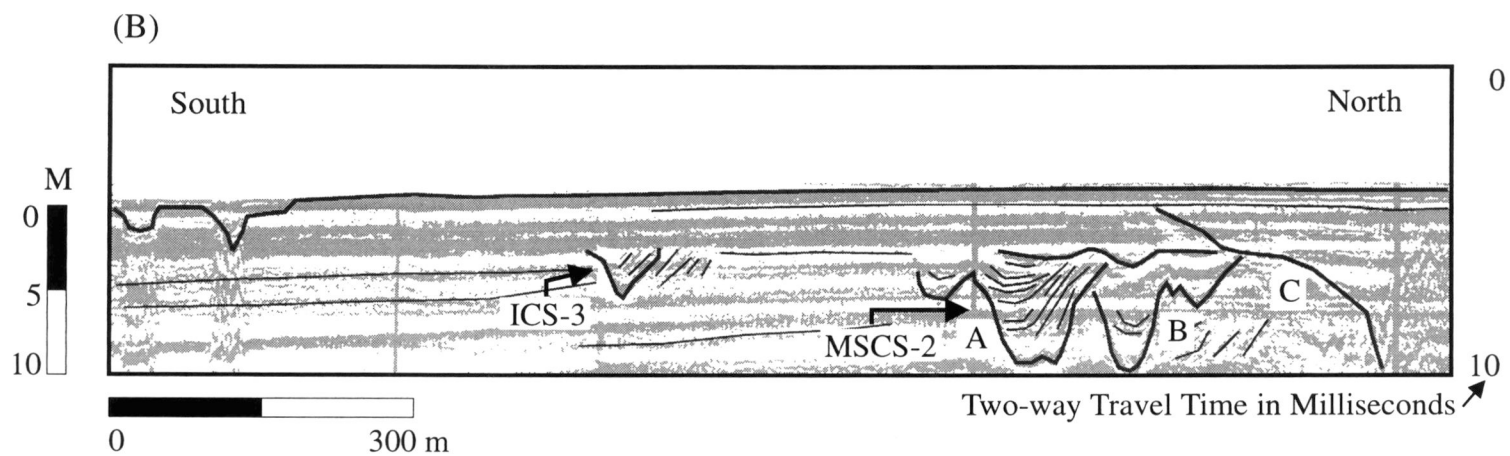
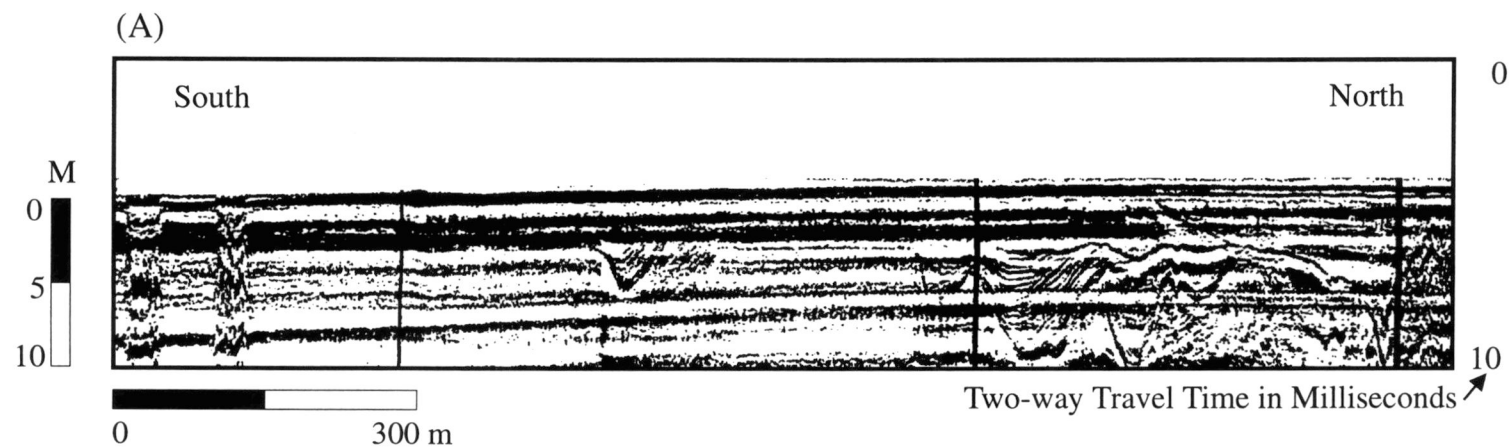


Figure 15: (A) Raw seismic data along A-A'. See Figure 3 for location of A-A'.
(B) Interpreted high-resolution seismic section along A-A'. This profile depicts multiple, stacked channel structure-3 (MSCS-3) which is > 1,420 meters wide. MSCS-3A is 440 meters wide and 5 meters deep with infill sequence characterized by seismic facies with concave-up reflectors, MSCS-3B is roughly 665 meters wide and 7 meters deep with infill sequence characterized by seismic facies with concave-up reflectors, and MSCS-3C is over 315 meters wide and approximately 4 meters deep with an infill sequence characterized by seismic facies with concave-up reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 6 for the location of MSCS-3.

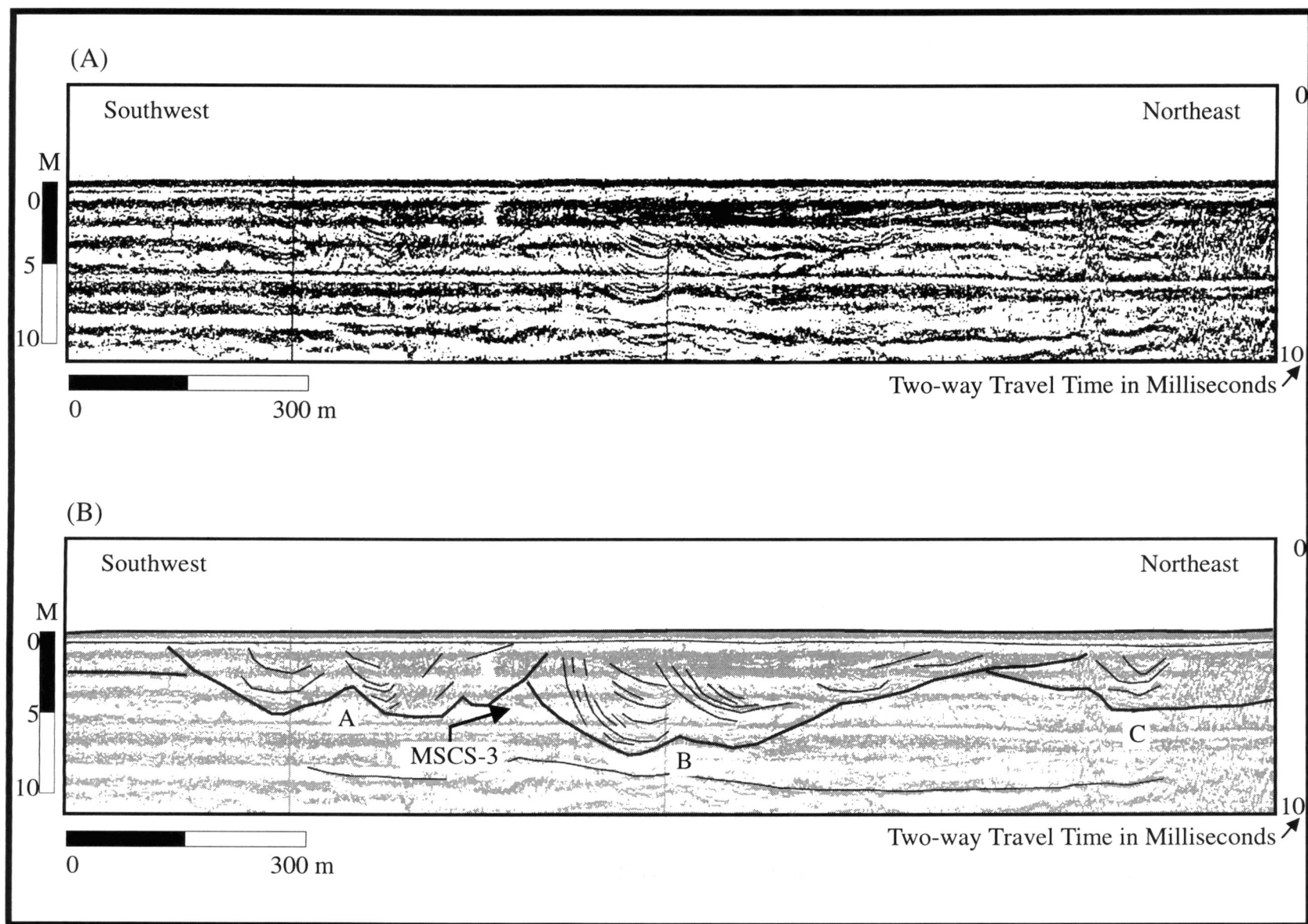


Figure 16: (A) Raw seismic data along A-A'. See Figure 3 for location of A-A'.
(B) Interpreted high-resolution seismic section along A-A'. This profile depicts multiple, stacked channel structure-4 (MSCS-4) which is approximately 785 meters wide. MSCS-4A is roughly 385 meters wide and 5 meters deep with an infill sequence characterized by seismic facies with concave-up reflectors, and MSCS-4B is nearly 400 meters wide and 3 meters deep with an infill sequence characterized by seismic facies with steeply-dipping internal reflectors. The vertical scale is approximated by assuming a subbottom velocity of 1700 meters/second. See Figure 6 for the location of MSCS-4.

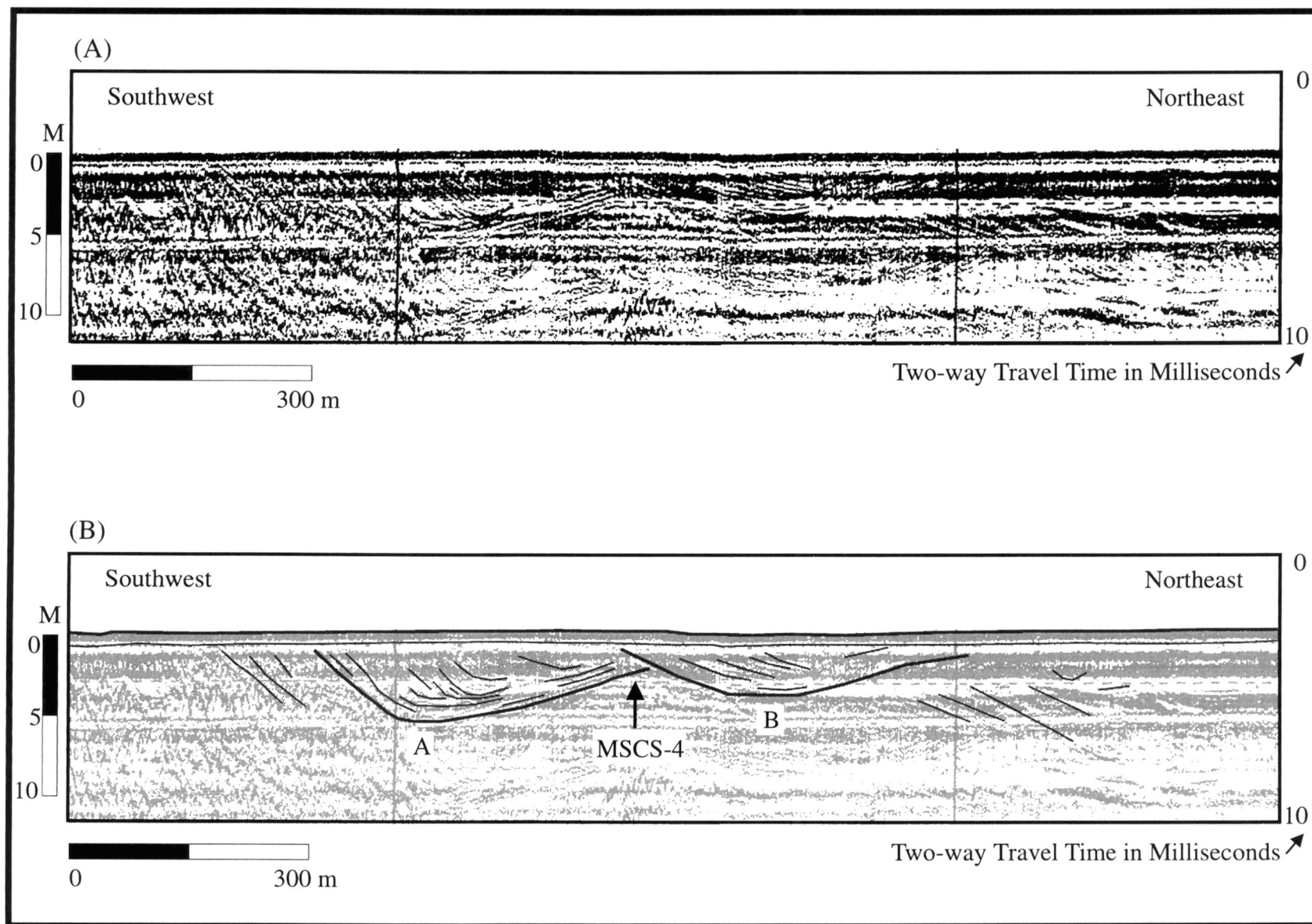


Table 3: Geometry and seismic facies of the multiple, stacked channel structures (MSCS).

Channel Structure	Structure Width (m)	Number of Channels	Channel Width (m)	Channel Depth (m)	Gradient (m/m)		Seismic Facies
					Northern Flank	Southern Flank	
MSCS-1	1260	3	420	4	0.02	0.09	No Reflectors
			525	4	0.02	N/A	Chaotic Reflectors
			315	4	0.04	0.05	Planar-dipping Reflectors
MSCS-2	>600	3	200	6	0.14	0.16	Planar-dipping and Concave-up Reflectors
			160	6	0.16	0.19	Concave-up Reflectors
			>240	8	N/A	0.05	No Reflectors
MSCS-3	>1420	3	440	5	0.06	0.05	Concave-up and Planar-dipping Reflectors
			665	7	0.02	0.05	Concave-up Reflectors
			>315	4	N/A	0.03	Concave-up Reflectors
MSCS-4	785	2	385	5	0.03	0.06	Concave-up Reflectors
			400	3	0.02	0.04	Planar-dipping Reflectors

CHARACTERIZATION OF NON-CHANNELIZED FRAMEWORK

The non-channelized framework of Albemarle Sound is characterized by nearly horizontal and planar inclined reflectors. In the shallow subsurface (20 ms or 17 m), the horizontal reflectors are discontinuous and rarely persist for more than 3 to 5 kilometers. Horizontal reflectors occur more frequently at depths greater than 17 m and extend over greater distances. Inclined reflectors are more common in the shallow subsurface where they are steeply dipping, discontinuous, and frequently occur adjacent to channel complexes. At depth, the angle of inclination decreases, and the reflectors extend further laterally.

LITHOSTRATIGRAPHY

LITHOFACIES

Vibracores were placed within and between channel complexes to determine the lithostratigraphic framework of Albemarle Sound. Lithologic logs (Appendix A) and cross-sections (Figures 17, 18, and 19) reveal that the Holocene sediments of Albemarle Sound are composed of 6 lithofacies (LF) summarized in Table 4: Quartz-rich sand (LF-1); Peat (LF-2); Laminated mud (LF-3); Fossiliferous, muddy sand (LF-4); Interlaminated mud and sand (LF-5); and Organic-rich mud (LF-6).

Channel Sand (LF-1)

A fine- to medium-grained sand lithofacies (LF-1) backfills channel complexes along B-B' and C-C' at various depths beneath the sediment-water interface (Figures 17 and 18). Variations in grain size, sedimentary structures, and paleontological evidence have been utilized to divide LF-1 into 2 subfacies: LF-1A and LF-1B.

Figure 17: Lithologic cross-section along profile B-B'. See Figure 3 for location of B-B'. Dashed lines represents inferred lithologic boundaries.

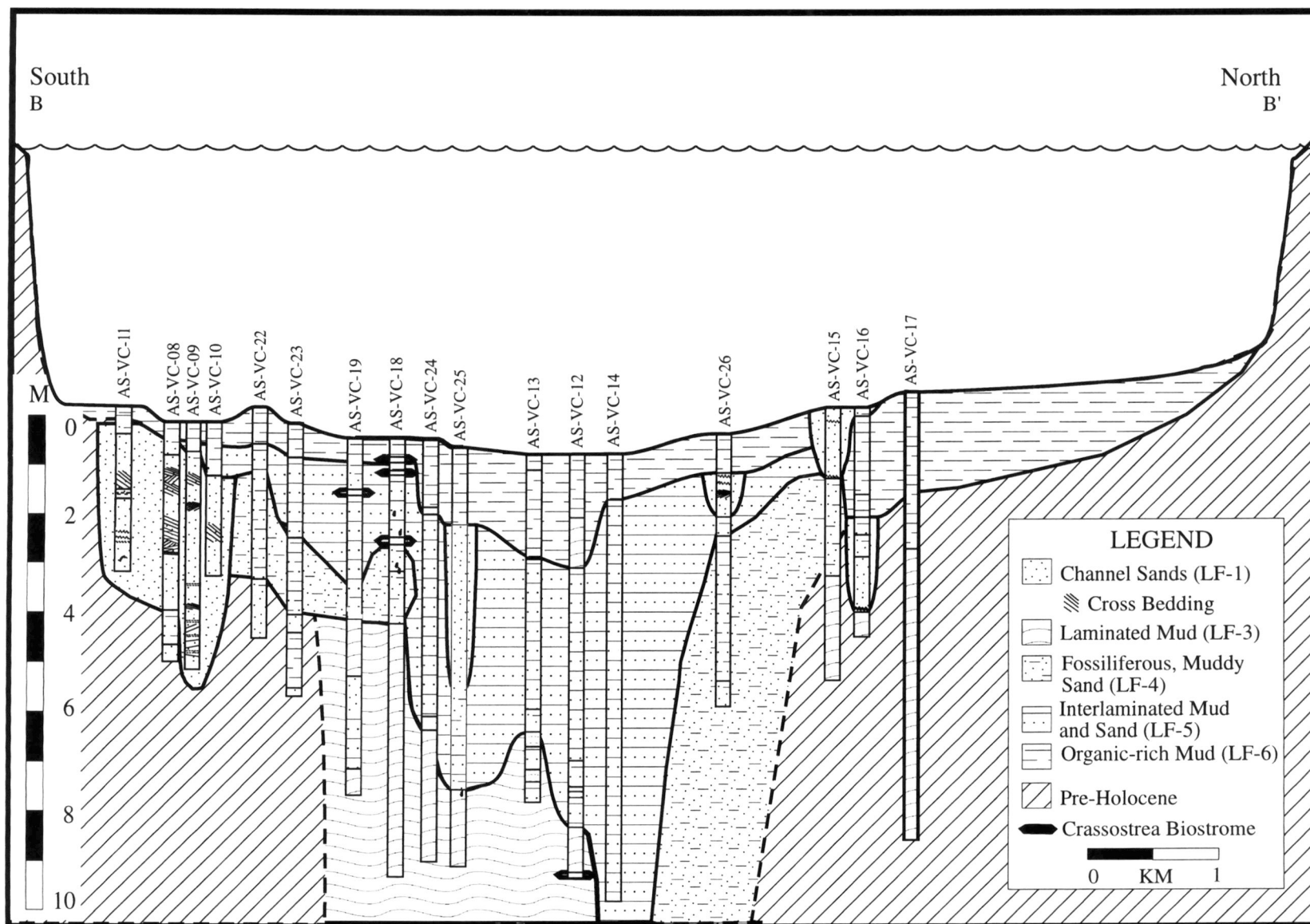


Figure 18: Lithologic cross-section along profile C-C'. See Figure 3 for location of C-C'.

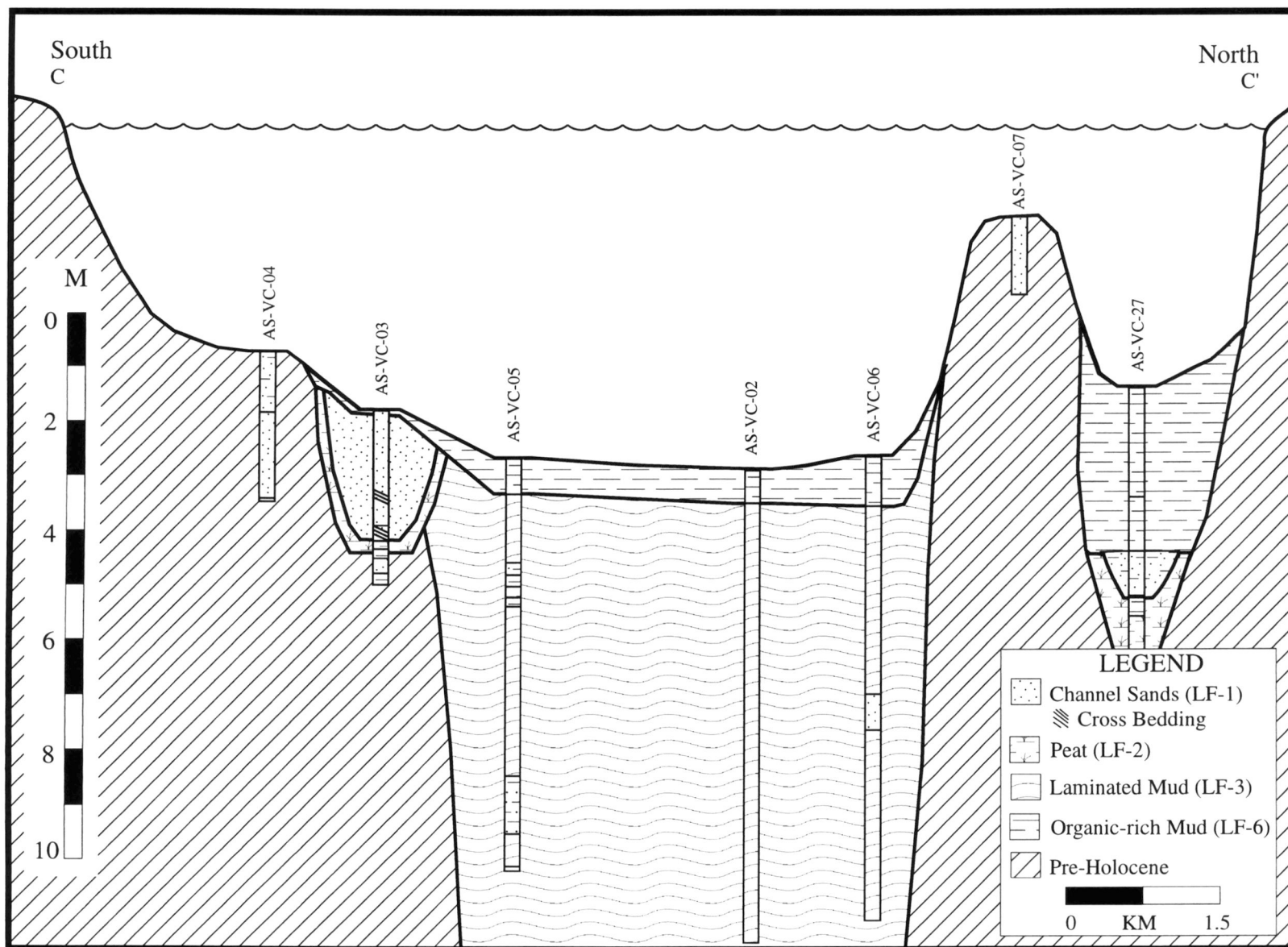


Figure 19: Lithologic cross-section parallel to the axis of Albemarle Sound. See Figure 3 for location of vibracore samples. Dashed lines represent inferred lithologic boundaries.

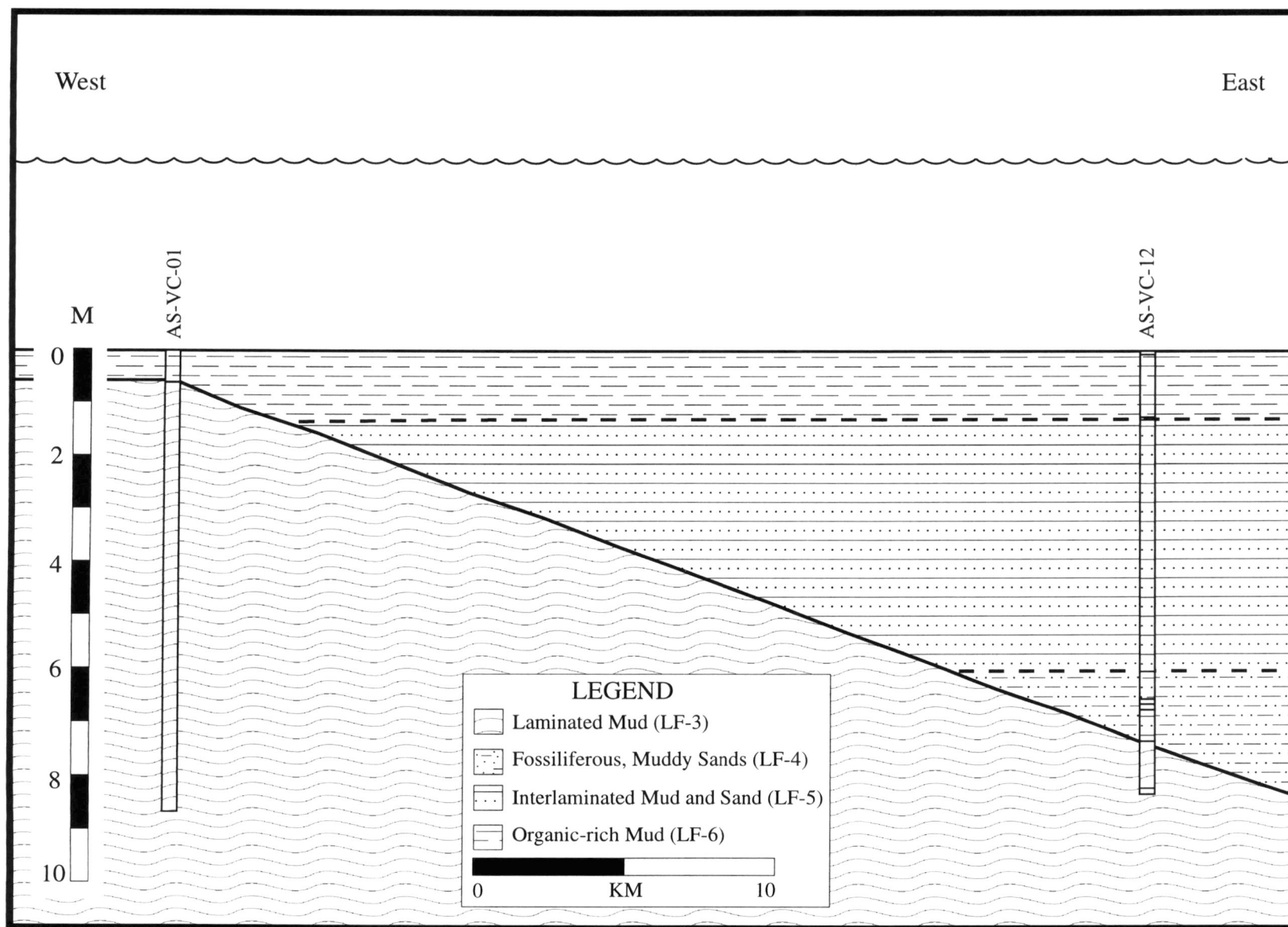


Table 4: Summary of the lithofacies that compose the Holocene section of the middle- and outer-Albemarle Sound, North Carolina and their sedimentologic characteristics.

Lithofacies	Description	Sedimentary Structures	Fauna	Dep. Env. (Salinity)
Quartz Sand LF-1A	Very fine- to fine-grained, quartz sand	Mud laminae	<i>Campylodiscus</i> <i>Elphidium</i>	Tidal Channel (Meso- to Polyhaline)
Quartz Sand LF-1B	Fine- to medium-grained quartz sand	Heavy mineral cross laminae	Absent	Fluvial Channel (Infrahaline)
Peat LF-2	Dark brown to black mud and organic detritus composed of plant fragments and wood	None	Absent	Swamp Forest (Infrahaline)
Laminated Mud LF-3	Laminae of very fine- to fine- grained sand within an organic- rich mud	Lenticular bedding	<i>Crassostrea</i> <i>Macoma</i> <i>Mulinia</i>	Restricted/Inner Estuary (Mesohaline)
Fossiliferous, Muddy Sand LF-4	Fossiliferous, muddy, fine- to medium-grained sand	Bioturbated	<i>Crassostrea</i> <i>Cyrtopleura</i> <i>Ensis</i> <i>Mercenaria</i> <i>Mulinia</i> <i>Tagelus</i> <i>Urosalpinx</i>	Tidal Flats in an Open Estuary (Polyhaline)
Interlaminated Mud and Sand LF-5	Laminae of mud and very fine- to fine-grained sand	Flaser bedding	<i>Crassostrea</i> <i>Cyrtopleura</i> <i>Macoma</i> <i>Mulinia</i> <i>Tagelus</i>	Shoal Complex in an Open Estuary (Polyhaline)
Organic-Rich Mud LF-6B	Loose sediment with elevated heavy metal concentrations	Homogenous	<i>Macoma</i> <i>Rangia</i>	Closed Estuary (Infra- to Oligohaline)
Organic-Rich Mud LF-6A	Dense sediment with low heavy metal concentrations	Homogenous	<i>Macoma</i>	Closed Estuary (Infra- to Oligohaline)

Sedimentologic and paleontologic evidence indicate that sediments of LF-1A were deposited in tidal channels. LF-1A is characterized by slightly muddy, very fine- to fine-grained, quartz sand (Table 5) with mud laminae ranging in thickness from 1-3 mm (Figure 20). The bedding is similar to flaser bedding and is indicative of deposition resulting from tidal processes (Reineck and Wunderlich, 1968; and Reineck and Singh, 1980). Mud is deposited by flocculation during quiescent conditions, and sand is transported and deposited as current ripples during high-energy events (Reineck and Wunderlich, 1968; and Reineck and Singh, 1980). Channels backfilled with LF-1A contain abundant high-brackish water microfossils dominated by either *Elphidium* or *Campylodiscus*. This supports the interpretation that LF-1A was deposited in tidal channels with salinity conditions ranging from meso- to polyhaline.

LF-1B is characterized by clean, fine- to medium-grained, quartz sand (Table 6) that contains no microfossils. LF-1B has uniform, planar-type cross-bedding (Figure 21) with occasional mud drapes (Figure 22) that are associated with point bar deposits (Reineck and Singh, 1980). LF-1B also contains convoluted laminae (Figure 24) that suggest high flow regimes and soft sediment deformation common in fluvial systems.

Peat (LF-2)

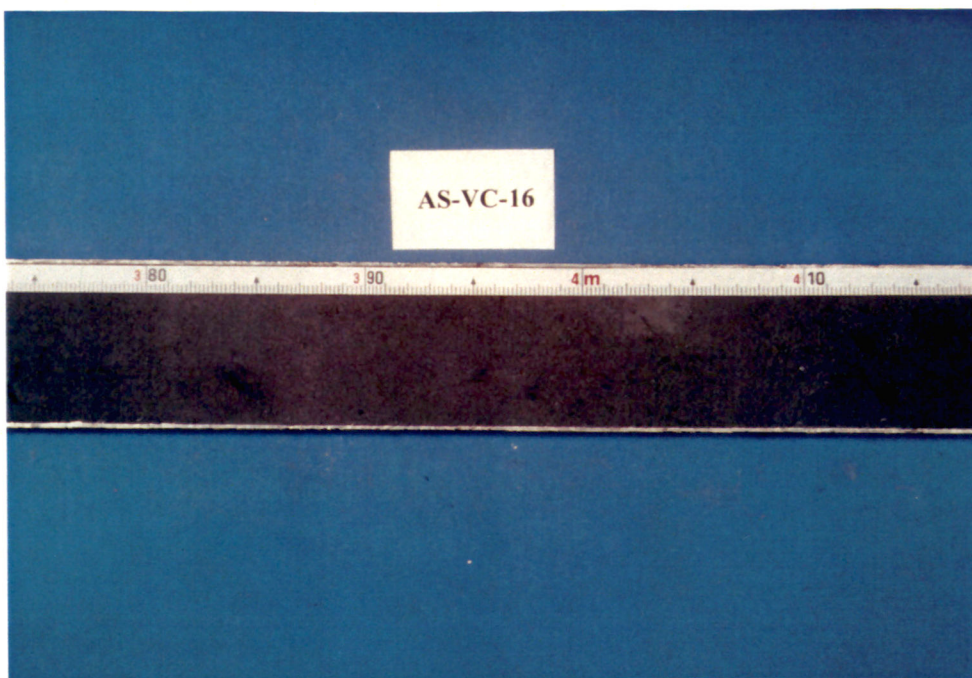
A muddy, dark brown to black peat (LF-2; Figure 23) ranges in thickness from 0.20-0.80 meters and occurs beneath channel complexes in two cores along C-C' (Figure 18). LF-2 is associated with fluvial sediments (LF-1B) and was deposited in swamp-forest floodplains that fringed these fluvial environments.

Table 5: Summary of grain size analyses from LF-1A.

Lithofacies	Core Number	Depth (m)	Weight Percentage			
			Medium Sand	Fine Sand	V. Fine Sand	Mud
LF-1A	AS-VC-16	2.50-2.55	31.2	30.0	18.8	20.0
LF-1A	AS-VC-16	3.25-3.30	62.7	26.2	5.9	5.1
LF-1A	AS-VC-16	3.75-3.80	26.1	41.0	26.1	6.8
LF-1A	AS-VC-16	MEAN	40.0	32.4	16.9	10.6
LF-1A	AS-VC-25	1.65-1.70	0.4	41.9	51.1	6.6
LF-1A	AS-VC-25	3.15-3.20	0.4	26.5	61.4	11.7
LF-1A	AS-VC-25	4.80-4.85	0.4	27.1	63.2	9.2
LF-1A	AS-VC-25	MEAN	0.4	31.9	58.6	9.2
LF-1A	AS-VC-29	0.25-0.30	2.3	47.3	43.7	6.7
LF-1A	AS-VC-29	1.75-1.80	5.1	72.7	17.7	4.5
LF-1A	AS-VC-29	3.75-3.80	25.2	52.6	15.4	6.8
LF-1A	AS-VC-29	MEAN	10.9	57.6	25.6	6.0
LF-1A		MEAN	17.1	40.6	33.7	8.6

Figure 20: Photograph of the quartz sand lithofacies (LF-1A) from AS-VC-16 (A) and AS-VC-25 (B). Note the mud laminae that are dispersed throughout this lithofacies in AS-VC-25. See Figure 3 for the location of vibracores.

