Shallow Stratigraphy of the Skagit River Delta, Washington, Derived from Sediment Cores

By Eric E. Grossman, Douglas A. George, and Angela Lam

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Conversion Factors

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, "North American Vertical Datum of 1988 (NAVD 88)"

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, "North American Datum of 1983 (NAD 83)"

Altitude, as used in this report, refers to distance above the vertical datum.

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Shallow Stratigraphy of the Skagit River Delta, Washington, Derived from Sediment Cores

By Eric E. Grossman, Douglas A. George, and Angela Lam

Abstract

Sedimentologic analyses of 21 sediment cores, ranging from 0.4 to 9.6 m in length, reveal that the shallow geologic framework of the Skagit River Delta, western Washington, United States, has changed significantly since 1850. The cores collected from elevations of 3.94 to -2.41 m (relative to mean lower low water) along four cross-shore transects between the emergent marsh and delta front show relatively similar environmental changes across an area spanning ~75 km^2. Offshore of the present North Fork Skagit River and South Fork Skagit River mouths where river discharge is focused by diked channels through the delta, the entire 5–7-km-wide tidal flats are covered with 1–2 m of cross-bedded medium-to-coarse sands. The bottoms of cores, collected in these areas are composed of mud. A sharp transition from mud to a cross-bedded sand unit indicates that the tidal flats changed abruptly from a calm environment to an energetic one. This is in stark contrast to the Martha's Bay tidal flats north of the Skagit Bay jetty that was completed in the 1940s to protect the newly constructed Swinomish Channel from flooding and sedimentation. North of the jetty, mud ranging from 1 to 2 m thick drapes a previously silt- and sand-rich tidal flat. The silty sand is a sediment facies that would be expected there where North Fork Skagit River sedimentation occurred prior to jetty emplacement.

This report describes the compositional and textural properties of the sediment cores by using geophysical, photographic, x-radiography, and standard sediment grain-size and carbon-analytical methods. The findings help to characterize benthic habitat structure and sediment transport processes and the environmental changes that have occurred across the nearshore of the Skagit River Delta. The findings will be useful for quantifying changes to nearshore marine resources, including impacts resulting from diking, river-delta channelization, shoreline development, and natural variations in fluvial-sediment inputs. These results also provide important quantitative data on the amount of sediment delivered to the nearshore from the Skagit River for use in calculating sediment budgets for application to watershed planning and wetland and coastal-ecosystem restoration.

Introduction

The Skagit River-Delta (fig. 1) provides critical habitat for all five species of Pacific Salmon, steelhead trout, and a variety of migratory waterfowl, many of which are listed as endangered and (or) threatened. The Skagit River alone furnishes ~30–35 percent of all freshwater input and annual salmonid production to Puget Sound (Beamer and others, 2005). Like many deltas in Puget Sound, the Skagit River Delta has experienced 70–80 percent loss of estuarine habitat since the 1850s as a result of wetland reclamation to support agriculture. The loss and disruption of deltaic habitat and biophysical processes threatens the recovery of Skagit Chinook by placing stress on limited space and food resources (Beamer and others, 2005); similar alteration of Puget Sound's other large river deltas is suspected to be limiting salmon-population recovery.

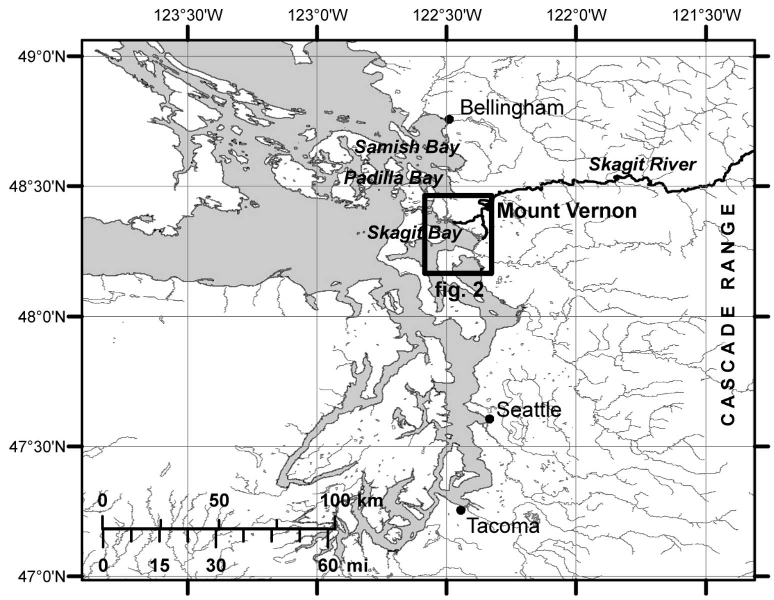

Figure 1. Location map of the study area and Skagit River Delta, Washington.

Restoration of Puget Sound's large river deltas has become a focus of accelerated habitat-restoration programs (Puget Sound Partnership, 2008). Although efforts are underway to restore wetlands and watershed processes, predictions of how nearshore ecosystems downstream will respond to those efforts are limited by a poor understanding of nearshore hydrodynamic processes, sediment transport, and the impacts of land-use, sea-level, and climate changes on nearshore environments. Additionally, assessments of "functioning" nearshore ecosystems are lacking because of sparse data and shifting baselines, highlighting the challenge of prioritizing restoration and conservation across Puget Sound's many nearshore ecosystems. The U.S. Geological Survey's Coastal Habitats in Puget Sound Project conducts research with federal, tribal, state and local partners to evaluate the vulnerability of nearshore ecosystems to land use and climate change where data is sparse, quantify processes driving nearshore change, and develop models and decision-support tools to help guide adaptive resource management. Investigations, like this study and report, that describe modern substrates and the extent of recent habitat changes provide important quantitative baseline information to assess the value of marine resources and habitats and help predict the outcomes of large-scale ecosystem restoration projects.

Study Objectives

This report describes the modern substrate and shallow sediment facies and stratigraphy of the Skagit River Delta, as recorded in sediment cores. The goal of this study is to quantify how sedimentation across the delta has changed, particularly changes to sedimentary facies, as reflected by sediment grain size, composition, and texture. These facies characteristics record variations in sediment source, transport, deposition, and preservation, which are helpful for understanding how processes and habitat structure and function have changed. One hypothesis is that river-delta channelization and jetty construction significantly increased sedimentation rate and changed sediment composition across Skagit Bay by redirecting a majority of the Skagit River's sediment load to a depositional area that is <5 percent of its historical extent. Quantification of the degree to which channelization has adversely impacted valued nearshore ecosystems and resources will provide guidance for sediment-management practices throughout the watershed. This report summarizes the stratigraphy and lithology of the Skagit River Delta and indicates that a significant transformation in substrate, sedimentary facies, and habitats has occurred since the 1850s.

Study Area

This study focuses on the present day Skagit River Delta between Martha's Bay in the north, to the north end of Camano Island in the south, and extending across the tidal flats from the Fir Island emergent marshes to the Skagit Delta front (fig. 2). Reconstructions show that historically, the Skagit River Delta extended to Samish, Padilla, and Skagit Bays, with a periodic connection to Port Susan and the Stillaguamish River Delta through West Pass to the south (figs. 1 and 2) (Collins, 2000). The Skagit River maintained a network of numerous shallow distributaries across the lowlands to Samish, Padilla, and Skagit Bays that spread freshwater and sediment across an area of 600 km^2 of flood plain, emergent delta, and tidal flats. Since the middle-to-late 1800s, the Skagit River has been rerouted through an extensive dike complex to its two present outlets in Skagit Bay as part of the reclamation of the delta for agriculture. The emplacement of this large dike complex between Mt. Vernon and Skagit Bay, and the removal of large, natural wood jams, effectively eliminated episodic flooding of the central lowlands toward Samish and Padilla Bays and instead redirected the entire flow to Skagit Bay. Historical maps and photographs show the marsh and shoreline at the North Fork Skagit River mouth to be limited in extent and landward of their present position (figs. 2 and 3). In addition, a jetty constructed in the 1930s and 1940s, from McGlinn Island to Goat Island and ~1 km beyond Goat Island into Skagit Bay, was built to control flooding and sedimentation along a 4 km stretch of the newly dredged Swinomish Channel (figs. 2 and 3*B*). Today, the Skagit lowlands are one of the most important agricultural centers along the west coast.

Maximum daily discharge of the Skagit River at Mt. Vernon ranges from 1,416 to more than 3,681 m^3s and is characterized by variable autumn and winter rain-fed runoff and generally predictable late spring—early summer snow-melt runoff. Extreme flooding below Concrete is common despite flood mitigation measures and the extensive dike infrastructure. The area of the Skagit River Delta that presently receives annual freshwater and sediment delivery is restricted to narrow regions outside of the Fir Island dike complex and the bayfront emergent marshes and tidal flats. The tidal flats cover an area of approximately 75 km^2 and range in width from 4 km in the vicinity of the North Fork Skagit River, to 5 km offshore of the central Fir Island bayfront, and up to 7 km off of the South Fork Skagit River. Aerial photographs taken in 2003 show that the tidal flats are characterized by heavily braided channels offshore of the modern North Fork Skagit River and South Fork Skagit River outlets, whereas the central tidal flats are smooth and nearly void of channels or bedforms (fig. 2). The emergent delta varies in elevation between +2 and +4 m (mean lower low water; mllw), while the tidal flats extend seaward to depths of 0 to -2 m (mllw). The delta-front slope ranges from 10 to 20 degrees and is steepest offshore of the North Fork Skagit River. This region of Puget Sound is characterized as mesotidal, with a Spring tide range of 3.5–4 m.

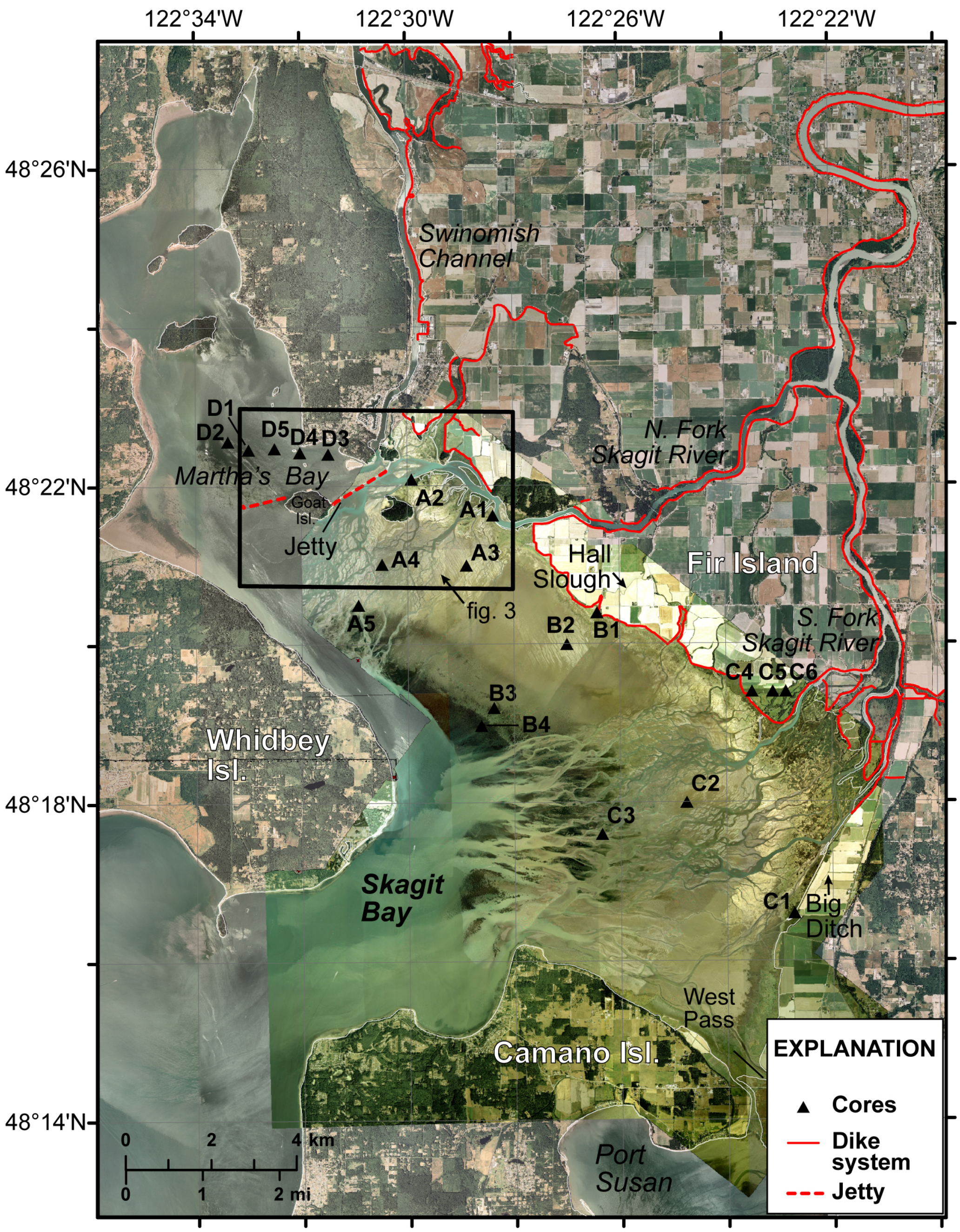

Figure 2. Map of the study area. 2003 aerial photograph showing core sites, dike complexes of Fir Island, Skagit Bay Jetty, and the braided tidal flats off of the North and South Fork Skagit River, Washington.

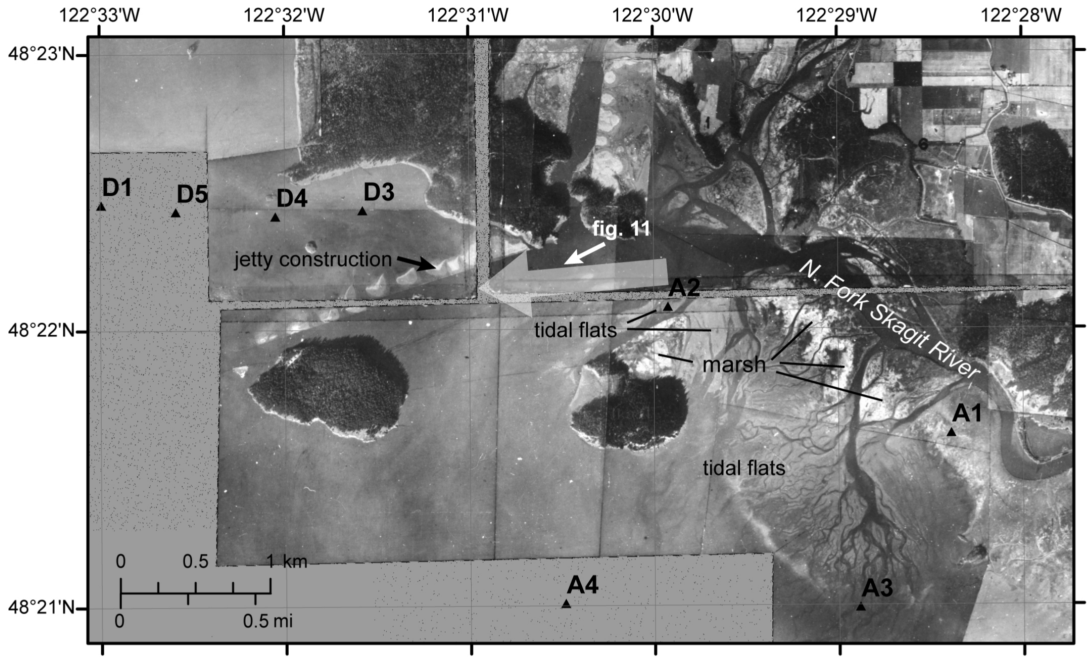

Figure 3. U.S. Army Corps of Engineers 1937 photograph showing initial jetty construction (black arrow) and location of current study core sites near North Fork Skagit River mouth. Sites D1–D5, now protected by the jetty, used to receive direct flow from the river (grey arrow). Site A2, located today within emergent marsh, was previously a tidal flat environment prior to 1937. The location of the view in figure 11 is indicated by the white arrow.

Geological Setting

The Skagit River watershed drains approximately 6,900 km^2 of the northern Cascade Range and the valleys below Mt. Baker that were glaciated during the Pleistocene Epoch. The Skagit lowlands are formed principally of sedimentary rocks of fluvial, alluvial, and glacial outwash origin intermixed with episodic lahar deposits (Easterbrook, 1969; Booth, 1994; Dragovich, Gilbertson, and others, 2002; Dragovich and Grisamer, 1998; Dragovich and DeOme, 2006). Isolated bedrock islands and ridges are composed of low-grade metamorphic rocks, formed during Late Jurassic or Early Cretaceous continental-margin subduction. Continental glaciers advanced into Skagit County several times during the Pleistocene Epoch as part of the Puget Lobe of the Cordilleran ice sheet; the most recent period, the Vashon Stade of the Fraser glaciation, began about 17,000 years ago. Beginning about 13,500 years ago, the Puget Lobe retreated from its terminus in southern Puget Sound as the climate warmed. Marine waters inundated the Puget Sound and Skagit-Whidbey Basins as glacial isostatic loading retarded. Postglacial filling of the Skagit River Valley, which had been excavated by subglacial meltwater, was accomplished through Holocene fluvial, estuarine, and deltaic deposition and volcanic-lahar deposits originating from Glacier Peak (Dragovich and others, 2000).