(A)



(B)

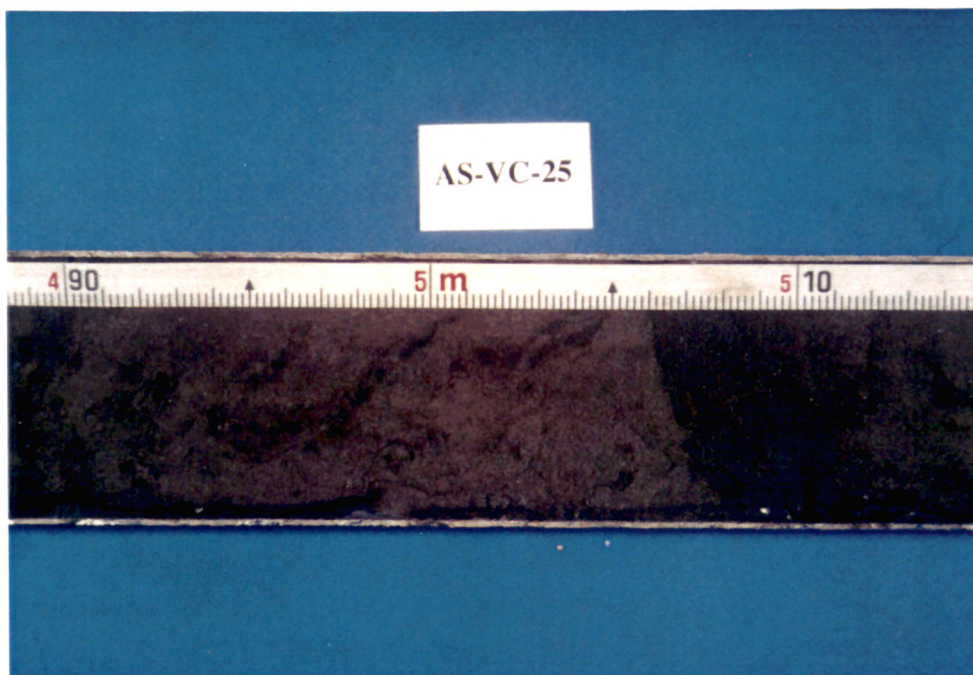
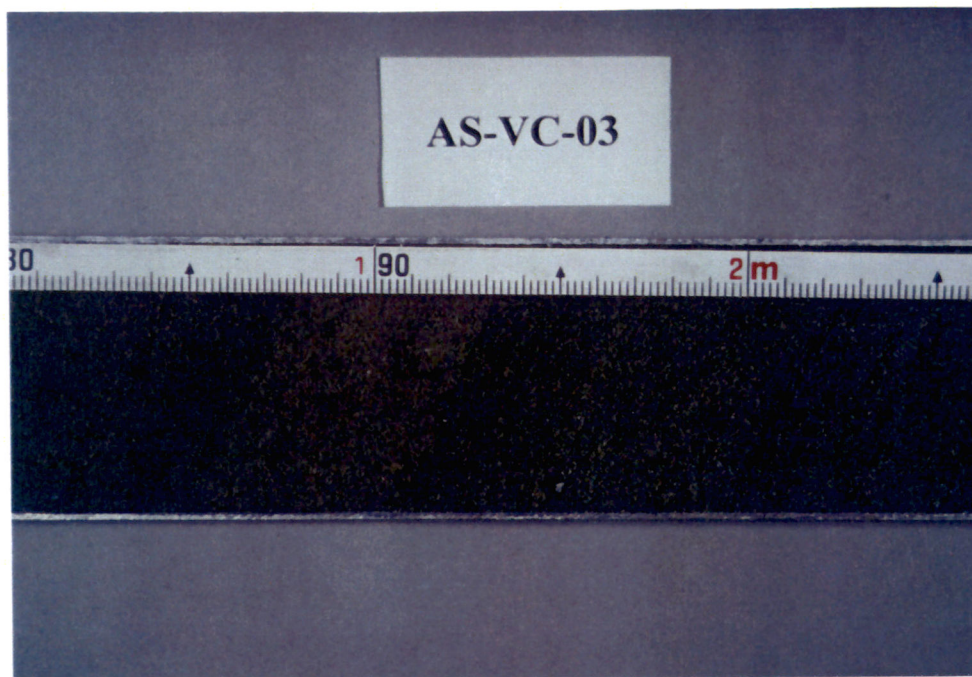


Table 6: Summary of grain size analyses from LF-1B.

Lithofacies	Core Number	Depth (m)	Weight Percentage			
			Medium Sand	Fine Sand	V. Fine Sand	Mud
LF-1B	AS-VC-08	0.75-0.80	16.9	62.5	13.8	6.8
LF-1B	AS-VC-08	2.10-2.15	38.5	52.6	5.6	3.4
LF-1B	AS-VC-08	3.60-3.65	33.7	46.0	16.3	4.0
LF-1B	AS-VC-08	MEAN	29.7	53.7	11.9	4.7
LF-1B	AS-VC-03	0.50-0.55	62.9	30.3	4.5	2.3
LF-1B	AS-VC-03	1.50-1.55	75.0	22.3	1.8	1.0
LF-1B	AS-VC-03	2.30-2.35	78.63	19.39	1.11	0.83
LF-1B	AS-VC-03	MEAN	72.2	24.0	2.5	1.4
LF-1B		MEAN	50.9	38.8	7.2	3.0

Figure 21: Photograph of the quartz sand lithofacies (LF-1B) from AS-VC-03 (A) and AS-VC-09 (B). Note the planar, cross laminations of heavy minerals in these samples. See Figure 3 for the locations of the vibracores.

(A)

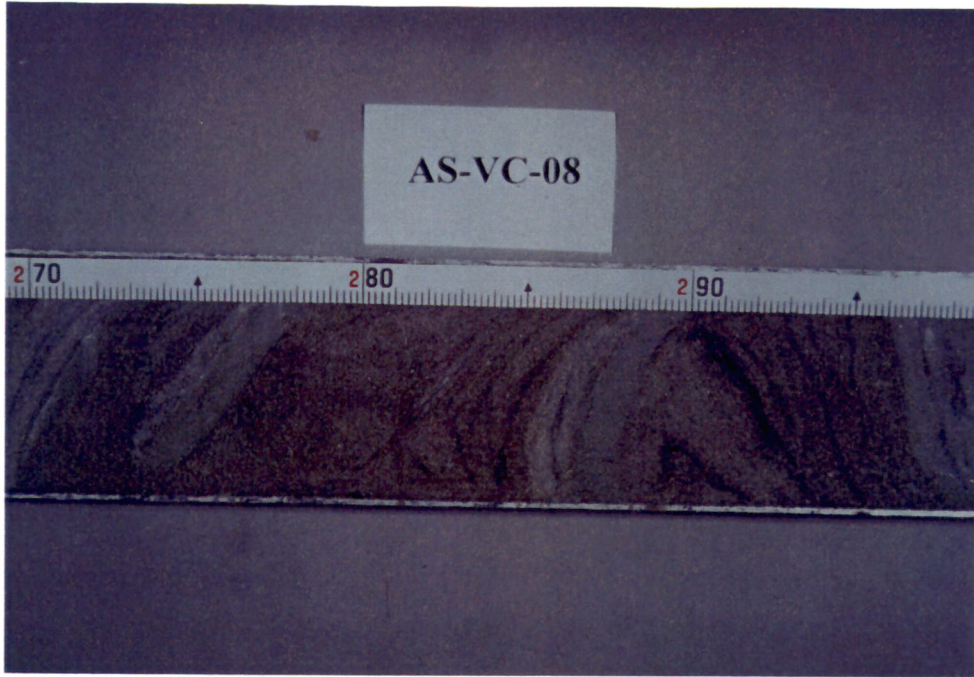


(B)



Figure 22: Photograph of the quartz sand lithofacies (LF-1B) from AS-VC-08 (A) and AS-VC-11 (B). Note the mud drapes above heavy mineral laminations in AS-VC-08 and the convoluted structures in AS-VC-11. See Figure 3 for the locations of the vibracores.

(A)



(B)

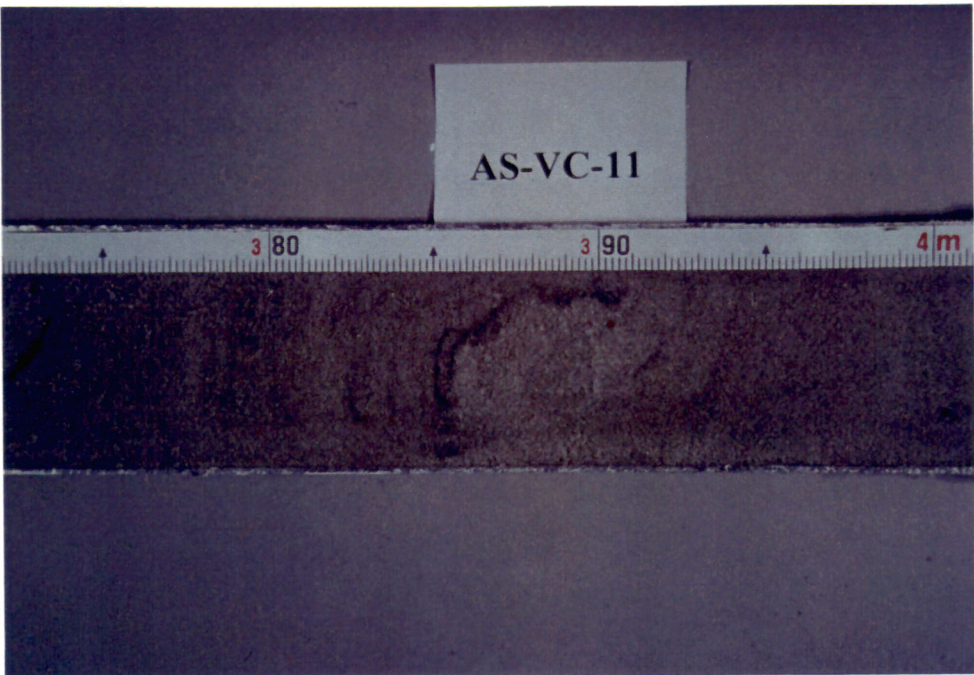
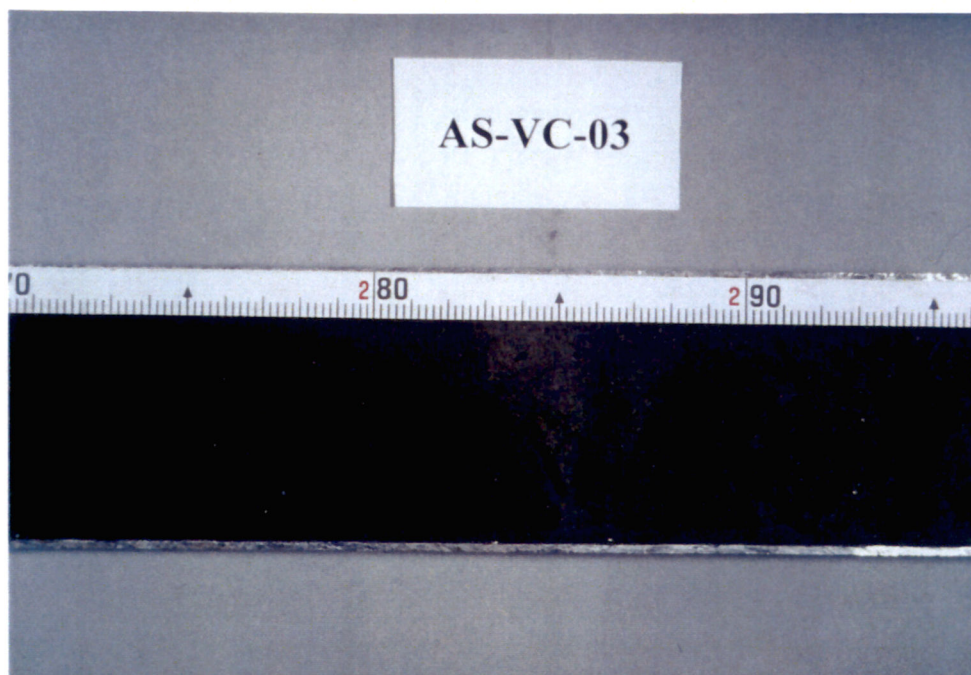
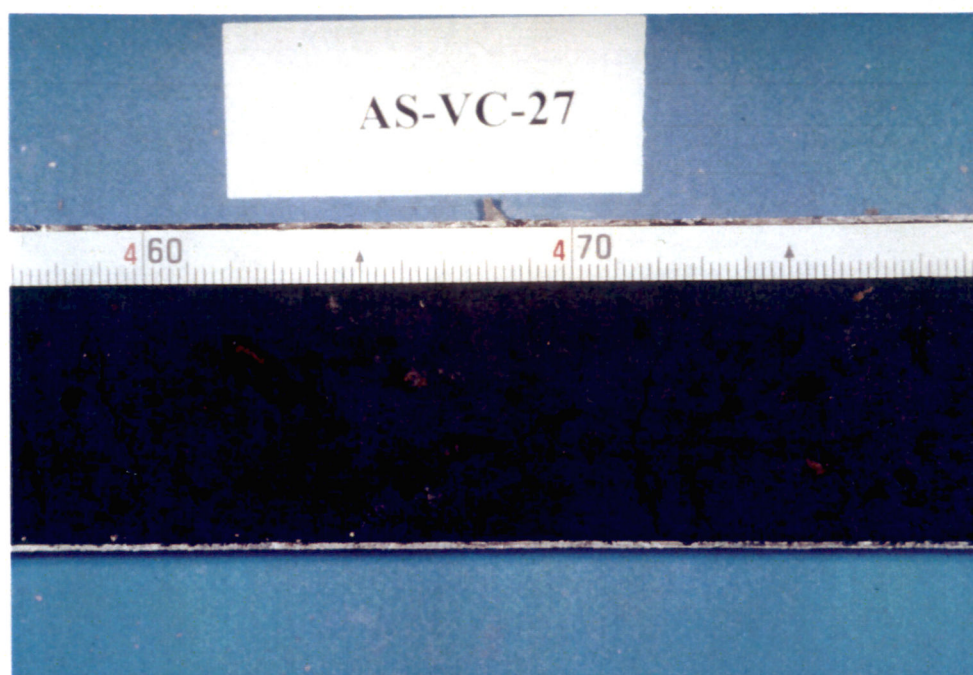


Figure 23: Photograph of the peat lithofacies (LF-2) from AS-VC-03 (A) and AS-VC-27 (B). See Figure 3 for the location of vibracores.

(A)



(B)



Laminated Mud (LF-3)

The laminated mud (LF-3) is stratigraphically the lowermost lithofacies (Figures 19-21). LF-3 is characterized by laminae of muddy, very fine-grained sand (Table 7) embedded in a mud matrix (Figure 24) and is similar to lenticular or coarsely interlayered bedding where “thicker mud layers alternate with relatively thin sand layers” as described by Reineck and Singh (1980). Such depositional patterns typically occur in subtidal- and intertidal-zones where “a change takes place between slack water and water turbulence” and where mud is available to the system (Reineck and Wunderlich, 1968). X-radiographs reveal that contacts between the sand and mud layers are sharp (Figure 25) and individual layers are uniform. The mean thickness of sand and mud layers of LF-3 is 3.0 and 18.3 mm, respectively, and the sand:mud ratio is 0.17 (Table 8). The fauna within the laminated mud lithofacies are dominated by articulated and disarticulated *Macoma* and *Mulinia*. Today, these organisms occur extensively in the Neuse and Pamlico Rivers and the western Pamlico Sound (Figure 1) (Stearns *et al.*, 1989) which are dominated by fine-grained sediments (Katuna, 1974) and mean annual salinity conditions of 7.5-15.7 ppt. (Williams *et al.*, 1973). This suggests that LF-3 was deposited in a similar environment under mesohaline conditions (3.0-16.5 ppt).

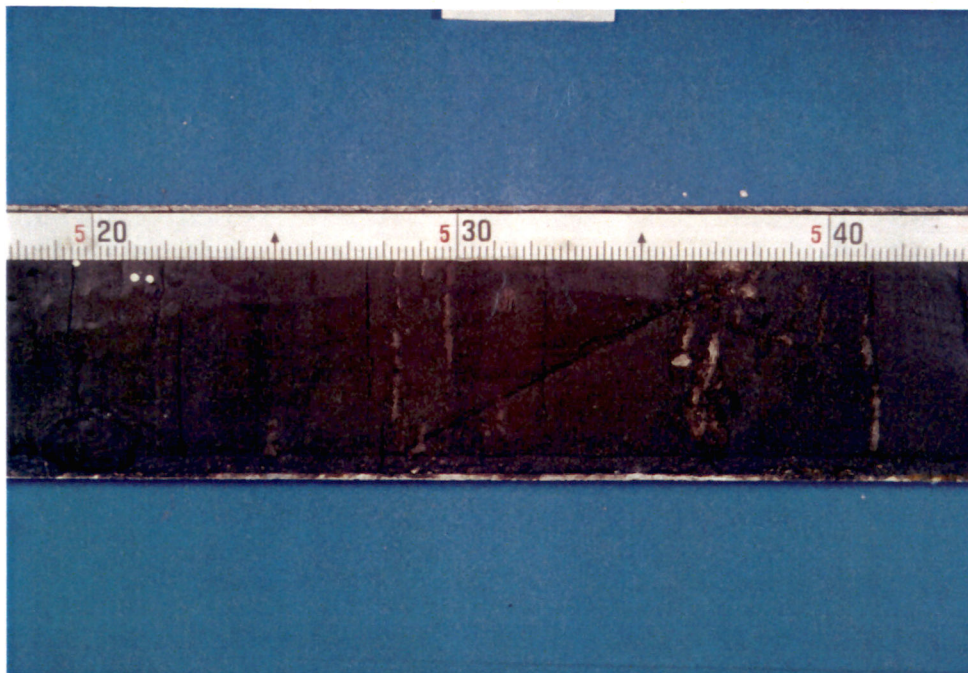
Multiple hypotheses exist for the development of the laminated mud lithofacies and include two major processes: 1) tidal currents and waves, or 2) settlement of suspended sediment derived from shoreline erosion during storm events. Each process produces a characteristic geometry and generates a suite of distinctive sedimentary structures.

Table 7: Summary of grain size analyses from sand layers of LF-3.

Lithofacies	Core Number	Depth (m)	Weight Percentage			
			Medium Sand	Fine Sand	V. Fine Sand	Mud
LF-3	AS-VC-24	6.23	0.3	1.3	72.3	26.1
LF-3	AS-VC-24	7.34	1.2	1.3	73.2	24.3
LF-3	AS-VC-24	8.24	0.1	1.9	49.5	48.5
LF-3	AS-VC-24	MEAN	0.5	1.5	65.0	33.0
LF-3	AS-VC-25	7.15	3.5	11.0	57.2	28.4
LF-3	AS-VC-25	7.59	0.1	6.0	70.6	23.3
LF-3	AS-VC-25	8.29	0.0	3.8	58.5	37.7
LF-3	AS-VC-25	MEAN	1.2	6.9	62.1	29.8
LF-3		MEAN	0.9	4.2	63.5	31.4

Figure 24: Photograph of the laminated mud lithofacies (LF-3) from AS-VC-01 (A) and AS-VC-24 (B). See Figure 3 for the location of vibracores.

(A)



(B)

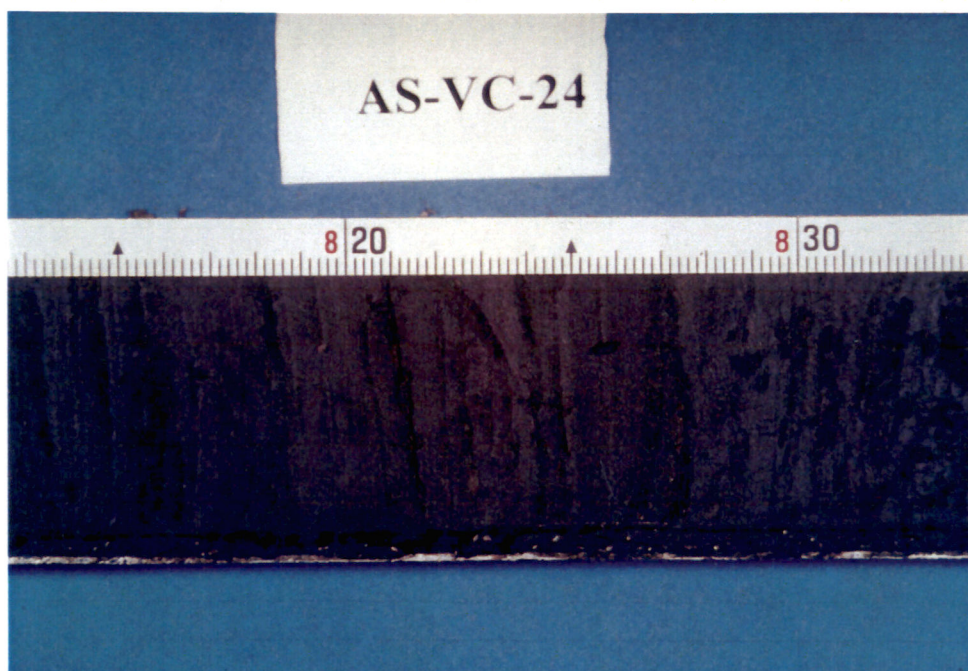


Figure 25: X-radiographs of AS-VC-05 depicting the sharp contacts between sand and mud layers of LF-3.

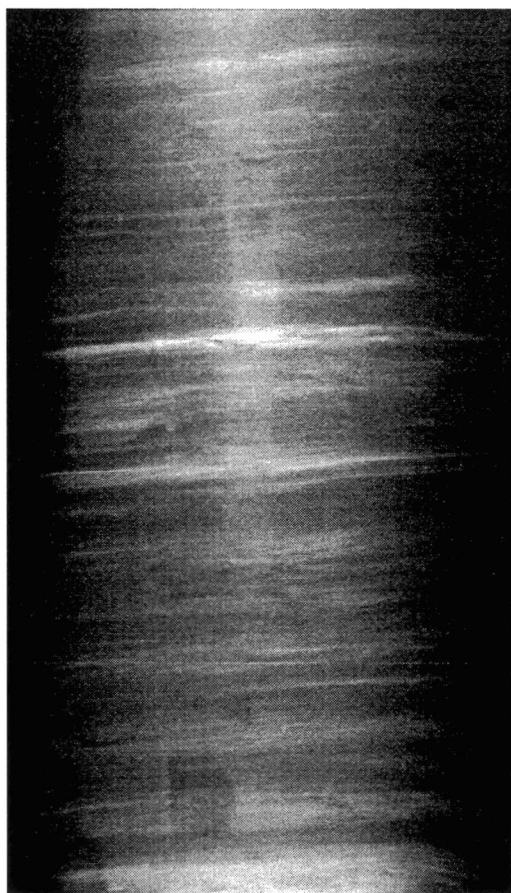


Table 8: Mean thickness of sand and mud layers and sand:mud ratios from LF-3 and LF-5.

Lithofacies	Core Number	Thickness (m)	Sand:Mud Ratio	SAND		MUD	
				Number of Layers	Average Thickness (mm)	Number of Layers	Average Thickness (mm)
LF-3	AS-VC-01	2.42	0.13	85	3.3	85	25.1
LF-3	AS-VC-06	2.98	0.21	167	3.8	168	18.6
LF-3	AS-VC-24	2.54	0.13	125	2.4	126	17.8
LF-3	AS-VC-25	1.47	0.21	102	2.5	103	11.7
LF-3	MEAN		0.17		3.0		18.3
LF-5	AS-VC-24	2.36	0.99	167	7	168	7.1
LF-5	AS-VC-25	1.04	0.65	70	5.9	71	8.7
LF-5	MEAN		0.82		6.5		7.9

Tidal Currents and Waves

Lenticular bedding is produced when sand ripples, created by tidal currents or waves, migrate across a mud substrate deposited during quiescent conditions (Reineck and Singh, 1980). The ripples are preserved as sand lenses within a muddy matrix and commonly display forset laminae. However, x-radiographs reveal that sand layers of LF-3 are planar, which suggests that they were not produced by migrating ripples created by tidal currents or wave activity. Furthermore, if the laminated mud lithofacies was created by tidal processes, the unit should be confined to the outer-estuarine zone where tidal influence is the greatest. Yet, the laminated mud occurs throughout the inner- and outer-estuarine zones (Figures 17-19)

Settlement of Suspended Sediment

Storm related deposition may produce coarsely interlayered bedding, alternating sand and mud layers that are uniformly thick and range from several millimeters to a few centimeters thick. Coarsely interlayered bedding commonly forms when mud deposition is periodically interrupted by large storm events that deposit horizontally laminated sand layers from entrained sediment (Reineck and Singh, 1980). Within the Albemarle estuarine system, sand may be derived from three sources: 1) sediment transported by trunk and tributary streams; 2) from the Atlantic ocean via eolian, overwash, or inlet processes; or 3) shoreline erosion of the estuarine system. If sand layers accumulated from sand transported from either the Atlantic or the trunk rivers, the thickness and proportion of the sand layers of sand should decrease away from the source. However, Table 8 shows that sand layers are uniformly distributed throughout Albemarle Sound,

which indicates that sand layers were not derived from either the Atlantic Ocean or trunk rivers.

Tributary estuaries occur throughout Albemarle Sound and may represent a source of fine-grained sands that were deposited within the estuarine system. These tributaries were characterized by steeper stream gradients during lower sea level, possibly resulting in the transportation of fine-grained sands during storm events. These sands would have been deposited at the mouths of the tributary streams onto muddy deltaic lobes similar the wedge of orange clay at the mouth of the Roanoke River (Riggs *et al.*, 1993). However, the present gradient of these tributaries is low, resulting in the transportation a dissolved and suspended sediment load that consists of silts and clays (Riggs *et al.*, 1993).

Also, the equal distribution of sand layers throughout Albemarle Sound suggests shoreline erosion during storm events may deliver sand to the central basin to accumulate as thin layers of coarser sediment. Today, sand layers do not occur within the central basin even though Pleistocene sediment bank shorelines constitute 62% of the Albemarle estuarine system, most of which are being actively eroded (Bellis *et al.*, 1975). Riggs *et al.* (1993) and Riggs (1996) have shown that the mean sand concentration in the organic-rich mud is 11.3%.

The deficiency of sand within the central basin may be explained, in part, by wind and tidal currents produced by storms and the Coriolis effect. The Coriolis effect causes differential movement of water and sediments along the margins of northern hemisphere estuaries (Davis, 1983; Biggs, 1985). During ebb tides, the water and sediment movement is primarily along the northern margin, whereas during flood tides the movement is

primarily along the southern margin. These currents would be amplified during storm events when sand is eroded from the adjacent shoreline and transported along the margins of Albemarle Sound. The orientation of shoals at the mouths of tributary streams suggest circulation in the Albemarle estuarine system may prevent the transport sediment into the central basin.

The absence of sand laminae in the central basin may also be explained by bioturbation by micro- and macrobenthos (Tenore, 1977) that thoroughly mix deposits and destroy sedimentary structures, changes in biological communities, or changes in the rates of sea-level rise and shoreline retreat that supplies sediment to the system.

Fossiliferous, Muddy Sand (LF-4)

LF-3 is overlain by a fossiliferous, muddy sand lithofacies (LF-4) that is 0.25-2.0 meters thick along the northern and southern portions of profile B-B' (Figures 18 and 19). Articulated, disarticulated, and fragmented *Mulinia* are commonly disseminated in a 0.5 meter zone along the base of this facies (Figure 26). LF-4 is characterized by burrowing invertebrates *Cyrtopleura* and *Tagelus* that occur in life position (Figure 27) with disarticulated and fragmented *Crassostrea*, *Ensis*, *Mercenaria*, *Mulinia*, and *Urosalpinx*. Microfossils were not examined from this unit because of the large number of macro-invertebrates. *Tagelus* and *Cyrtopleura* are common in open-estuarine environments with polyhaline conditions (16.5-30.0 ppt). *Tagelus* is common in intertidal areas and in water depths of 6 meters, while *Cyrtopleura* commonly bores into soft, sandy mud at or just below the low-water mark in open bays and inlets (Abbott, 1974). In North Carolina, these organisms occur along the edges of marshes and on muddy sand shoals adjacent to

Figure 26: Photograph of the fossiliferous, muddy sand lithofacies (LF-4) from AS-VC-18. Note the concentration of *Mulinia* disseminated at the base of this lithofacies. See Figure 3 for the location of vibracores.

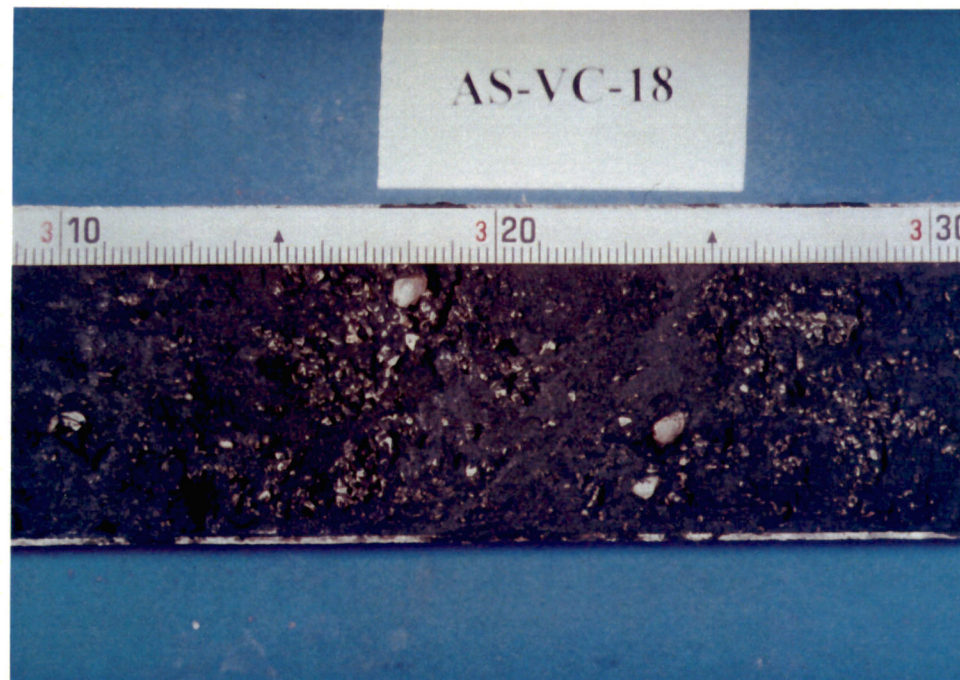
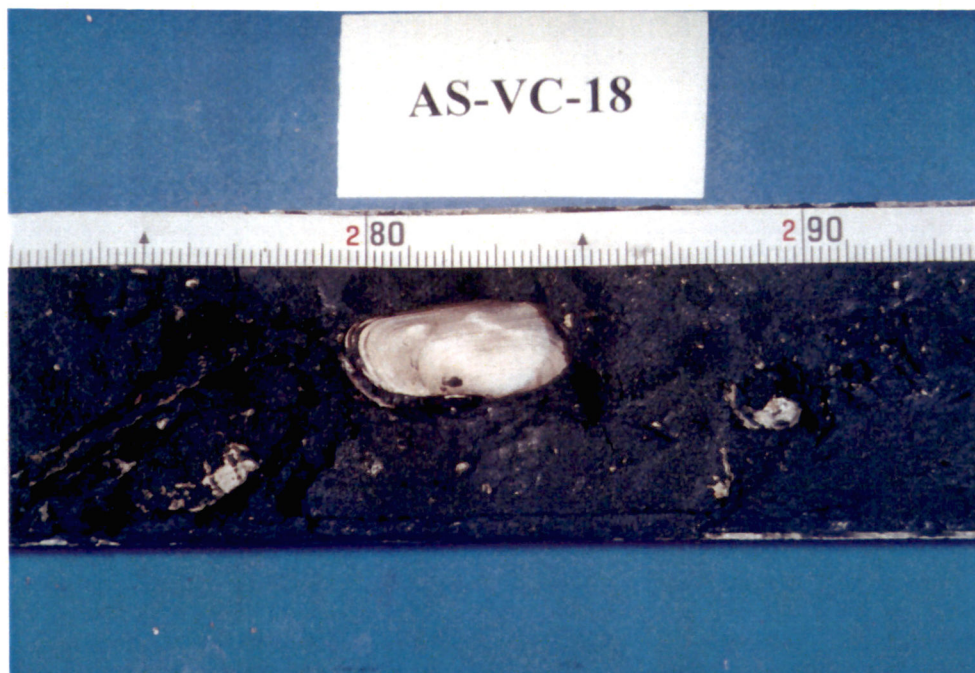


Figure 27: Photograph of the fossiliferous, muddy sand lithofacies (LF-4) from AS-VC-18. Note the articulated *Tagelus* (A) and articulated *Cyrtopleura* (B). See Figure 3 for the locations of the vibracore.

(A)



(B)



inlets through the barrier island complex (Kirby-Smith and Gray, 1973; and Wilson, 1979). The abundance of *Tagelus* and *Cyrtopleura* within the fossiliferous, muddy sand lithofacies suggest shallow-water, intertidal environments were extensive along the margins of Albemarle Sound.

Interlaminated Mud and Sand (LF-5)

The fossiliferous, muddy sands of LF-4 grade vertically and laterally into the interlaminated mud and sand lithofacies (LF-5). LF-5 ranges from 0.75 to >8 meters in thickness and is confined to the central portion of Albemarle Sound along B-B' (Figure 17). LF-5 is distinguished by alternating laminae of very fine- to fine-grained sand (Table 9) and mud (Figure 28) that are comparable to flaser or coarsely interlayered bedding. Reineck and Wunderlich (1968) and Reineck and Singh (1980) described this type of sediment as “sand and mud layers are almost equally thick”. X-radiographs reveal that the contacts between the mud and sand layers are sharp, with sand layers displaying forset laminae (Figure 29). The sand:mud ratio of LF-5 is 0.82, whereas the mean thickness of sand and mud layers is 6.5 mm and 7.9 mm, respectively (Table 8). Faunas within LF-5 are dominated by *Mulinia* with some *Crassostrea*, *Cyrtopleura*, *Macoma*, and *Tagelus* that are common in meso- to polyhaline conditions. Microfossils are abundant and dominated by *Elphidium*.