Methods

Core Collection and Handling

Thirty-two sediment vibracores, three auger cores, and three push cores were collected throughout the larger Skagit River Delta (Padilla and Skagit Bays and Stillaguamish River Delta), 21 of which are presented here (table 1; figs. 2, 3, 4*A-D*, and 5). The vibracores varied in length from 1.6 to 4.5 m long and were obtained from elevations ranging from -2.5 to + 3.9 m relative to mean lower low water based on recently collected, lidar-derived digital elevation models (Finlayson, 2005). Standard 3-inch diameter aluminum irrigation tubes, 20 or 30-ft in length, were deployed into the sediment on land by hand or into the seabed from small boats or by snorkeling (fig. 4). Penetration into the sediment was made using a heavy (15–25 kg) vibrating head (weight) attached to the top of the tube that was driven by a portable, modified cement-mixer coil and engine operating at variable speed (60–1,800 RPM). The tube tops were capped with standard irrigation fittings to create a vacuum seal prior to recovering with a jack or come-along. The cores were cut into 1.2 or 1.5 m segments for transport and stored at the USGS Sediment Storage Refrigerator in Menlo Park, California, at 4°C until processing could commence. The 14 cores collected from the modern Skagit River Delta were used to construct the four cross-delta transects summarized in this report (table 1; fig. 5).

Sediments also were subsampled from three augers (C4, C5, and C6) and collected by GeoEngineers of Mt. Vernon, Washington within the Wiley Slough area using an M-55 track-mounted drill with a 4¼-inch inner-diameter hollow-stem auger (table 1; figs. 2 and 4*E*). Samples were recovered with a California-type split-spoon sampler, and subsamples were collected at intervals of 0.75 m downcore. Samples were analyzed visually in the field and interpretations of the lithofacies were made back in the laboratory in consult with the driller's logs.

Three push cores (D3, D4, and D5) were collected across the Martha's Bay tidal flats using 36-cm-long, 5-cm-diameter clear-acrylic core tubes (table 1; figs. 2, 3,and 4*F*). These cores were characterized visually in the field, capped, sealed, and labeled prior to transport. Interpretation of the lithofacies were made in the laboratory.

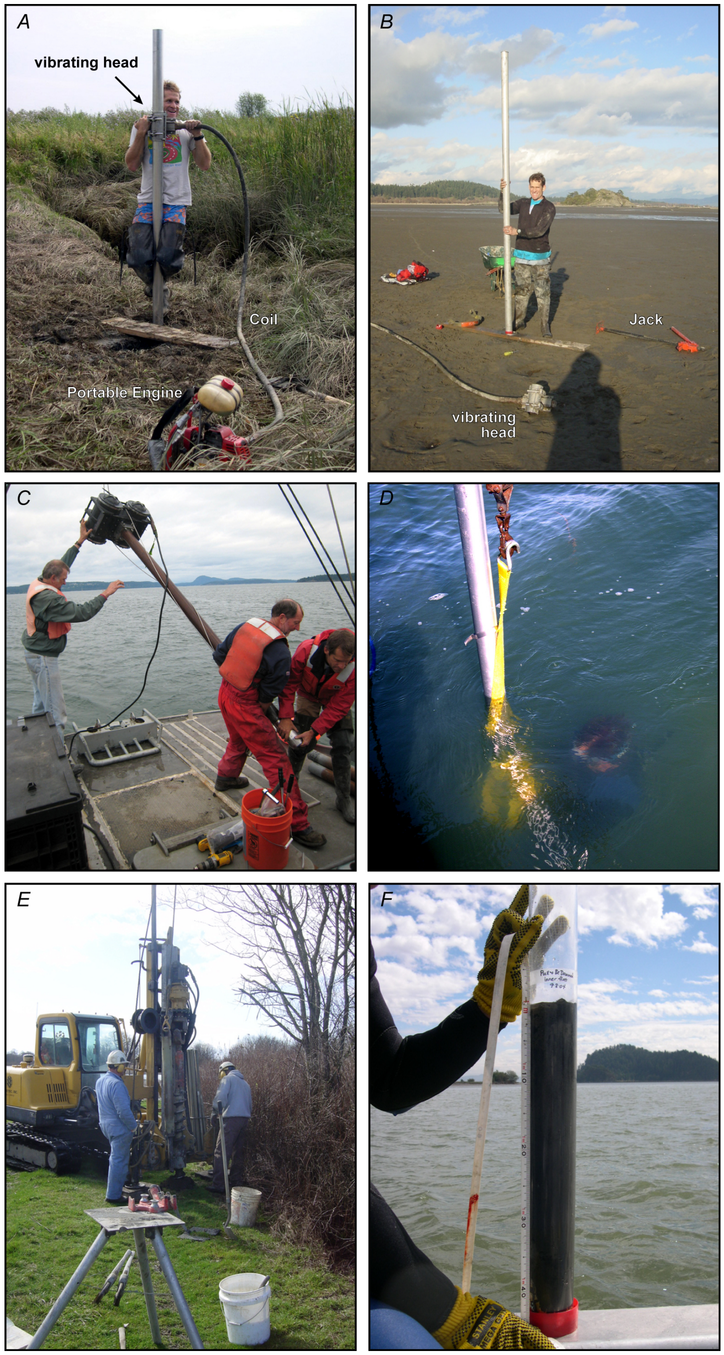

Figure 4. Photographs showing vibracore components and methods in *A*, marsh; *B,* tidal flats; *C* and *D*, underwater. *E*, Photograph of auger; and *F*, acrylic push core, Skagit River Delta, Washington.

Table 1. List of core sites and sample information, Skagit River Delta, Washington.

Core ID	Activity	Collection Date, UTC	Latitude	Longitude	Elevation (m,mllw)	Penetration, in meters	Recovery, in meters
A1-A	K-01-04-PS	3/12/2004 1900	48.36039	-122.47315	3.94	2.12	2.12
A1-B	K-01-04-PS	3/12/2004 2000	48.36039	-122.47315	2.69	2.27	2.23
A2	W-01-04-PS	9/9/2004 2237	48.36805	-122.49872	3.26	3.02	3.00
A3	K-01-04-PS	3/12/2004 2200	48.34990	-122.48143	0.97	1.60	1.50
A4	W-01-04-PS	9/6/2004 1730	48.35018	-122.50808	-0.15	1.95	1.95
A5	S-01-06-PS	9/22/2006 2033	48.34166	-122.51555	-2.41	3.81	3.81
B1	W-01-04-PS	9/10/2004 2159	48.33994	-122.44053	3.12	2.15	2.15
B2	W-01-04-PS	9/6/2004 2005	48.33333	-122.45000	1.51	1.84	1.84
B3	W-01-04-PS	9/8/2004 1623	48.32000	-122.47306	-1.23	3.60	3.60
B4	W-01-04-PS	9/10/2004 1630	48.31627	-122.47701	-1.53	4.50	4.50
C1	W-01-04-PS	9/5/2004 1944	48.27669	-122.37889	3.10	1.91	1.91
C2	W-01-04-PS	9/6/2004 2133	48.30004	-122.41257	0.30	1.82	1.80
C3	W-01-04-PS	9/8/2004 1620	48.29340	-122.43924	-0.62	3.95	3.95
C4	W-01-04-PS	3/9/2004 1600	48.32278	-122.39154	2.10	9.60	9.60
C5	W-01-04-PS	3/9/2004 1730	48.32274	-122.38660	2.10	9.60	9.60
C6	W-01-04-PS	3/9/2004 2000	48.32273	-122.38205	2.10	9.60	9.60
D1	S-01-06-PS	9/20/2006 1729	48.37431	-122.54993	-0.19	3.00	3.00
D2	S-01-06-PS	9/21/2006 1933	48.37638	-122.55591	-0.92	2.40	2.40
D3	W-01-04-PS	9/8/2004 1844	48.37222	-122.52667	0.75	0.50	0.70
D4	W-01-04-PS	9/8/2004 1947	48.37516	-122.54240	0.50	0.40	0.45
D5	W-01-04-PS	9/8/2004 1954	48.37343	-122.53554	0.35	0.40	0.40

Core Analyses

Analyses of the vibracores were performed at the USGS Menlo Park, Calif., laboratories and included high-resolution multisensor logging of physical properties of each unsplit core, followed by visual interpretation and description, x-radiography, digital photography, and subsampling on a “working” half of the core. The other half of the core was stored as an archive for future reference. Facies characteristics from the augers and push cores were interpreted visually in the laboratory.

Multisensor Logging of Physical Properties

The geotechnical and geoacoustic properties of the recovered, unsplit sediment cores were logged on a Geotek multisensor whole core sediment-logging device in 1 cm increments using a motor-driven track system to automate scanning. Room temperature sediment cores were placed horizontally upon a transport sled and moved by a computer-controlled stepper motor through a frame supporting the sensors. In a sequence, the logging device measured attenuation of gamma rays from a ^{137}Cs source to compute soil wet bulk density followed by the core diameter and p-wave travel time to compute p-wave velocity.

Wet-Bulk Density

The configuration of the logging device allows for a sediment core to pass between the scintillation counter and a vessel emitting a 1-cm columnated beam of gamma rays from a radioisotope ^{137}Cs source. The logging system beams gamma rays across the entire core section, and sediment bulk density (ρ_b) is calculated from the gamma-ray attenuation characteristics of the cores according to Lambert's law.

Compression-Wave Velocity

The compression-wave (p-wave) velocity of sediment was calculated from the measured core diameter and wave-travel time, correcting for the liner thickness, electronic-signal delays associated with the travel time within the transducer head, and core-liner travel time. In the logger system, a transmitter and receiver transducer sit opposite one another and orthogonal to the direction of core motion. Spring-loaded transducer heads are used to couple the sensors to the core liner. Linear displacement transducers are mounted on the acoustic transducers and used to determine the diameter of the core passing through the sensors.

Calibrations

Density measurements of soil contained within an unsplit core were calibrated to the known standards of water (ρ_w=1.00 g/cc) and aluminum (ρ_{al}=2.70 g/cc). These two standards serve as end-members that fully-bound the limits of soil density. To account for the influence of the aluminum tube, a water-aluminum standard was prepared by inserting an aluminum cylinder milled to 2.5–5.0 cm diameter in 0.5 cm increments into an unsplit section of core liner identical to the liner used for soil sampling. The length of milled aluminum filled one-half the total length of the "calibration standard"-core liner, and distilled water filled the remaining portion. Caliper measurements of the liner diameter and wall thickness were made to determine the travel path-length through the liner and interior space. During the density calibration, the number of scintillations was logged for transmission of gamma rays through the 5 cm segment of the standard in 30 sec. This was repeated three times, and the average value was recorded. This procedure was performed for each segment of the standard and water-only section to develop a density calibration curve. Checks on the calibration curve were performed during the logging process, and new values were generated if substantial drift was observed.

Calibration for p-wave velocity calculations involved placing the water-only section of the standard between the transmitter and receiver transducers and recording the speed of sound after fluctuations subsided. The value and the ambient temperature of the room were entered into a spreadsheet that generated calibration numbers.

After production of calibration values for density and p-wave velocity was complete, the standard was logged in its entirety. The raw data were processed immediately after logging by using the calibration values generated. If the velocity and density results for the water-only section were within 1 percent of known values, calibration was considered successful and logging of sediment cores could commence. Typical run-time for driving a 150 cm core through the sensor array was approximately 40 min. Raw data were processed immediately to produce text files of output data. All unsplit sediment cores were logged, although the results for Core C3 were lost owing to computer-hardware problems.

Core-Splitting and Visual Descriptions

Each core segment was split lengthwise by slicing the aluminum core liner on opposite sides with an electric shearer. The surface tension within the sediment was broken into two halves by drawing fine-gauge piano wire the length of the core, using the cuts in the aluminum as guides to achieve as equal halves as possible. The core was separated, and one half of the core was designated as an archive to be stored intact; the other half was designated as the working piece. Visual descriptions of sediment texture, color and detritus, and lithofacies units and contacts were recorded by depth for the length of the working piece.

Digital Photographing

Each working piece was photographed by using a Geotek imaging system attached to the multisensor logging apparatus. A core segment was placed on the transport sled and moved under the open lens of the camera. Pixel resolution for the width of the core and black and white calibration were done before digitally photographing the segments, although not all cores received the horizontal-resolution setting. Lengthwise scales were placed on the images taken with the horizontal-resolution setting by using a customized Geotek post-photograph program; scales were placed on images without the horizontal-resolution setting by using Adobe Photoshop to resize the images to a standard dimension.

X-Radiographing

All but three of the cores were x-radiographed to examine textural and density differences among the stratigraphic layers. The working piece was exposed to x-rays (60kV/20mA) from a veterinary x-ray machine, and the film was immediately developed. The x-ray system can image film up to 0.5 m in length, so several overlapping sections were required to complete individual core segments.

The developed films were scanned digitally in full color to retain as much information as possible from the film. The overlapping sections were assembled to reconstruct a single segment of a core, and the images were converted to grayscale to generate more manageable file sizes.

Sediment Grain Size

Samples for determining sediment grain size were extracted from the working piece only after completion of photography and x-radiography. Sediment samples (2-cm-thick) were analyzed every 20 cm down the length of the core, and additional samples were taken where significant shifts in sediment texture were observed. Approximately 40 g of homogenized sediment from each 2-cm-thick sample was placed in a beaker with approximately 100 ml of deionized water and 5 ml of 30 percent hydrogen peroxide and allowed to stand overnight to remove organics. Salts were removed by boiling and two centrifuge rinses. Gravel and sand fractions were separated by 2.00 mm and 0.0625 mm sieves, respectively, and then were dried and weighed. The cumulative percentage of material of dried sand was analyzed on the Rapid Sediment Analyzer, or settling tubes. The remaining fine-grained material was dispersed in 1,000 ml of deionized water and 5 ml of Calgon to defloculate organic matter and disaggregate the grains. After sitting overnight, the material was agitated for two minutes, and a 20 ml aliquot was taken at 20-cm depth and analyzed on a Beckman Coulter Laser Particle Analyzer 230 following standard USGS methods (Stevens and Hubbell, 1986). Results of these analyses were entered into SedSize, a customized software program that produces sediment particle-size statistics, cumulative particle-size distribution and sediment-class percentages.

Carbon Analyses

Organic, inorganic, and total carbon (TC) content in sediment samples was analyzed using standard USGS coulometry methods. To determine carbon content, approximately 5 g of sediment was subsampled and dried in a 80°C oven overnight. Samples were then ground into a fine powder. To obtain TC, approximately 20 mg of the pulverized sample was weighed and wrapped in a foil tray. A UIC CM 5200 furnace attached to a CM 5014 coulometer was used to burn the samples at 950°C, which converted the produced CO_2 into a value for TC as percent dry weight. For total inorganic carbon (TIC), approximately 20 mg of sample was weighed and inserted into glass tubes, which were loaded into a UIC CM 5130 acid digester attached to a CM 5012 coulometer. The samples were digested in perchloric acid to obtain a TIC value as percent dry weight. For percent calcium carbonate, the TIC value was multiplied by the stochiometric factor 8.33, relating percent calcium carbonate to TIC (Morse and Mackenzie, 1990). The total organic carbon (TOC) value was determined by subtracting the TIC value from the TC value. Two analyses were run per system, and the results were averaged.

Results

The sampling strategy produced four cross-delta transects (Transects A–D) consisting of four to six coring sites per transect (fig. 5). Site and stratigraphic elevations are shown and described relative to mean lower low water. Data generated by the multisensor logger, digital photography, x-radiography, sediment grain size (mean grain size, sediment classifications), carbon, and interpreted sedimentary lithofacies were compiled for each core segment, relative to core depth, and are described in detail in appendix 1. Summary statistics were calculated for the bulk density, P-wave compression velocity, mean grain size, and sediment classifications and are shown in appendix 2.

Sedimentary Facies

Six sedimentary facies are observed in the cores collected across the modern emergent marshes, tidal flats, and delta front (fig. 6): (1) massive sand; (2) cross-bedded sand; (3) silty-sand; (4) mud; (5) laminated mud; and, (6) peat/marsh. These facies are classified based on the sediment grain size, compositional, and textural characteristics observed and presented in the detailed core descriptions in appendix 1. These facies reflect unique sedimentary environments commonly found in deltaic settings, which may change vertically through a sequence as a result of a change in environment through time, or laterally through a deposit where variations or gradients in processes at the same time form different environments (Boggs, 2009).

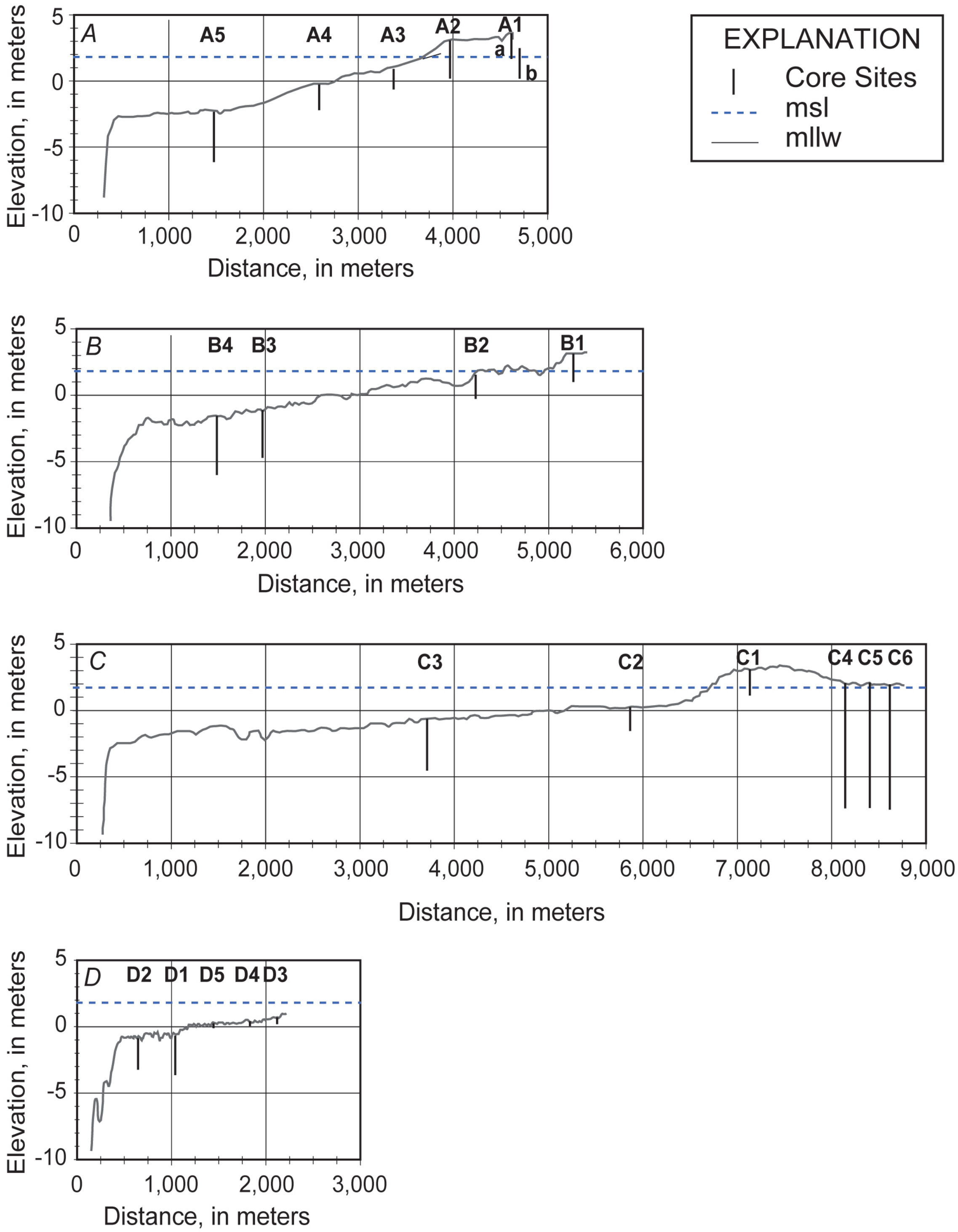

Figure 5. Plots showing topographic cross-sections and coring depths relative to mean sea level (msl) and mean lower low water (mllw) along *A*, transect A; *B*, Transect B; *C*, transect C; and *D*, transect D, Skagit River Delta, Washington.

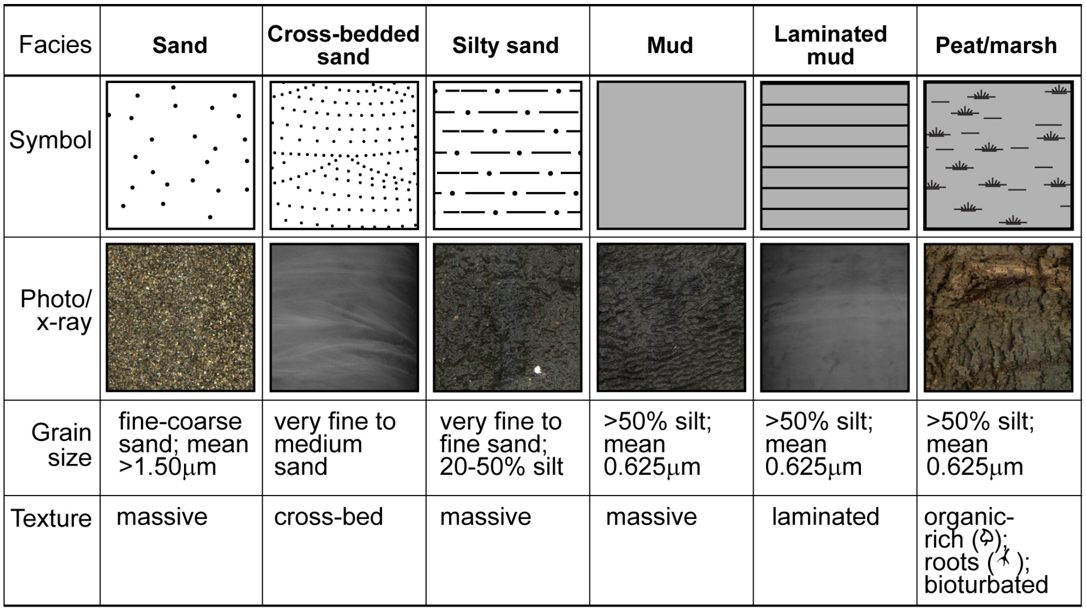

Figure 6. Diagram showing sediment-facies properties, Skagit River Delta, Washington.

The massive sand facies is classified based on sediments containing fine to coarse sands and lacking any significant textural properties. The massive sand facies generally has a mean grain size of >150 µm. The cross-bedded sand facies is composed of generally very fine to medium sands displaying distinct cross-bedding. Cross-bedding is best observed in x-radiograph images but occasionally is detected in photographs and visually in hand samples. The silty sand facies is classified based on sediment composition of very fine to fine sand with 20–50 percent silt and lacks any significant texture. It generally has a mean grain size ranging from 0.625 to 1.25 µm. The mud facies is based on a composition of >50 percent silt and a mean sediment grain size <0.625 µm and is massive, lacking texture. In a few cases, namely thin interfingered layers within sand units, where mud was evident and grain-size analyses were skipped by our 20-cm subsampling interval, we interpret mud facies based on visual inspection in hand sample. The laminated mud facies also contains >50 percent silt and has a mean grain size <0.625 µm, however, it displays fine horizontal laminae. The peat/marsh facies is comprised of organic-rich mud, generally containing dense roots and (or) marsh peat mats in growth position or detrital-root material.

Skagit Delta Stratigraphy

Transect A

Transect A was oriented across the North Fork Skagit River Delta marsh and tidal flats and was composed of six cores at 5 stations, A1, A2, A3, A4, and A5, ranging in elevation from +3.92 m to -2.41 m (mllw) (fig. 7). Cores A1 and A2 were located along the North Fork Skagit River in emergent marsh, although the 1937 photograph shows that the station sampled for core A2 was a located then on sandy island or tidal flat within the North Fork Skagit River Channel (fig. 3). Core A1 has a combined length of 3.45 m and is composed of two cores, A1A and A1B. A1A was located on the marsh surface about 5 m from the river bank; Core A1B was located in a small blind tidal channel 3 m seaward. Core A1B was collected to extend the sediment record below the depth of penetration of A1A. Core A2 is 3.02 m long and was located 5 m from the bank of the river channel. Core A3 penetrated 1.6 m and was collected seaward of the vegetated marsh on the inner tidal flat. Core A4 reached 1.95 m deep and was obtained from the outer tidal flat. Core A5 is 3.81 m long and was sampled near the delta front offshore of the North Fork Skagit River.

The stratigraphy of the North Fork Skagit River Delta along Transect A is characterized by silty-peat marsh facies comprising the emergent marsh between +4 and +1 m (mllw), cross-bedded sands and massive sand facies across the tidal flats between +1 and -2 to -3 m (mllw), and silty to muddy sand below the outer tidal flats between -3 and -6 m (mllw) (fig. 7). In the emergent marsh stations, the 1–2 m thick silty-peat facies of Cores A1 and A2 are interfingered with sand units ranging from 3 to 10 cm thick occur and are likely flood deposits associated with large river flow events that overwash the river banks (appendix 1, Cores A1 and A2). Below the peat facies in Cores A1 and A2, a notable sand facies occurs and is composed of well-sorted fine to coarse sands. Across the tidal flats, the upper 1–2 m is composed of cross-bedded sands as revealed by Cores A3, A4, and A5. A sharp contact occurs between the cross-bedded sands and underlying silty-sand and mud facies of Cores A4 and A5 (appendix 1). Several of the silty sand and mud units of Cores A4 and A5 show delicate laminated beds.

Transect B

Transect B was oriented halfway between the North and South Forks of the Skagit River and was composed of four cores spanning the central Skagit Delta (figs. 2 and 5). Core B1 was located in the emergent marsh at an elevation of 3.12 m and is 2.15 m long. Core B2 was collected from the inner tidal flats at 1.51 m and is 1.84 m long. Core B3 was collected near the delta front at an elevation of -1.23 m and is 3.6 m long. Core B4 also was collected near the delta front, to provide replication. It was collected at an elevation of -1.53 m and is 4.5 m long.

Similar to Transect A, the stratigraphy offshore of the bayfront of central Fir Island along Transect B, is characterized by silty-peat facies overlying the cross-bedded and massive-sand facies, which in turn overlie the finer silty-sand and mud facies (fig. 8). Between elevations of +3 and +1 m, the peat-marsh facies occurs within the emergent marsh. Across the tidal flats, between elevations of +1.5 and -3.0 m, massive-sand facies compose the upper 1–2 m on the inner tidal flats (Core B2), and cross-bedded sand facies extend from the surface down 1–2 m along the outer tidal flats (Cores B3 and B4). Along the outer tidal flats, sharp contacts occur between the cross-bedded sand facies and underlying silty-sand and laminated-mud facies at elevations of -3 and -4 m. The silty-sand facies range from 0.5 to 1.0 m thick; the laminated mud facies range from 1 to 2 m thick. In Core B4, a 0.4-m-thick silty-sand facies was observed under the laminated mud, overlying a 0.1-m-thick sand facies at the base (appendix 1, core B4).

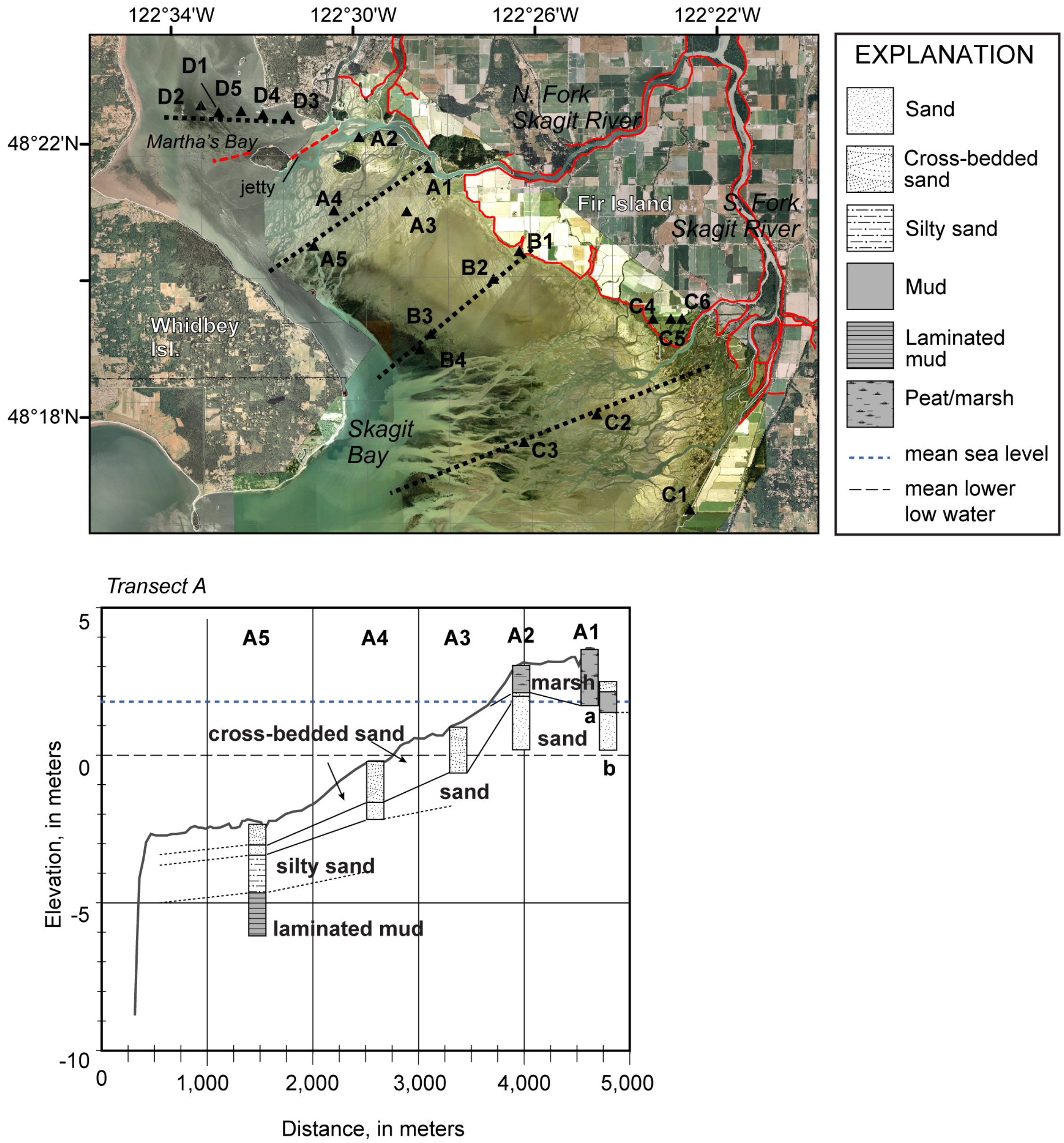

Figure 7. Diagram showing stratigraphy of Transect A, Skagit River Delta, Washington.

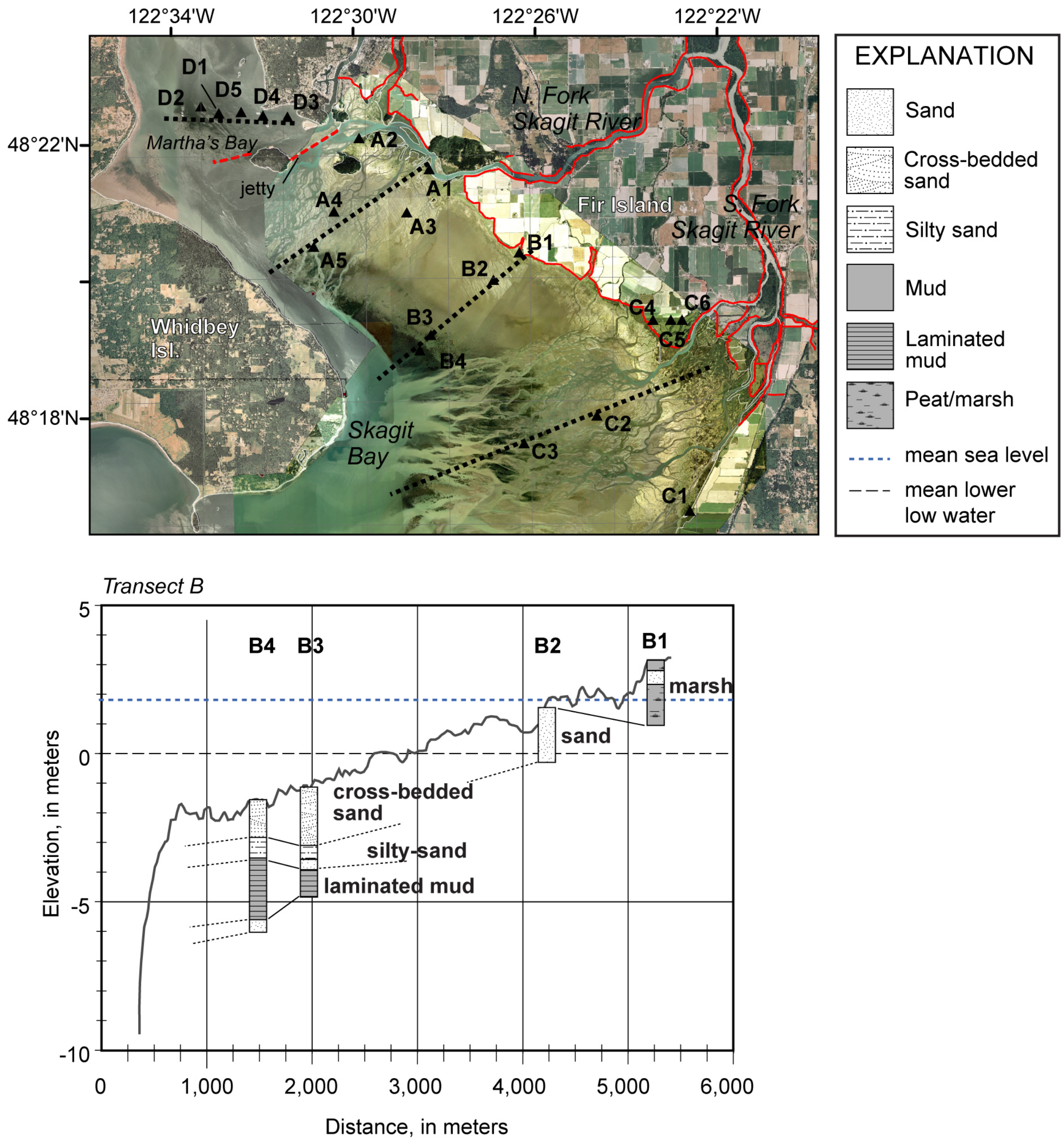

Figure 8. Diagram showing stratigraphy of Transect B, Skagit River Delta, Washington.

Transect C

Transect C was oriented across the South Fork Skagit River Delta and was composed of three vibracores and sediment samples obtained from three augers. Core C1 was collected in the emergent marsh at an elevation of 3.1 m and is 1.91 m long. Core C2 was collected on the inner tidal flats at an elevation of 0.3 m and is 1.82 m long. Core C3 was obtained along the outer mid-tidal flats at an elevation of -0.62 m and is 3.95 m long. The three augers were situated between 0.2 and 1.0 km landward of the shoreline and outer dike complex at an elevation of +2.1 m. Each auger is 9.6 m long and was collected areas converted from wetland to agricultural land beginning in the mid-1880s.