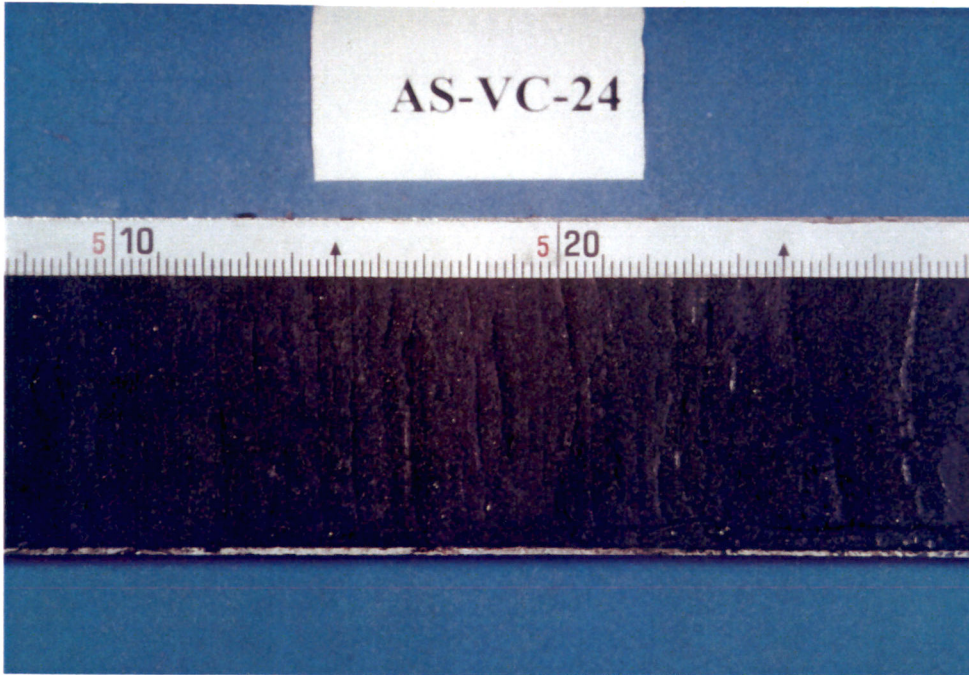
The interlaminated mud and sands can originate from tidal currents and waves or suspension settlement following storm events and shoreline erosion in a similar fashion to LF-3.

Table 9: Summary of the grain size analyses from LF-5.

Lithofacies	Core Number	Depth (m)	Weight Percentage			
			Medium Sand	Fine Sand	V. Fine Sand	Mud
LF-5	AS-VC-15	3.49	12.8	35.8	24.0	27.4
LF-5	AS-VC-15	4.68	1.0	8.6	54.9	35.6
LF-5	AS-VC-15	5.28	0.3	8.0	49.9	41.8
LF-5	AS-VC-15	MEAN	4.7	17.5	42.9	34.9
LF-5	AS-VC-23	1.50	0.1	2.9	64.3	32.7
LF-5	AS-VC-23	1.60	0.2	1.7	65.7	32.5
LF-5	AS-VC-23	1.90	0.1	3.2	53.3	43.4
LF-5	AS-VC-23	MEAN	0.1	2.6	61.1	36.2
LF-5	AS-VC-24	3.41	0.1	1.3	84.0	14.6
LF-5	AS-VC-24	4.43	0.1	3.6	72.0	24.3
LF-5	AS-VC-24	5.26	0.6	13.8	76.6	23.4
LF-5	AS-VC-24	MEAN	0.3	6.2	77.6	20.8
LF-5	AS-VC-25	6.10	4.8	35.7	35.9	23.7
LF-5	AS-VC-25	6.55	0.3	64.1	37.1	0.0
LF-5	AS-VC-25	MEAN	2.5	49.9	36.5	11.8
LF-5		MEAN	1.9	19.0	54.5	25.9

Figure 28: Photograph of the interlaminated mud and sand lithofacies (LF-5) from AS-VC-24 (A) and AS-VC-25 (B). See Figure 3 for the location of the vibracore.

(A)



(B)

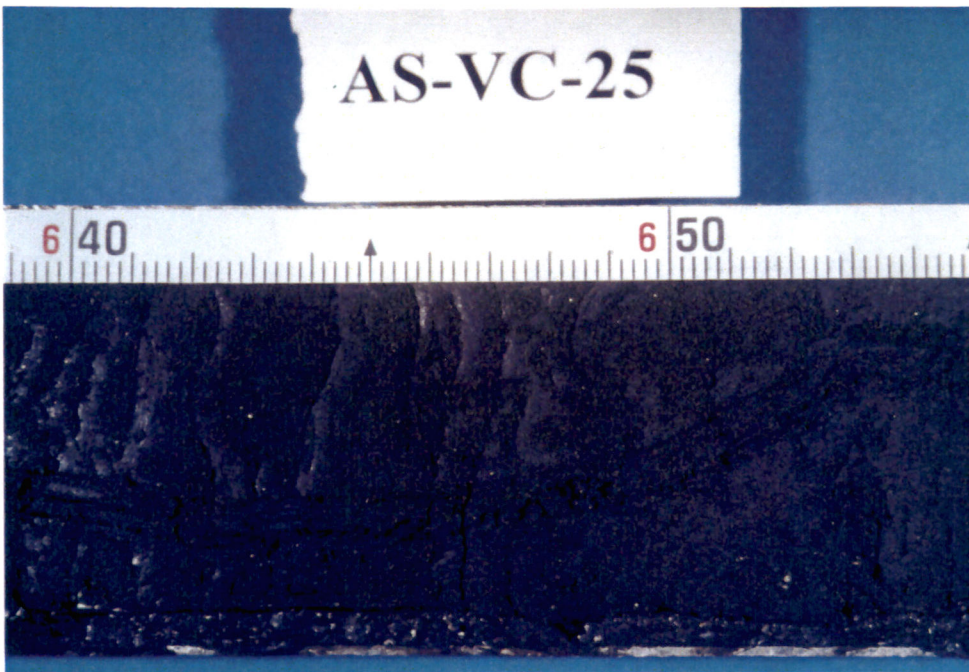
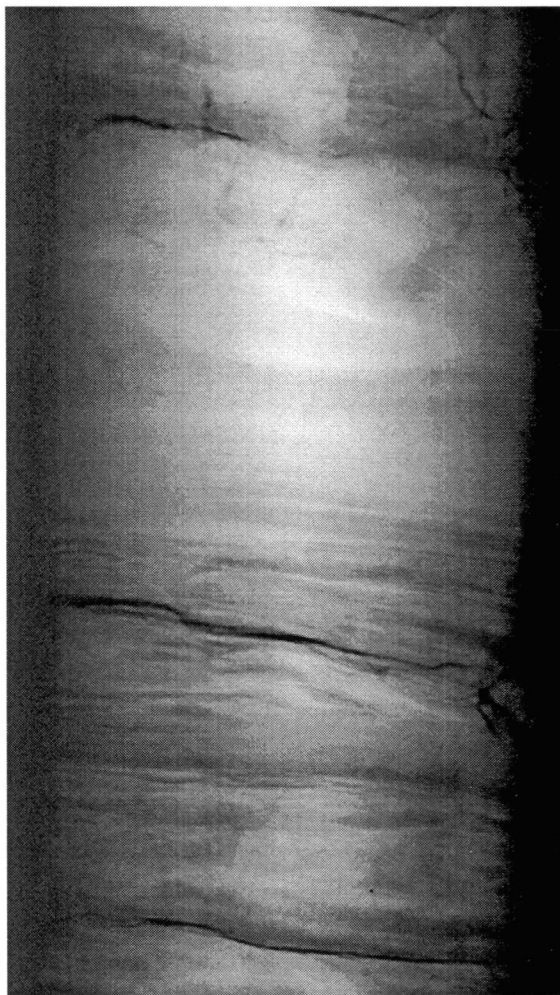


Figure 29: X-radiographs from AS-VC-24 reveal forset laminae within sand layers of LF-5. Note the sharp contacts between sand and mud layers.



Storm Events and Shoreline Erosion

LF-5 is confined to the outer-estuarine zone, which suggests sand may be derived from overwash processes associated with the Atlantic Ocean. In Rehoboth and Indian River Bays, overwash processes deposited sand lenses between lagoonal muds (Kraft, 1971; Kraft and John, 1979). These sand lenses display horizontal or graded bedding and contain microfossils indicative of a marine environment. This facies typically grades upward into backbarrier overwash sands as the barrier island migrates landward (Demarest and Kraft, 1987). In North Carolina, overwash, eolian, and inlet processes have produced a surficial sand apron that extends 5-10 km west of the modern barrier island complex (Eames, 1983; Riggs *et al.*, 1993; Riggs, 1996), and may have resulted in the deposition of LF-5. However, x-radiographs (Figure 29) reveal that the sand layers of LF-5 exhibit well defined forset laminations, which is inconsistent with structures described by Kraft (1971) and Kraft and John (1979) and indicates that LF-5 was not produced by storm processes. Furthermore, the sand layers of LF-5 are dominated by *Elphidium*, which is consistent with an estuarine environment.

Tidal Currents and Waves

The interlaminated mud and sand facies is similar to flaser and coarsely interlayered bedding common in meso- and macrotidal flats (Reineck and Wunderlich, 1968). LF-5 occurs adjacent to the tidal channel facies (LF-1A) and may represent shoal complexes associated with tidal channels in the central basin. Demarest and Kraft (1987) have shown that tidal shoal and channel lithosomes will occur in a vertical transgressive sequence produced in an open-estuary environment. Weil (1976) described similar

sediment types in shoal complexes adjacent to flood-tidal channels in Delaware Bay. Delaware Bay is an open-estuarine system characterized shoals that occur adjacent to “finger-like” flood tidal channels (Figure 30). These shoals are 1.5-6.0 meters thick, asymmetrical in cross section, and exhibit well developed internal cross beds produced by the lateral migration of tidal channel and shoal complexes.

Tidal channels formed as the water volume of Delaware Bay increased during the Holocene transgression (Weil, 1976). The hydraulic efficiency of removing water from subtidal flats surrounding Delaware Bay was increased by the development of tidal channels. Shoals formed adjacent to the tidal channels by similar processes that create subaerial levees; sediments were deposited along the channel margin as tidal currents decreased away from the channels (Weil, 1976). These “tidal current ridges” are shaped by and oriented parallel to tidal currents (Weil, 1976) with flaser bedding resulting from alternating periods of current activity and quiescence. Formation of the shoals may be analogous to the processes responsible for the deposition of LF-5 in an open-estuarine environment in the central basin of Albemarle Sound.

Organic-rich Mud (LF-6)

Organic-rich mud (LF-6; Figure 31) is the dominant surficial sediment type within the central basin of the Albemarle estuarine system (Riggs, 1996; Riggs *et al.*, 1993). LF-6 is composed of inorganic sediments delivered to the estuary as suspended load by trunk rivers during high discharge periods and organic matter derived from erosion of the extensive swamp forests and marshes fringing the Albemarle estuarine system (Riggs *et al.*, 1993; Riggs, 1996). Fine-grained sediments are deposited by flocculation and by

Figure 30: Distribution of flood tidal channels and shoal complexes in Delaware Bay (modified from Weil, 1976).

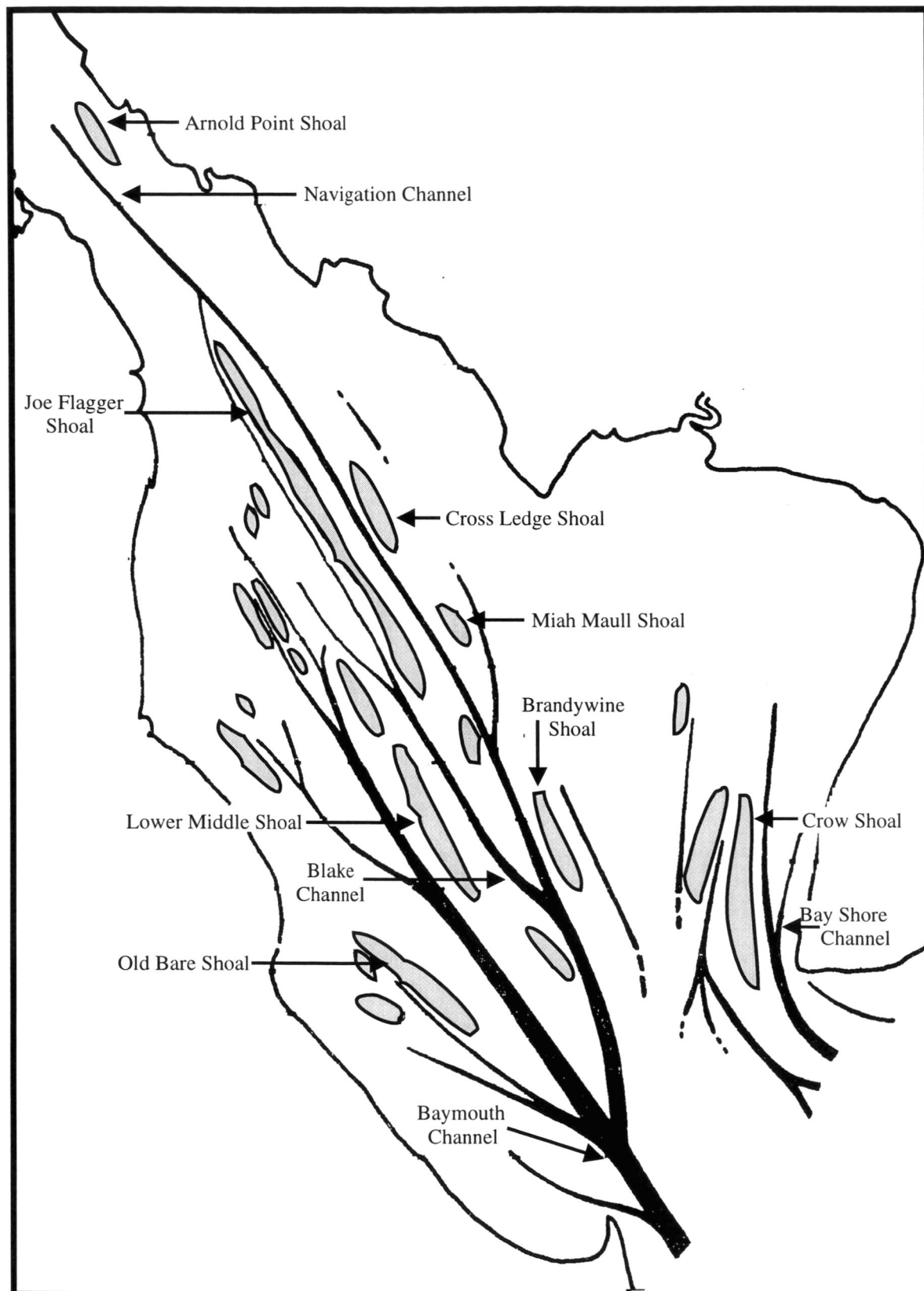
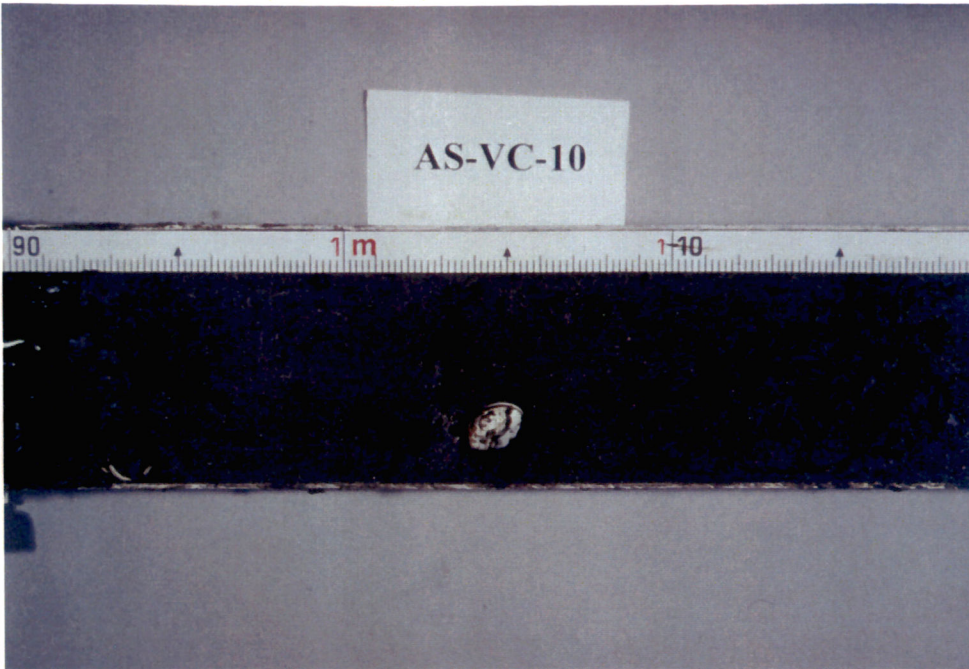
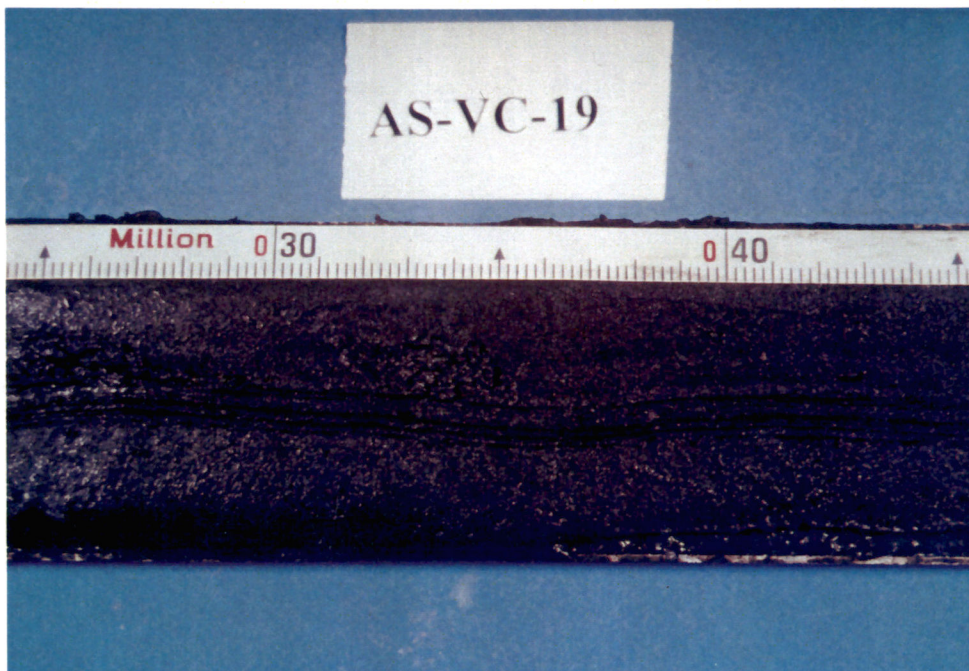


Figure 31: Photograph of the organic-rich mud lithofacies (LF-6) from AS-VC-10 (A) and AS-VC-19 (B). Note the articulated *Macoma* in AS-VC-10. See Figure 3 for the locations of the vibracores.

(A)



(B)



filter and detritus feeding organisms that pelletize the fine-grained material (Riggs *et al.*, 1993; Riggs, 1996). LF-6 is currently being deposited in a closed estuary under infra- to oligohaline salinity conditions in response to the establishment of a continuous barrier island complex during the early 1800's (Riggs and O'Conner, 1974). The organic-rich muds of LF-6 cap the entire Holocene sequence within Albemarle Sound and rest upon LF-5 along B-B' (Figure 17) and LF-3 along C-C' (Figures 18 and 19). Sediment texture, heavy metal concentrations, and paleontological evidence were utilized to divide LF-6 into two subfacies: LF-6A and LF-6B. LF-6B comprises the surficial sediments and rests upon a denser organic-rich mud substrate (LF-6A). LF-6B consists of loose sediment, ranging from 0 to 2 m in thickness with a mean thickness of < 0.5 m (Riggs, 1996), that SCUBA divers can readily penetrate. Riggs *et al.* (1993) analyzed 156 short cores for heavy metal contaminants and discovered elevated concentrations within LF-6B, which they attributed to urbanization and industrialization during post-colonial times (< 400 years). The decreased concentration in heavy metals in the underlying LF-6A, in conjunction with the increased degree of compaction, is attributed to a previous depositional episode during pre-colonial times. Macrofauna within LF-6A include articulated *Macoma*, whereas LF-6B contains both *Macoma* and disarticulated *Rangia*. The environment and processes of the deposition of the underlying LF-6A are probably analogous to the modern environment and processes responsible for LF-6B.

SEISMIC FACIES ANALYSIS OF CHANNEL COMPLEXES

Seismic facies analysis (Mitchum *et al.*, 1977) utilizes the configuration, continuity, amplitude, and frequency of reflectors to interpret depositional processes and

environments. Sangree and Widmier (1977) integrated seismic facies analysis with well lithostratigraphy to model the depositional processes and predict lithologies of shelf, shelf margin, and basin slope environments. A similar approach has been utilized to model the seismic facies patterns that characterize the infill sequence of tidal and fluvial channels in the shallow subsurface of Albemarle Sound.

The seismic facies that characterize the infill sequence of the channel complexes of Albemarle Sound consist of four distinct reflector patterns: 1) concave-up ; 2) planar dipping; 3) chaotic; and 4) no internal reflectors (Figures 32-37). Channel complexes may display several seismic facies, but individual channels exhibit only one facies. The depositional processes and environment creating each seismic facies was determined by integrating the seismic facies with the lithostratigraphy. This seismic facies model is important because it can be utilized to interpret the depositional history of other channel complexes in the Albemarle region without lithologic control.

Tidal channel sediments of LF-1A typically backfill channels with concave-up or no internal reflectors (Figures 32-34). No internal reflectors result from the absorption of seismic signal by fine-grained sediments capping the tidal channel complexes, whereas concave-up reflectors are produced along bedding surfaces that mimic the channel geometry. Mitchum (1985) attributed the concave-up reflector pattern of submarine canyons to down-gradient filling. Figure 35 is backfilled with LF-1A and characterized by planar inclined reflectors, which probably resulted from seismic profile A-A' transversing Albemarle Sound at an oblique angle.

Figure 32: ICS-2 is backfilled with LF-1A and the seismic facies is characterized by concave-up reflectors. See Figure 7 for the location of ICS-2.

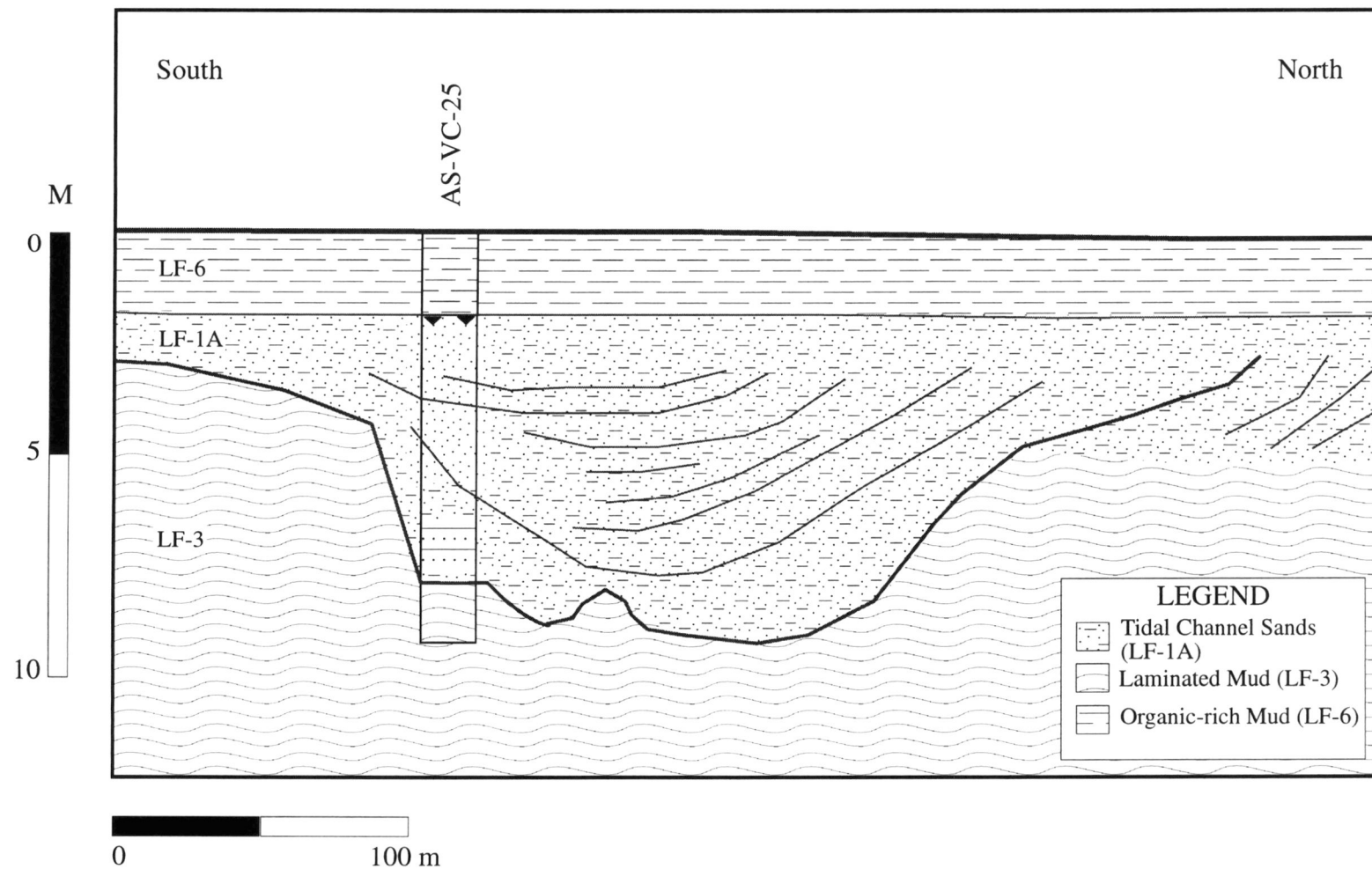


Figure 33: MSCS-2 is backfilled with LF-1A and the seismic facies is characterized by no internal reflectors. See Figure 7 for the location of MSCS-2.

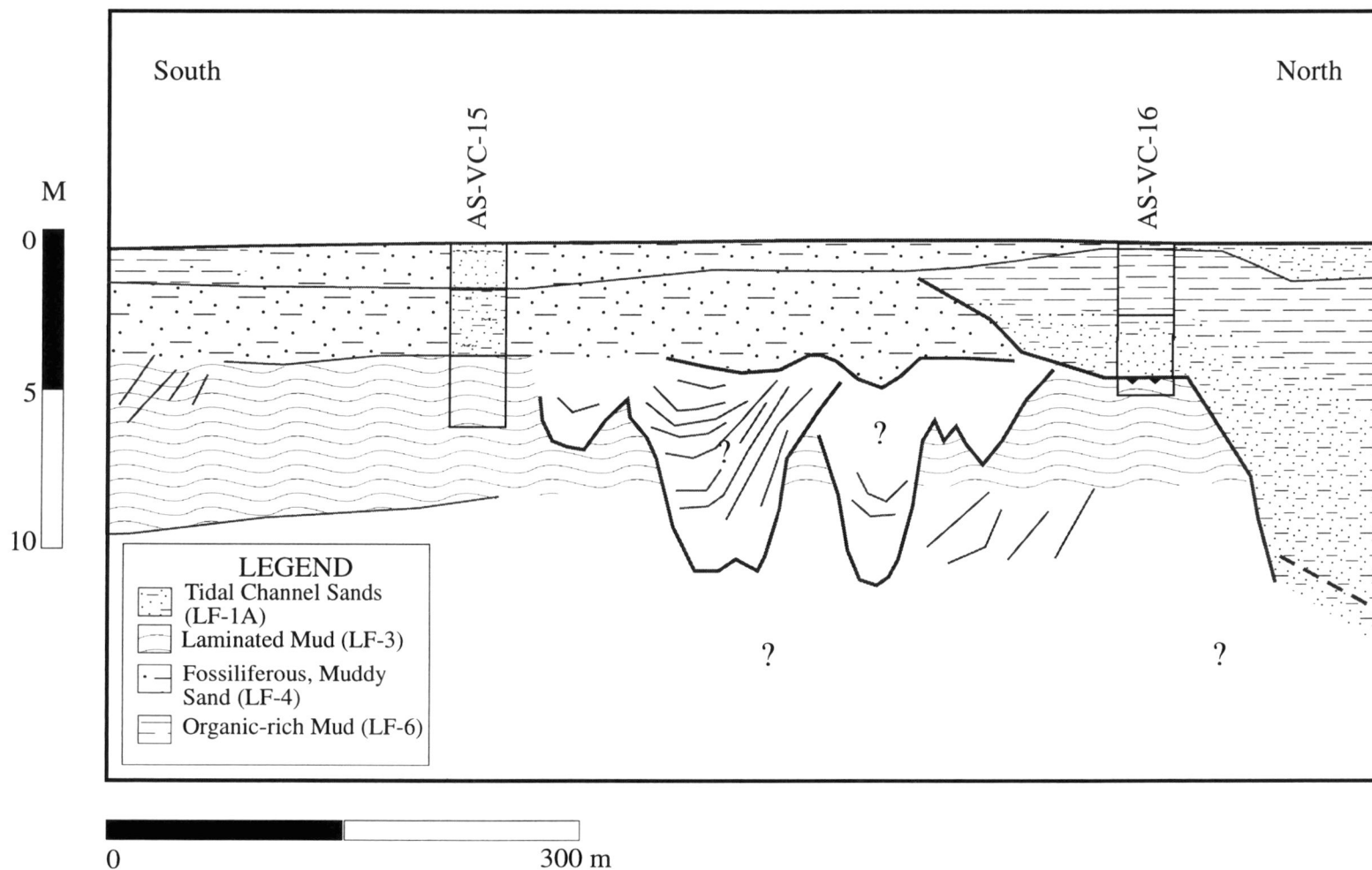


Figure 34: MSCS-3 is backfilled with LF-1A and the seismic facies is characterized by concave-up reflectors. See Figure 6 for the location of MSCS-3.

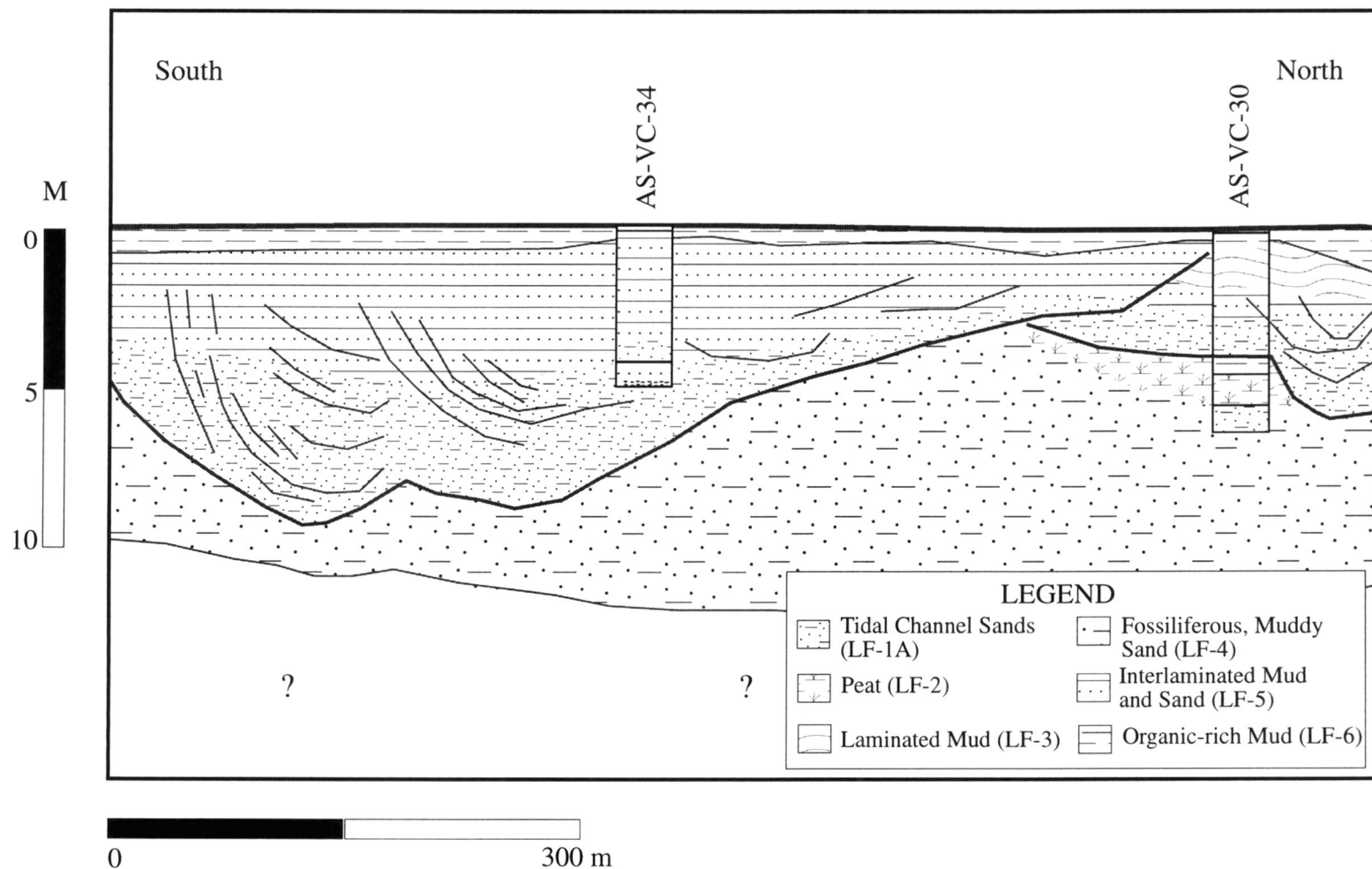
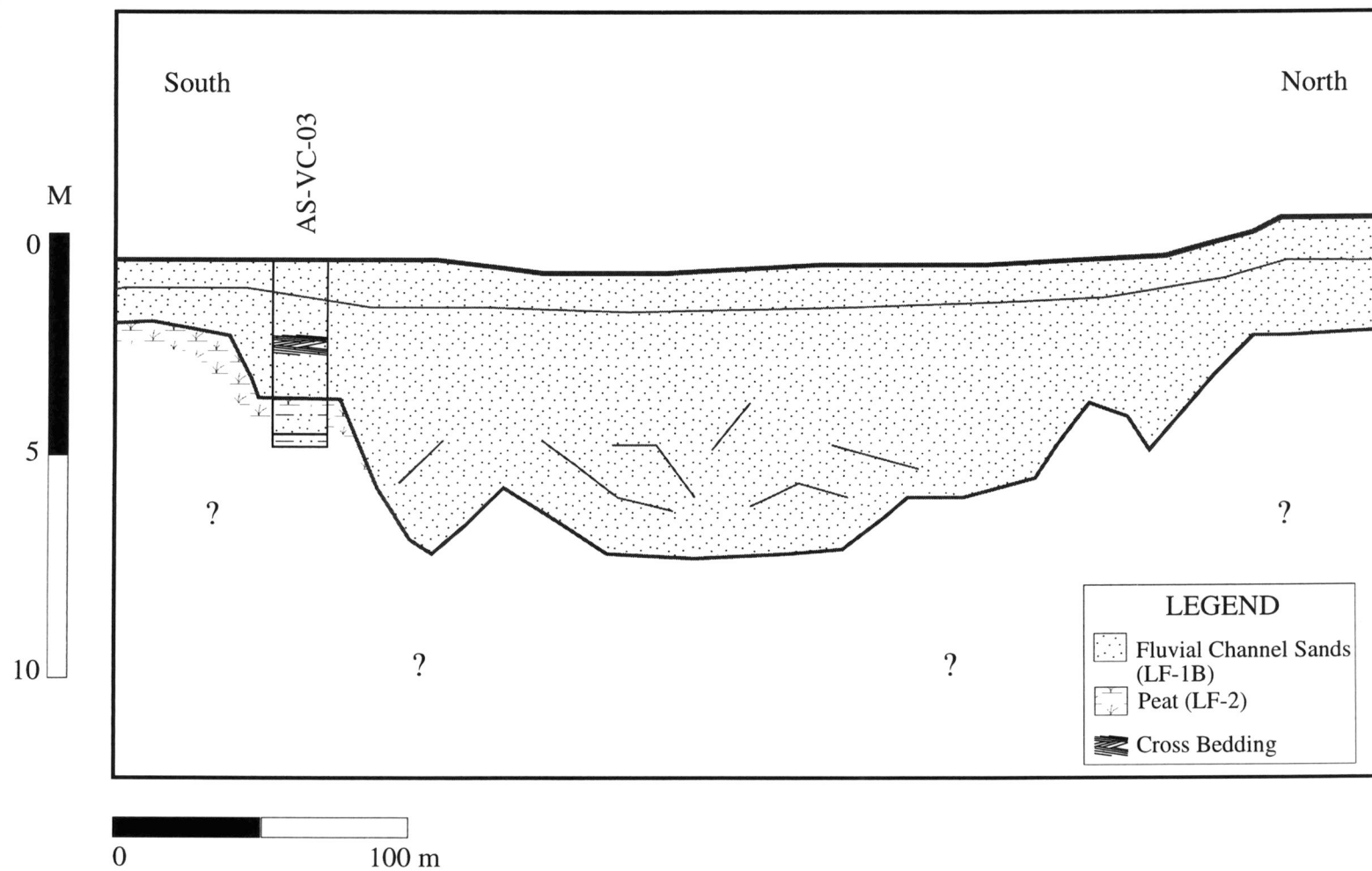


Figure 35: ICS-1 is backfilled with LF-1B and the seismic facies is characterized by chaotic reflectors. See Figure 6 for the location of ISC-1.