The stratigraphy across the South Fork Skagit River Delta along Transect C also showed the prevalence of peat-marsh facies in the emergent marshes and sand facies that overlie silty-sand facies along the tidal flats (fig. 9). The peat-marsh facies of core C1 occurred between elevations of +3.0 to

+1.5 m. The upper 0.5 m sections of the augers C4, C5, and C6 were composed of sod at elevations of +2.1 to +1.6 m (appendix 1), likely having replaced any existing marsh materials that occurred there prior to reclamation for agriculture. At the auger sites, a silty-sand facies extended 1 to 3 m below the sod. Below the silty-sand facies, a massive-sand facies extended down to the base of the augers at 9.6 m. Across the inner tidal flats, a massive-sand facies composed the upper 2 m at elevations of +0.3 to -1.8 m. Along the outer tidal flats, the cross-bedded sand facies, reaching 2.5 m thick, extended down from the surface from -0.6 to -3.1 m. A sharp contact was found between the cross-bedded sand facies and the underlying silty-sand facies that was 1.5 m thick.

Transect D

Transect D was oriented across the Martha's Bay tidal flats, immediately north of the North Fork Skagit River and the Skagit Bay jetty. This transect was composed of two vibracores and three push cores. Core D1 was collected along the middle-to-outer tidal flats at an elevation of -0.19 m and was 3.0 m long. Core D2 was located seaward about 500 m, was collected at an elevation of -0.92 m, and is 2.4 m long. Push core D3 was collected on the inner tidal flats at an elevation of -0.2 m and is 0.7 m long. Push cores D4 and D5 were obtained about 300 m successively seaward at depths of 0.5 and 0.75 m, respectively. Core D4 is 0.45 m long and Core D5 is 0.40 m long.

Across Martha's Bay tidal flats, the stratigraphy of Transect D was dominated by two facies: the mud facies between 0 and -2 m, and the cross-bedded sand facies between -2 and -3 m (fig. 10). The transect did not extend landward into emergent marsh and, therefore, this transect is representative only of the tidal flats. The inner tidal flats were characterized by the mud facies, but only the upper 0.4–0.7 m was sampled by Core D3, D4, and D5. The outer tidal flats were composed of mud facies ranging from 1.6 to 1.7 m thick as observed in Cores D1 and D2. Below this upper mud, cross-bedded sand facies ranged from 0.6 to 0.7 m thick. In Core D1 a 0.8 m-thick mud facies was observed below the cross-bedded sand facies between -2.6 and -3.4 m. The mud facies in Martha's Bay was different from mud facies found along the Skagit Bay transects. In Martha's Bay, the mud was at the surface and was fluffy, likely due to mixing and reworking with the overlying water and, perhaps, because of greater bioturbation. The underlying silty-sand facies between -2 and -3 m (mllw) was similar in characteristics to the silty-sand facies underlying the tidal flats along Transects A, B, and C (fig. 3).

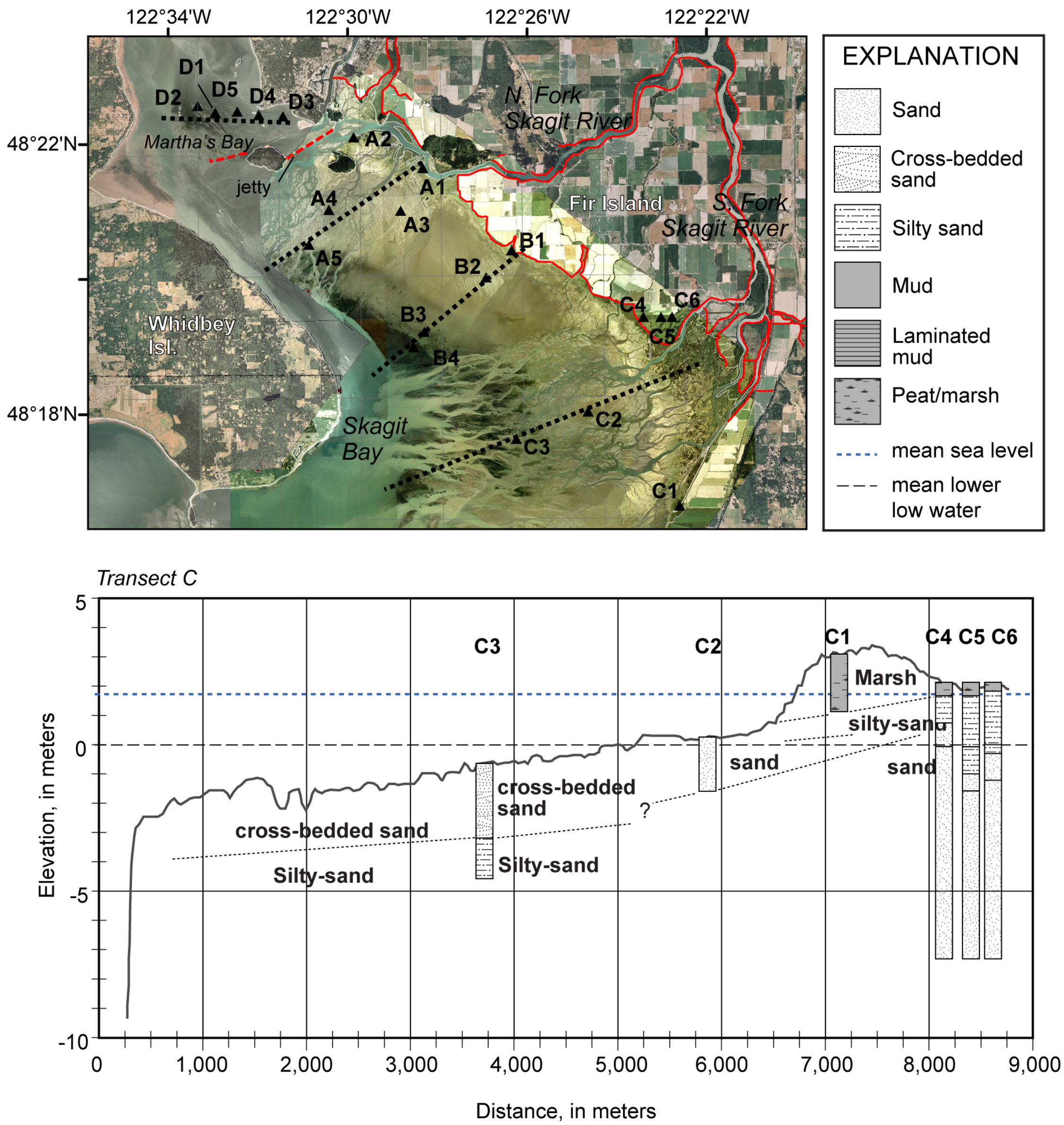

Figure 9. Diagram showing stratigraphy of Transect C, Skagit River Delta, Washington.

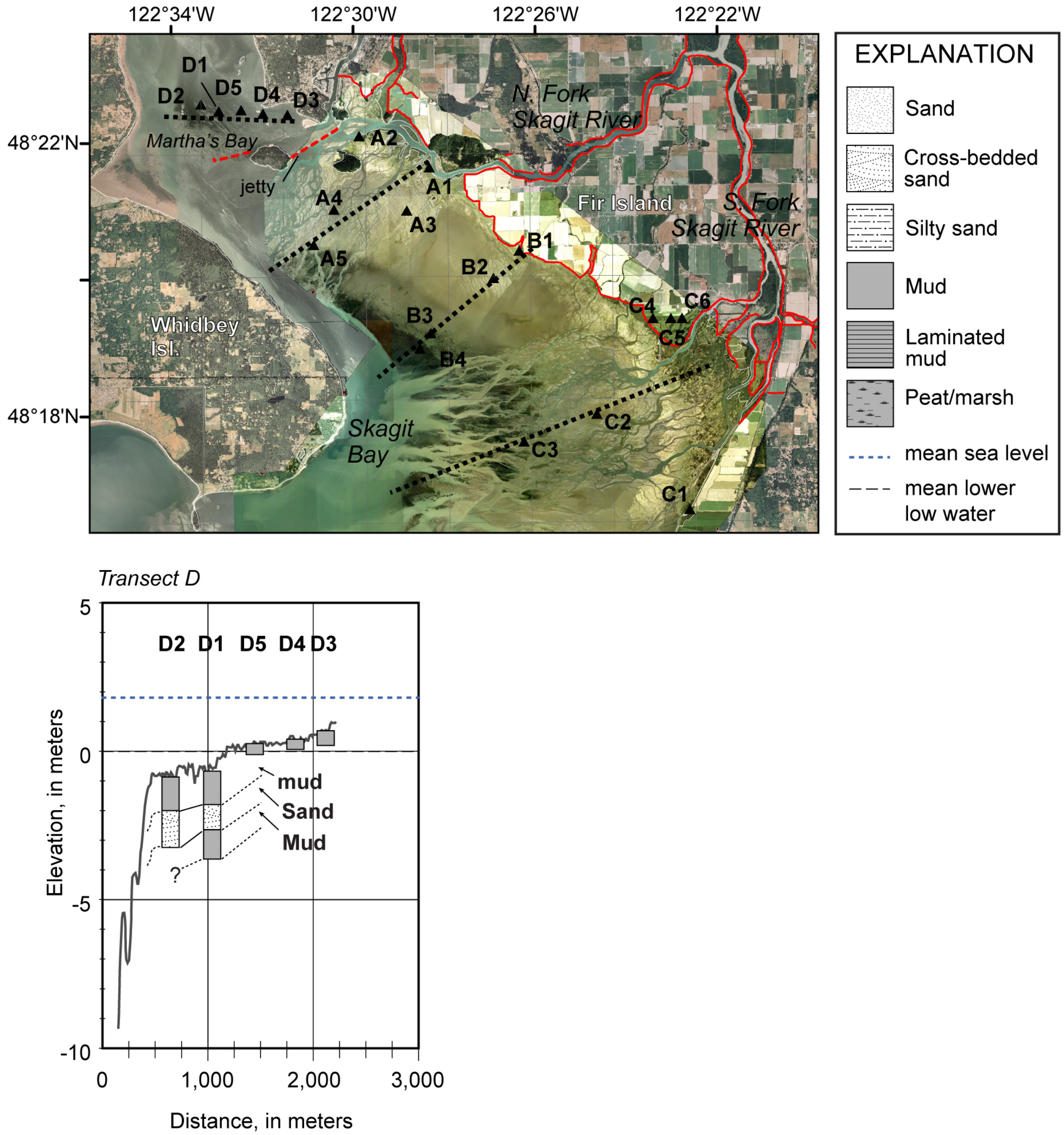

Figure 10. Diagram showing stratigraphy of Transect D Skagit River Delta, Washington.

Discussion

Shallow Sedimentary Facies of the Skagit Delta

The six sedimentary facies observed in our cores (massive sand, cross-bedded sand, silty sand, massive mud, laminated mud, and peat/marsh) reflect unique environmental conditions. These facies record primary depositional processes, including source materials, sediment-transport processes, and depositional environments, as well as secondary processes or those that influence sediment-facies preservation, such as reworking, bioturbation, or diagenesis (Boggs, 2009). The dominant source for materials observed in our cores is the Skagit River and watershed, but nearby beaches and bluffs and detrital submarine-aquatic vegetation (seagrass, macroalgae, and kelp) also may contribute materials. A brief description of the primary and secondary features and environmental interpretations of each facies follows.

The sand facies that lacks notable structure commonly is referred to as massive sand. Massive sand can reflect variable composition of material delivered, varying depositional processes that lead to varying rather than dominant structures, and (or) reworking or bioturbation (Boggs, 2009; Tucker, 2001). It also has been interpreted to indicate rapid deposition from suspension without reworking, notably flood or sediment-rich flow deposits (Barnhardt and Sherrod, 2006). The cross-bedded sand facies, in contrast, is indicative of active, energetic depositional environments common of tidal flats, beaches, inlets, and estuaries, where current velocities are sufficient and persistent to move sediments in bedforms (Boggs, 2009). Bedforms of this type generally occur as ripples and sand waves, and the thickness of the cross-bedding preserved is generally only a fraction of the thickness of the bedform itself. The silty-sand facies observed is massive and lacks structure. It likely reflects deposition similar to that of the massive-sand facies, but in a calmer environment, where the finer silt fractions settle out of suspension (Boggs, 2009; Tucker, 2001).

The mud facies that lacks texture and is referred to as massive-mud reflects either sedimentation under low-current velocities (calm environment), where input of fines is high, or rapid accumulation of mud under variable processes, which do not favor development of a dominant structure. This is in contrast to the laminated mud facies, displaying fine horizontal laminae, which is indicative of very calm depositional environments that allow muds to settle out and be preserved in delicately stratified layers. The peat/marsh facies, which is high in organic-rich mud content, reflects either in place, below-ground marsh vegetation, or detrital marsh and peat biomass.

Both normal and reverse grading occur in the facies and units observed. Normal grading refers to fining upward and commonly reflects environments in which depositional energy decreases with time, leading to finer materials accumulating over time (upward in the sequence). Normal grading also can form during rapid depositional events (Boggs, 2009). In contrast, reverse grading refers to coarsening upward and reflects deposition of sediments that coarsen with time or elevation within the unit. These deposits generally are reflective of sedimentation associated with grain flows and debris flows. A steady coarsening upward of sediments is common in deltas where sedimentation leads to shallowing and a seaward movement or progradation as the delta develops over itself. In several cores, a sharp transition in sediment grain size is observed, indicating rapid change in sedimentation history and the processes influencing it.

Modern Depositional Environments in the Skagit Delta

The Skagit Delta can be classified into four principal regions of modern (present-day) sediment deposition: (1) the emergent marshes below the influence of the Skagit River dike complex; (2) the tidal flats offshore of the North and South Forks of the Skagit River; (3) the tidal flats offshore of the bayfront of central Fir Island; and (4) the Martha's Bay tidal flats (fig. 2). The tops of the cores reveal the composition of sediments that accumulate in these areas today, or that accumulated in the recent past (years to decades) if they have been subject to erosion.

The upper 0.5 to 1.0 m of the cores in the emergent marshes downstream of the dike complexes are largely composed of mud and marsh/peat facies with interfingered units of sands that range from 5 to 20 cm thick, as observed in Cores A1, A2, B1, and C1 (figs. 7–9; appendix 1). The muds and marsh/peat material are thought to reflect generally calm depositional environments where muds from the river and tidal exchange settle out and provide ideal substrate for wetland marsh complexes. The occasional sand deposits in the emergent marshes that range from 5 to 20 cm thick are likely flood deposits associated with periodic events when the Skagit River overflows its banks. Correlation of these deposits to historical floods of the Skagit River measured at the

USGS Streamflow-gaging station in Mt. Vernon (USGS Streamflow gage 12200500) is being tested.

Tidal flat surface sediments of the North and South Forks of the Skagit River are dominated by medium to coarse sands as represented by Cores A3, A4, A5, C2, and C3 (figs. 7–9; appendix 1). These surface sediments generally are cross-bedded, indicating energetic environments where ripples and bedforms actively migrate. Meandering- and braided-channel complexes observed in aerial photographs (fig. 2) support the interpretation that there is active sediment transport across the tidal flats of the North and South Forks of the Skagit River; and the cross-bedded sands within braided channels are indicative of sediment bypassing (Boggs, 2009; Einsele, 2000). The absence of mud in these surface sediments suggests that the finer mud fractions delivered by the river are exported out of the study area (seaward). This is consistent with high current velocities that produce braided tidal-flat channels and would greatly exceed the threshold allowing muds to settle and deposit. Periodically, muds likely deposit on the tidal flats of the North and South Forks of the Skagit River during flood events or periods of high mud delivery (landslides in the watershed); however, the high nearshore tidal currents (Grossman and others, 2007) likely winnow this material before it can accumulate, leaving heavier, coarser sands behind, as observed in our cores.

In contrast, the tidal flats offshore of the bayfront of central Fir Island lacks braided channels (fig. 2) and are composed largely of massive sands with lower mean grain size, as observed in Cores B2, B3, and B4 (fig. 8; appendix 1). Although cross-bedding is observed in some of the core sections, the surface sediments generally lack cross-bedding and instead are more massive in nature. As a result, the depositional environment of the central Skagit River Delta tidal flats is interpreted to be calmer than the tidal flats offshore the North and South Forks of the Skagit River, and aerial photographs support this idea showing the region to be much smoother in surface texture (fig. 2).

In stark contrast, the surface sediments of the Martha’s Bay tidal flats, north of the Skagit Jetty, are composed of fluffy, massive, featureless mud, as observed in Cores D1—D5 (fig. 10; appendix 1), and are very different from the surface sediments offshore of Fir Island and the North and South Forks of the Skagit River. Surface sediments of Martha’s Bay tidal flats are indicative of very calm conditions that allow very fine sediments, such as muds, to settle out of suspension and accumulate. The calm conditions that allow muds to settle out of the water column were precisely the goal of the 1940s Skagit jetty construction, which aimed to keep the energetic North Fork Skagit River to the south and retard sedimentation in the Swinomish Channel and improve navigation. The mud found across the surface of the Martha’s Bay tidal flats likely is sourced from the tidal delivery of suspended fine sediments emanating from the Skagit River plume that commonly are observed to be advected northward by tidal currents (fig. 11*A*) and to be consistent with a net northward surface transport of Skagit Bay (Grossman and others, 2007).

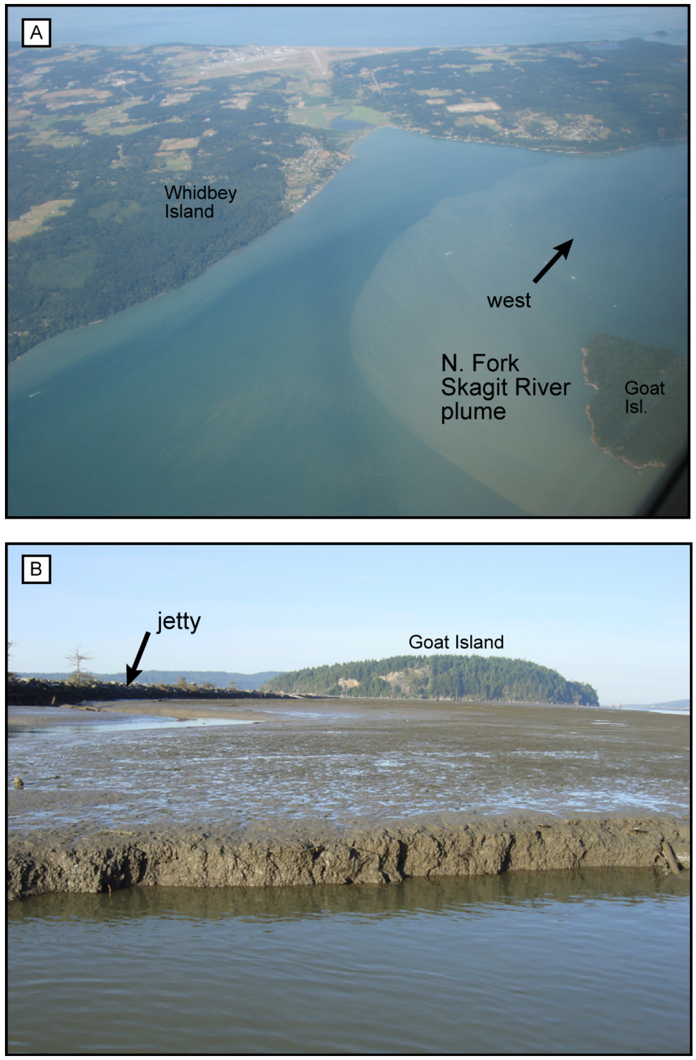

Figure 11. Photographs of the northern portions of the Skagit River Delta, Washington. *A*, View of the turbid North Fork Skagit River plume being advected northward during ebb tidal flow (Photograph courtesy of Chris Chickadel). *B*, View showing the extensive mud flat that has formed along the north side of the Skagit Jetty.

Historical Nearshore Environmental Change in Skagit Bay

The transformation from a mud-rich tidal flat to an energetic, sandy tidal flat across the 75 km^2 area of the modern Skagit Delta tidal flats represents a significant change in environment. A natural coarsening of the delta is expected as it grows seaward over itself. The sharp changes in lithofacies, observed as distinct contacts between the underlying laminated mud, mud, and silty-sand facies and the overlying cross-bedded and massive-sand facies across the tidal flats and delta front, suggest that this transformation was abrupt and likely correlated to changes in sedimentation expected from emplacement of the Skagit Bay jetty in 1940 and the extensive dike complex along the Skagit River beginning in the late 1800s. Similarly, the abrupt transition from a silty, sandy tidal flat to a mud-dominated tidal flat across Martha's Bay also can be best explained by the emplacement of the Skagit Bay jetty.

Skagit Delta Tidal Flats

The braided channels and cross-bedded nature of the upper unit of the tidal flat sands offshore of the North and South Forks of the Skagit River, are indicative of active sediment transport and sediment bypassing. This energetic environment is in stark contrast to the environment that formed when the underlying mud-rich facies were deposited. The laminated texture and finer sediments of the mud-rich facies reflect a much calmer environment where muds settled out of the water column in fine, delicate laminated sequences.

The sharp facies transition between the cross-bedded sands and underlying mud-rich sediments, as observed at 1.0 m depth in Core A5, at 1.9 and 2.7 m depth in Core B3, at 1.3 and 1.8 m in Core B4, and at 2.5 m in Core C3, is suggestive of an abrupt change in environmental conditions rather than a steady shallowing of the delta that would invoke a steady coarsening. The abrupt change to a coarser sedimentary environment is consistent with a significant increase in sediment delivery and an increase in current velocities capable of transporting coarser sediment. An increase in sediment delivery and current velocities across the tidal flats would be expected as a result of the extensive diking and channelization of the Skagit River between Mt. Vernon and Skagit Bay and around Fir Island, beginning in the 1800s. This hypothesis is formulated on the mass-balance argument that redirection of the entire Skagit River flow and sediment delivery to a depositional area less than 5 percent of its historical size (Samish, Padilla, and Skagit Bays and flood plains; fig. 1) would significantly increase the sediment load to its present outlets. The channelization of the Skagit River through fewer distributaries (fig. 1) would increase velocities where flow has been focused, enhancing sediment delivery to the tidal flats and bays beyond. Focusing the entire Skagit River sediment load through the delta would be sufficient to transform the tidal flats from a previous mud-rich tidal flat to an energetic sand-rich tidal flat. Validation of this hypothesis relies on constraining the timing of the tidal-flat facies transformation to the emplacement of the Skagit River dike complexes beginning in the 1800s. This hypothesis is being tested through sediment-age dating of the cores presented here and will be the subject of a subsequent report.

A slight sediment coarsening downward near the base of Core B4 (fig. 8; appendix 1) was observed and may be associated with a sedimentary unit associated with the last great Lahar deposit from Glacier Peak estimated near this depth (Dragovich, McKay and others, 2000), or with a past fluvial flood deposit. The lithology and composition of these basal sediments are being investigated to determine their source.

The transition from a mud-rich tidal flat to an energetic braided-channel network composed of migrating sands offshore of the North and South Forks of the Skagit River (figs. 2, 7, and 9) would have greatly impacted substrate conditions for invertebrates and plants. The energetic sands that move across the tidal flats appear in aerial photographs to abrade and fragment eelgrass meadows offshore of the North and South Fork Skagit Rivers, unlike offshore of the central delta where eelgrass meadows are left continuous and intact. The transition in depositional regime also would be expected to impact the composition of benthic invertebrate and submerged aquatic-vegetation communities that have close affiliations with sediment grain size, organic content, pore-water nutrients, and sediment-accumulation rate. Many benthic invertebrates serve as key food-prey resources for salmon, forage fish, crab, and birds. Improved understanding of the importance and role of these flora and fauna to salmon recovery, ecosystem restoration, and human livelihood, and the degree to which changes in sedimentation influence them, is needed to guide adaptive resource management.

Martha’s Bay Tidal Flats

The historical 1937 photograph (fig. 3) shows the Martha’s Bay tidal flats during the initial stages of the Skagit Bay jetty construction and their previous exposure to the direct delivery of Skagit River freshwater flow and sediment delivery. Completion of the jetty in the 1940s to protect the newly dredged Swinomish Channel from Skagit River floods and sedimentation, cut off direct delivery of sand to the Martha’s Bay tidal flats and instead created a protected area in the lee of the jetty that is favorable for accumulation of mud exported from the river. Fine sediments transported in suspension within the Skagit River plume are advected to the northwest during flooding tides (fig. 11*A*) consistent with a net northward surface transport (Grossman and others, 2007). Mud likely settles out of the water column and Skagit River plume where current velocities are expected to be reduced in the lee of the jetty. A photograph taken at low tide in 2008 shows the vast amount of mud that ranges from 1 to 3 m thick and extends along the entire north side of the jetty (fig. 11*B*).

The transformation from a sand-rich tidal flat to a mud-rich tidal flat is hypothesized here to be correlated with emplacement of the jetty in 1940, as this is the best mechanism to explain enhanced deposition and preservation of muds where the North Fork of the Skagit River used to flow. The basal units of Cores D1 and D2 are similar to the basal units of Cores A4, A5, B3, B4, and C3, with respect to mean grain size and relative proportion of silt (greater than sand). This indicates that the tidal-flat compositions of Martha’s Bay and Skagit Bay were similar in the past relative to today, and that a change occurred, which promoted mud accumulation across Martha’s Bay and coarser sand accumulation across the Skagit tidal flats. Although a change in sediment source could explain an increase in delivery of coarser sand to the Skagit tidal flats (and mud farther seaward, including Martha’s Bay) today, the preservation of more mud on the Martha’s Bay tidal flats requires a calmer depositional environment than in the past. The emplacement of the jetty is a mechanism that would produce a calmer environment for greater amounts of mud to settle their today than in the past.

The increase in accumulation of mud across the Martha’s Bay tidal flats would impact substrate and water-column conditions for invertebrates and plants, many of which support salmon, crab, forage fish, and birds of interest to human livelihood. Examples include, burying sand-associated benthic flora and fauna with mud and promoting more turbid conditions for light-sensitive plants and animals, including eelgrass meadows that are essential nursery and forage habitat for salmonids and forage fishes.

Summary and Conclusions

Twenty-one sediment cores were collected from across the Skagit River Delta at elevations ranging from 3.94 to -2.41 m relative to mean lower low water and were analyzed to quantify how depositional settings across the marshes, tidal flats, and delta front have changed in the recent past. The findings indicate that the Skagit River Delta and nearshore out to the delta front have experienced significant large-scale environmental change in substrate and benthic habitat structure, as well as sediment transport and depositional processes, in the recent past. An abrupt change across a vast area of the outer tidal flats and delta front offshore of Fir Island occurred in the form of silty mud-rich sand being abruptly replaced by a 1–2-m-thick unit of medium and coarse sands. Sediment textures, including cross-bedding, variability in physical properties of bulk density, sediment grain size, and vertical trends in grain size, indicate an increase in sediment-transport energy across the tidal flats commonly associated with sediment progradation, bedform migration, and sediment bypassing that can lead to burial and abrasion of sessile plant and animal communities such as eelgrass and many valued invertebrates. This is in stark contrast to the underlying massive and laminated muds that were deposited under calmer environmental conditions and likely supported different plant and animal communities that provided important food-prey resources for salmon and other valued fishes.

The replacement of a silty, sand tidal flat by a 1–2-m-thick mud deposit across Martha's Bay tidal flats is hypothesized here to have resulted from the emplacement of the Skagit Bay Jetty, which cut off direct sedimentation from Skagit River. In so doing, it sheltered Martha's Bay from strong current velocities that used to transport sands and muds. Although the jetty reduced sand transport from the river, it has allowed for the deposition of mud delivered by tidal currents that advect in the Skagit River plume northward and around the jetty. The transformation of Martha's Bay to a mud-dominated tidal flat likely influences turbidity, light levels for plants, and substrate conditions for many different flora and fauna.

Acknowledgments

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Appendix 1. Detailed Core Descriptions

Cores A1-A and A1-B

Two cores were obtained at site A1. The first core (A1-A) is 2.12 m long and was collected on the marsh platform at an elevation of 3.94 m (mllw). The second core (A1-B) is 2.27 m long, and it penetrated down from within a marsh channel 1.25 m below the marsh surface at an elevation of 2.69 m (mllw). As a result, the upper 0.87 m of core A1-B overlaps the lithology and stratigraphy of the lower section of core A1-A, and together they represent the depositional sequence of the upper 3.1 m at site A1. Core A1A contains a large amount of silt, peat, and mud, with interspersed fine sand in the upper 0.4 m (fig. A.1.1) Between 0.4 and 0.9 m the core is silty sand. The bottom half of the core is dominated by marsh peat and mud. Roots and wood pieces are found throughout the core, primarily in the mud and silt lithofacies. The bulk density ranges from 1.11–2.22 g/cm^3, with some fluctuations in the top 20 cm and between 1.0 and 1.1 m. Below 1.1 m, variability in density is low, with a mean of 1.74±0.19 g/cm^3. P-wave compression velocity ranges from 1,100 to 2,060 m/s and has a mean of 1,548±164 m/s, and is much more variable above 1.4 m than below. The mean grain size varies in the upper 0.5 m, ranging between 25 µm and 200 µm where fine-sand deposits are interfingered in muddy marsh deposits. Below 0.4 m, marsh muds are characterized by mean grain sizes of less than 75 µm, with a slight coarsening downward to 2.1 m. The composition of sand, silt, and clay mimics mean grain size, with sand comprising between 50 and 90 percent of the upper 0.4 m and less than 20 percent below 0.4 m where silt and clay range from 50 to 75 percent and from 25 to 50 percent, respectively, down to 1.7 m. Below this depth, Core A1-A, coarsens as sand increases in composition to 75 percent. The digital photographs show a wide range in sediment color and laminations. Medium-to coarse-sand deposits ranging from 3 to 5 cm thick (fig. A.1.1, inset A) are common in the upper core sections, while below 0.4 m, muds rich in clay are common (fig. A.1.1, inset B). Laminations are evident in the clay-rich mud in x-radiograph images (fig. A.1.1, inset C).

Core A1-A - Section 1

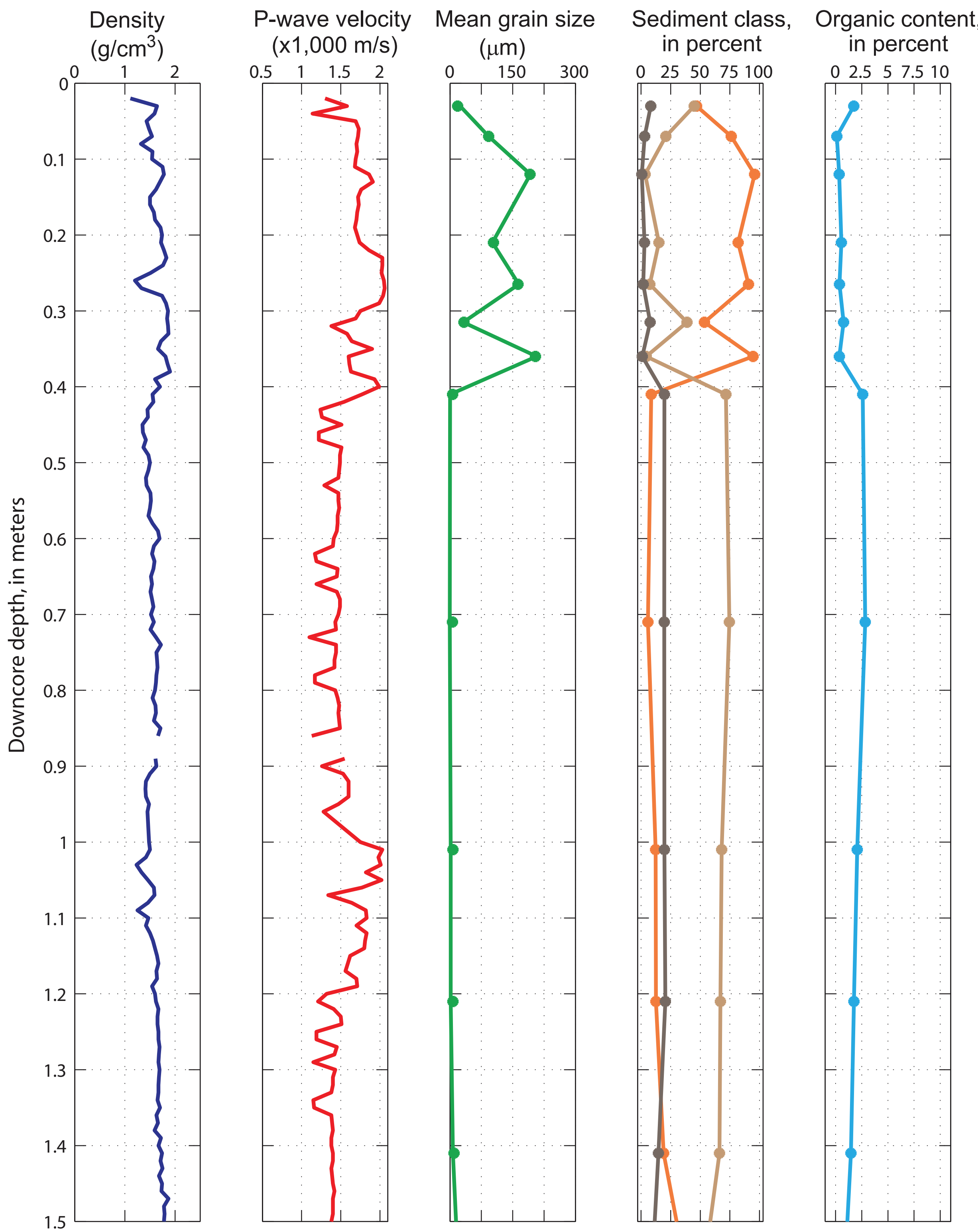

Figure A.1.1. Diagram of physical properties and lithology of sediments from Core A1-A, Skagit River Delta, Washington.

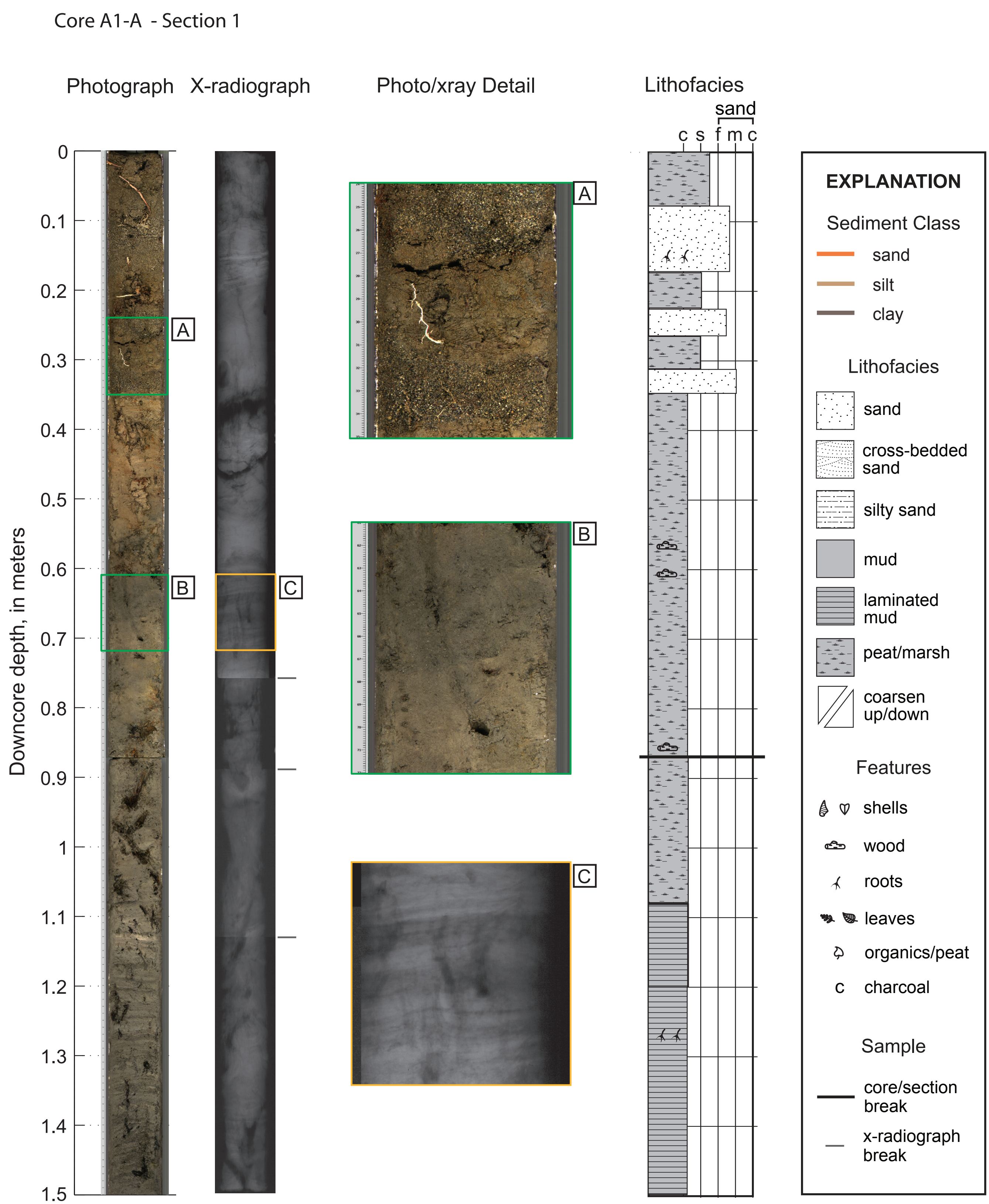

Figure A.1.1, cont.