ICS-1



Channel structures backfilled with fluvial sediments (LF-1B) are characterized by chaotic and planar inclined internal reflectors (Figures 36 and 37). The planar inclined reflectors represent prograding clinoforms associated with point bar migration that produce planar-type cross beds. Chaotic reflectors are typically associated with high flow regimes (Mitchum *et al.*, 1977) that result in convoluted laminae.

Eames (1983) identified a network of Holocene fluvial channels within the shallow subsurface of outer Albemarle and Roanoke Sounds using low-resolution seismic data. The geometry of the Eames channels is comparable to the tidal channels identified in the present study. Based upon Eames (1983) and the present study, the distribution of channels in the Albemarle and Roanoke Sounds suggests that the central basin is characterized by an intricate network of channels (Figure 38). These channels were active when the sounds operated as an open-estuarine system. However, few radiocarbon dates exist from the channel complexes because organic carbon is not abundant in these lithofacies. Therefore, additional dates are needed to establish if this network of channels represents a single episode or multiple episodes of open-estuarine conditions.

DISCUSSION

The Holocene infill history of Albemarle Sound was developed along two different avenues utilizing 1) lithostratigraphic data and 2) a multi-disciplinary approach that integrates seismic-, litho-, and chronostratigraphic evidence. The lithostratigraphic model (LM) is based on Walther's Law of Facies and assumes that depositional environments migrated systematically westward and upward in response to a continuous Holocene transgression. The integrated seismic-, litho-, and chronostratigraphic model

Figure 36: MSCS-1 is backfilled with LF-1B and the seismic facies is characterized by planar inclined and chaotic reflectors. See Figure 7 for the location of MSCS-2.

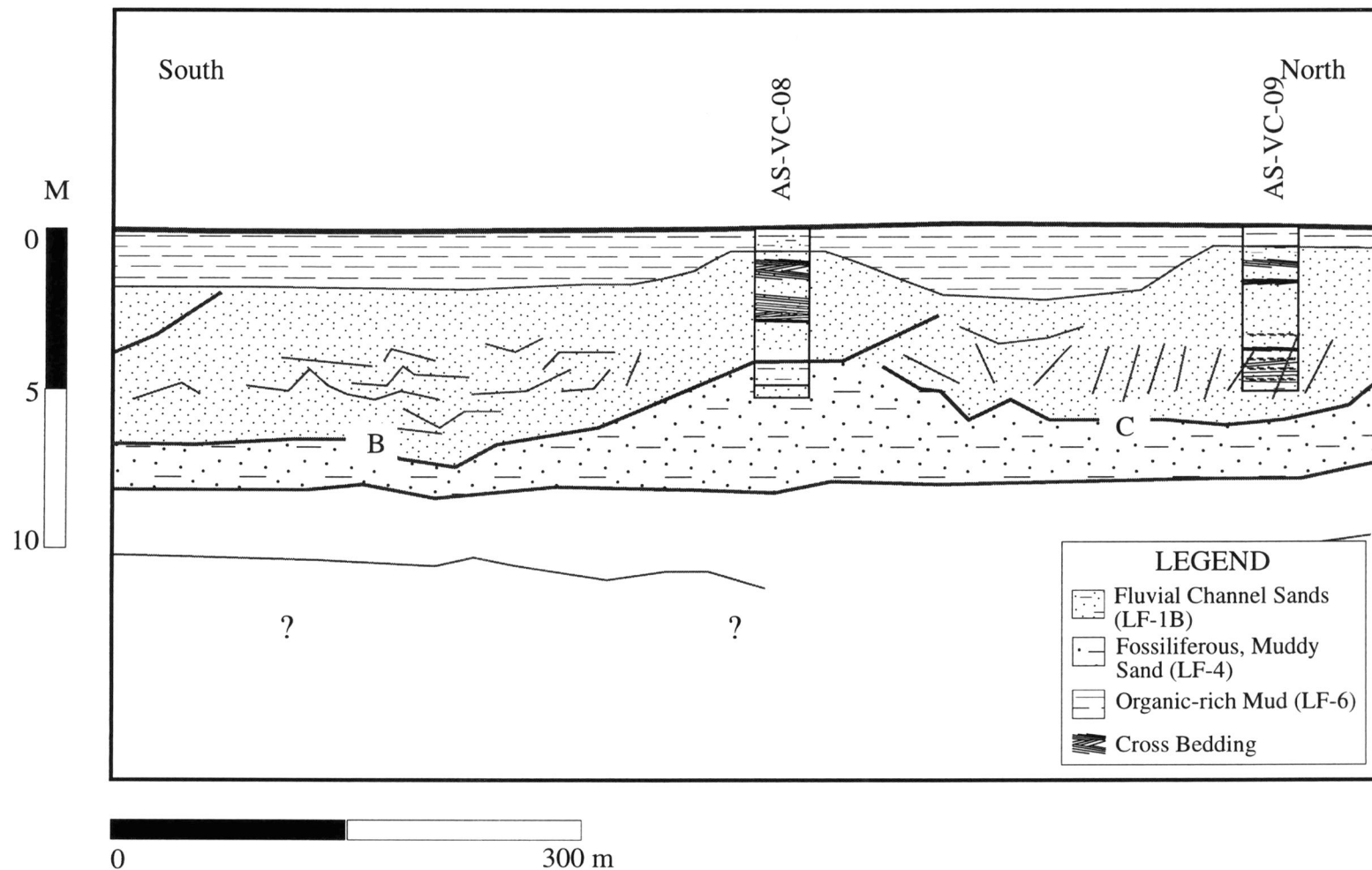


Figure 37: ICS-4 is backfilled with LF-1A and the seismic facies is characterized by planar inclined reflectors. The orientation of the reflectors probably results from the seismic profile intersecting the axis of the channel at an oblique angle. See Figure 6 for the location of ICS-4.

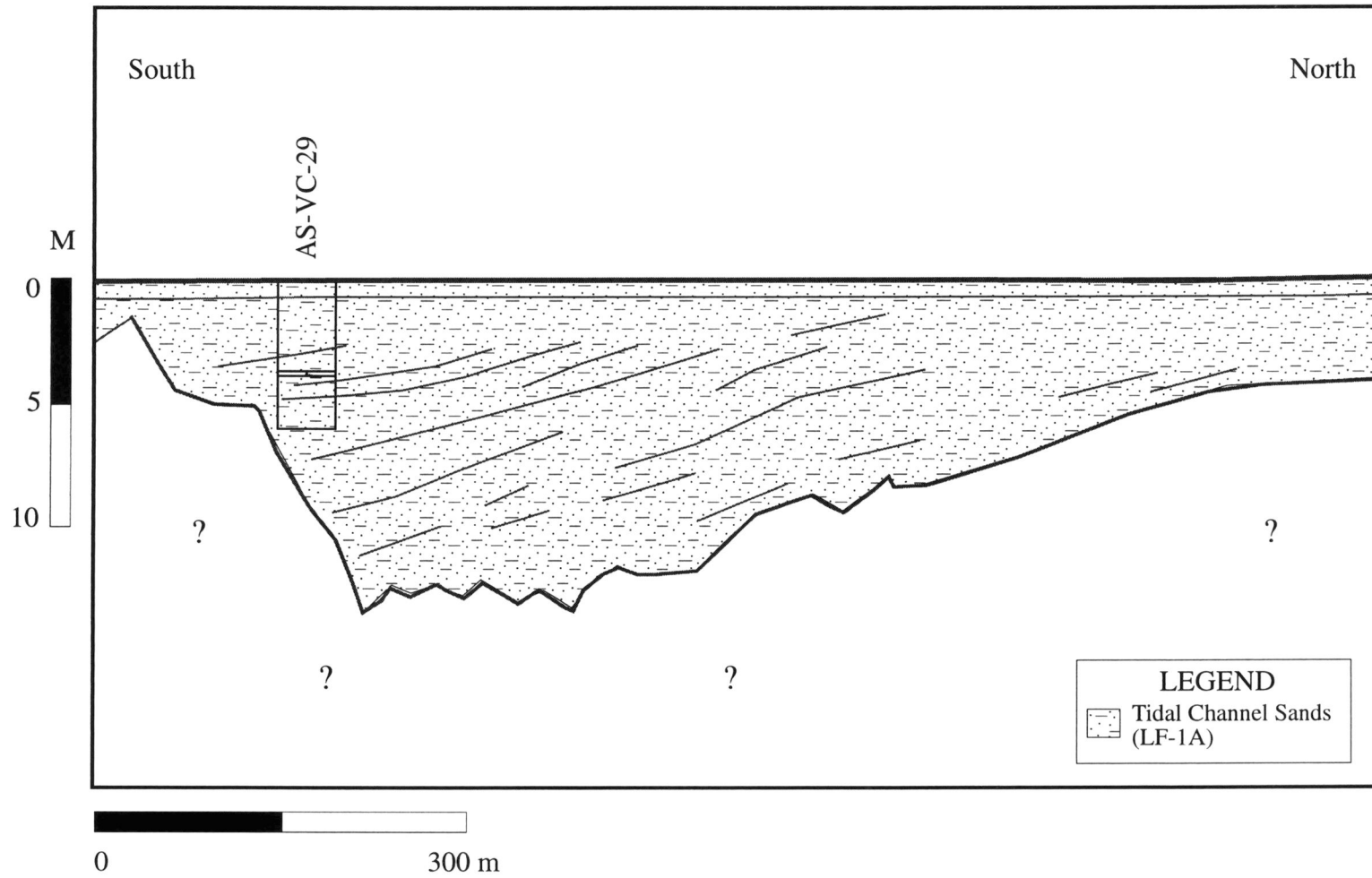
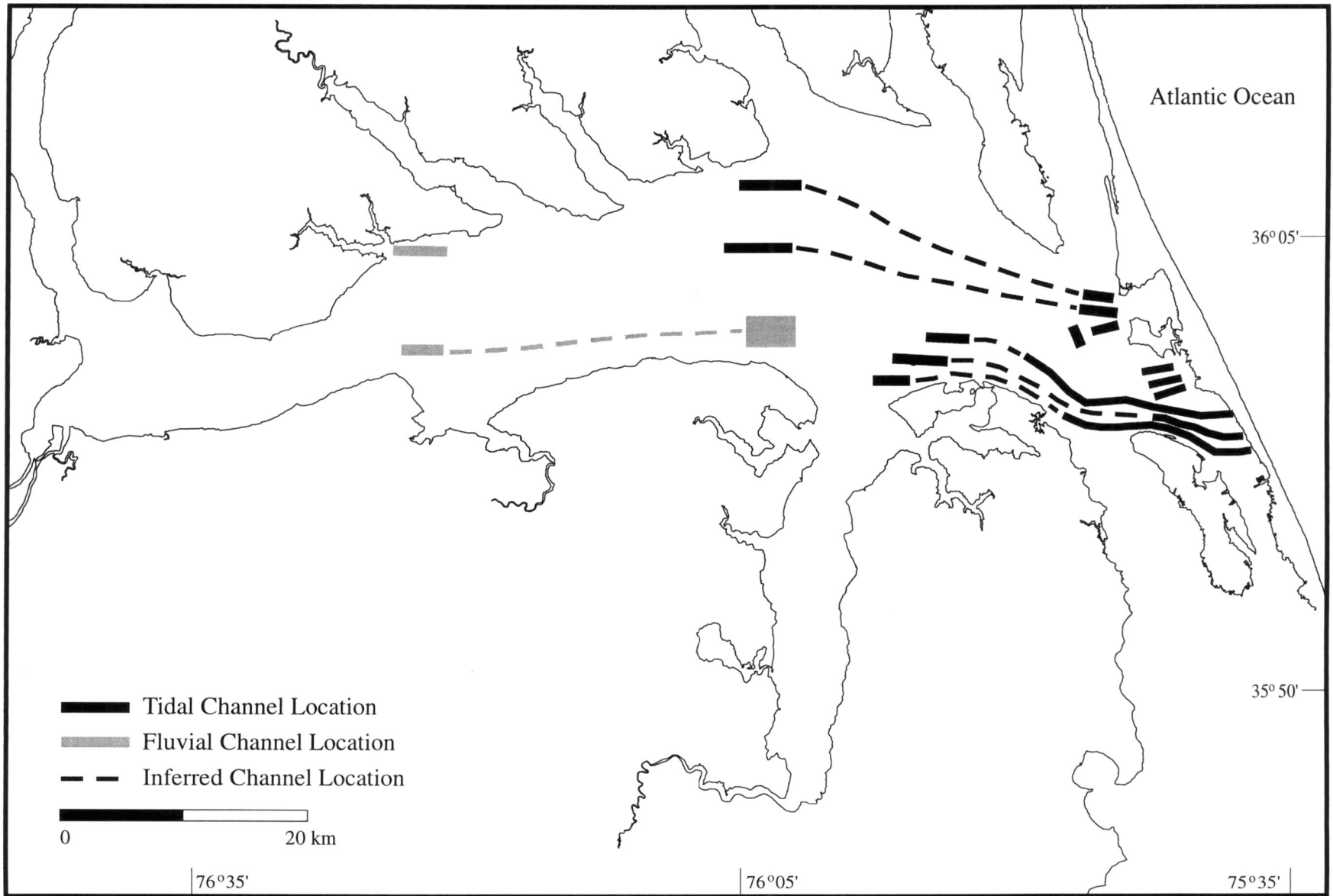


Figure 38: Distribution of fluvial and tidal channels in Albemarle Sound and Roanoke Sound based on this study and Eames (1983).



(ISLCM) is utilized to evaluate the LM and ascertain a more detailed Holocene infill history of the Albemarle region.

LITHOSTRATIGRAPHIC MODEL

Utilizing only the lithostratigraphy, vibracores reveal that the lithologic framework of Albemarle Sound consists of 6 major lithofacies that appear to display a simple infill history (Figure 39 and 40). The lowermost lithofacies is a laminated mud (LF-3) deposited in the inner-most estuarine environment (Figure 40A) during the initial marine flooding of the paleo-Roanoke River. LF-3 is overlain by a fossiliferous, muddy sand (LF-4) characterized by burrowing invertebrates such as *Cyrtopleura* and *Tagelus*. LF-4 was deposited in an open-estuarine environment resulting from the continuous rise of sea level and westward migration of the estuarine habitats up the Roanoke valley (Figure 40B). LF-4 grades into the interlaminated mud and sand lithofacies that was deposited behind a semi-enclosed barrier island system that had migrated into its present location by this time (Figure 40C). The entire sequence is capped by an organic-rich mud (LF-6) deposited in a restricted-estuarine environment generally closed to the ocean by the formation of an almost continuous barrier island complex, as it occurs today (Figure 40D).

INTEGRATED SEISMIC-, LITHO-, AND CHRONOSTRATIGRAPHIC MODEL

The LM is based upon the principle of superposition and assumes that deposits are laterally continuous and relatively flat lying. However, Quaternary sea-level fluctuations produced a complex succession of lithologically similar deposits that were dissected and modified during low stands of sea level (Belknap and Kraft, 1981; Hine and Snyder,

Figure 39: Geologic cross-section of Albemarle Sound along B-B' depicting the infill history of the region based solely upon the lithostratigraphic model (LM). See Figure 3 for the location of B-B'.

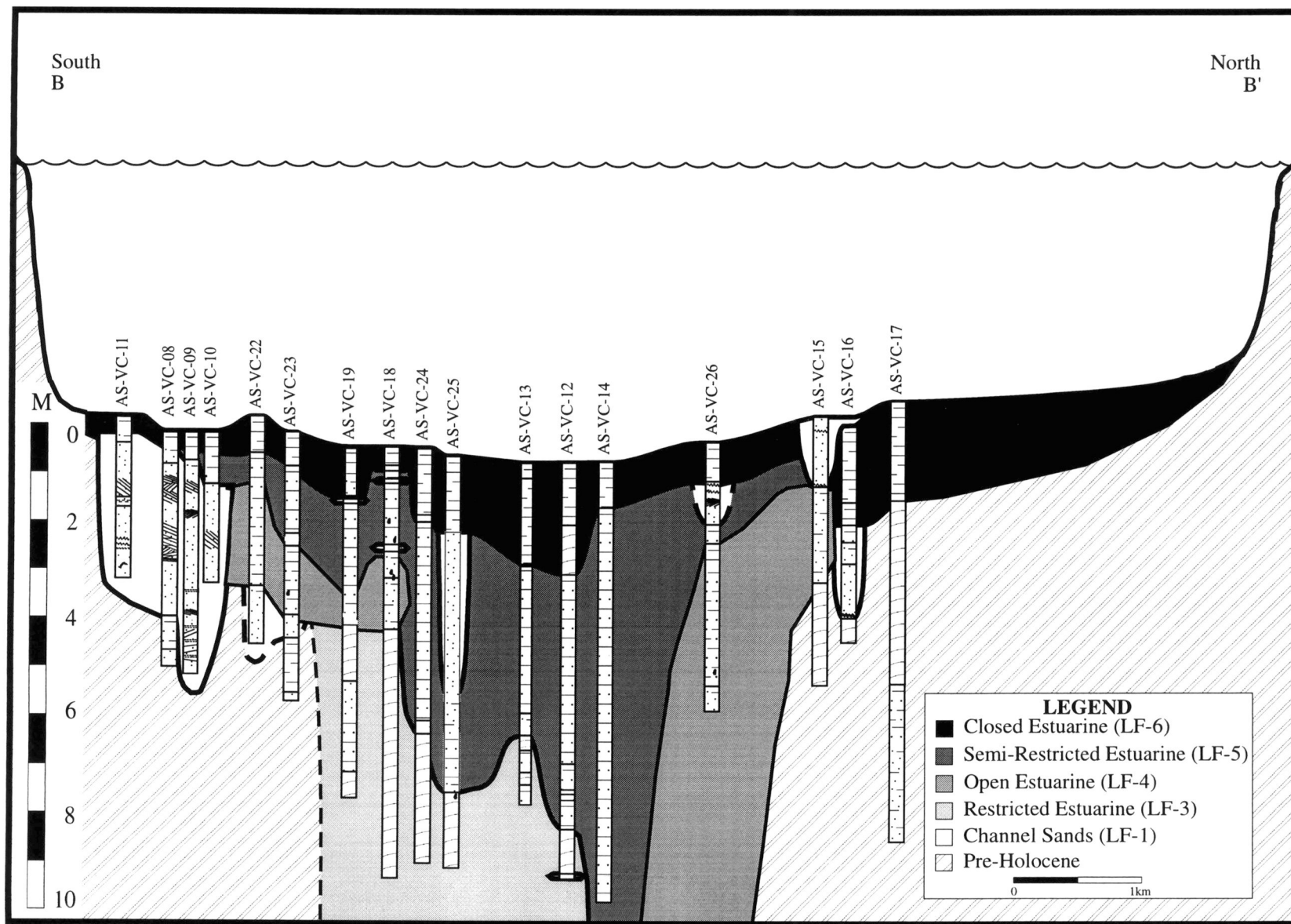
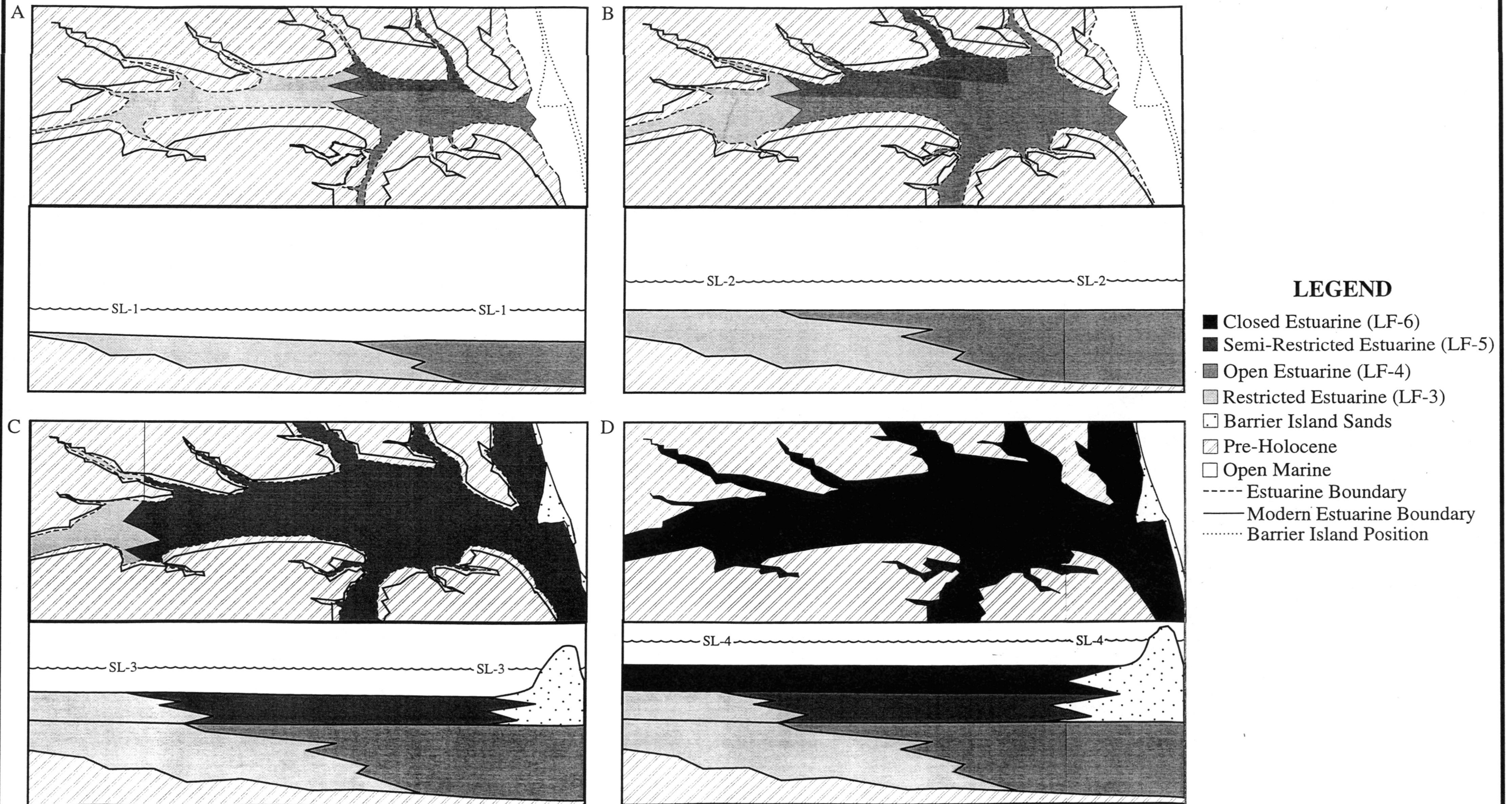


Figure 40: Schematic diagrams of the infill history of Albemarle Sound developed with the lithostratigraphic model. Top panel in each time segment is the map view, whereas the bottom panel is the geologic cross section (A) The laminated mud (LF-3) lithofacies was deposited in the inner-most estuarine environment during the initial marine flooding of the paleo-Roanoke River. (B) A continuous sea-level rise resulted in the westward migration of the open estuary which deposited sediment of LF-4 upon LF-3. (C) Migration of the barrier island complex into the region created a restricted-estuarine system (LF-5). (D) Development of a continuous barrier island complex generated a closed-estuary dominated by organic-rich muds (LF-6).



1985; Riggs and Belknap, 1988). If similar sea-level oscillations occurred within the Holocene, the lithostratigraphic approach alone would not be sufficient to recognize these events because lithologically similar units may not be geometrically or time correlative.

A re-evaluation of the lithostratigraphic model (LM) utilizing a multi-disciplinary approach that integrates high-resolution seismic stratigraphy and radiocarbon dating with the lithostratigraphy results in a very different interpretation. The lithostratigraphic framework is utilized to interpret the processes and environments of deposition. Seismic stratigraphy provides a continuous record that can trace seismic sequences laterally through a basin permitting correlation of time-synchronous strata between sample localities, regardless of lithology. Seismic sequence analysis is utilized to define the depositional sequence, a conformable succession of genetically related strata deposited during a given interval of time and bounded by unconformities and their correlative conformities (Vail and Mitchum, 1977). The identification of seismic sequences is based on the recognition of these unconformities that terminate internal reflectors in onlap, toplap, and downlap relationships (Mitchum *et al.*, 1977). The concept of sequence analysis and recognition of depositional sequences is important because the unconformities are chronostratigraphic markers that separate older strata from younger strata. Utilizing this concept, a relative chronostratigraphic framework can be established utilizing the basic principles of superposition and cross-cutting relationships.

Radiocarbon dating permits an absolute chronology to be superimposed upon the seismic data and allows each depositional sequence to be temporally positioned. Also, radiocarbon dates provide a critical method for distinguishing between depositional

sequences because each sequence consists of similar lithofacies. Integration of these data sets suggests a more complex Holocene sea-level history for Albemarle Sound than indicated by the LM.

Lithologic and seismic data collected along profile B-B' reveal that the Holocene section of Albemarle Sound consists of three distinct depositional sequences (Figures 41 and 42) that are characterized in Table 10. Figure 43 is a schematic representation of the Holocene infill history of this region developed from the ISLCM. The oldest Albemarle Sound Depositional Sequence (ASDS-1) identified in this study has an apparent southward dip, and is incised into Pleistocene sediments along Sequence Boundary-1 (SB-1). ASDS-1 has a maximum thickness of > 8 meters along the northern segment of profile B-B' where it is truncated by both SB-2 and SB-3 and thins to the south where it is truncated by SB-2. Radiocarbon dates indicate that ASDS-1 was deposited between 7.5-7.6 ka and 6.2-6.4 ka (Table 1). Litho- and seismic stratigraphy reveal that Albemarle Sound was an open-estuarine environment characterized by tidal channels (LF-1A) from at least 7.5-7.6 ka until approximately 6.5-6.7 ka (Figure 43A). Sedimentation patterns changed about 6.5-6.7 ka from open- (LF-1A) to restricted-estuarine (LF-3) conditions, presumably in response to the emplacement of a barrier island system with few inlets that produced mesohaline conditions within the outer-estuarine zone (Figure 43B).

ASDS-1 is truncated by ASDS-2, which ranges in thickness from 5.5 to 6.0 meters in the central portion of profile B-B', from 1.0 to 2.0 meters in the north-central section, and is < 0.5 meters thick along the southern margin. ASDS-2 was deposited between 5.5-5.6 ka and 1.4-1.6 ka (Table 1). The sequence boundary (SB-2) separating

Figure 41: Interpreted seismic section along B-B' depicting three Albemarle Sound depositional sequences (ASDS) that comprise the Holocene section. Each ASDS is bounded by an erosional unconformity that forms the sequence boundaries (SB). See Figure 3 for the location of B-B'.

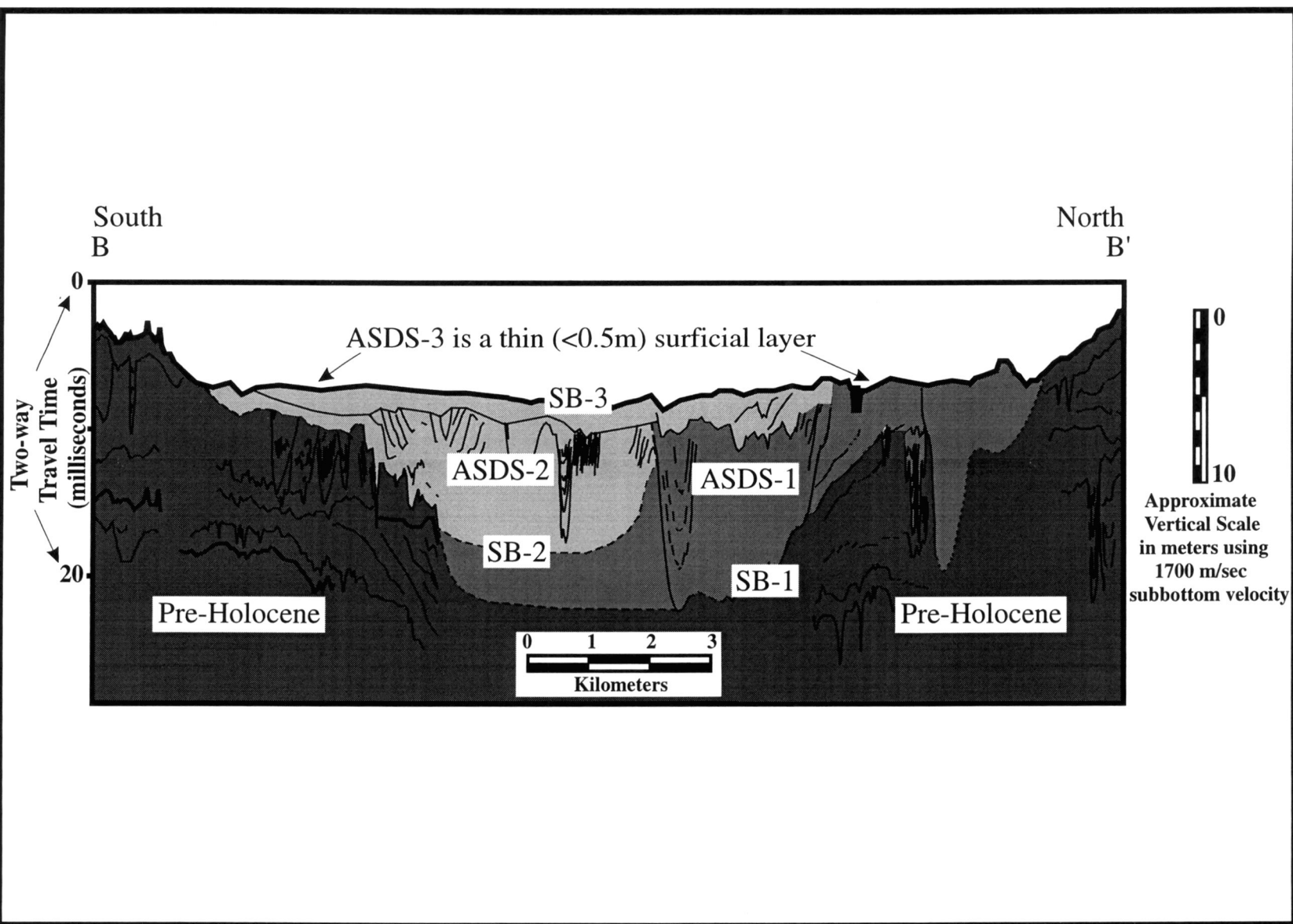


Figure 42: Synthesis of the chronostratigraphic framework for Albemarle Sound constructed from high-resolution seismic reflection data and radiocarbon dating.

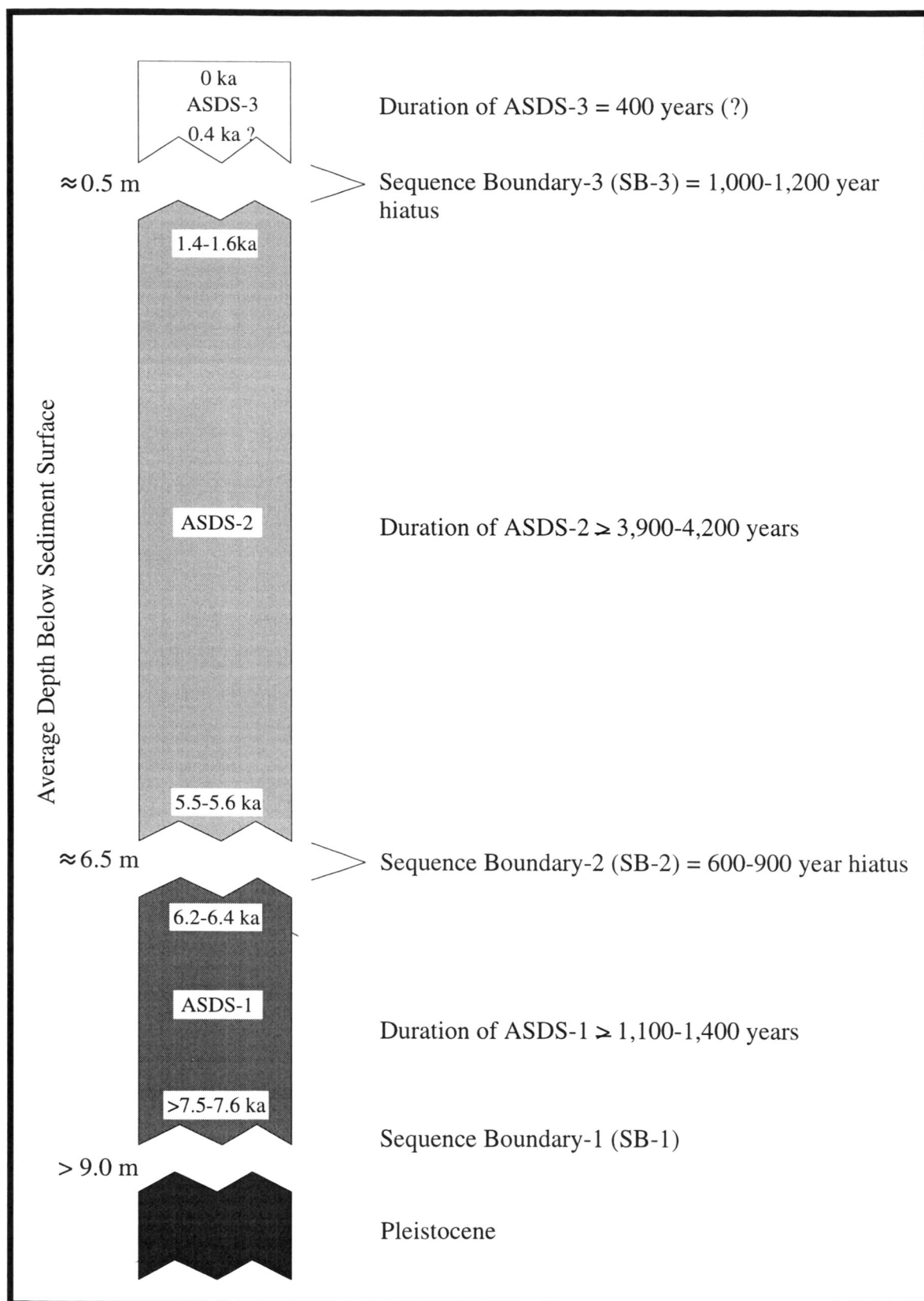
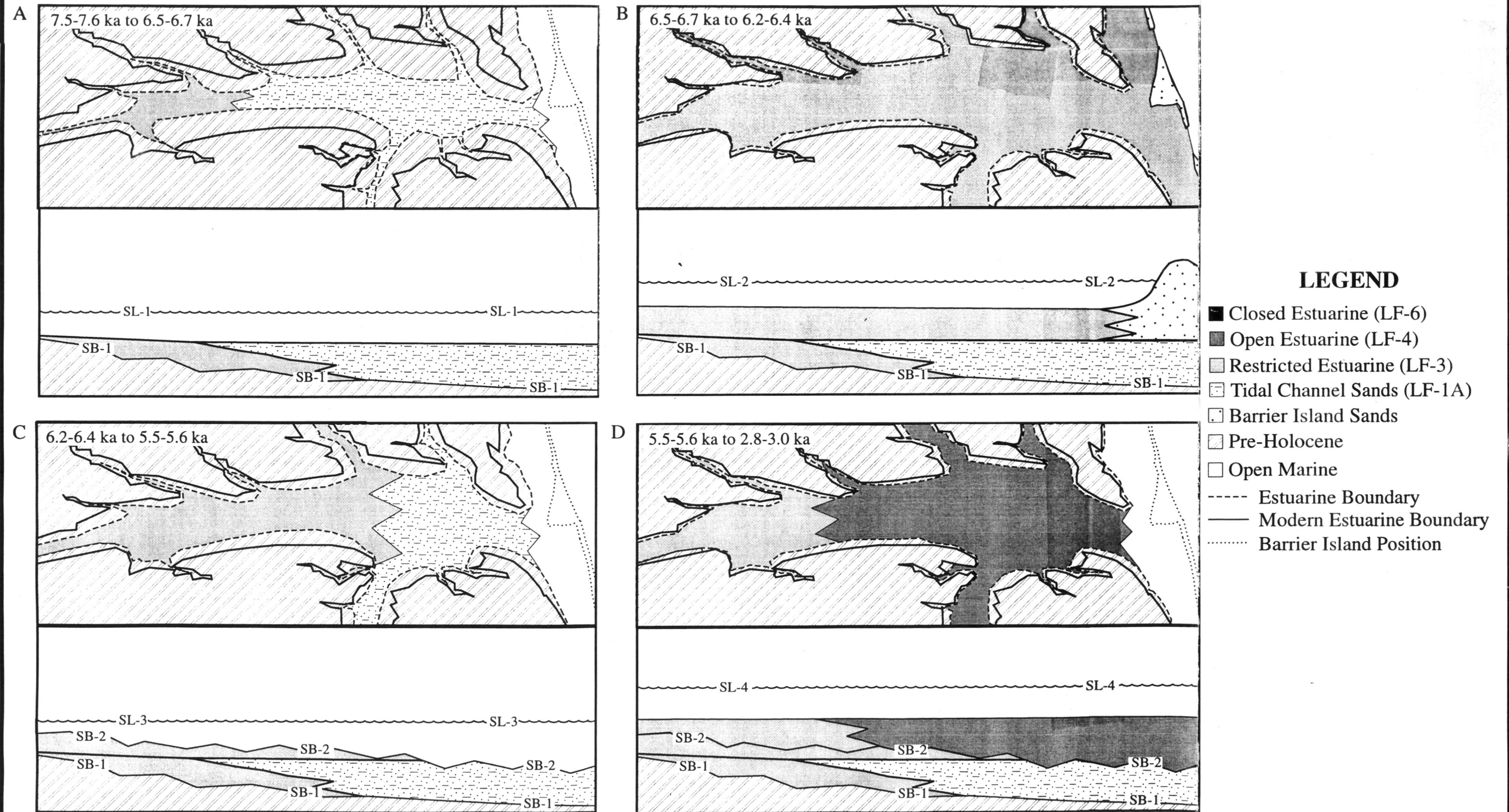
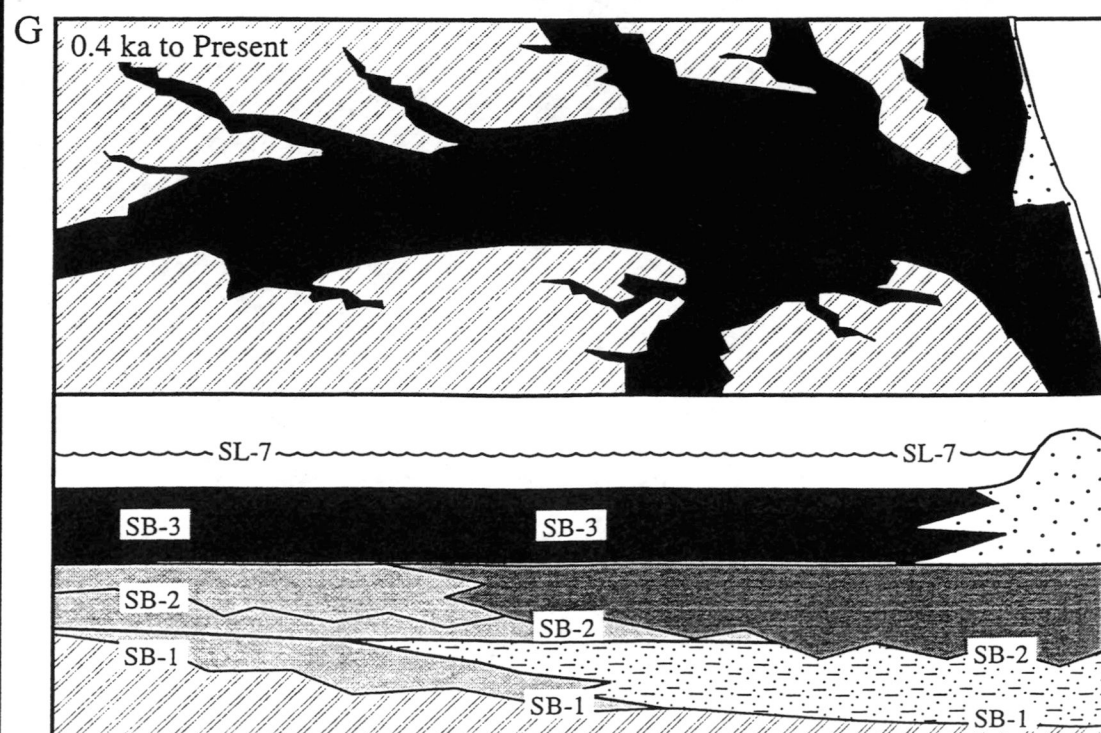
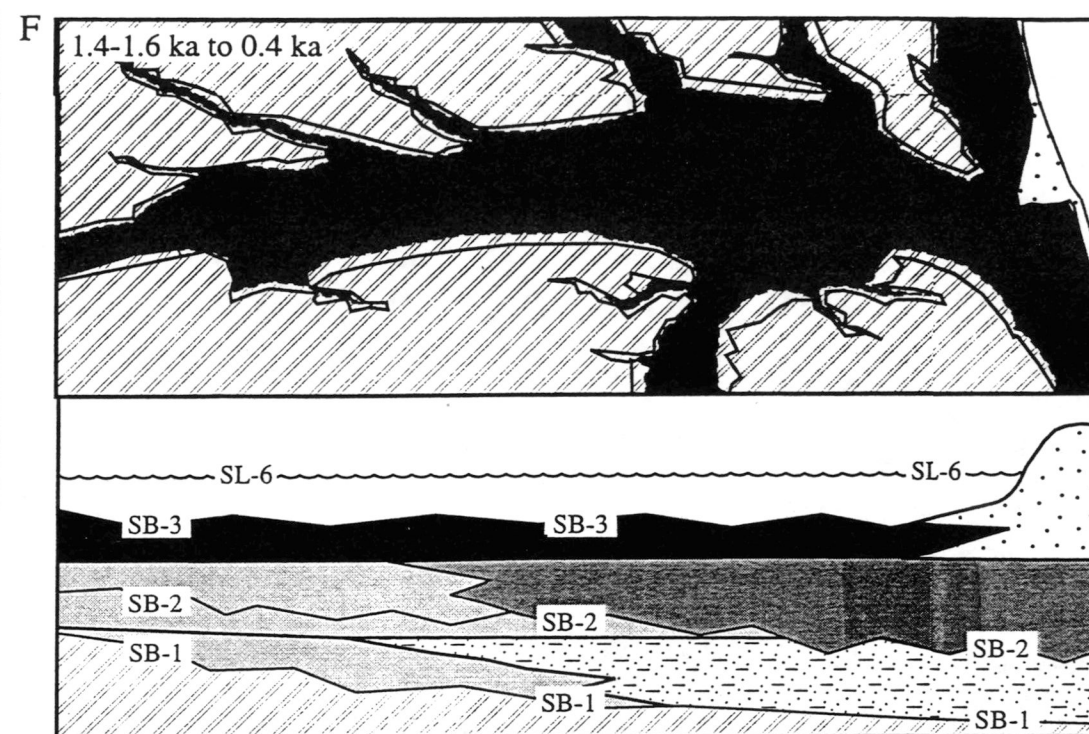
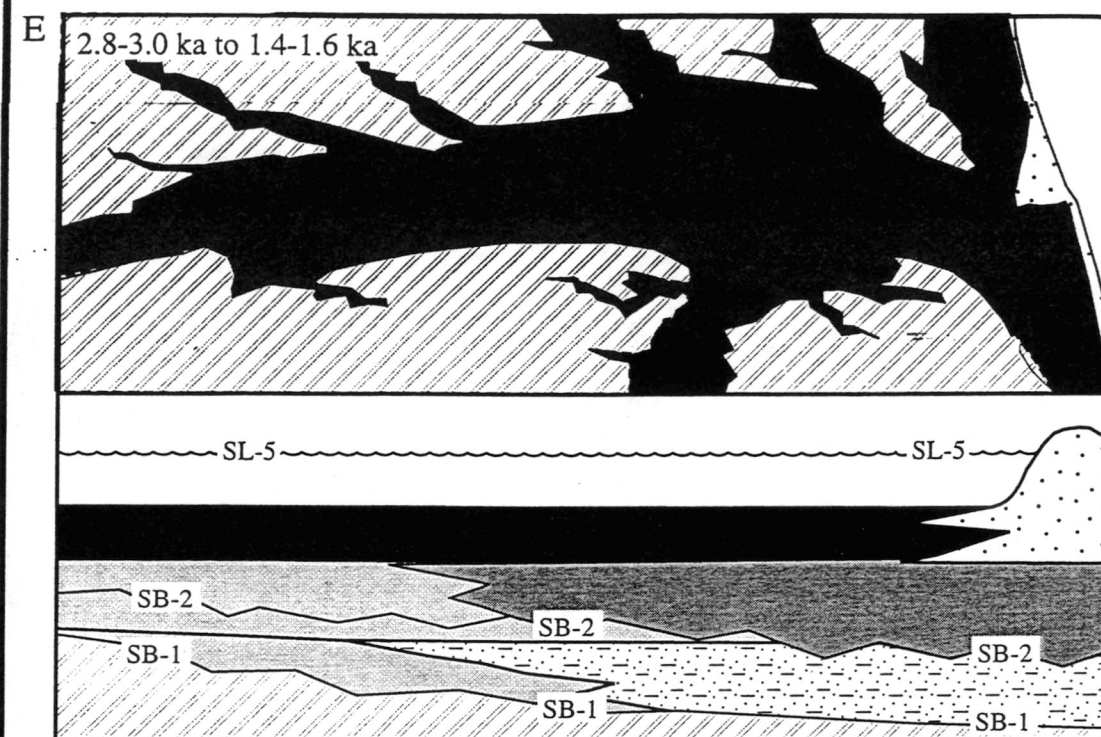


Table 10: Chronology and depositional history of the Albemarle Sound depositional sequences.

Depositional Sequence	Time Interval	Lithofacies	Environment	Barrier Island
ASDS-3	0.4 ka - Present	LF-6B	Closed-estuary	Continuous
ASDS-2	2.8-3.0 ka to 1.4-1.6 ka	LF-6A	Closed-estuary	Continuous
ASDS-2	5.5-5.6 ka to 2.8-3.0 ka	LF-1A LF-4 LF-5	Open-estuary with tidal channels and shoal complexes	Minimal/Absent
ASDS-1	6.5-6.7 ka to 6.2-6.4 ka	LF-1A	Open-estuary with tidal channels	Minimal/Absent
ASDS-1	> 7.5-7.6 ka to 6.5-6.7 ka	LF-3	Restricted-estuary	Partial

Figure 43: Schematic diagrams of the infill history of Albemarle Sound developed from the integrated seismic-, litho-, and chronostratigraphic model (ISLCM). Top panel in each time segment is the map view, whereas the bottom panel is the geologic cross section. (A) An open-estuarine system characterized by tidal channels (LF-1A) characterize the basal sediments of ASDS-1 in the outer-estuarine zone between 7.3 ka and 6.2 ka. ASDS-1 is incised into the underlying sediment along SB-1. (B) Sedimentation patterns changed about 6.2 ka from open- (LF-1A) to restricted-estuarine (LF-3) conditions in response to the emplacement of a barrier island system with few inlets that produced mesohaline conditions within the outer-estuarine zone. (C) A decline in sea level (< 6 m) between 5.2 ka and 4.7 ka produced an extensive erosional surface (SB-2) throughout the middle- and outer-estuarine zones. (D) Deposition resumed in outer Albemarle Sound by 4.7 ka with the formation of ASDS-2 under open-estuarine conditions that existed until 2.8 ka. This suggests that the barrier island previously developed between 6.2 ka and 5.5 ka had been either extensively breached or totally eliminated. (E) ASDS-2 is capped by organic-rich muds (LF-6A) deposited between 2.8 ka and 1.6 ka in a closed estuarine system behind a continuous barrier island complex. (F) Another slight drop (1-2 m) of sea level between 1.6 ka and 0.4 ka produced an erosional surface (SB-3) that truncated ASDS-1 and ASDS-2. (G) Deposition resumed (ASDS-3) in a closed-estuarine system (LF-6A). This suggests that the barrier island developed by 2.8 ka had not been abandoned by a drop in sea level nor destroyed by erosion.





LEGEND

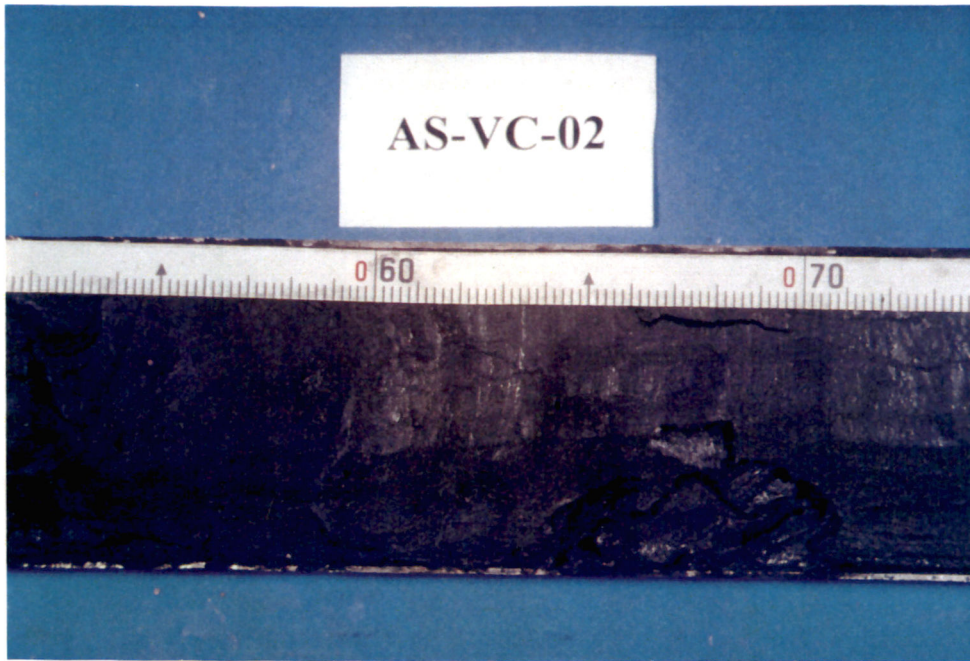
- Closed Estuarine (LF-6)
- Open Estuarine (LF-4)
- Restricted Estuarine (LF-3)
- ▨ Tidal Channel Sands (LF-1A)
- ▨ Barrier Island Sands
- ▨ Pre-Holocene
- Open Marine
- Estuarine Boundary
- Modern Estuarine Boundary
- Barrier Island Position

ASDS-1 and ASDS-2 represents a 600 to 900 year hiatus and occurs within 1.0 meter of the sediment-water interface (6.75 meters below sea level [MBSL]) within the middle Albemarle Sound and slopes eastward to 12.5 MBSL along profile B-B'. The seismic- and lithostratigraphic data do not reveal fluvial incision, oxidation, or pedogenesis along SB-2. Along C-C', SB-2 is recognized by a burrowed surface separating LF-6 from LF-3 (Figure 44), as well as a hiatus (Table 11). Along profile B-B', SB-2 is characterized by an abrupt change in lithology in which sediments of LF-3 are overlain by LF-4, a concentration of *Mulinia* disseminated within a 0.5 m zone at the base of LF-4 (Figure 45), and a hiatus (Table 12). This erosional surface is interpreted to represent a drop of sea level between 6.2-6.4 ka and 5.5-5.6 ka (Figure 43C). Sea level could not have fallen more than 6 m during this period because subaerial conditions conducive to fluvial incision and soil formation have not been recognized in the middle-estuarine zone. During the lowered sea level, the climate was probably colder with increased storminess in the mid-latitudes. Increased numbers and intensities of storm surge and wave energy, in combination with lowered sea level, would have eroded large portions (up to 6.5 m) of ASDS-1 and created SB-2.

Deposition resumed in outer Albemarle Sound by 5.5-5.6 ka with the formation of ASDS-2 under open-estuarine conditions that existed until 2.8-3.0 ka (Figure 43D). This suggests that the barrier island, interpreted to have been present between 6.5-6.7 ka and 6.2-6.4 ka, had been either extensively breached or totally eliminated. The shallow portions of the outer-estuarine zone were dominated by intertidal flats (LF-4) while an extensive network of migrating tidal channels (LF-1A) and shoal complexes (LF-5)

Figure 44: Sequence boundary-2 (SB-2) is recognized in the middle-estuarine zone (Profile C-C') by a burrowed surface separating LF-3 and LF-6.

(A)



(B)

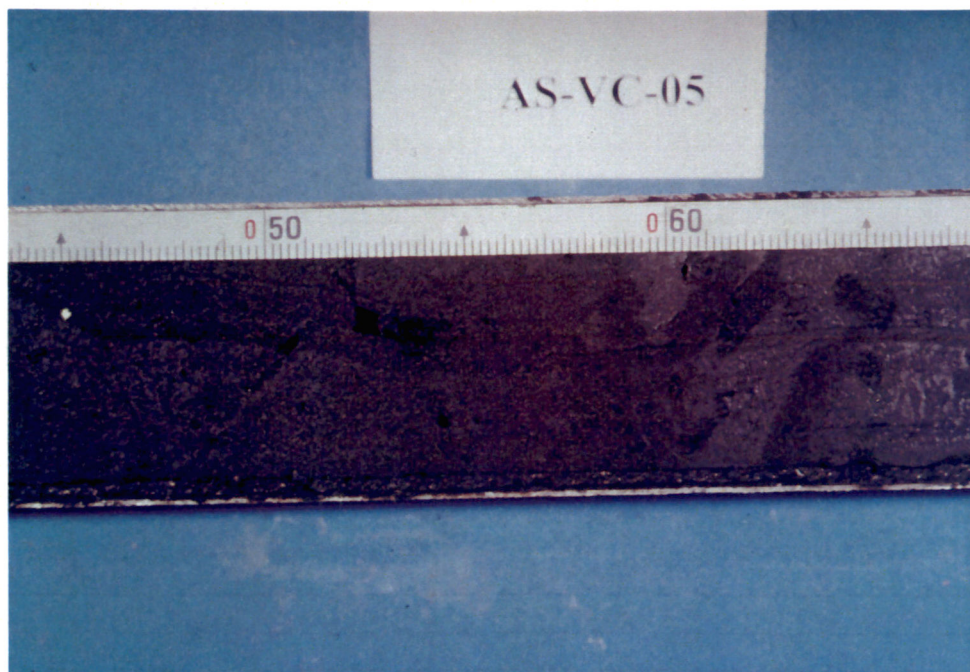
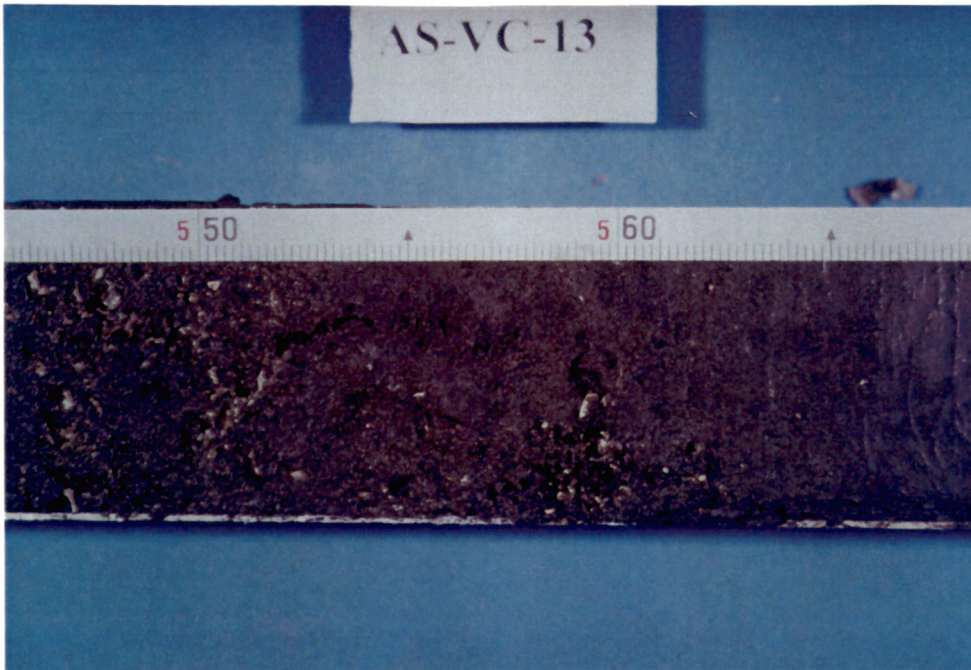


Table 11: Radiocarbon dates from the inner-estuarine zone (C-C') that demonstrate erosion has created a hiatus between ASDS-1 and ASDS-2.

Sample Number	Core Depth (m)	Lithofacies	Dep Seq	Material Dated	Calibrated C-14 Age (1 sigma)	Calibrated C-14 Age (2 sigma)
AS-VC-01	0.75-0.85	LF-4	ASDS-2	Organic-Rich Sed	3365-3480 BP	3330-3595 BP
AS-VC-01	1.05-1.15	LF-1	ASDS-1	Organic-Rich Sed	5770-5810 BP or 5885-5945 BP	5735-6030 BP
AS-VC-05	0.50-0.60	LF-4	ASDS-2	Organic-Rich Sed	3360-3475 BP	3265-3580 BP
AS-VC-05	0.70-0.80	LF-1	ASDS-1	Organic-Rich Sed	6875-7170 BP	6755-7215 BP

Figure 45: Sequence boundary-2 (SB-2) is characterized in the outer-estuarine zone (Profile B-B') by an abrupt change in lithology in which sediments of LF-3 are overlain by LF-4 and by a concentration of *Mulinia* disseminated within a 0.5 m zone at the base of LF-4.

(A)



(B)

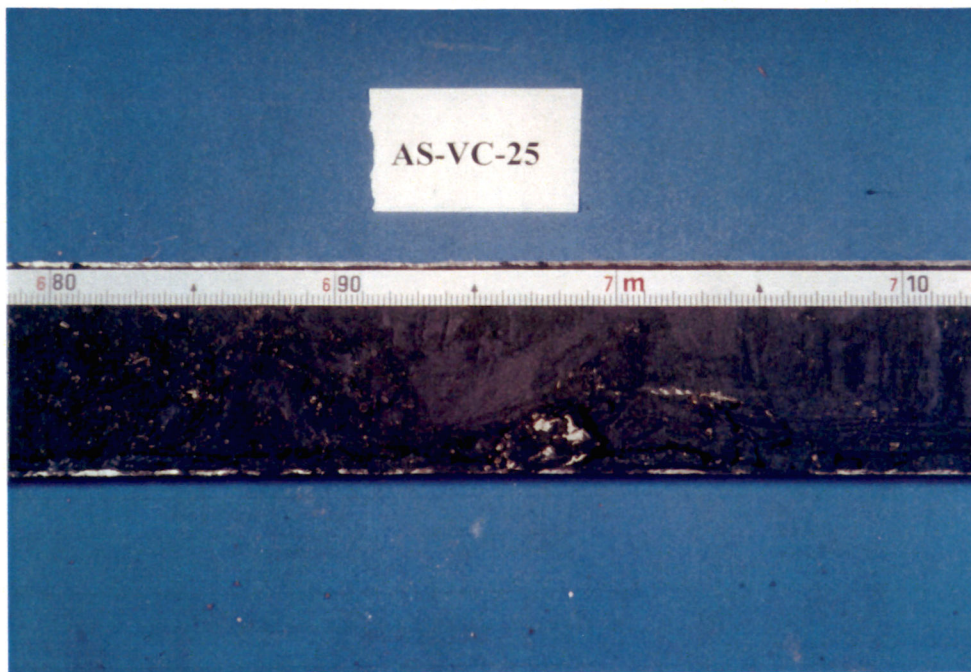


Table 12: Radiocarbon dates from the outer-estuarine zone (B-B') that demonstrate erosion has created a hiatus between ASDS-1 and ASDS-2.

Sample Number	Core Depth (m)	Lithofacies	Dep Seq	Material Dated	Calibrated C-14 Age (1 sigma)	Calibrated C-14 Age (2 sigma)
AS-VC-12	5.80-5.90	LF-3	ASDS-2	Organic-Rich Sed	5080-5115 BP or 5130-5170 BP or 5270-5330 BP or 5395-5445 BP	5020-5480 BP 5530-5565 BP
AS-VC-12	7.53-7.63	LF-1	ASDS-1	Organic-Rich Sed	6280-6420 BP	6185-6500 BP
AS-VC-18	2.75-2.85	LF-2	ASDS-2	<i>Tegulus</i>	4125-4405 BP	3975-4525 BP
AS-VC-18	3.78-3.88	LF-1	ASDS-1	Organic-Rich Sed	7385-7515 BP	7295-7540 BP
AS-VC-25	6.95-7.05	LF-2	ASDS-2	<i>Cyrtopleura</i>	4975-5290 BP	4835-5440 BP
AS-VC-25	7.05-7.15	LF-1	ASDS-1	Organic-Rich Sed	7970-8140 BP	7930-8195 BP

characterized the central basin. ASDS-2 is capped by organic-rich muds of LF-6A that were deposited between 2.8-3.0 ka and 1.4-1.6 ka in the outer-estuarine zone (Figure 43E). LF-6A was deposited in response to the formation of a continuous barrier island complex by 2.8-3.0 ka that produced closed-estuarine conditions similar to those of the modern system.

ASDS-3 consists of a veneer (average thickness = 0.5 m) of organic-rich mud sediment (LF-6B) that occurs everywhere in the central basin and truncates ASDS-1 and ASDS-2. ASDS-3 can not be resolved seismically, but the sequence boundary (SB-3 at 6.0 MBSL) separating ASDS-3 from ASDS-1 and ASDS-2 is recognized by a dramatic change in the 1) sediment density and 2) heavy metal concentration (Riggs *et al*, 1993). ASDS-3 is composed of sediments of LF-6B and is interpreted to represent < 400 years of deposition. Radiocarbon dates below SB-3 range from 1415-1570 years BP (ASDS-2) to 6210-6420 years BP (ASDS-1) and indicate that erosion has removed up to 1,000 years of the estuarine record. This erosional surface is interpreted to represent another slight drop (1 to 2 meters) of Holocene sea level for some portion of the interval between 1.4-1.6 ka and 0.4 ka (Figure 43F). After 0.4 ka deposition resumed in the outer Albemarle Sound in a closed-estuarine system (Figure 43G). This suggests that the barrier island developed by 2.8-3.0 ka had neither been abandoned by a major drop in sea level nor destroyed by erosion based on the absence of an open-estuarine facies in ASDS-3. Thus, the drop in sea level was probably no more than 1 to 2 m, allowing for the erosion of the previously deposited sediments in the shallow basin. Sediments of ASDS-3 are currently being

deposited by the ongoing Holocene transgression behind a continuous barrier island system.

SUMMARY

Comparison of the LM and ISLCM yields different interpretations of the infill history of Albemarle Sound. The lithostratigraphic model reveals that Albemarle Sound consists of six lithofacies and supports the hypothesis that sea-level has risen continuously throughout the Holocene. However, the integrated seismic-, litho-, and chronostratigraphic model demonstrates that the Holocene transgression has been characterized by several, low-amplitude sea-level oscillations that resulted in basinwide unconformities and produced a succession of similar lithofacies. A more detailed coastal history can be developed from the ISLCM because the interpretation is based upon several lines of evidence. The lithostratigraphy is utilized to interpret depositional environments, and the seismic sequence stratigraphy provides a relative chronological framework that is used to differentiate between lithologically correlative units. Radiocarbon dating establishes an absolute chronology and provides another method of distinguishing between depositional sequences with similar lithologies. Development of the ISLCM indicates that a more detailed approach is needed to resolve the complex coastal record preserved in incised, valley-fill systems.

CONCLUSIONS

1. The lithostratigraphic framework of Albemarle Sound consists of six lithofacies.
 - a) The quartz sand lithofacies (LF-1) backfills channel complexes and consists of two subfacies: LF-1A and LF-1B. LF-1A is slightly muddy, very fine- to fine-grained

sand with dispersed mud laminae with abundant brackish-water microfossils suggesting deposition within tidal channels. LF-1B consists of very clean, fine- to medium-grained sands with heavy mineral laminations, mud drapes, and convoluted bedding characteristic of fluvial systems.

- b) The peat lithofacies (LF-2) is associated with fluvial sediments of LF-1B and was deposited in swamp forests associated with these fluvial environments.
- c) The laminated mud lithofacies (LF-3) consists of layers of very fine- to fine-grained sand in a mud matrix. LF-3 was deposited in a restricted-estuarine environment under mesohaline conditions. Sand layers were formed from sediments eroded from Pleistocene sediment banks and accumulated as thin veneers of sand that settled from suspension following storm events. The absence of sand layers in the modern environment (LF-6B) may be explained, in part, by bioturbation and circulation in the closed-estuarine environment of modern Albemarle Sound.
- d) The fossiliferous, muddy sand lithofacies (LF-4) is characterized by abundant *Cyrtopleura* and *Tagelus* that inhabited an extensive open-estuarine intertidal environment along the margins of Albemarle Sound.
- e) The interlaminated mud and sand lithofacies (LF-5) is characterized by flaser bedding that results from alternating energy conditions associated with tidal processes. The sand is deposited during ebb and flood conditions while the mud laminae are deposited during quiescent conditions of slack tides. LF-5 was

deposited by the lateral migration of tidal channels and associated shoal complexes within the central basin of Albemarle Sound.

- f) The organic-rich mud lithofacies (LF-6) occurs throughout the central basin of Albemarle Sound. LF-6 consists of a modern, surficial sediment (LF-6B) that rests upon older sediments of LF-6A. Both LF-6A and LF-6B were deposited in a closed-estuarine environment in response to the establishment of a well-developed, continuous barrier island system.
2. Utilizing the lithostratigraphy, alone, the Holocene infill history of Albemarle Sound appears to show a westward migration of depositional environments resulting from a continuous Holocene transgression. Basal sediments (LF-3) were deposited in the inner-most estuarine environment during the initial marine flooding of the paleo-Roanoke River. As sea level continued to rise, open-estuarine environments migrated westward depositing sediments of LF-4 upon LF-3. Emplacement of a dissected barrier island initiated restricted-estuarine conditions during which time LF-5 was deposited. The entire sequence is capped by organic-rich muds (LF-6) that were deposited under restricted estuarine conditions formed by the development of a continuous barrier island complex.
3. High-resolution seismic reflection surveys reveal that the shallow subsurface of Albemarle Sound is dominated by numerous channel complexes that truncate the underlying stratigraphy. The channels occur as both isolated and multiple, stacked channel structures with seismic facies consisting of reflectors that are either chaotic, planar inclined, concave-up, and absent. Channels characterized by chaotic and planar

inclined reflectors are backfilled with fluvial sediments (LF-1B), whereas channels with no internal reflectors or concave-up reflectors were formed by tidal processes.