Core A1-A - Section 2

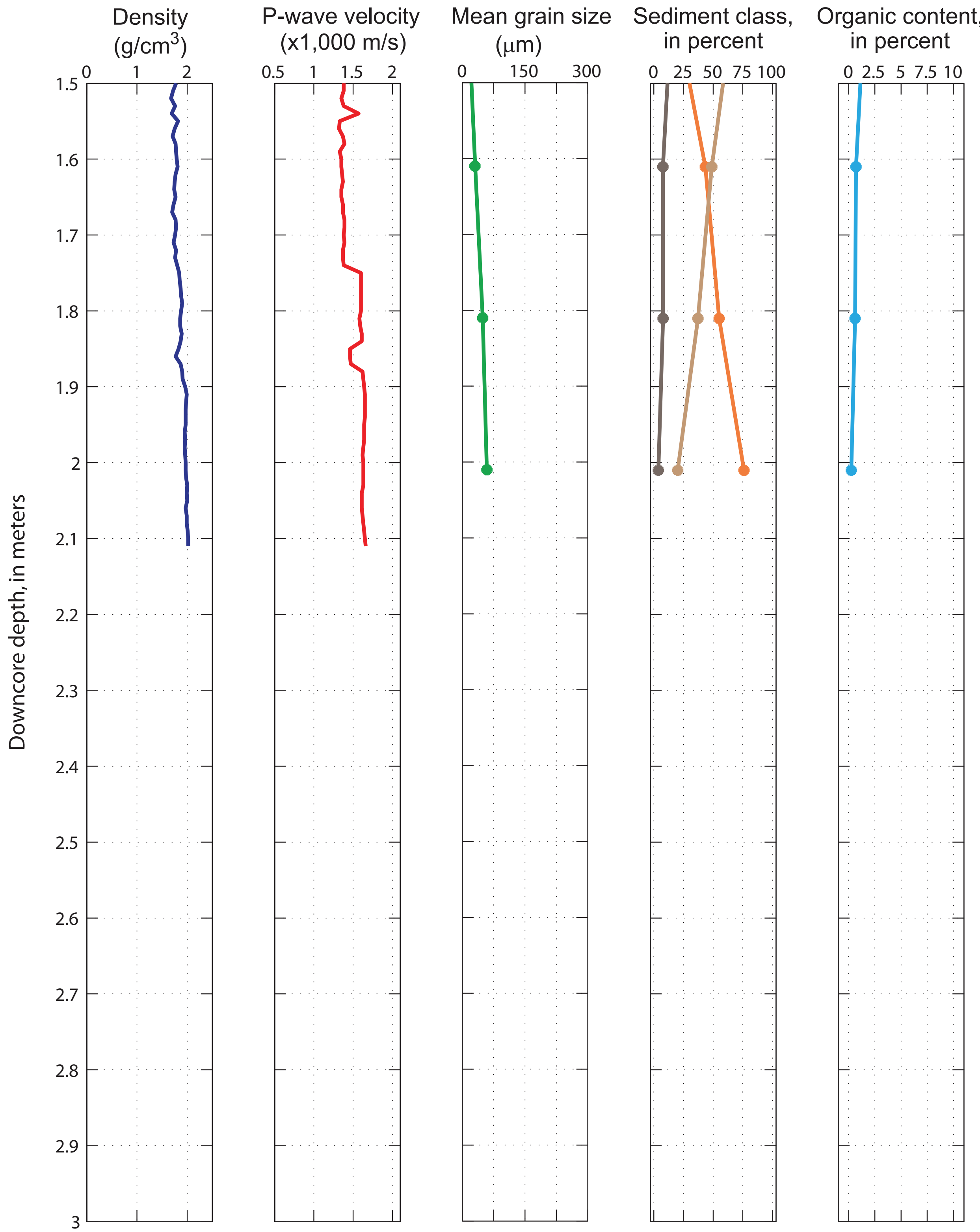

Figure A.1.1, cont.

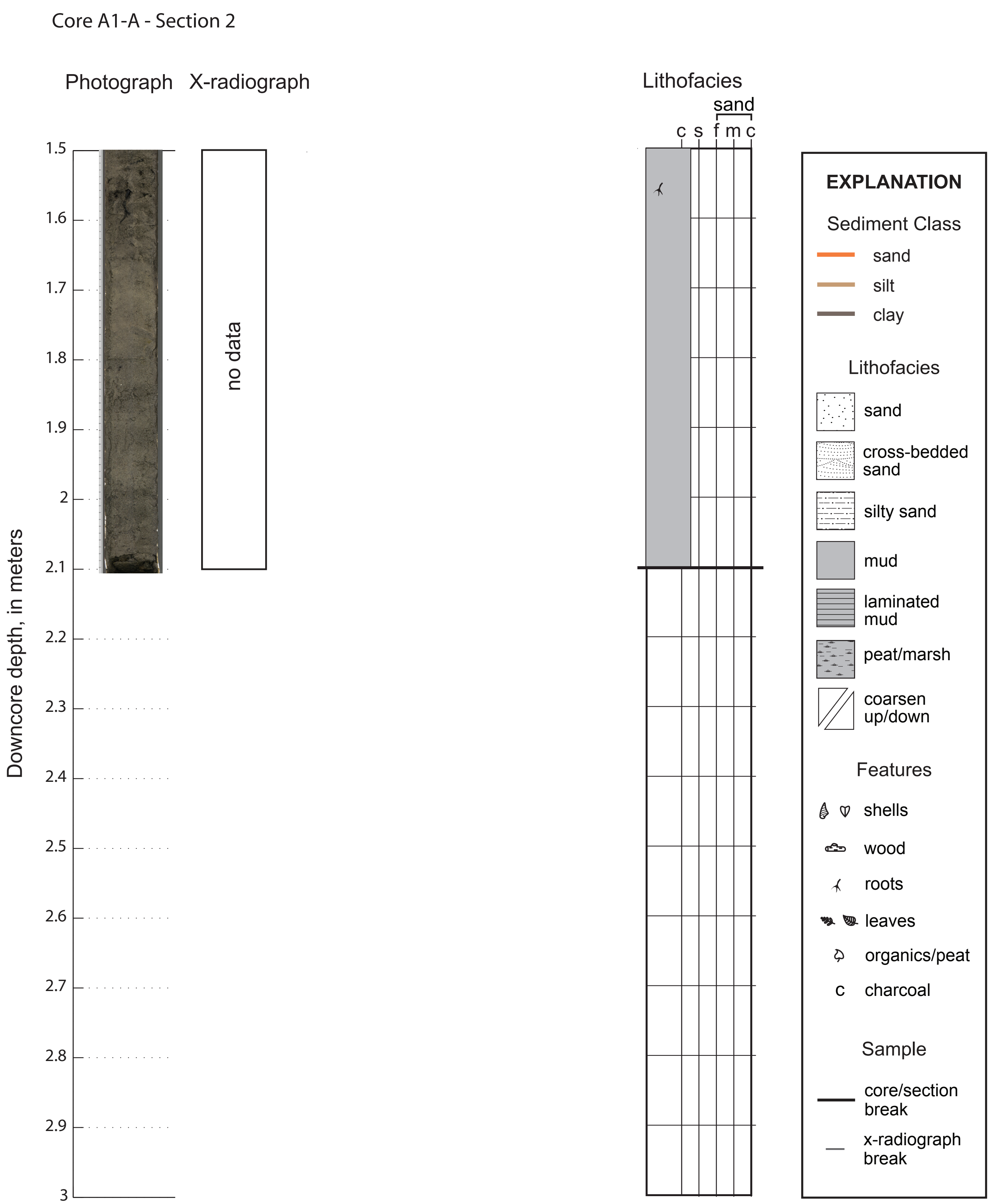

Figure A.1.1, cont.

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Core A1-B, collected at 2.69 m (mllw) elevation, penetrated 2.2 m, and the upper 0.87 m overlaps the base of Core A1-A. It is characterized by a coarse sand lens at the top (0 to 10 cm) that is associated with a sandy lag deposit on the marsh channel floor (fig. A.1.2). Below this sand lens, the core is dominated by silts grading into mud down to 1 m, with a slight coarsening into silts between 1.0 and 1.4 m. Below 1.4 m the core is dominated increasingly by fine sand. The bulk density is slightly higher (2.2 g/cm^3) and more variable in the upper 0.3 m than in the middle section, and it increases again to 2.2 g/cm^3 near the base. The P-wave compression velocity ranges from 1,500 to 1,700 m/s and it also is more variable in the upper 0.3 m. Below this depth, P-wave velocity is uniform through the silts and muds to -1.7 m, below which it rises to between 1,700 and 1,800 m/s in two slight oscillations. The mean grain size reaches 338 µm in the upper sand fill of the channel and generally is finer than very fine sand (125 µm) between 0.3 m and 1.4 m. Two prominent coarse layers at 1.60 and 1.85 m reach 581 and 412 µm, respectively. The contrast between the coarser sand units and surrounding muds is clear in digital photographs and x-radiograph images of core sections at 0 to 0.12 m (fig. A.1.2, insets A and B) and at 1.73 to 1.84 m (fig. A.1.2, insets D and E). Scattered root marks and borings from worms or other animals also are evident throughout the cores as is buried wood (fig. A.1.2, inset C).

Core A1-B - Section 1

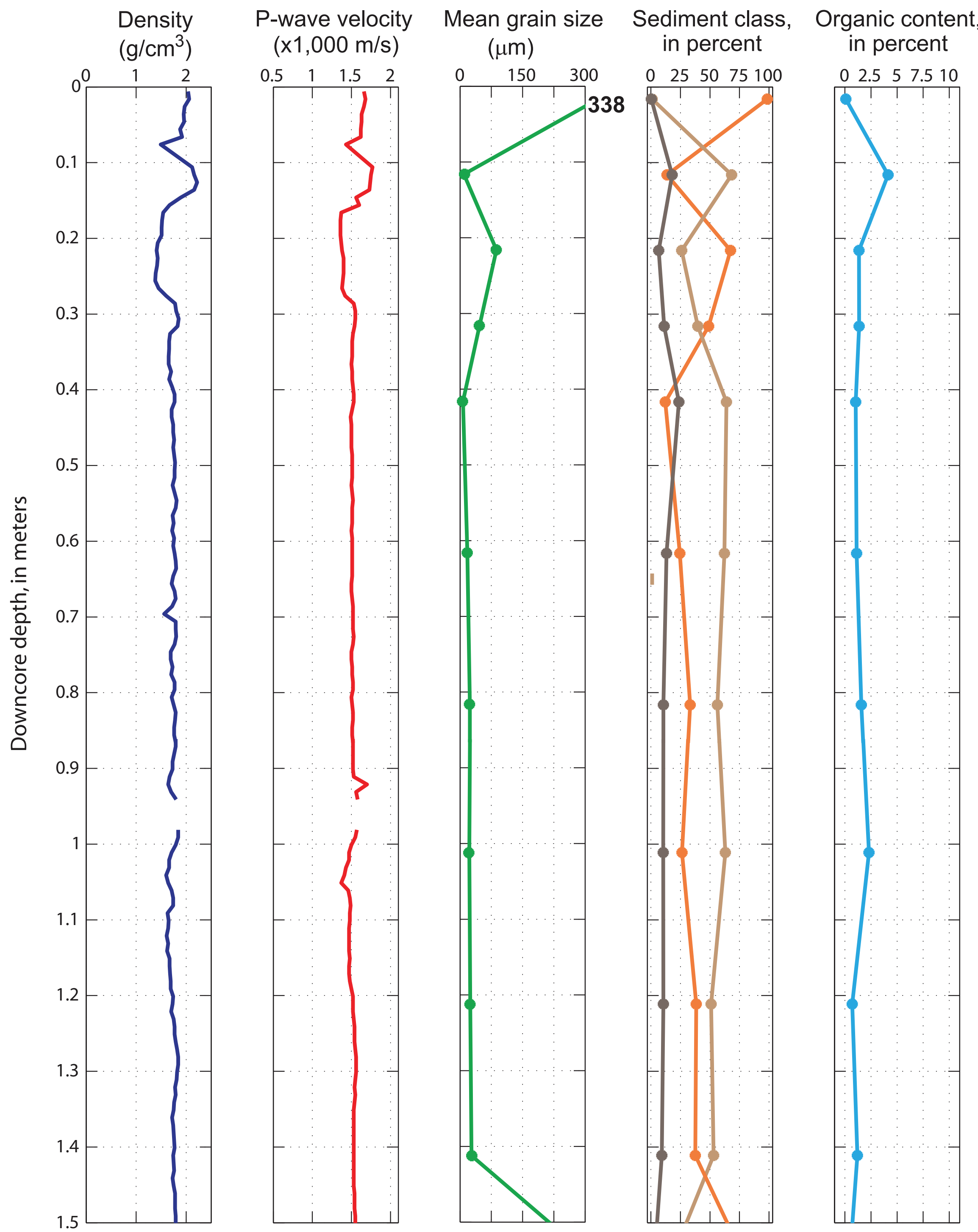

Figure A.1.2. Diagram of physical properties and lithology of sediments from Core A1-B, Skagit River Delta, Washington.

[an issue with Core A1B-section 2 was that we lost material between ~2.19 cm and 2.28 cm) so it did not go through core logger and other analyses.]

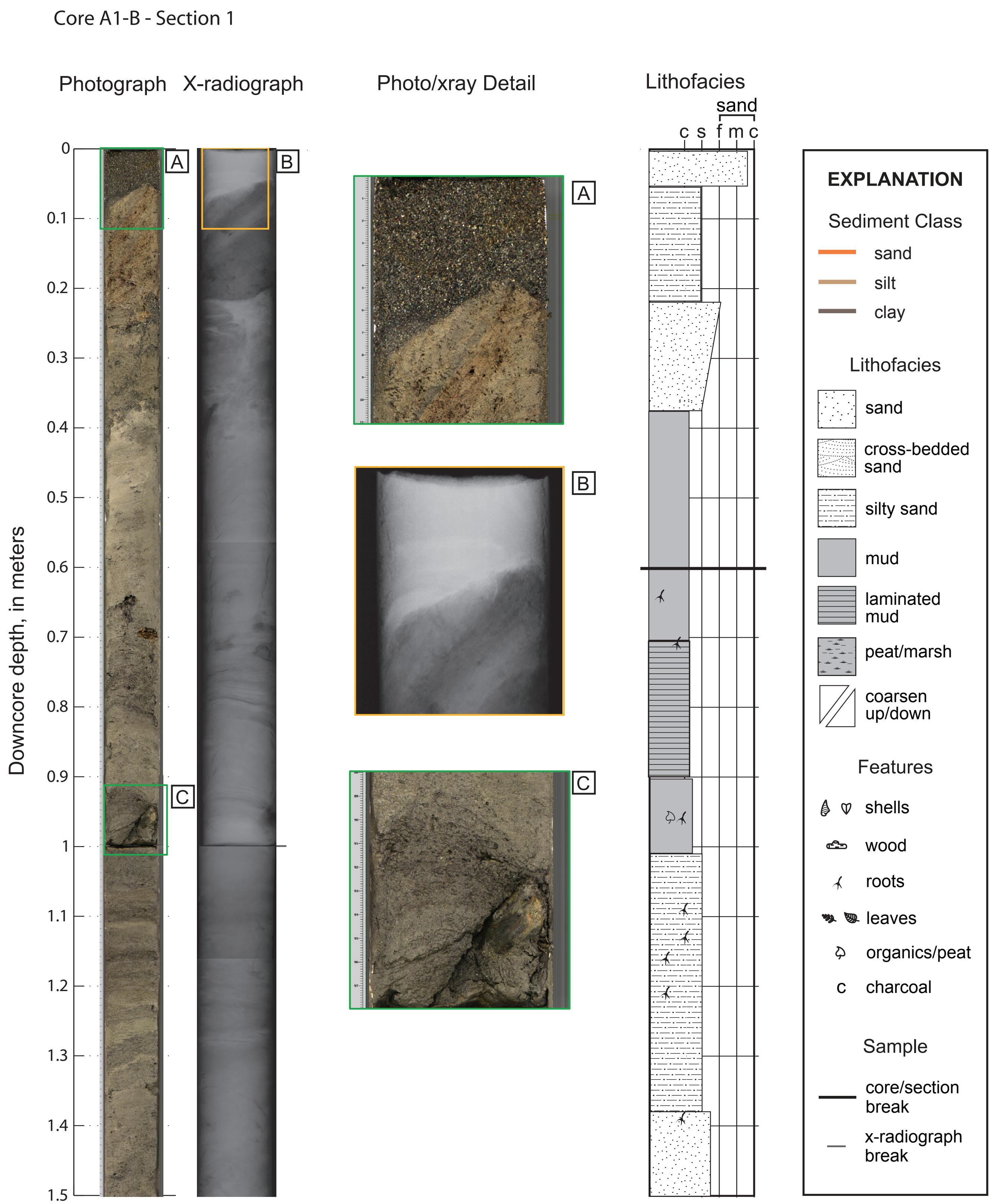

Figure A.1.2, cont.

Core A1-B - Section 2

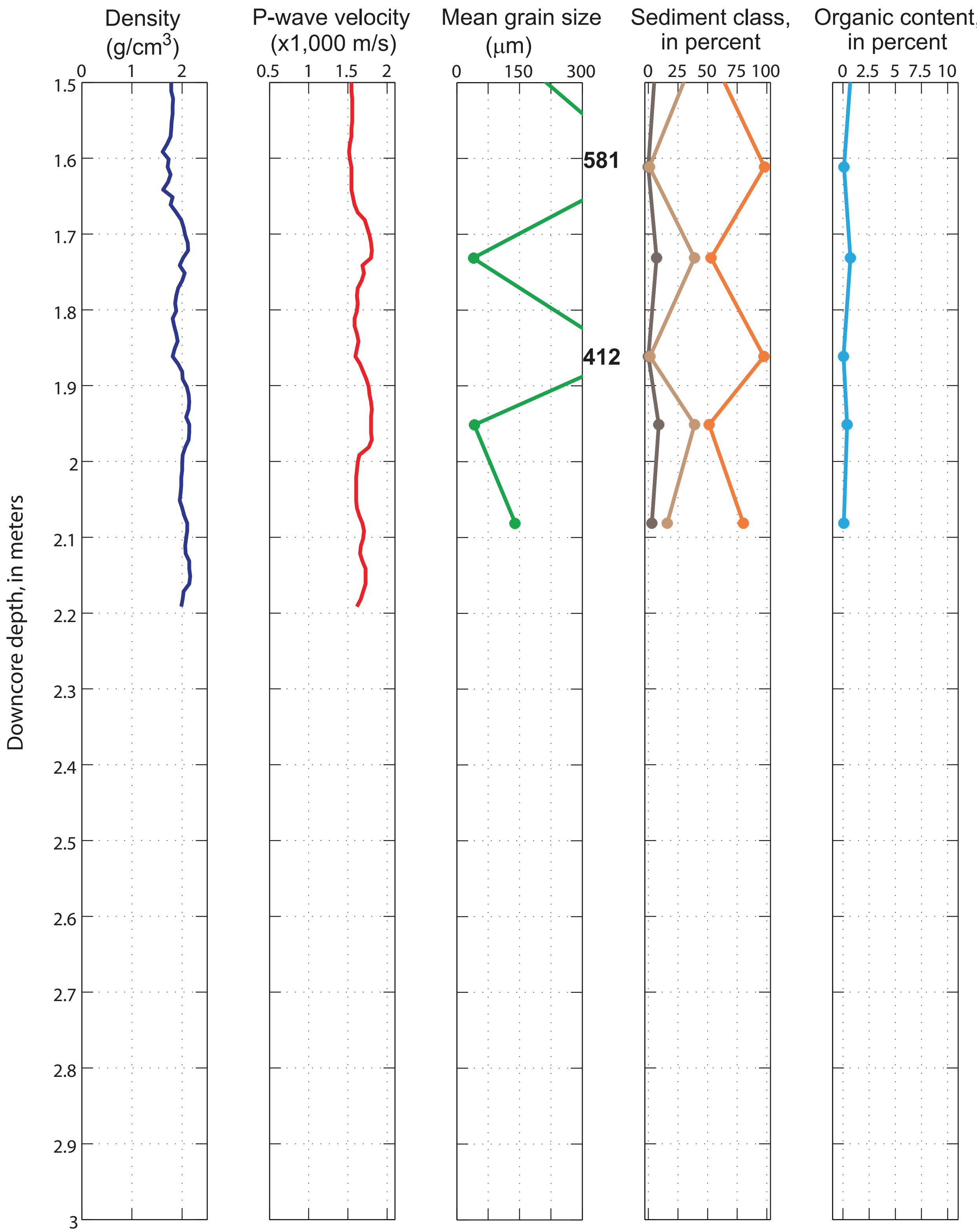

Figure A.1.2, cont.

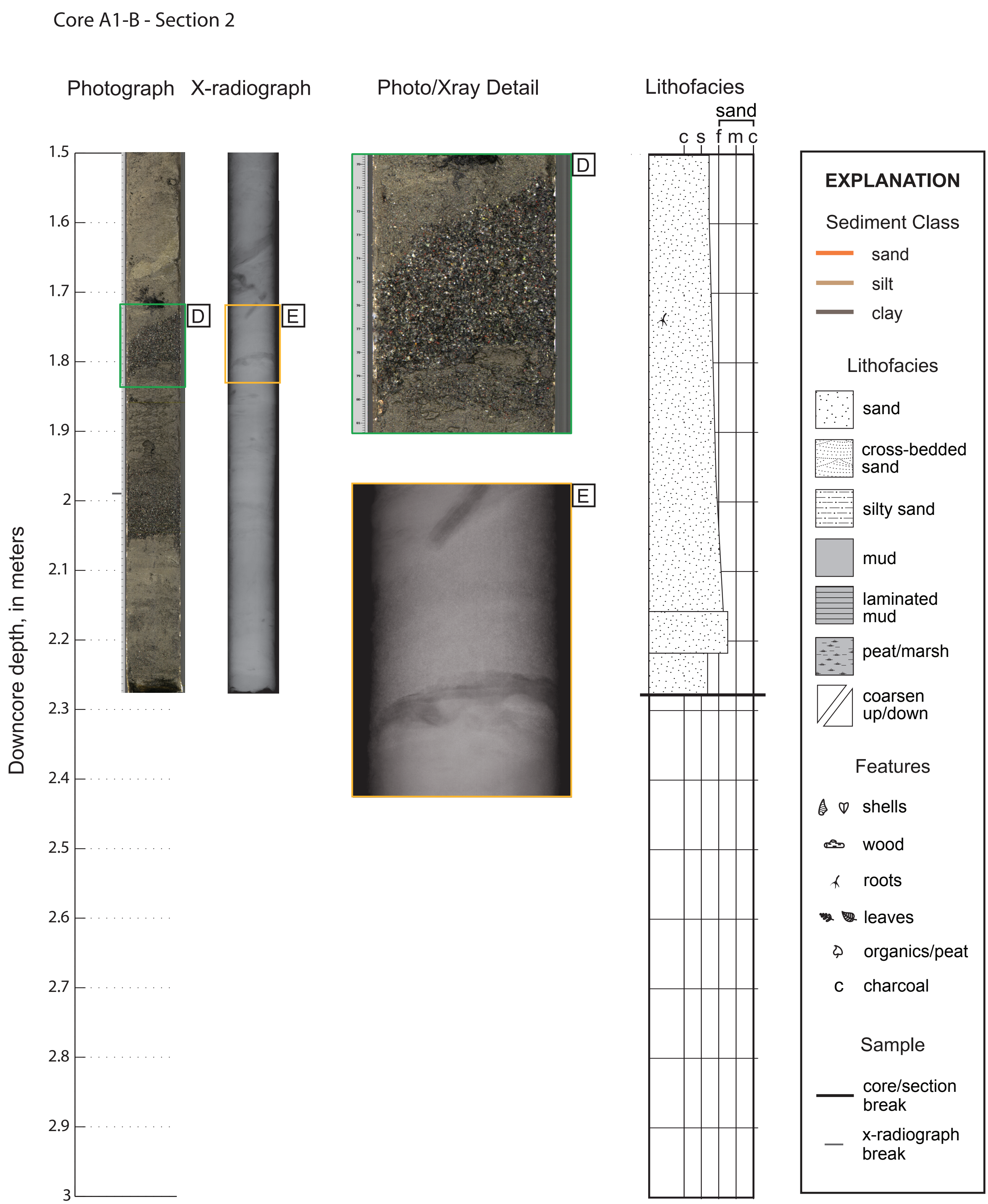

Figure A.1.2, cont.

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Core A2

This core also was collected on the modern marsh platform, but in an area that, in 1937, was a tidal flat at the mouth of the North Fork Skagit River (fig. 3). The elevation was 3.26 m (mllw), and the core length is 3.02 m. Two major lithofacies were observed with peat/marsh in the top 0.95 m and predominately sand units below this contact point. Roots, charcoal, and wood pieces are found throughout the core. The bulk density ranged from 0.19-2.09 g/cm^3 with fluctuations throughout the core, particularly in the top 0.60 m and 2.55–2.70 m. A mean of 1.60±0.28 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 814 to 1443 m/s and has a mean of 1225±113 m/s, but it does not show any notable downcore trends. The two major lithofacies were identified in the mean grain size with mud and very fine sand in the top 0.95 m and fine to medium sand for the remainder of the core. A slight fining occurs near the base of the core. Silt and clay fractions reflect this and are greatest in the top 0.95 m of the core, decrease to less than 10 percent below the contact point, and then increase slightly near the base. The digital photographs show peaty sediment (fig. A.1.3, inset A) underlain by brown and tan sand (fig. A.1.3, inset B). The x-radiograph images show lamina in the peaty region overlying the slight cross-bedded sands between 0.90 and 1.03 m (fig. A.1.3, insets B and C). Alternating coarser sand units and silty units also occur between 1.2 and 1.4 m, 1.5 and 1.6 m, and 1.86 and 1.98 m (fig. A.1.3, insets D and E). Photographs show a notable contact between dark sand with black and red lithics and mud at 2.86 m, with mud extending to the base of the core at 3.02 m (fig. A.1.3, inset F).

Core A2 - Section 1

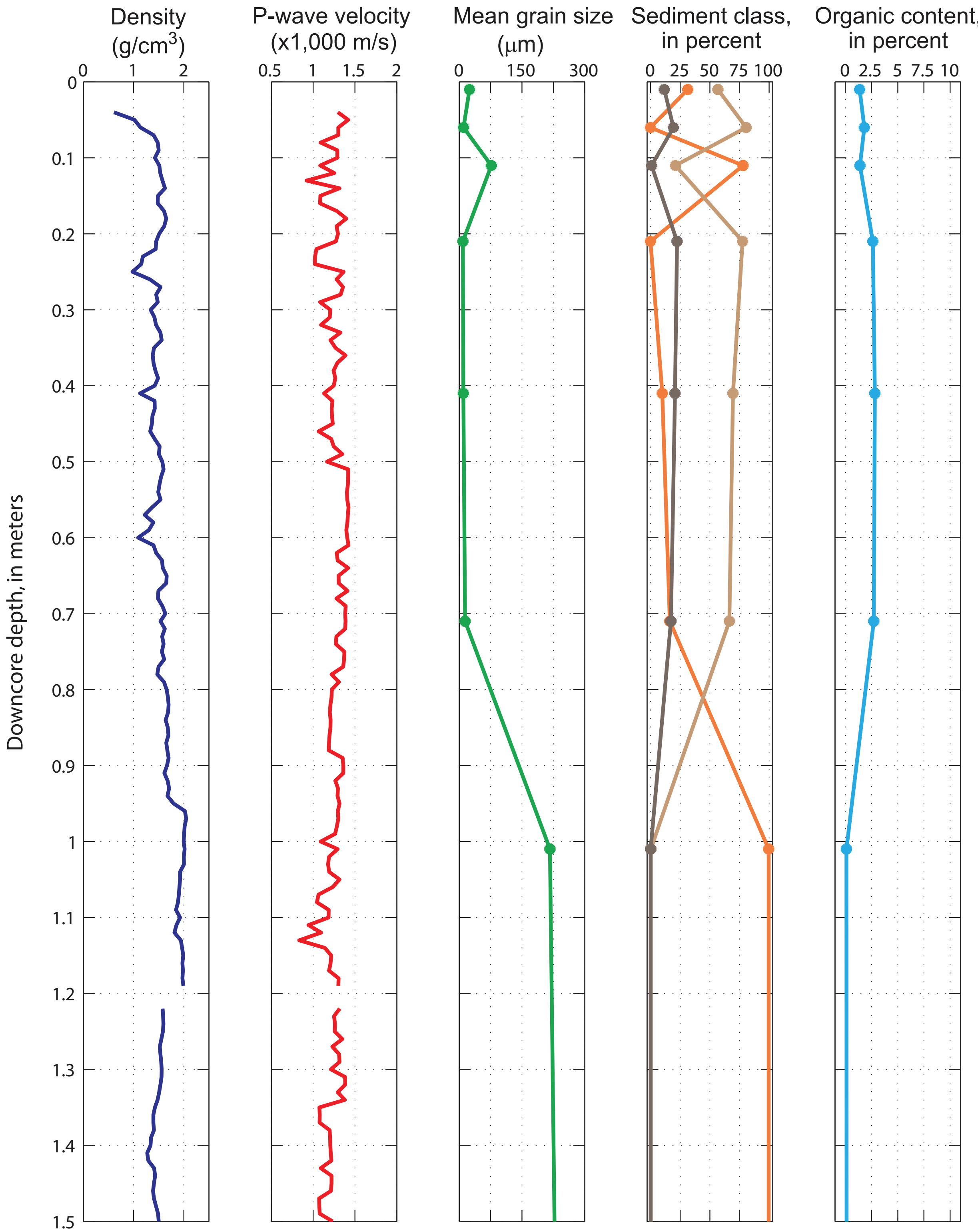

Figure A.1.3. Diagram of physical properties and lithology of sediments from Core A2, Skagit River Delta, Washington.

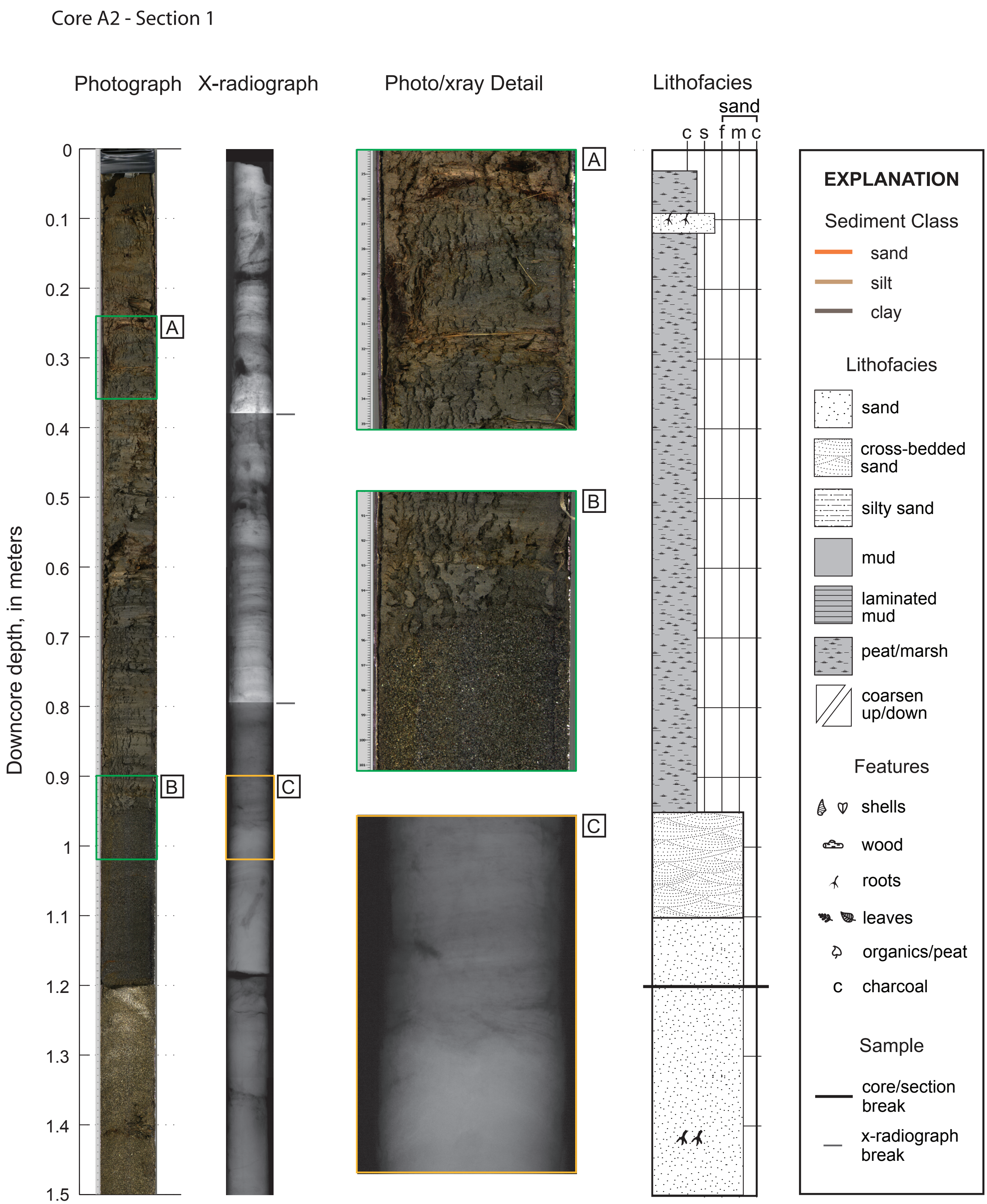

Figure A.1.3, cont.