4. Integration of litho-, chrono-, and seismic-stratigraphy provides the basis for a different approach than the traditional lithostratigraphic method. The integrated seismic-, litho-, and chronostratigraphic model reveals that the Holocene section of Albemarle Sound consists of three depositional sequences that resulted from several, low-amplitude sea-level fluctuations during the Holocene transgression.
 - a) The oldest depositional sequence (ASDS-1) was formed between 7.5-7.6 ka and 6.2-6.4 ka. Basal sediments of ASDS-1 were deposited in an open-estuarine environment (LF-1A) that existed until 6.5-6.7 ka.
 - b) Sedimentation patterns changed from open- to restricted-estuarine conditions (LF-3) at 6.5-6.7 ka in response to the emplacement of a partial barrier island system.
 - c) Between 6.2-6.4 and 5.5-5.6 ka, a decline in sea level (< 6 m) produced an extensive erosional surface that extends throughout the middle- and outer-estuarine zones and separates ASDS-1 and ASDS-2.
 - d) As sea level began to rise the basal sediments of ASDS-2 were deposited in an open-estuarine system that prevailed between 5.5-5.6 ka and 2.8-3.0 ka. This suggests that the previous barrier island complex created between 6.5-6.7 ka and 6.2-6.4 ka had been breached or destroyed.
 - e) From 2.8-3.0 ka to 1.4-1.6 ka closed-estuarine conditions existed within outer Albemarle Sound in response to the re-establishment of a continuous barrier island complex.

- f) Another small drop (1-2 m) of sea level occurred between 1.4-1.6 ka and 0.4 ka causing the erosion and truncation of both ASDS-1 and ASDS-2.
- g) Deposition resumed in the outer-estuarine zone by 0.4 ka in a closed-estuarine environment. The absence of open-estuarine sediments indicates that the barrier island system was not abandoned or destroyed during the previous drop in sea level or subsequent transgression. Rather, it probably underwent a progradational episode during the regression. Modern sediments of ASDS-3 are currently being deposited by the Holocene marine transgression behind a continuous barrier island complex.

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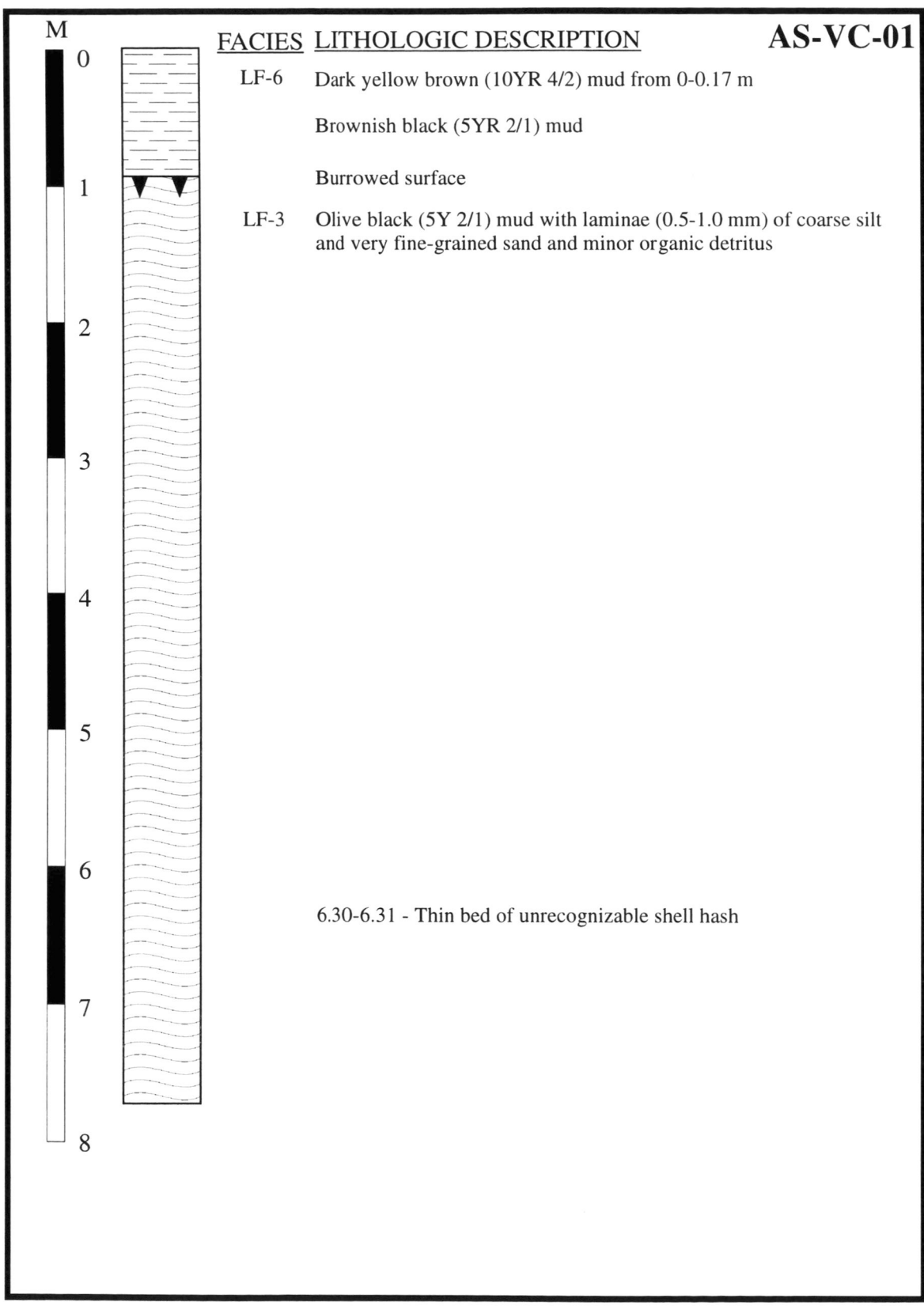
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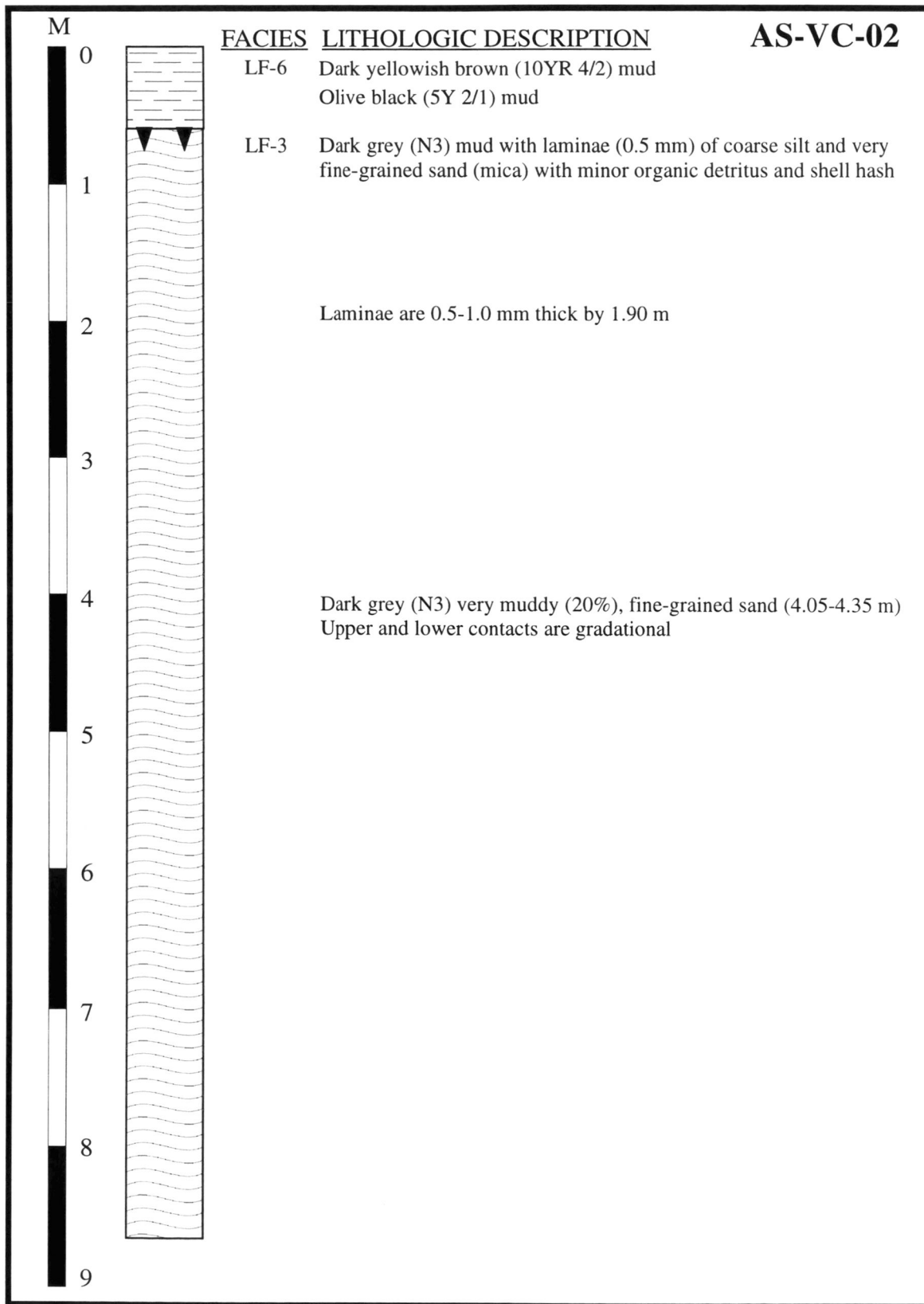
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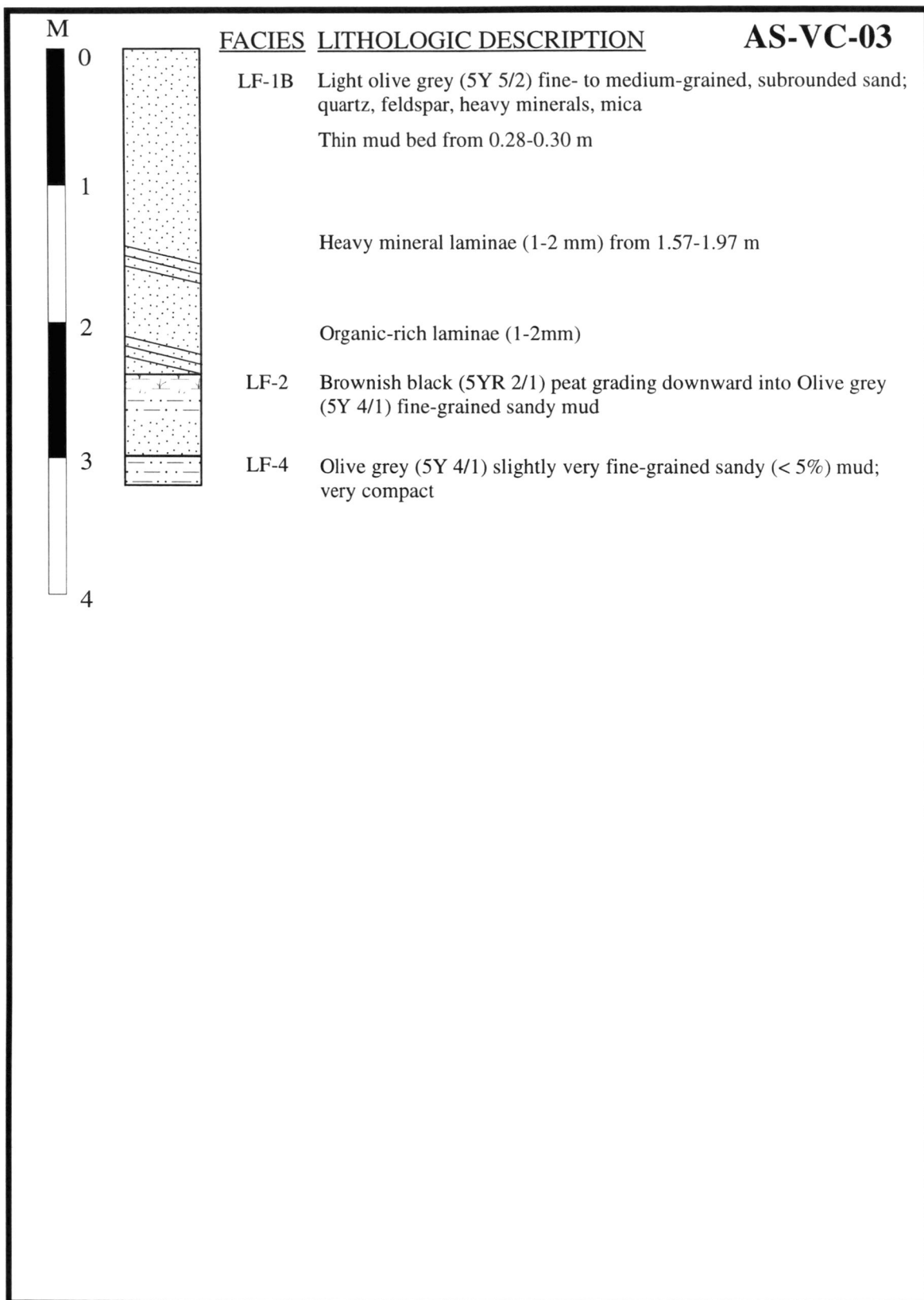
Appendix A: Vibracore Positions and Conventional Radiocarbon Ages

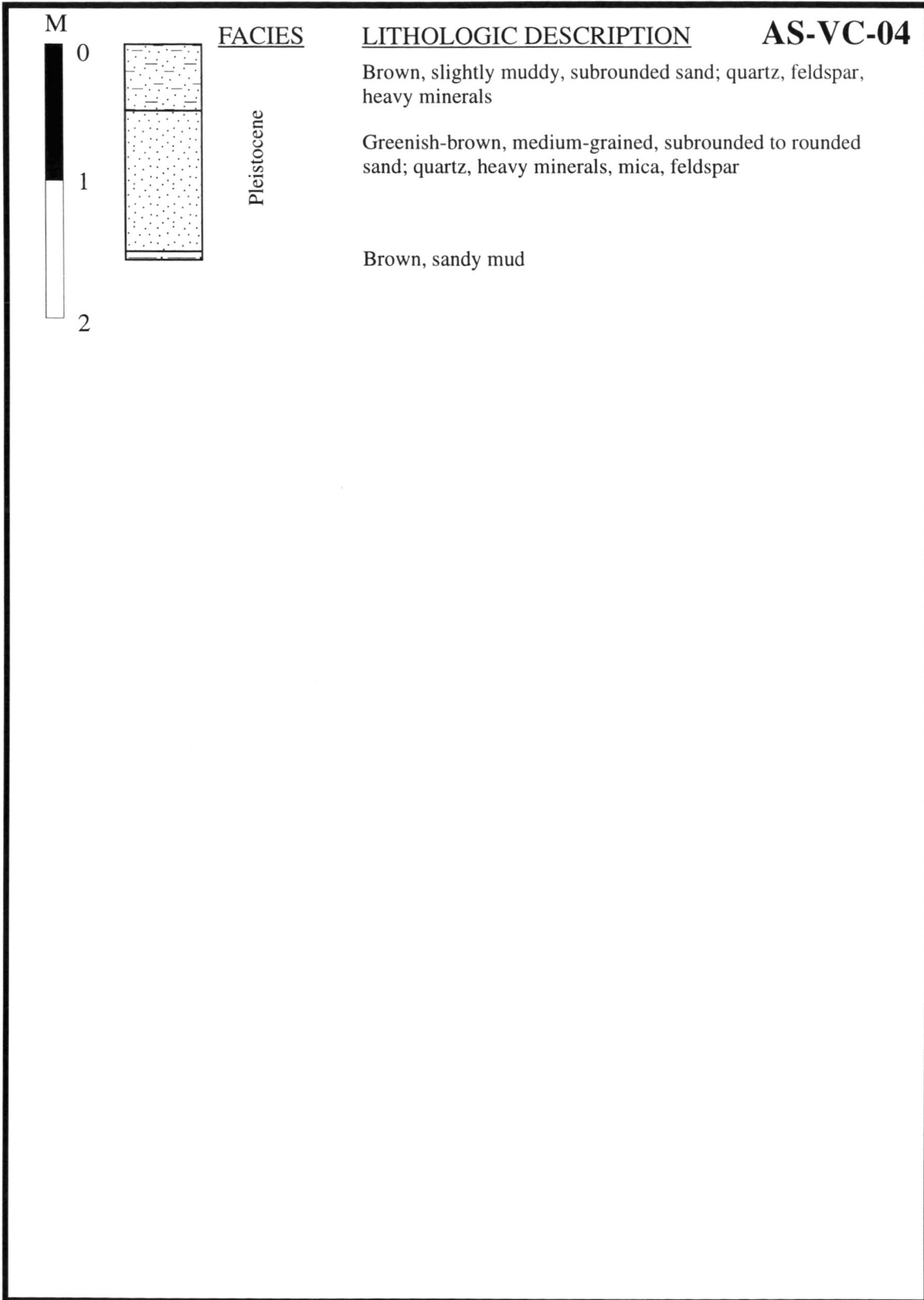
Sample Number	Core Depth (m)	Water Depth (m)	Location (Lat/Long)	Lithofacies	Dep Seq	Material Dated	Conventional C-14 Age
AS-VC-01	0.75-0.85	6.4	36.02.260 / 76.22.508	LF-6	ASDS-2	Organic-Rich Sed	3220 +/- 70
AS-VC-01	1.05-1.15	6.4	36.02.260 / 76.22.508	LF-3	ASDS-1	Organic-Rich Sed	5150 +/- 70
AS-VC-01	7.80-7.90	6.4	36.02.260 / 76.22.508	LF-3	ASDS-1	Organic-Rich Sed	5990 +/- 90
AS-VC-03	2.42-2.47	5.5	36.00.203 / 76.23.043	Pre-Holo	Pre-Holo	Peat	21360 +/- 140
AS-VC-05	0.50-0.60	6.1	36.00.953 / 76.22.799	LF-6	ASDS-2	Organic-Rich Sed	3210 +/- 70
AS-VC-05	0.70-0.80	6.1	36.00.953 / 76.22.799	LF-3	ASDS-1	Organic-Rich Sed	6130 +/- 100
AS-VC-08	3.98-4.03	5.5	36.01.099 / 76.04.508	LF-2	Pre-Holo	Organic-Rich Sed	23800 +/- 1000
AS-VC-10	0.15-0.25	5.5	36.01.417 / 76.04.504	LF-6	ASDS-2	Organic-Rich Sed	2090 +/- 80
AS-VC-12	1.53-1.63	6.1	36.04.497 / 76.04.457	LF-3	ASDS-2	Organic-Rich Sed	4160 +/- 80
AS-VC-12	2.82-2.87	6.1	36.04.497 / 76.04.457	LF-5	ASDS-2	Organic-Rich Sed	5320 +/- 160
AS-VC-12	5.80-5.90	6.1	36.04.497 / 76.04.457	LF-5	ASDS-2	Organic-Rich Sed	4600 +/- 80
AS-VC-12	7.53-7.63	6.1	36.04.497 / 76.04.457	LF-3	ASDS-1	Organic-Rich Sed	5550 +/- 90
AS-VC-12	8.45-8.50	6.1	36.04.497 / 76.04.457	LF-3	ASDS-1	<i>Crassostrea</i>	5730 +/- 80
AS-VC-13	0.23-0.33	6.1	36.04.043 / 76.04.505	LF-6	ASDS-2	Organic-Rich Sed	1630 +/- 70
AS-VC-13	1.53-1.63	6.1	36.04.043 / 76.04.505	LF-3	ASDS-2	Organic-Rich Sed	4750 +/- 80
AS-VC-16	0.22-0.32	5.2	36.06.607 / 76.04.493	LF-6	ASDS-1	Organic-Rich Sed	5530 +/- 110
AS-VC-16	2.15-2.25	5.2	36.06.607 / 76.04.493	LF-6	ASDS-1	Organic-Rich Sed	6470 +/- 260
AS-VC-16*	4.02	5.2	36.06.607 / 76.04.493	LF-1B	ASDS-1	Wood	6150 +/- 60
AS-VC-16	4.07-4.17	5.2	36.06.607 / 76.04.493	Pre-Holo	Pre-Holo	Organic-Rich Sed	> 37480
AS-VC-18	0.18-0.28	5.8	36.02.809 / 76.04.466	LF-6	ASDS-2	Organic-Rich Sed	2810 +/- 60
AS-VC-18	0.37	5.8	36.02.809 / 76.04.466	LF-5/LF-6	ASDS-2	<i>Crassostrea</i>	2470 +/- 60
AS-VC-18	2.75-2.85	5.8	36.02.809 / 76.04.466	LF-4	ASDS-2	<i>Tagelus</i>	3790 +/- 90
AS-VC-18	8.78-8.88	5.8	36.02.809 / 76.04.466	LF-3	ASDS-1	Organic-Rich Sed	6580 +/- 70
AS-VC-23*	3.38-3.48	5.5	36.02.030 / 76.04.560	LF4	ASDS-2	<i>Cyrtopleura</i>	4450 +/- 40
AS-VC-23	4.26-4.36	5.5	36.02.030 / 76.04.560	Pre-Holo	Pre-Holo	Organic-Rich Sed	> 25950
AS-VC-25	1.40-1.50	6.0	36.03.394 / 76.04.542	LF-6	ASDS-2	Organic-Rich Sed	4720 +/- 80
AS-VC-25	5.30-5.55	6.0	36.03.394 / 76.04.542	LF-4	ASDS-2	<i>Mercenaria</i>	3200 +/- 50
AS-VC-25	6.95-7.05	6.0	36.03.394 / 76.04.542	LF-4	ASDS-2	<i>Cyrtopleura</i>	4450 +/- 100
AS-VC-25	7.05-7.15	6.0	36.03.394 / 76.04.542	LF-3	ASDS-1	Organic-Rich Sed	7310 +/- 80
AS-VC-25	8.35-8.45	6.0	36.03.394 / 76.04.542	LF-3	ASDS-1	Organic-Rich Sed	6760 +/- 70
AS-VC-27	4.30-4.35	4.7	36.04.260 / 76.22.496	LF-2	ASDS-1	Peat	6000 +/- 80

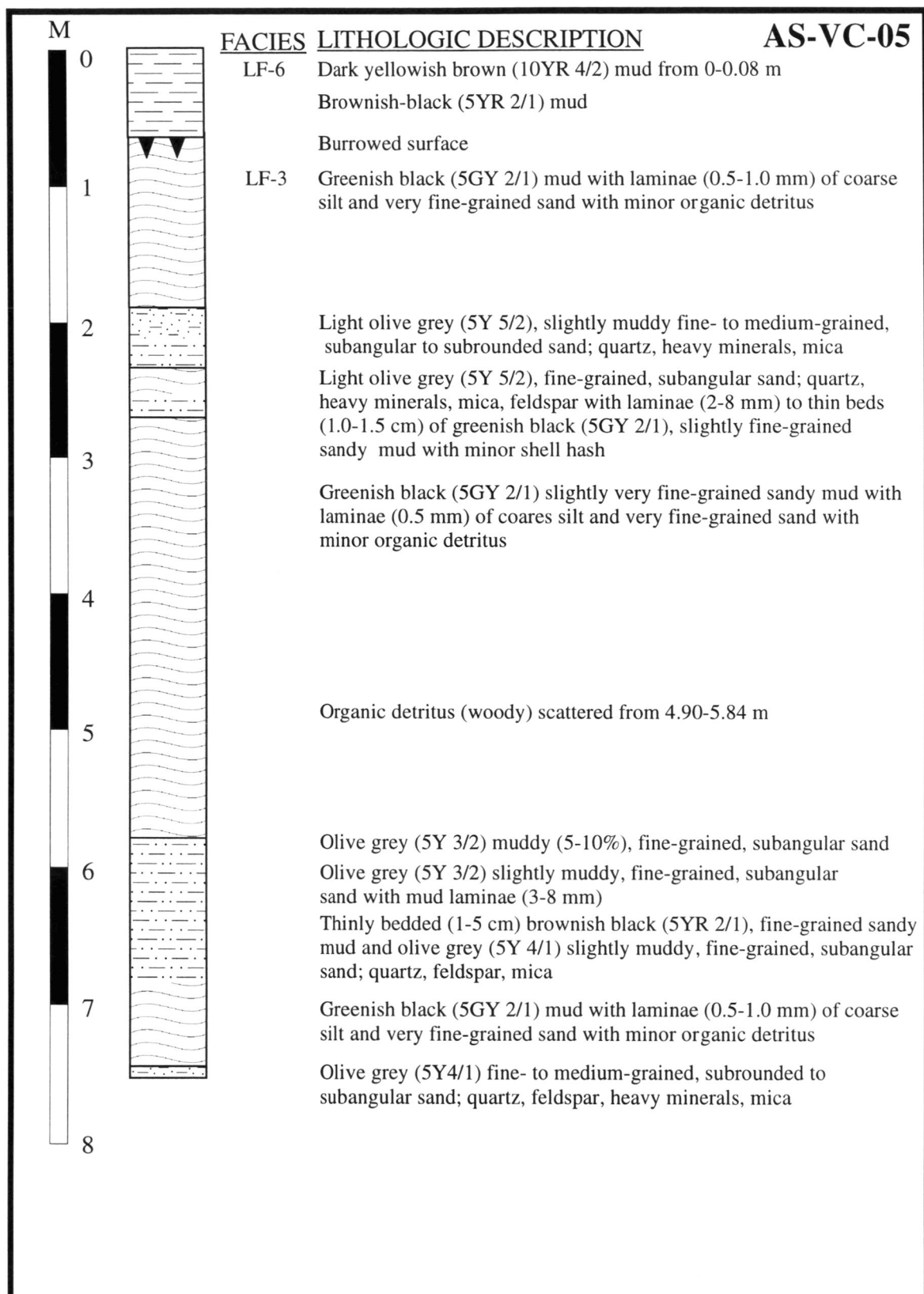
Appendix B: Lithologic Logs

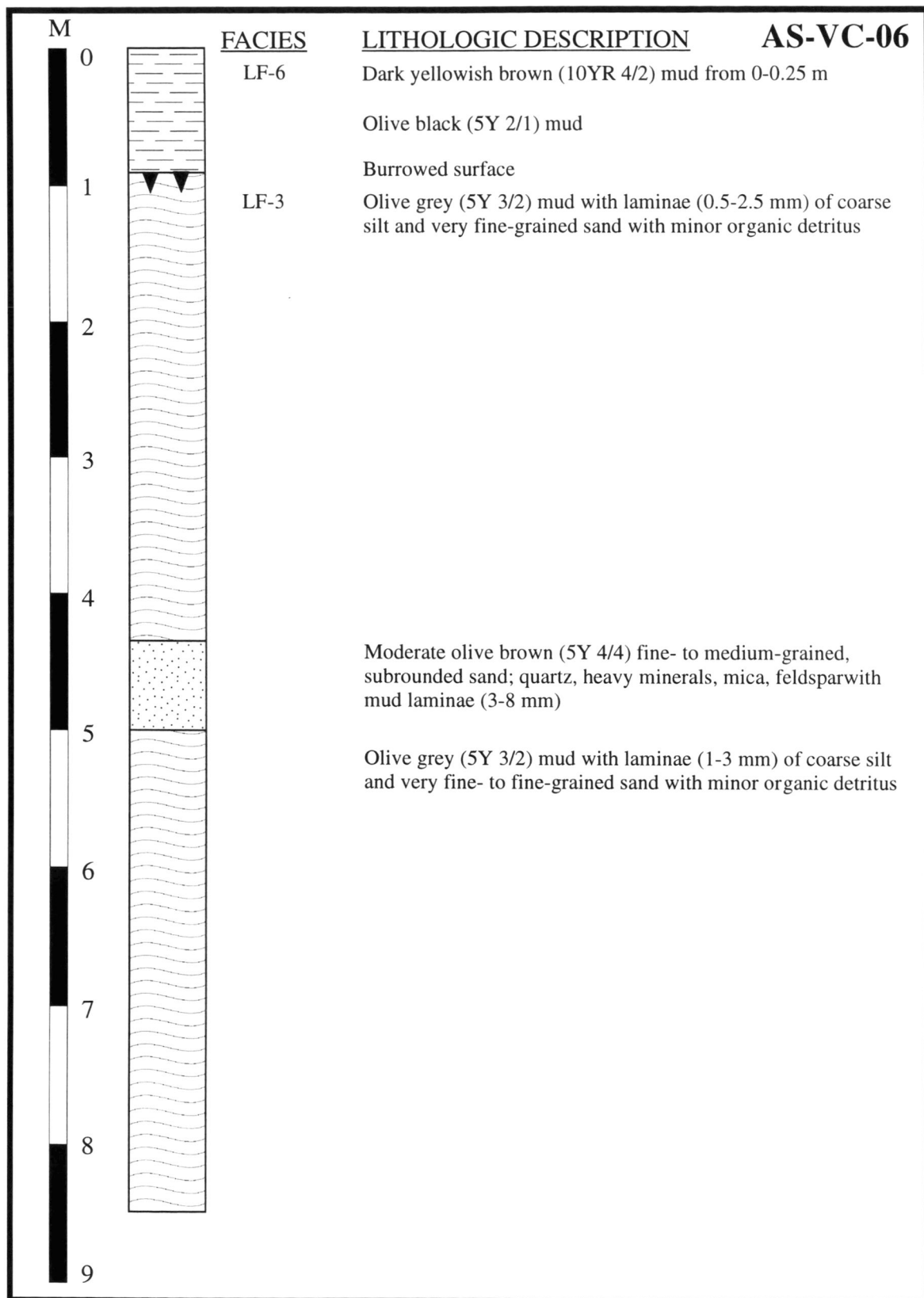


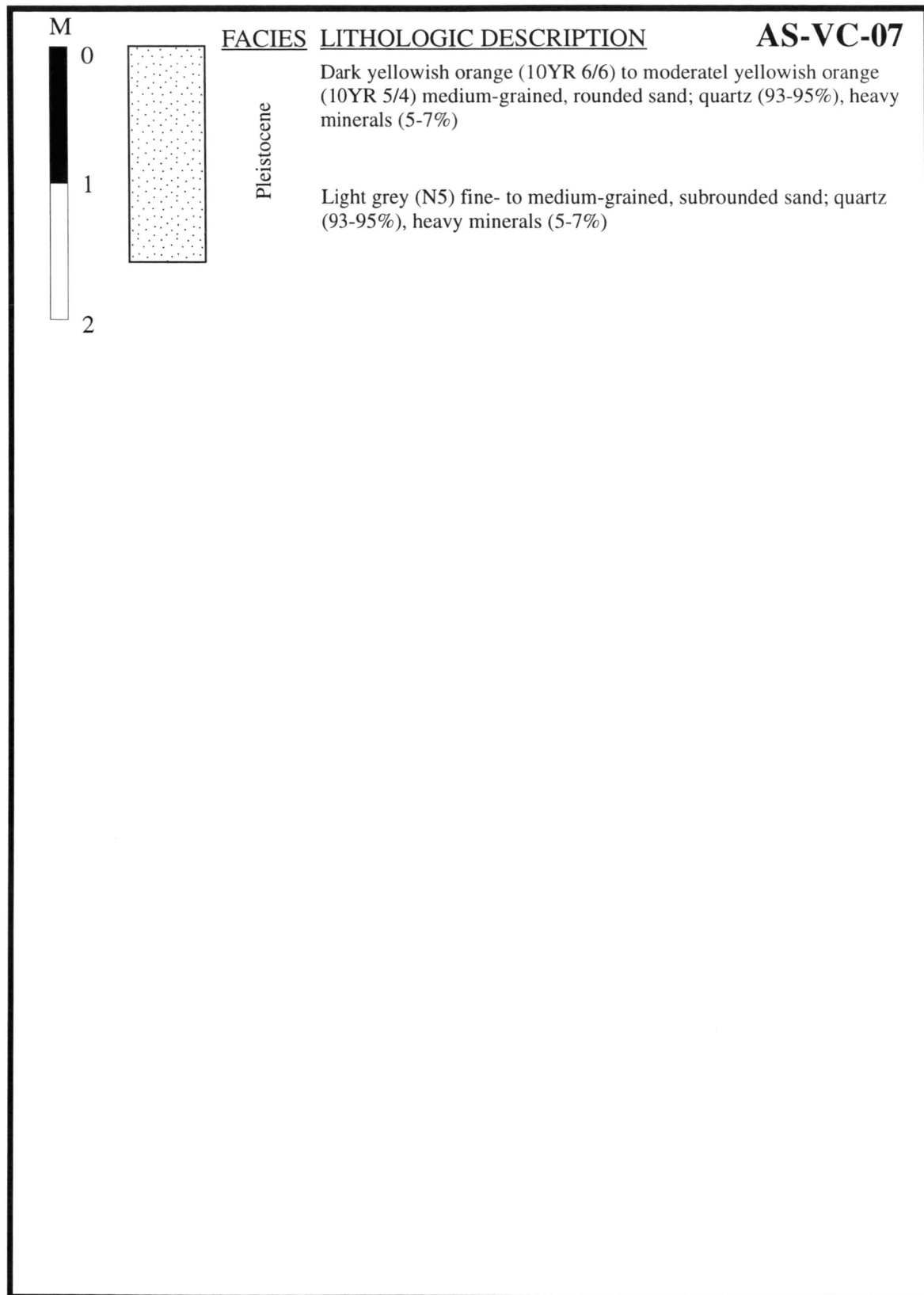


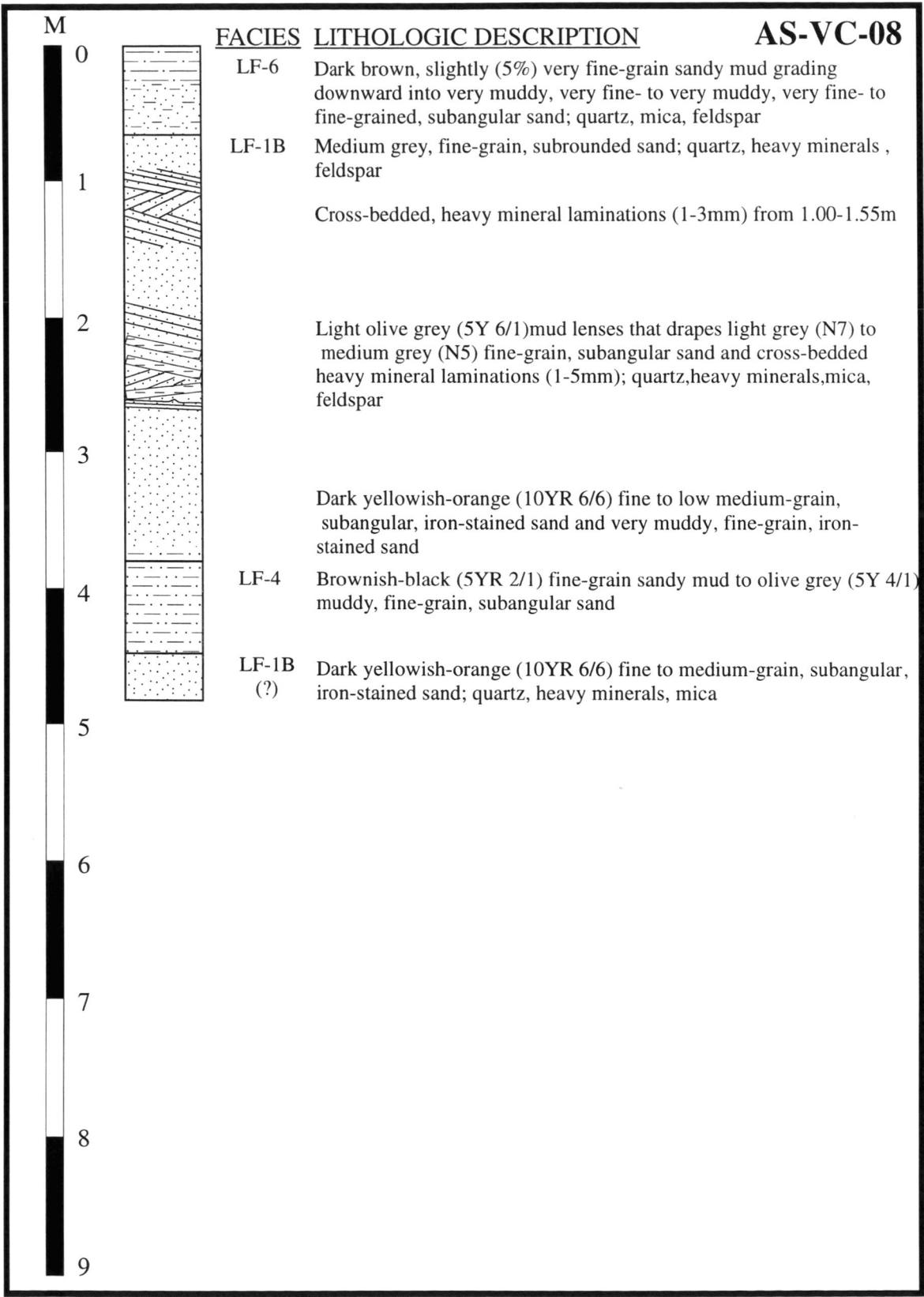


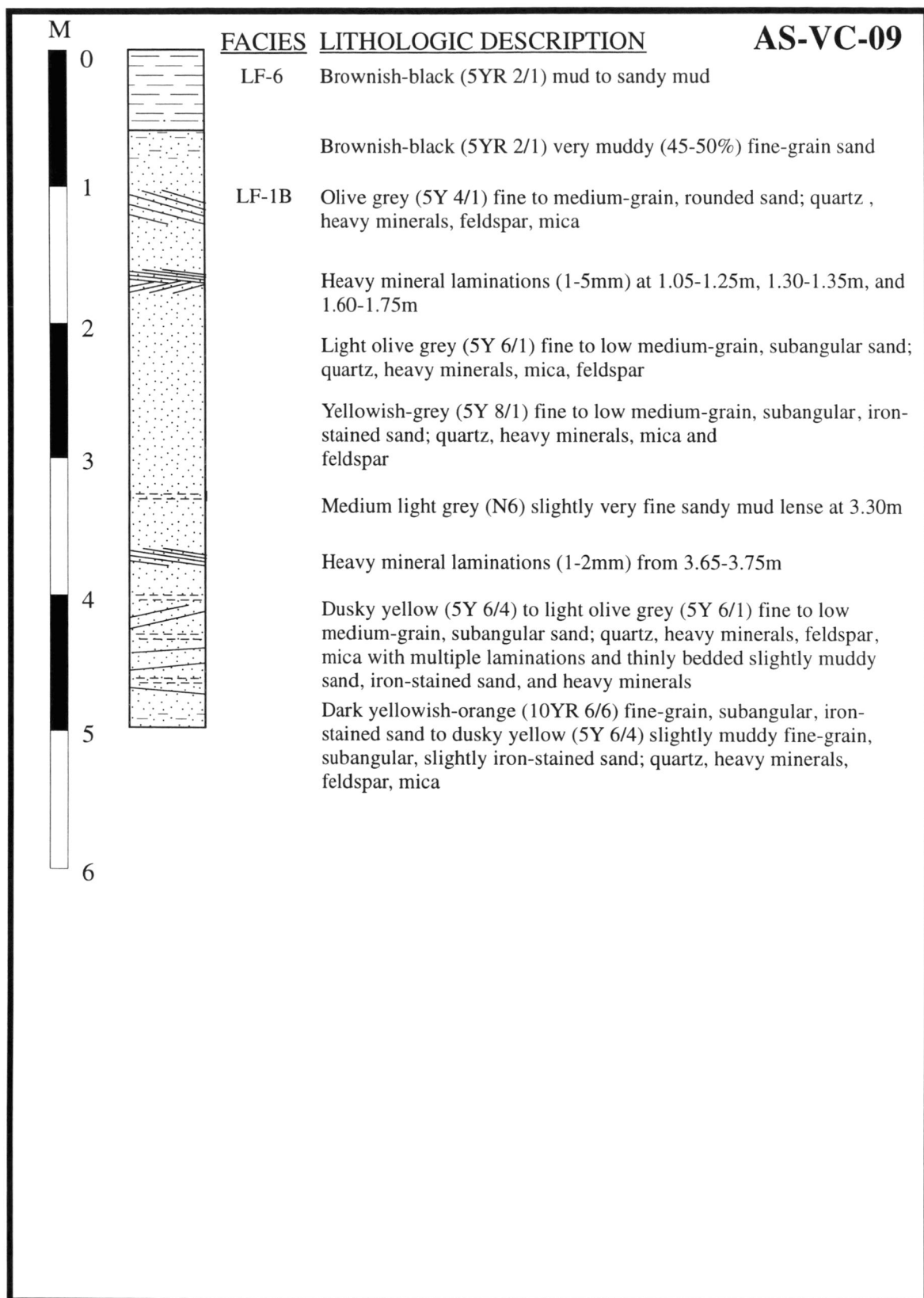


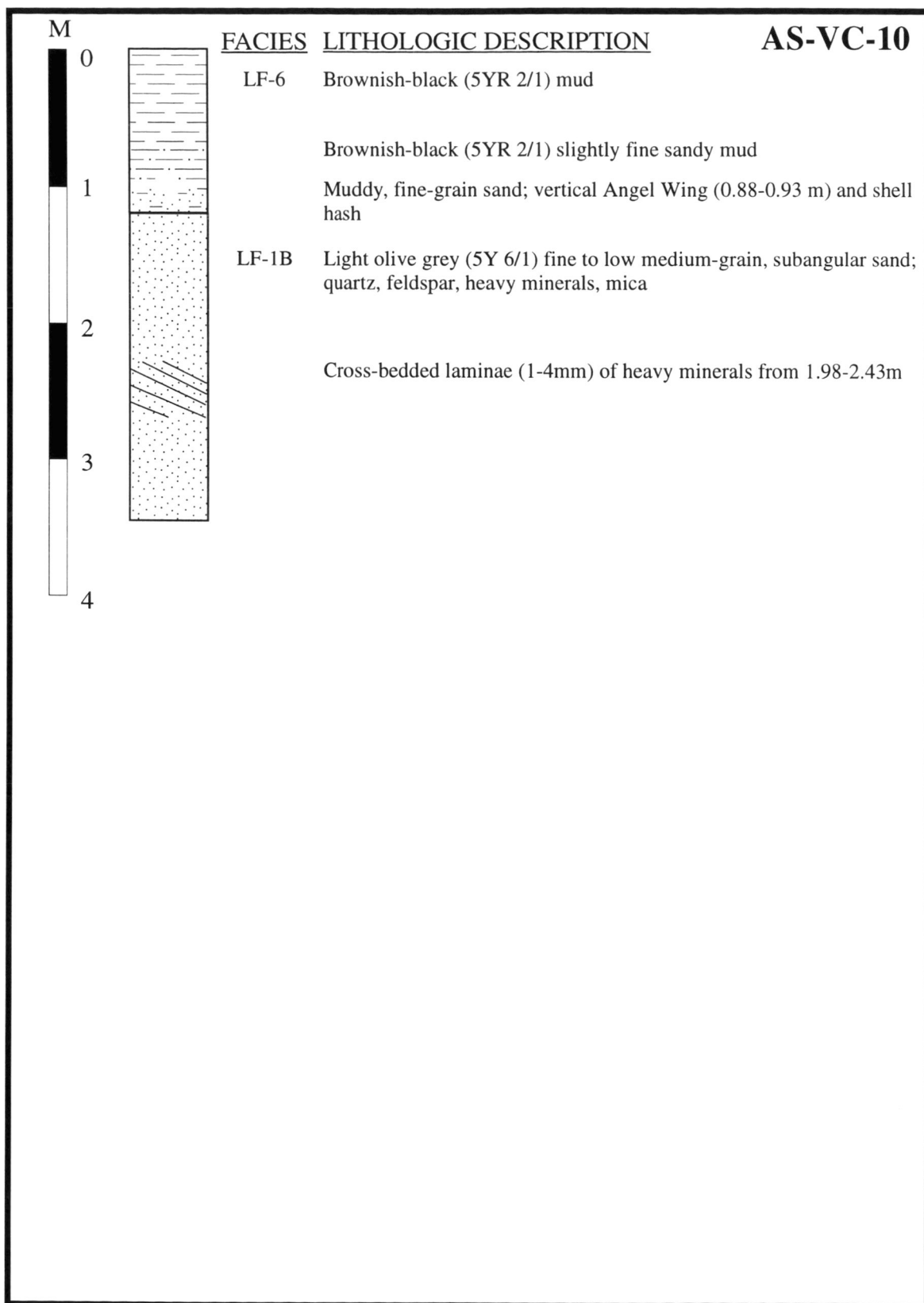




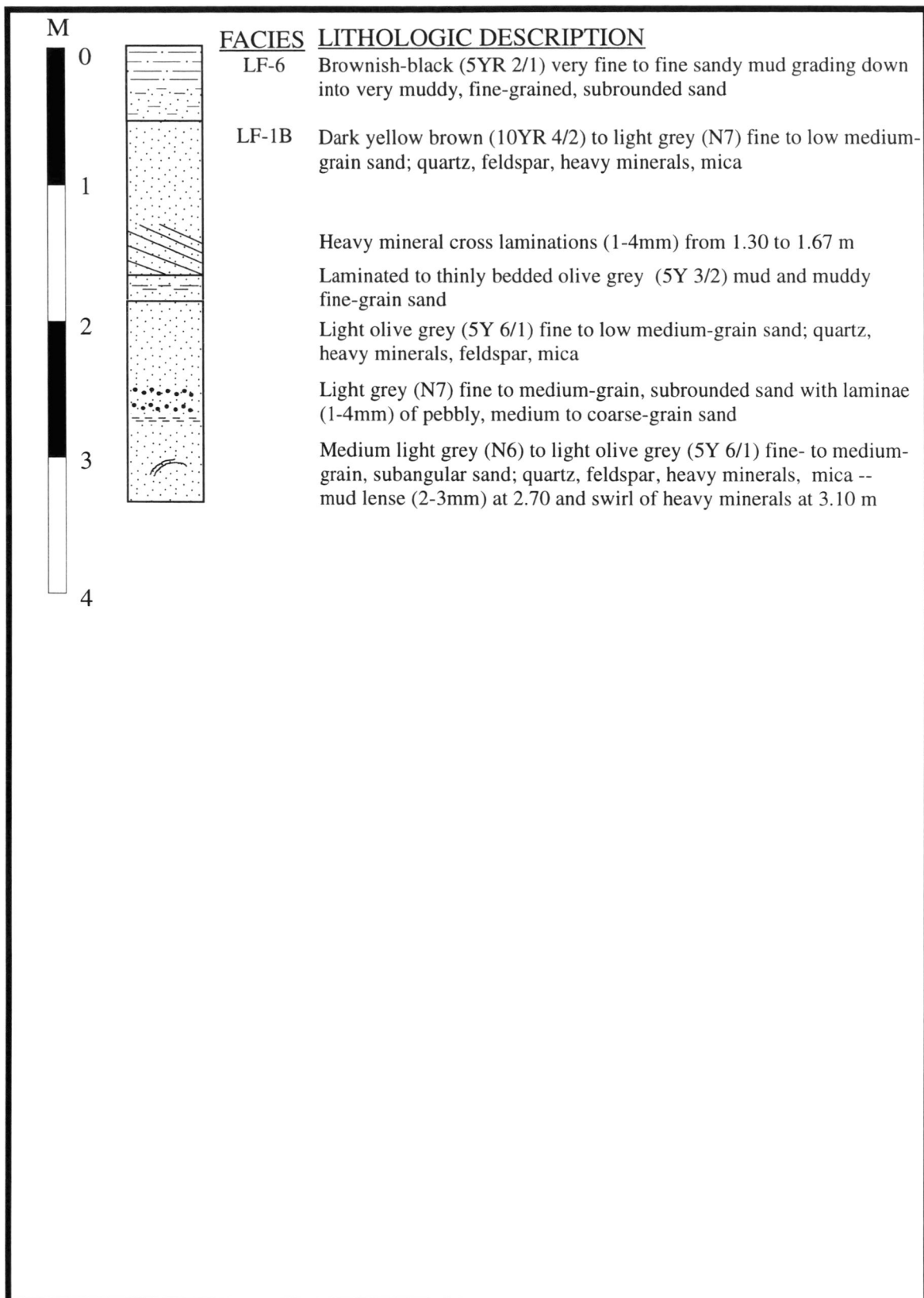


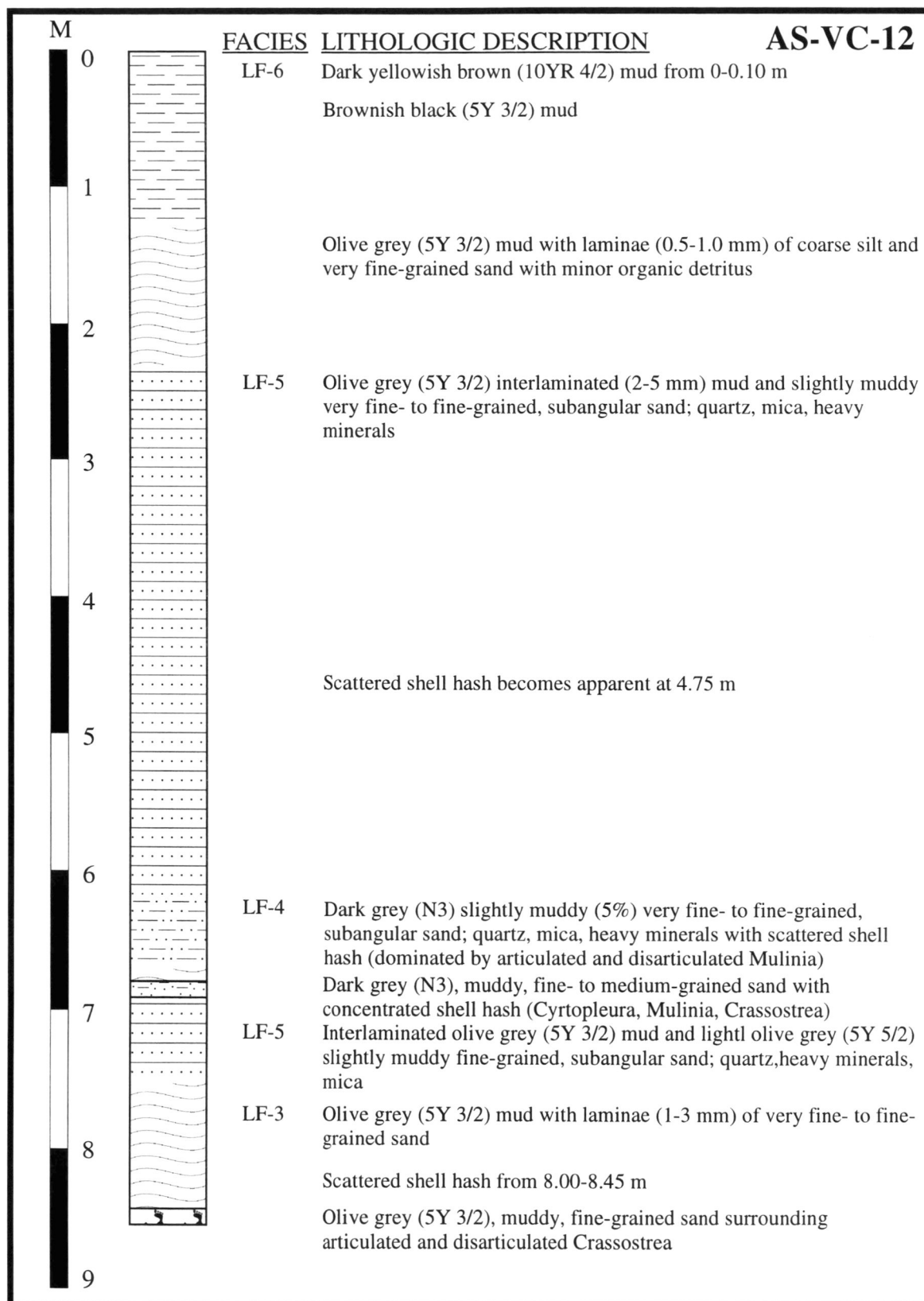


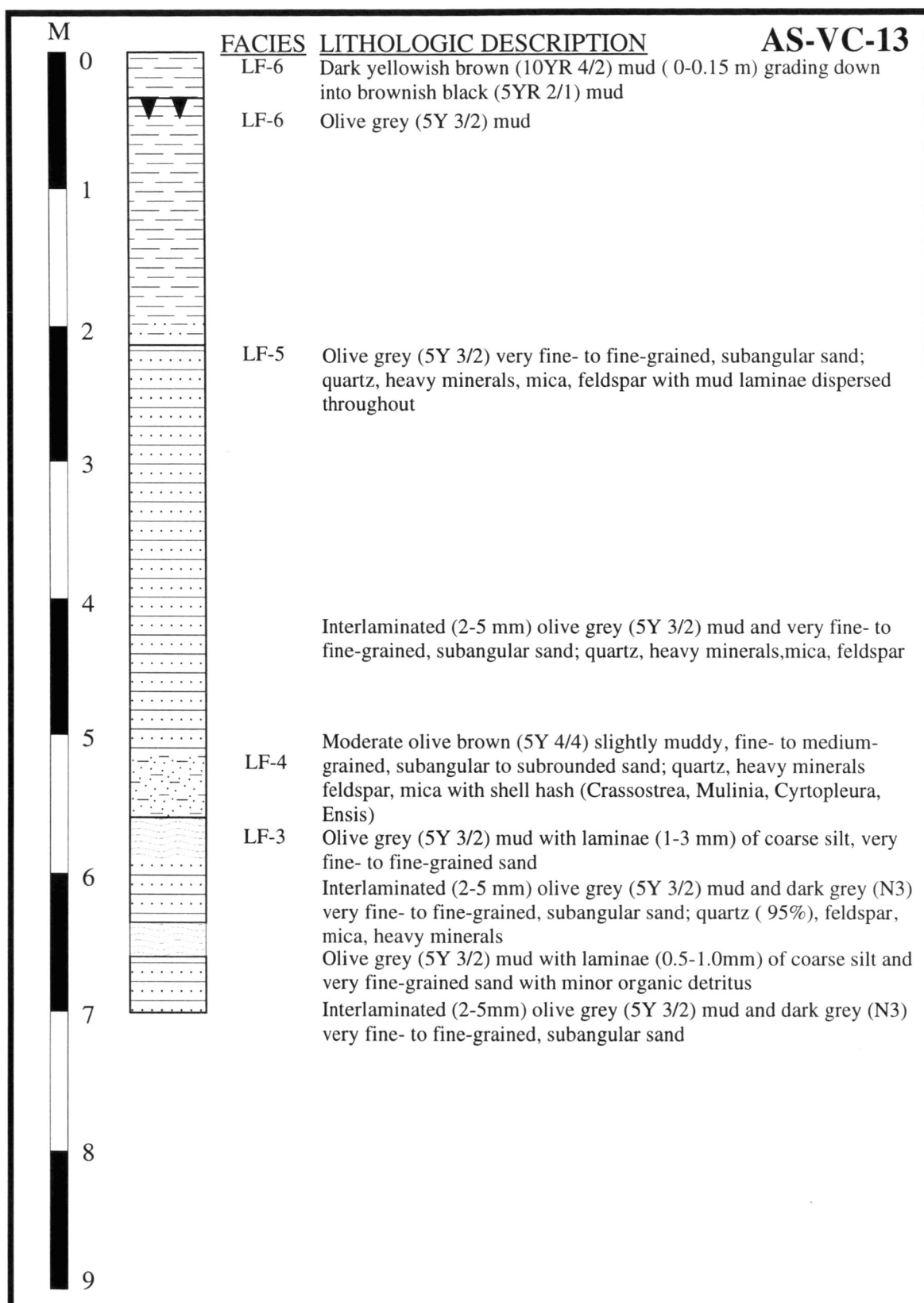


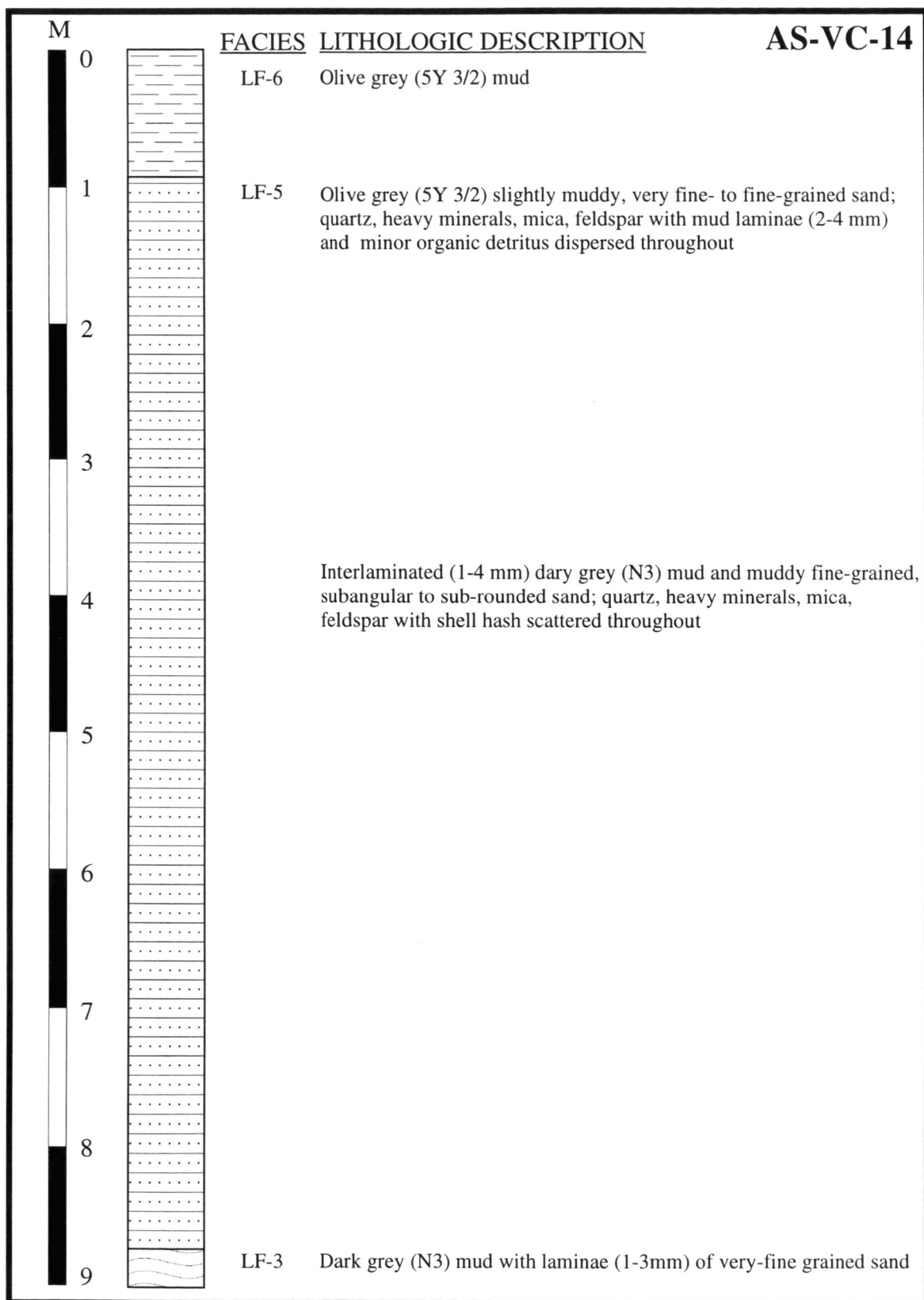


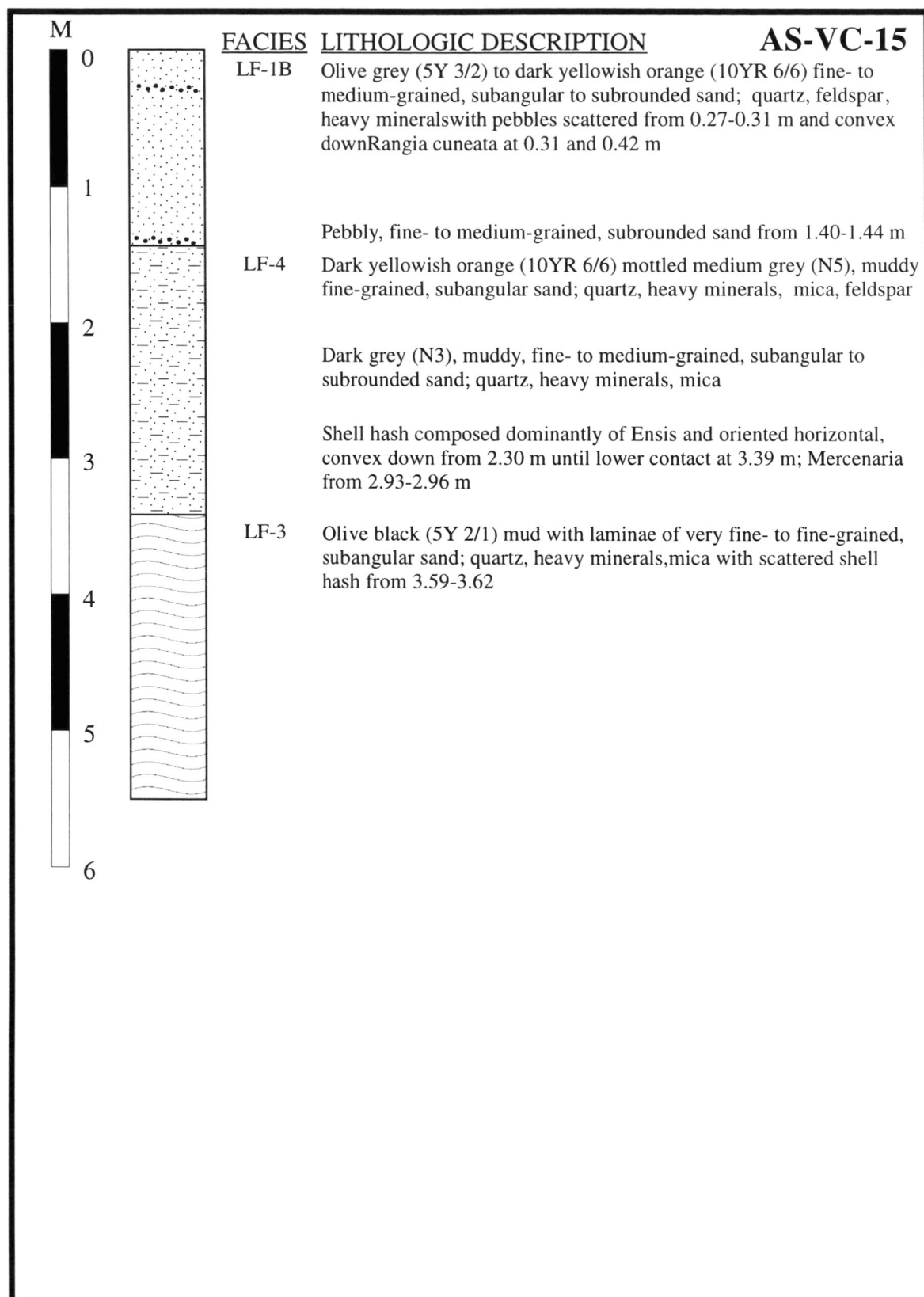
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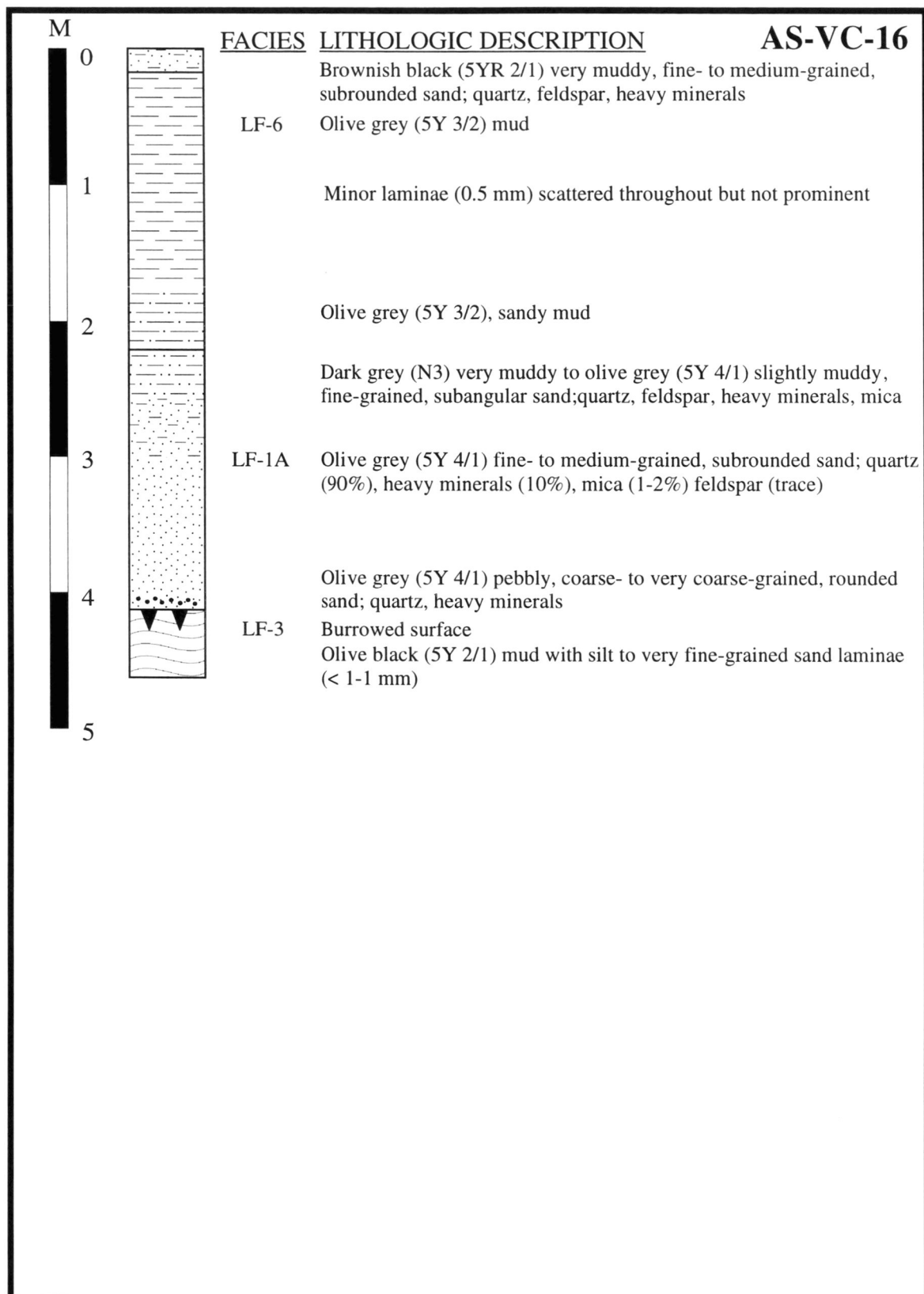


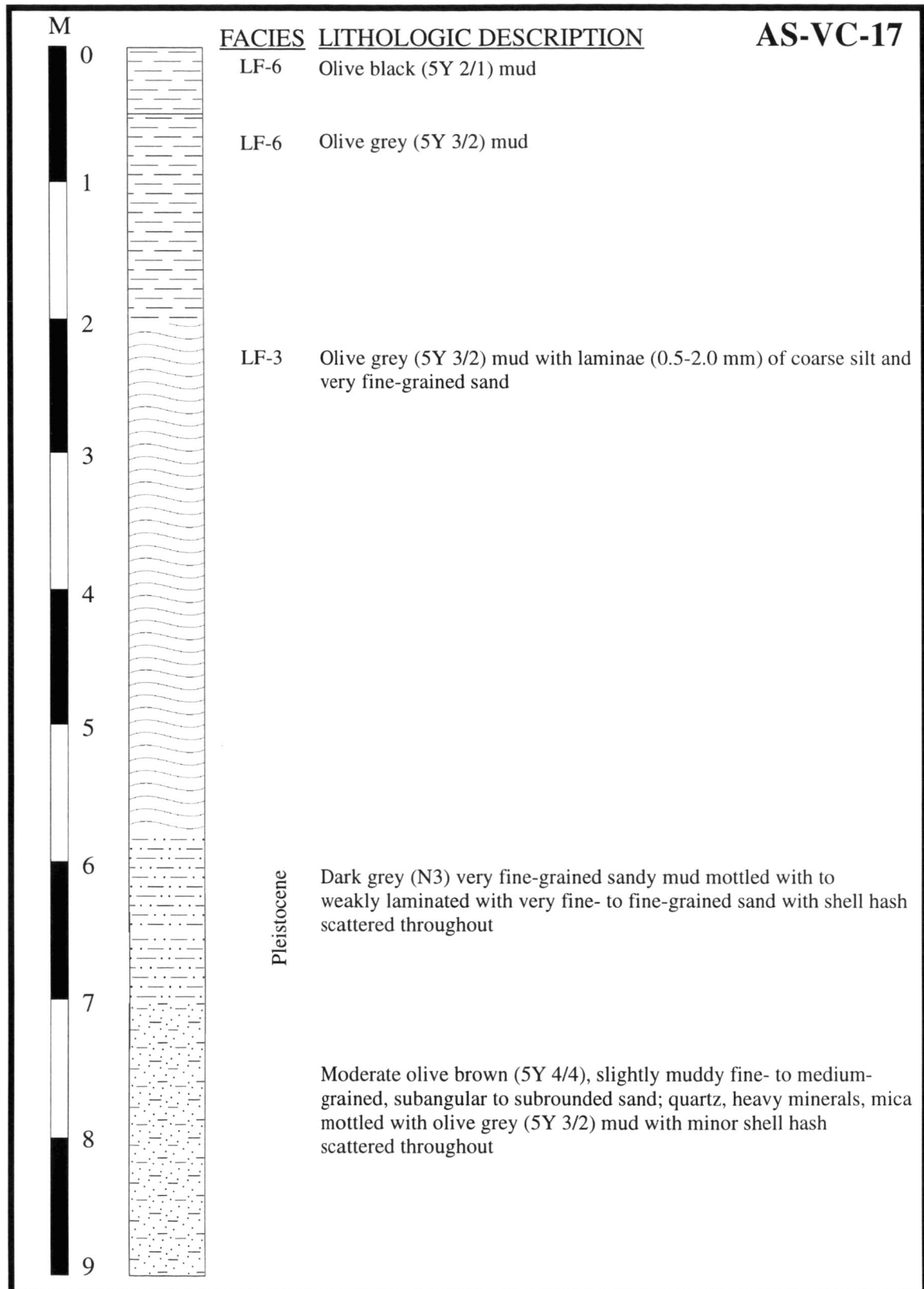


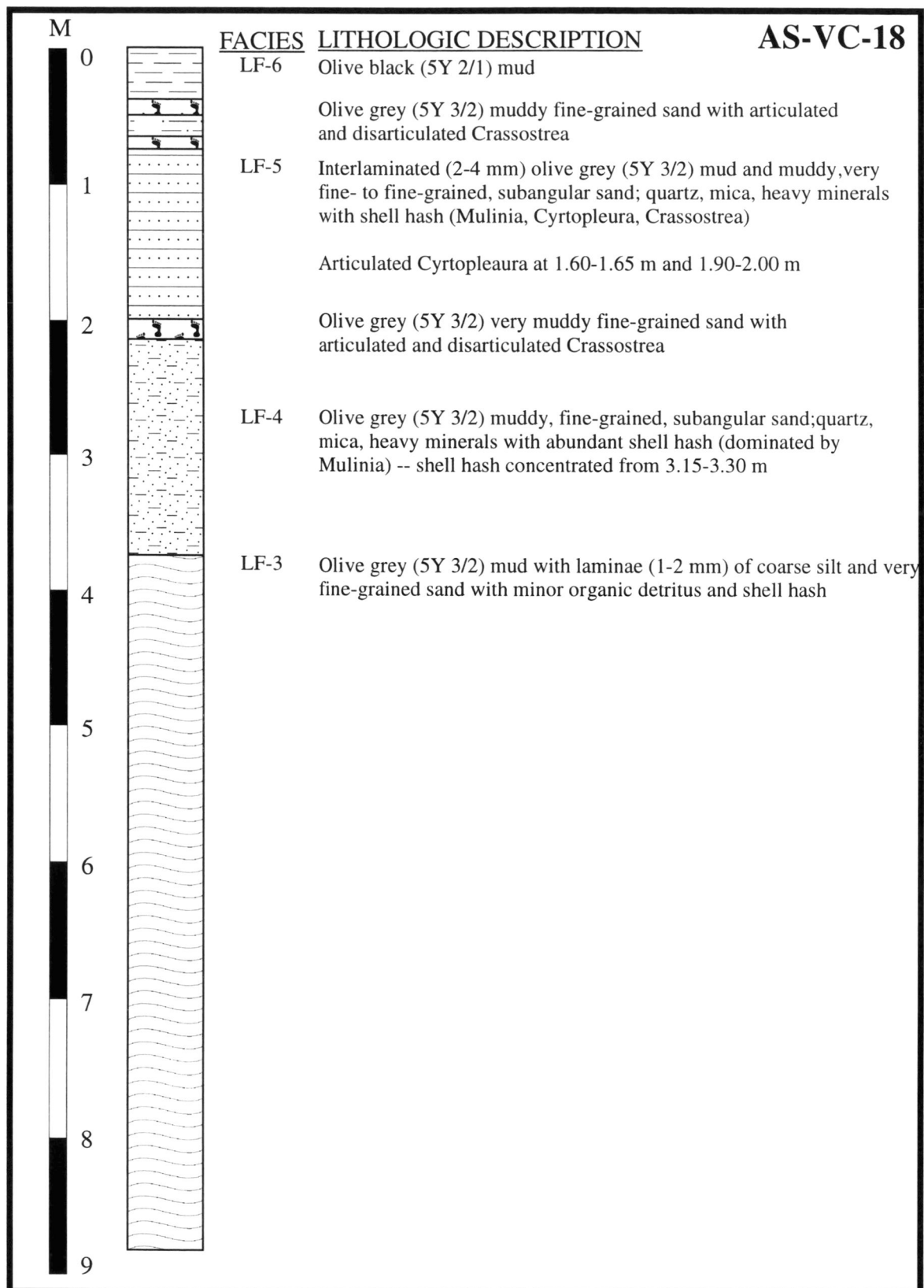


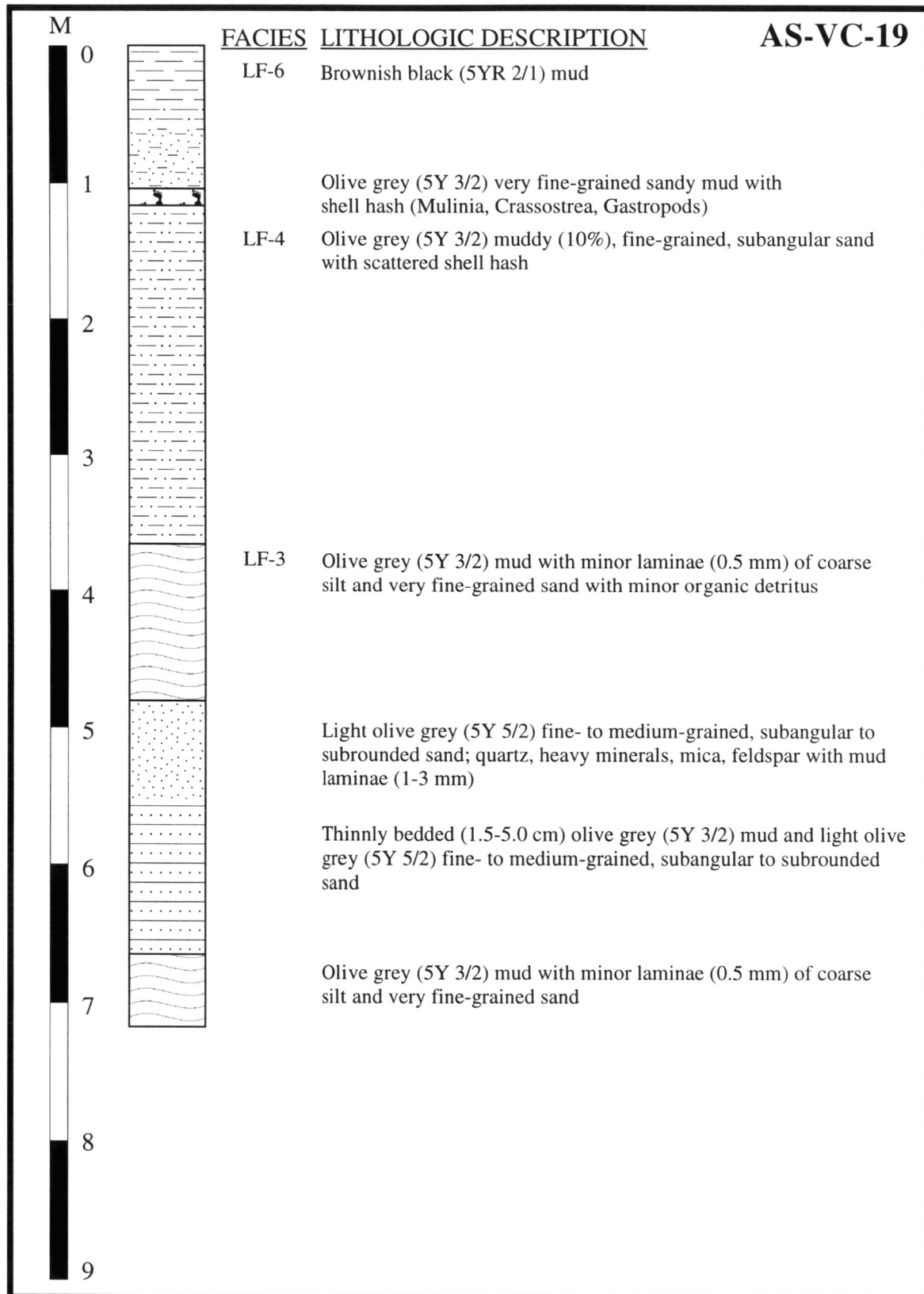


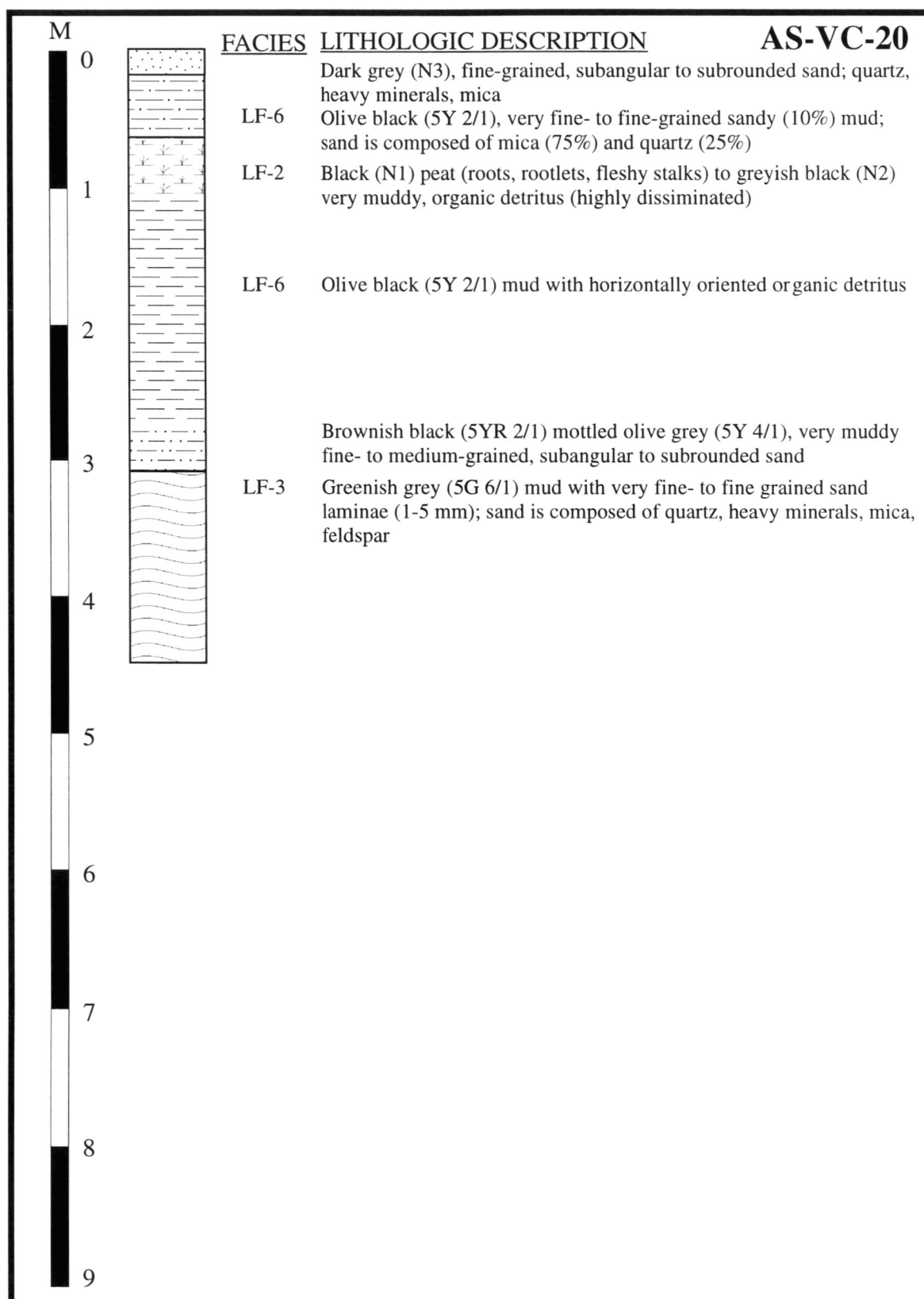


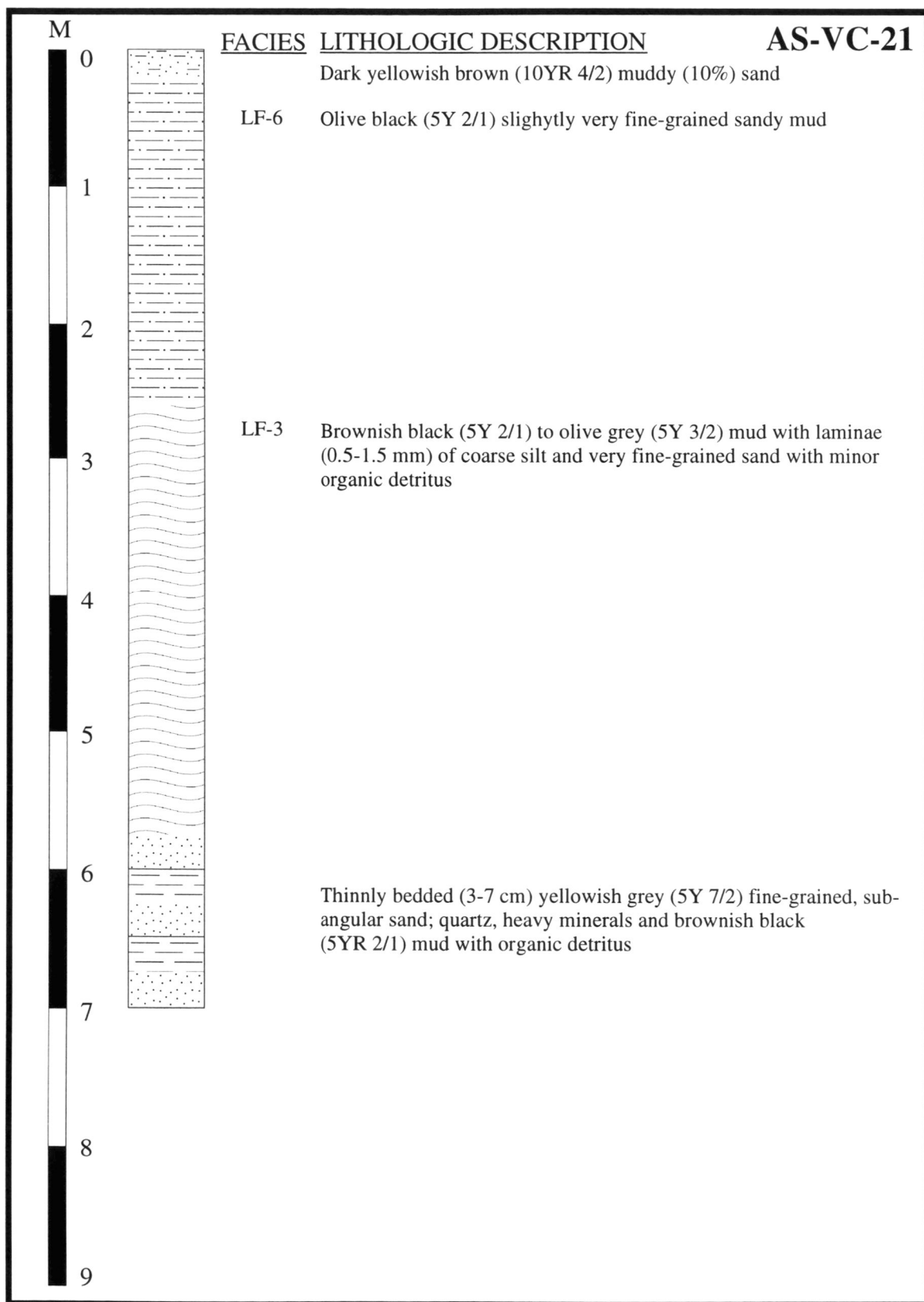


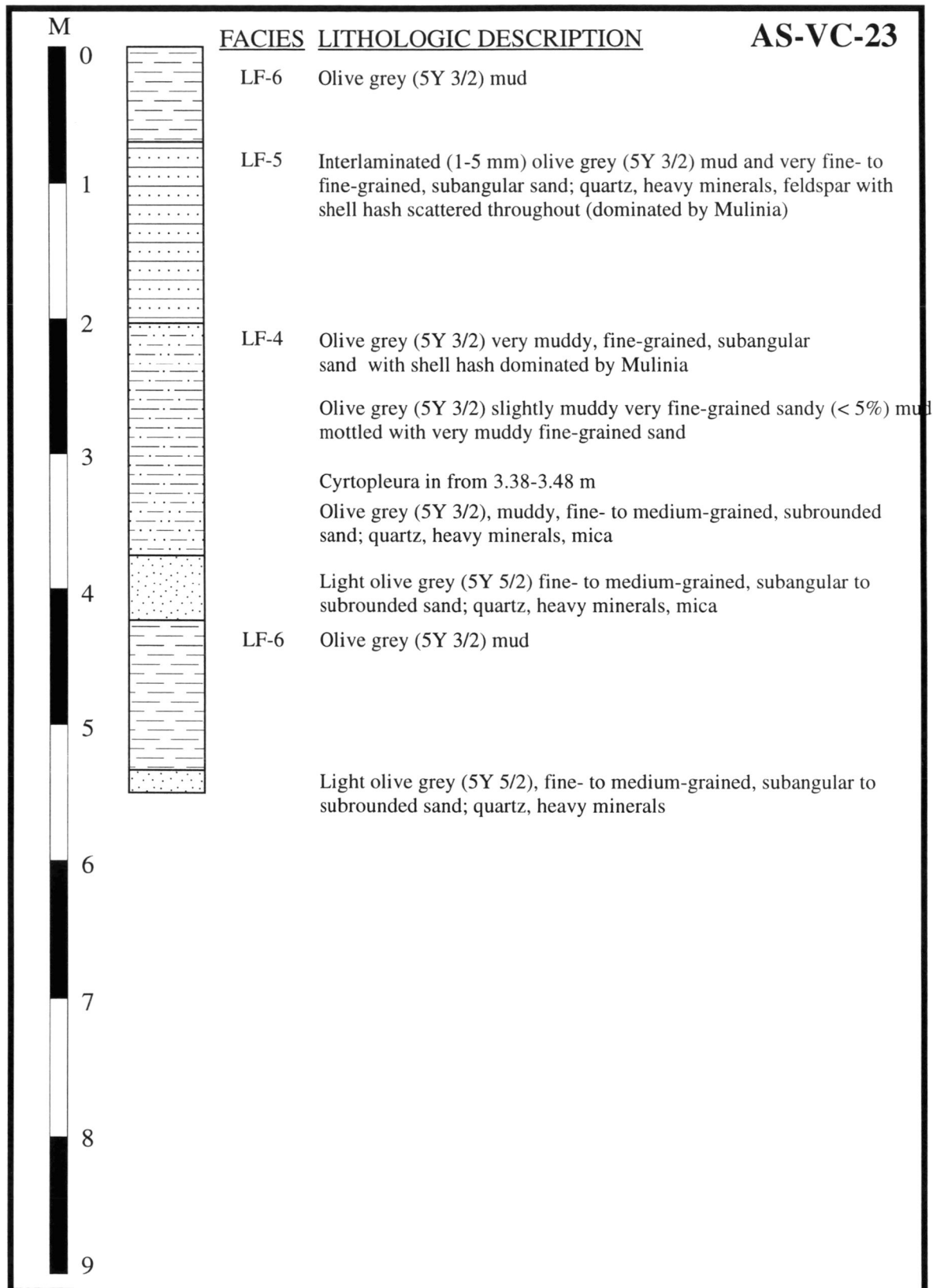


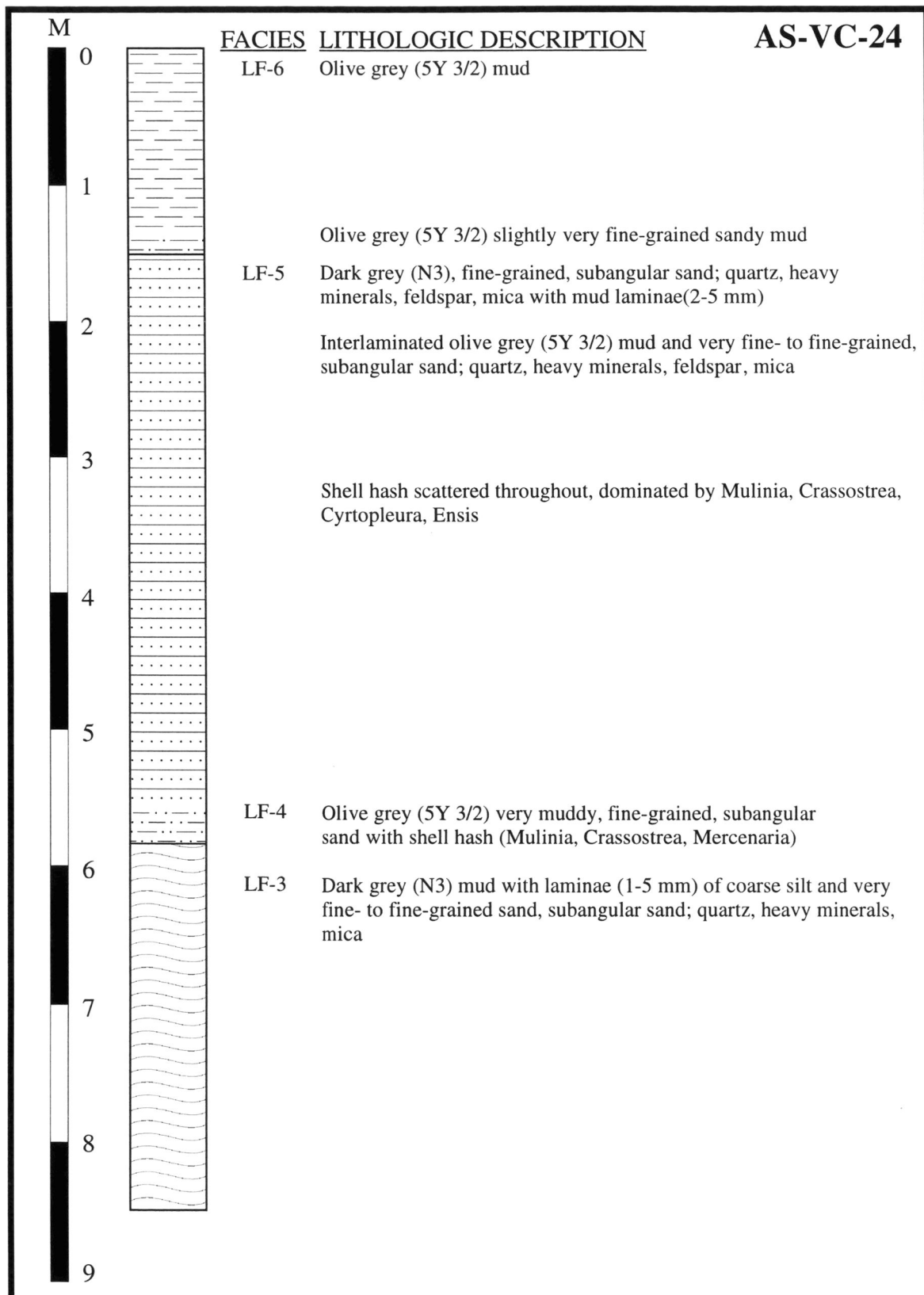


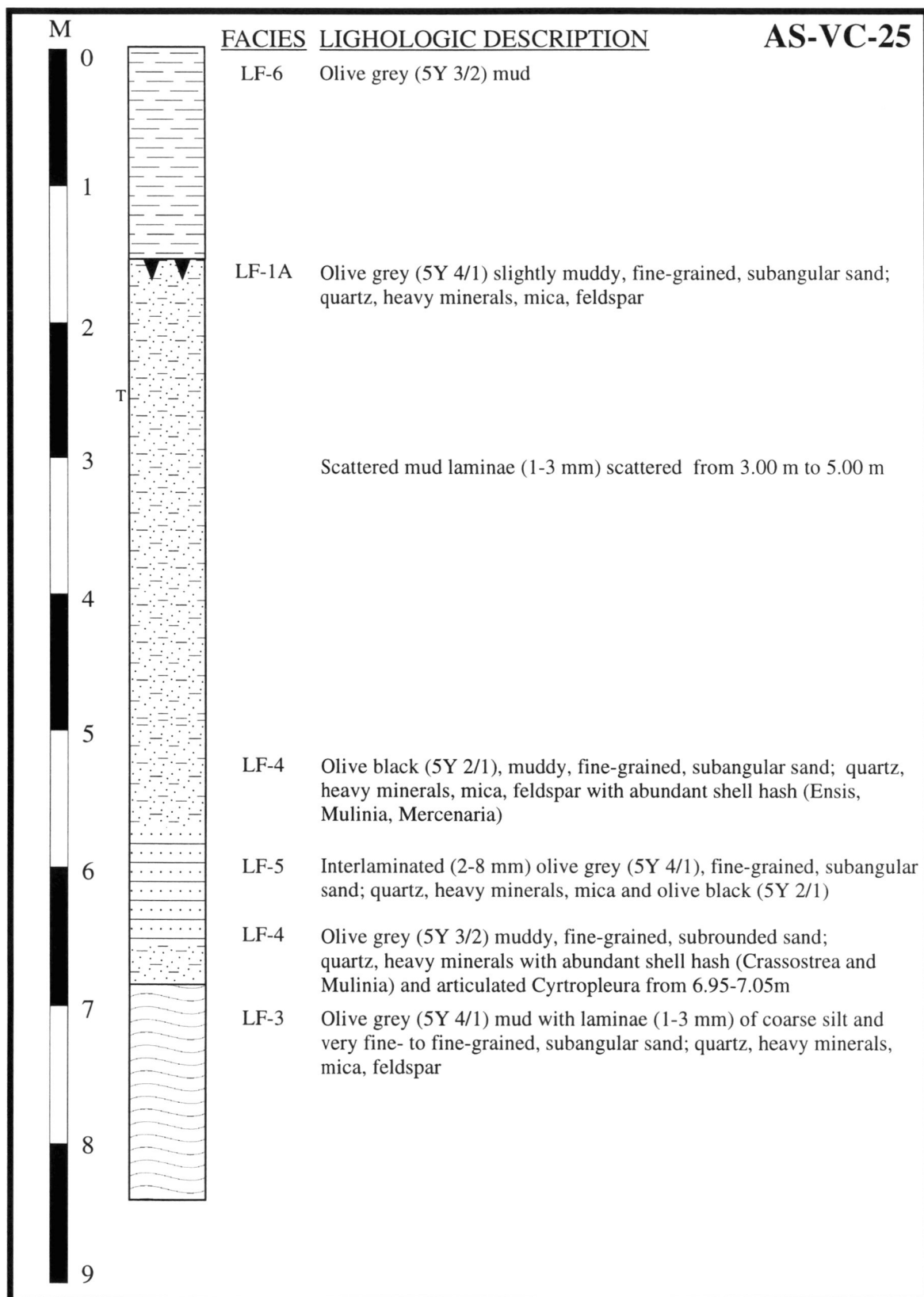


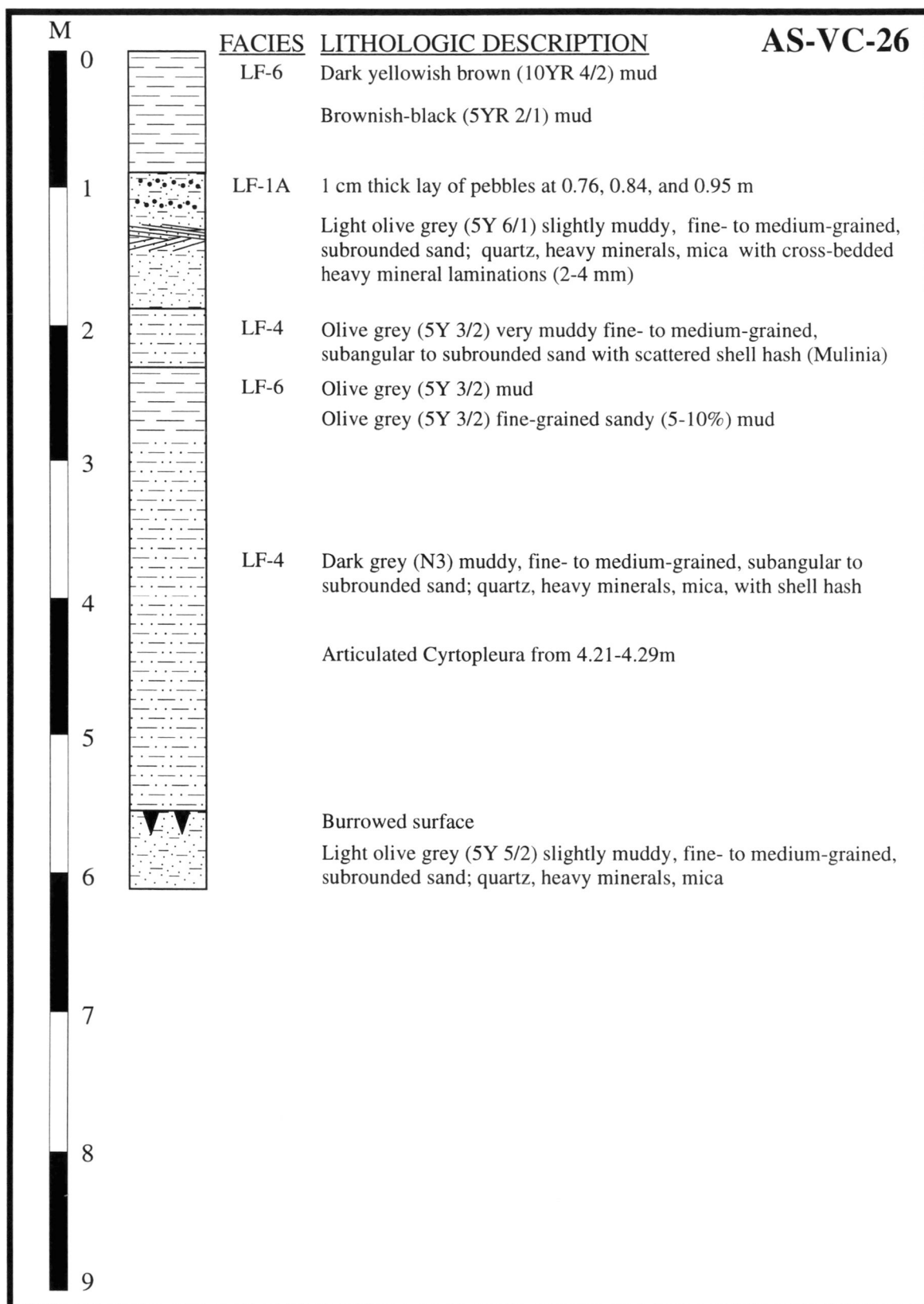


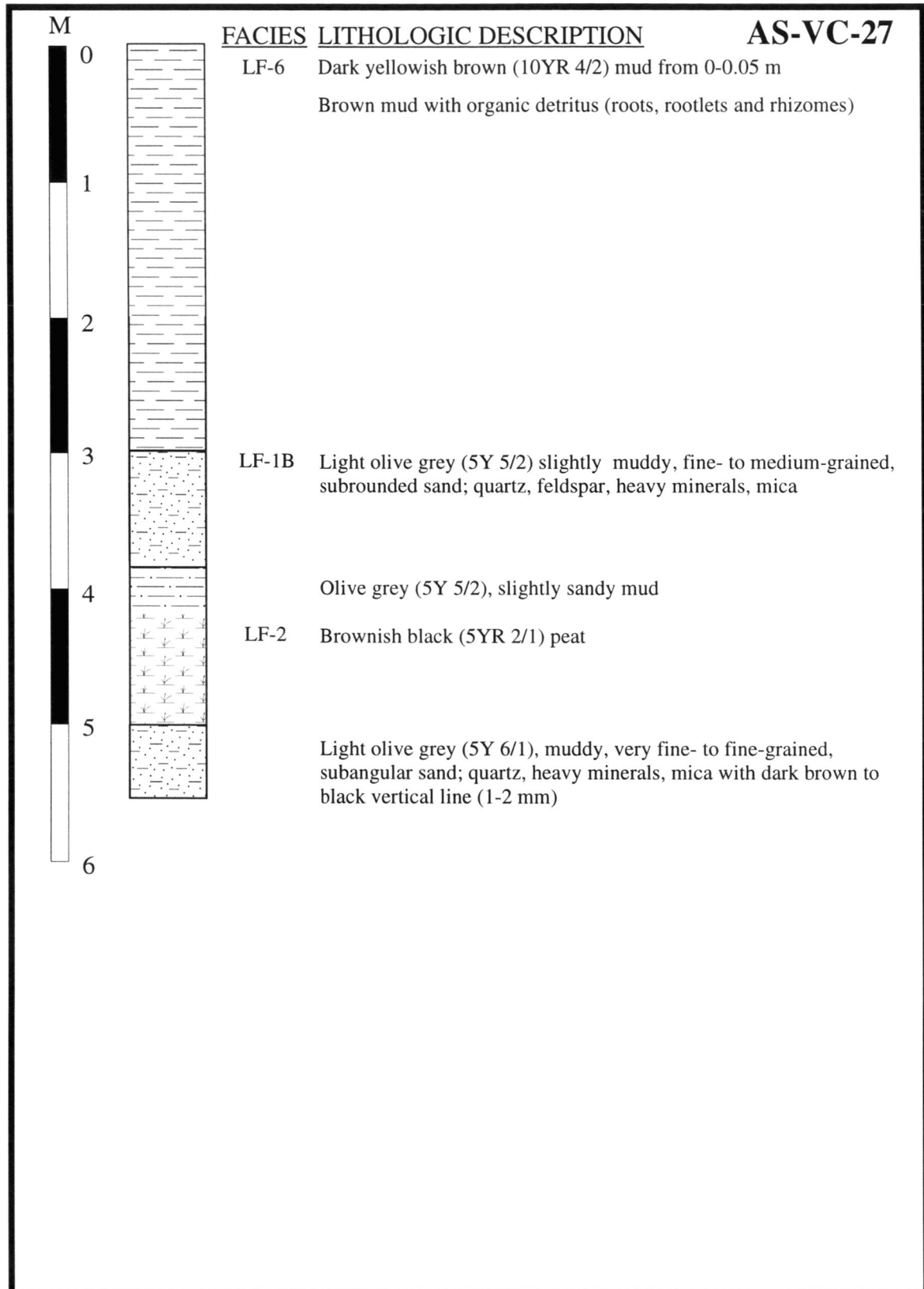












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