Core A2 - Section 2

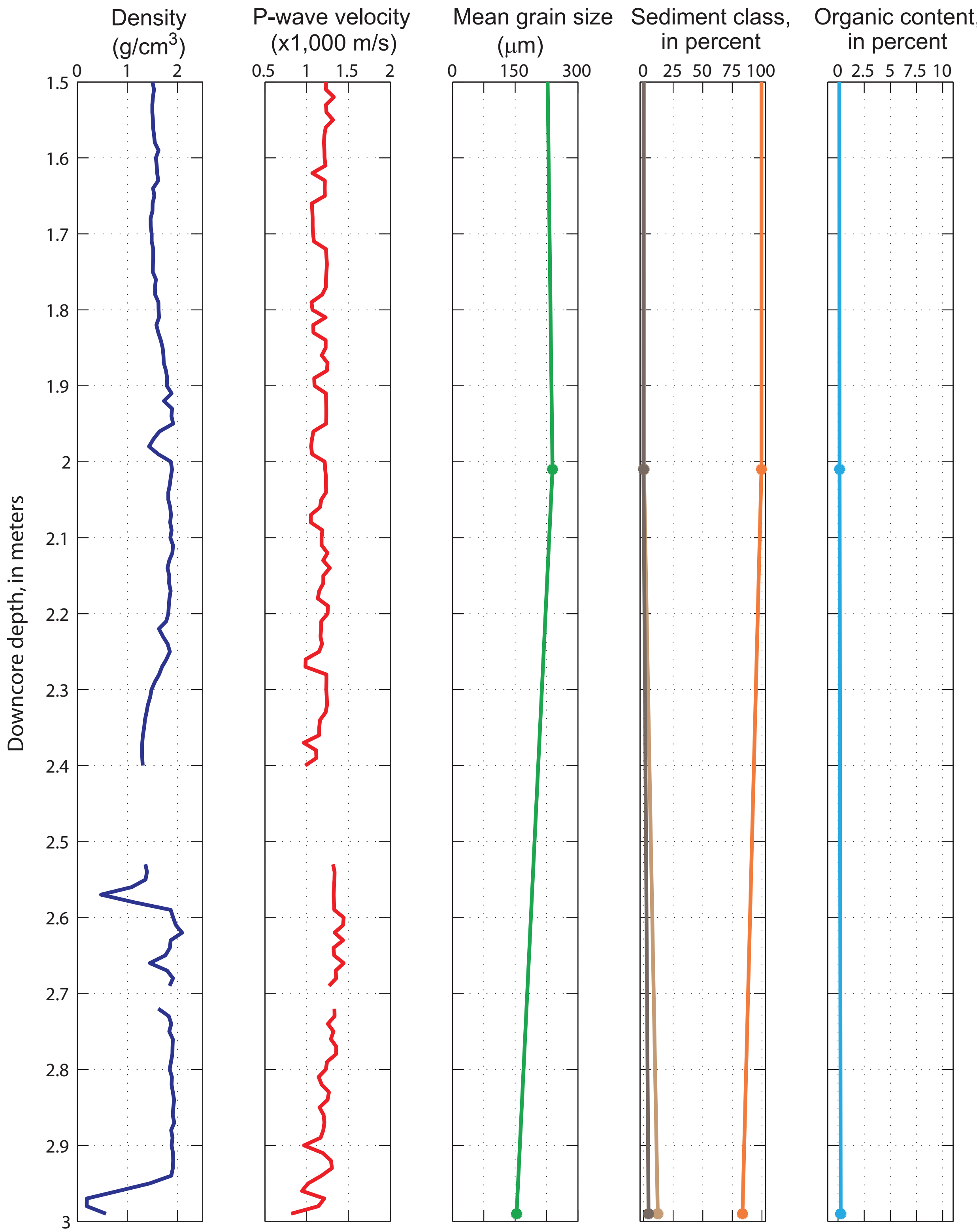

Figure A.1.3, cont.

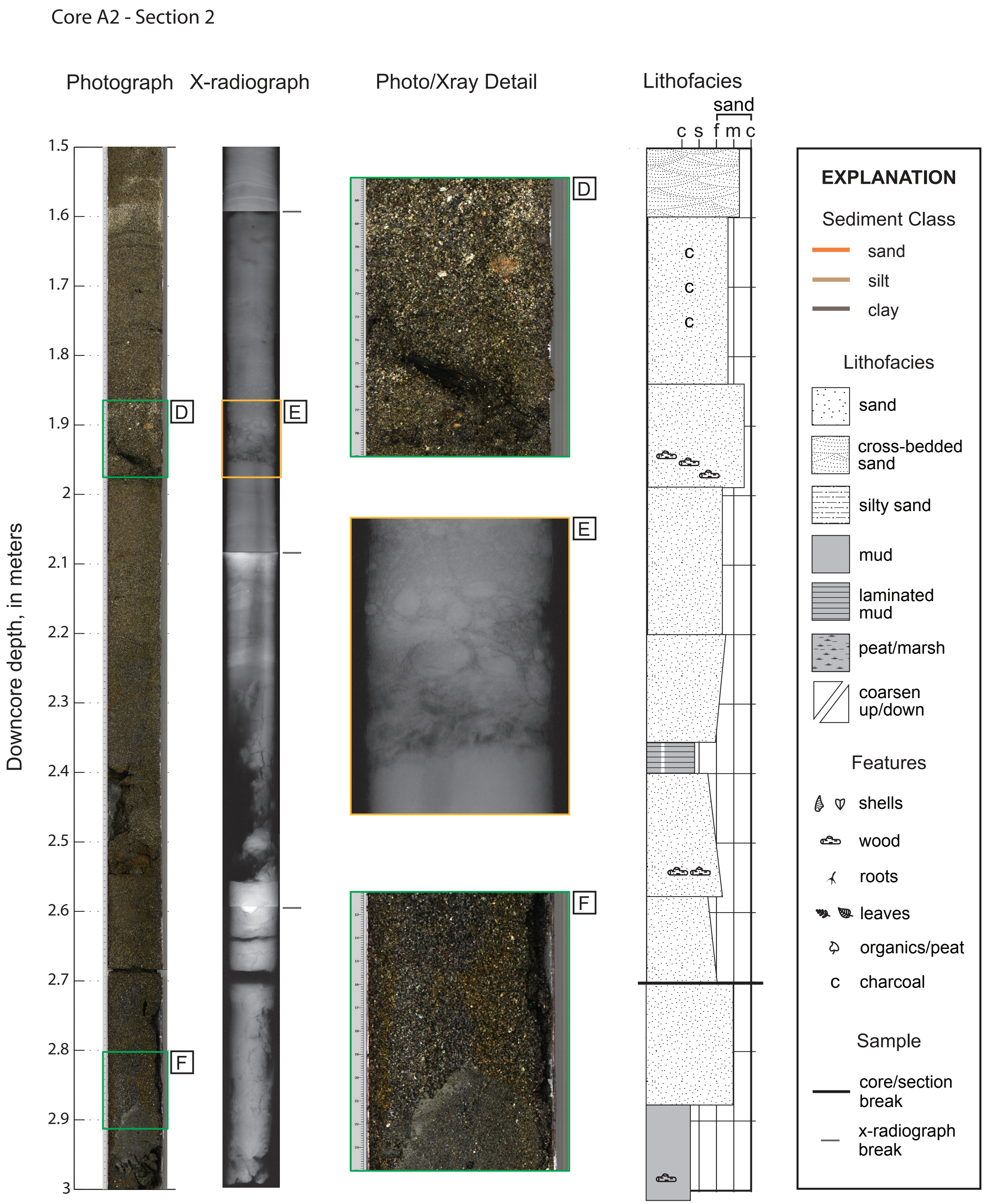

Figure A.1.3, cont.

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Core A3

This core was collected on the tidal flats at an elevation of 0.97 m (mllw) and is 1.60 m long. Fine to medium sand dominate this core, and one prominent contact was observed at 0.84 m. Wood pieces are found below 1 m. The bulk density increases from 0.96 g/cm^3 to approximately 2 g/cm^3 in the top 0.12 m and remains steady for the remainder of the core: A mean of 2.01±0.20 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 1,205 to 1,870 m/s and has a mean of 1,672±115 m/s. Fluctuations were observed only in the top 0.90 m. The mean grain size and sediment classes reflect the sand-dominated nature of this core; the classes coarsen from 160 µm at the top of the core to a coarse sand unit with a mean size of 370 µm at 0.62 m, then fined to 150 µm at 0.93 m. The bottom section of the core appears to be composed of similar-size sands and was not analyzed further. Sand composes more than 89 percent of this core. The digital photographs showed the brown and brownish-gray sand that dominate the core. They also show the more uniform and finer sand near the top (fig. A.1.4, inset A) and the alternating size units between 0.6 and 1.1 m, as shown in fig. A.1.4, inset B and from 0.76 to 0.87 m. No x-radiograph images were collected. Visual inspection indicated evidence of cross-bedding throughout the core, including the area between 0.75 and 0.82 m.

Core A3 - Section 1

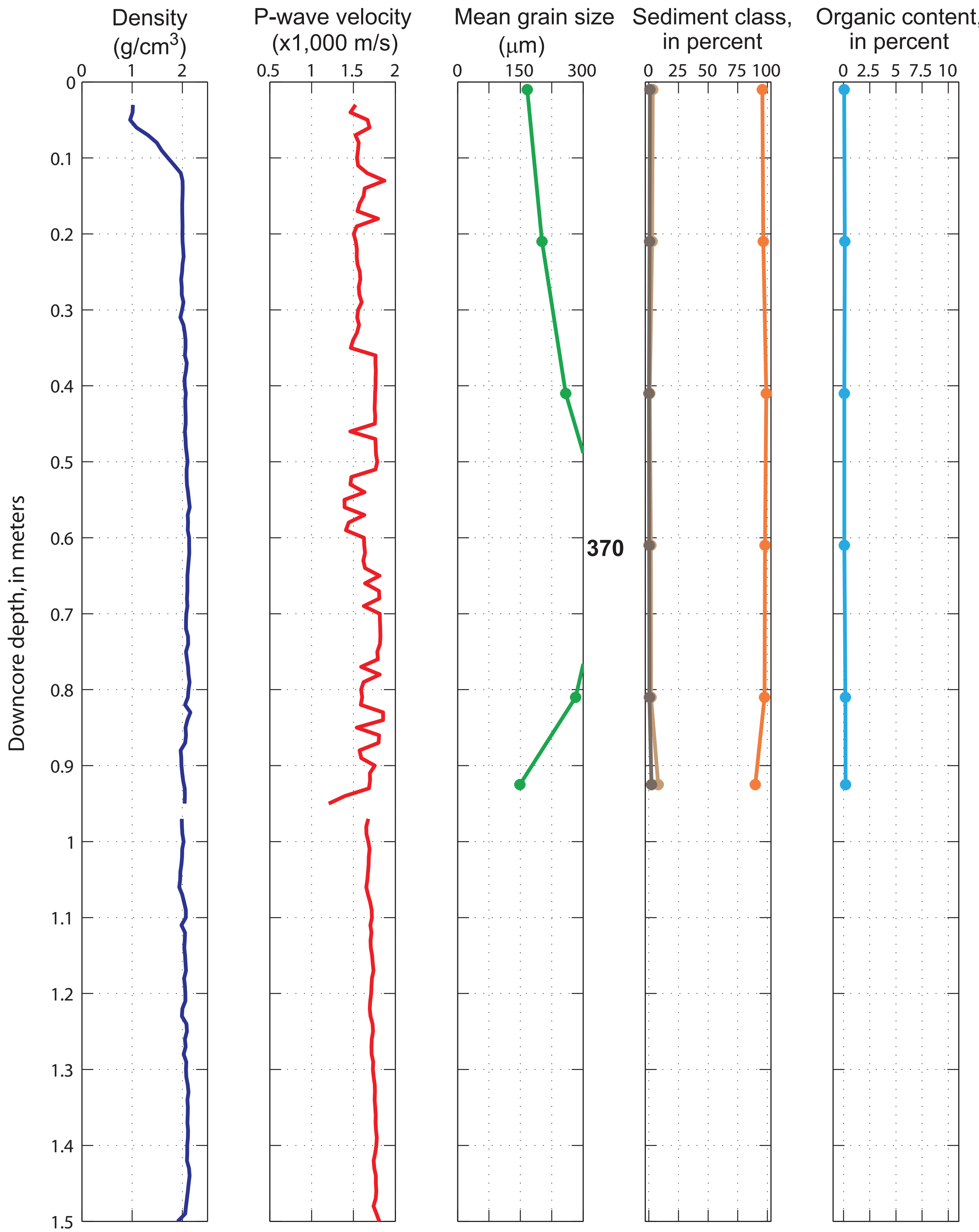

Figure A.1.4. Diagram of physical properties and lithology of sediments from Core A3, Skagit River Delta, Washington.

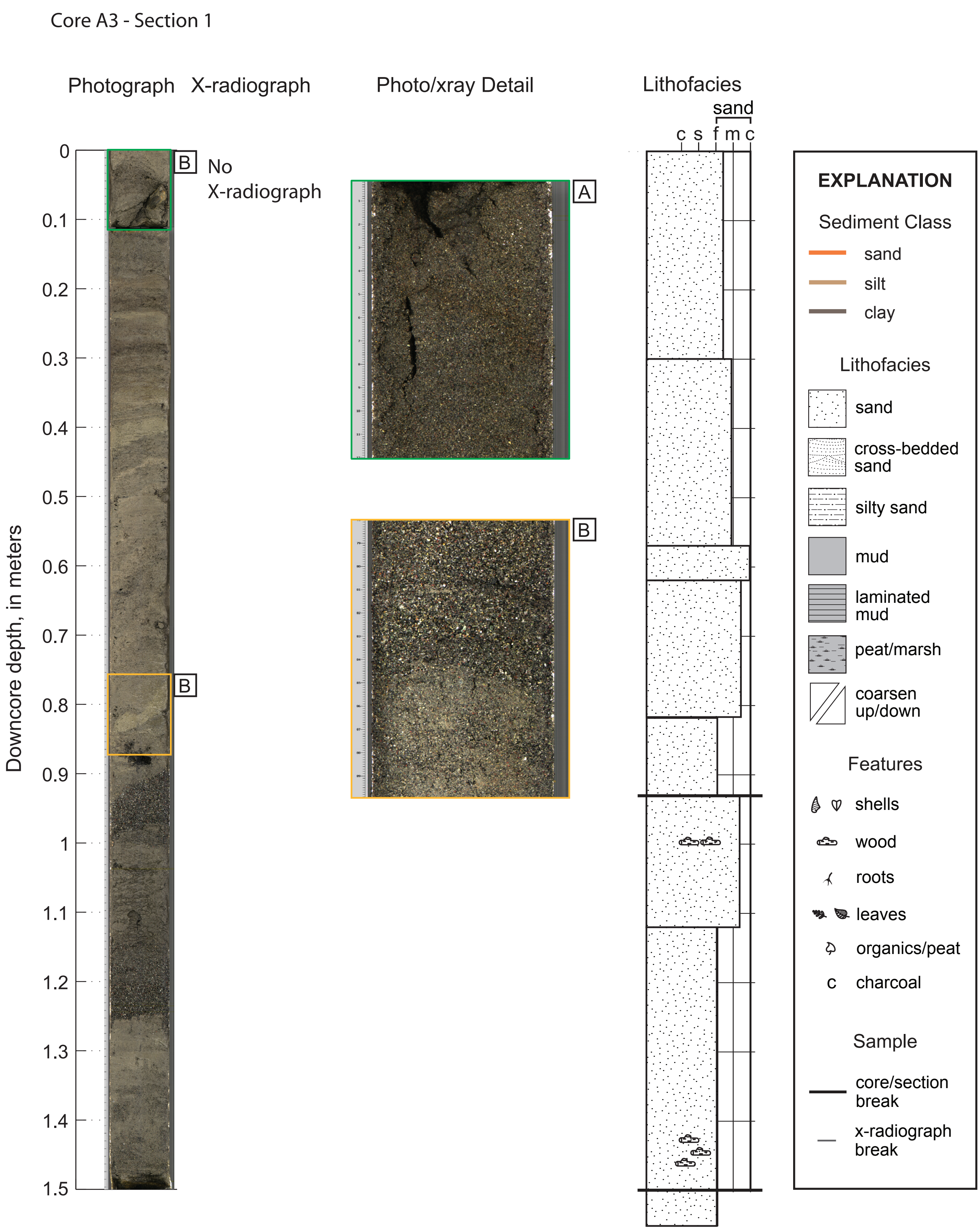

Figure A.1.4, cont.

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Core A4

This core was collected on the outer delta flats at an elevation of -0.15 m (mllw) and is 1.95 m long. Fine to medium sand dominate this core, with one muddy section observed at 1.42–1.50 m. Wood pieces are found below 1.40 m in both muddy and sandy sections. A layer of shells is found at 1.35–1.42 m. The bulk density fluctuated in the top 1.50 m before stabilizing just above 2 g/cm^3; a mean of 1.94±0.27 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 1,274 to 1,862 m/s and has a mean of 1,651±104 m/s. Fluctuations were observed only in the top 1.65. The mean grain size and sediment classes show that sand dominates the upper 1.4 m of the core, with mean grain size ranging from 110 to 275 µm between 0 and 0.9 m. A coarse layer occurs at 1.07 m of 401 µm. Between 0.9 m and the base of the core, percent sand decreases and silt and clay increases such that the base of the core has a mean grain size of 0.75 µm. The digital photographs and x-radiograph images show that brown, brownish-gray, and dark gray sand dominate the core between 0 and 1.36 m (including fig. A.1.5, inset A). Cross-bedding is evident in the sands in x-radiograph images (fig. A.1.5, inset B), and a sharp contact between sands and underlying mud was observed at 1.37 m and 1.48 m (fig. A.1.5, inset C). Insets D and E show the finer texture of silty mud near the base of the core.

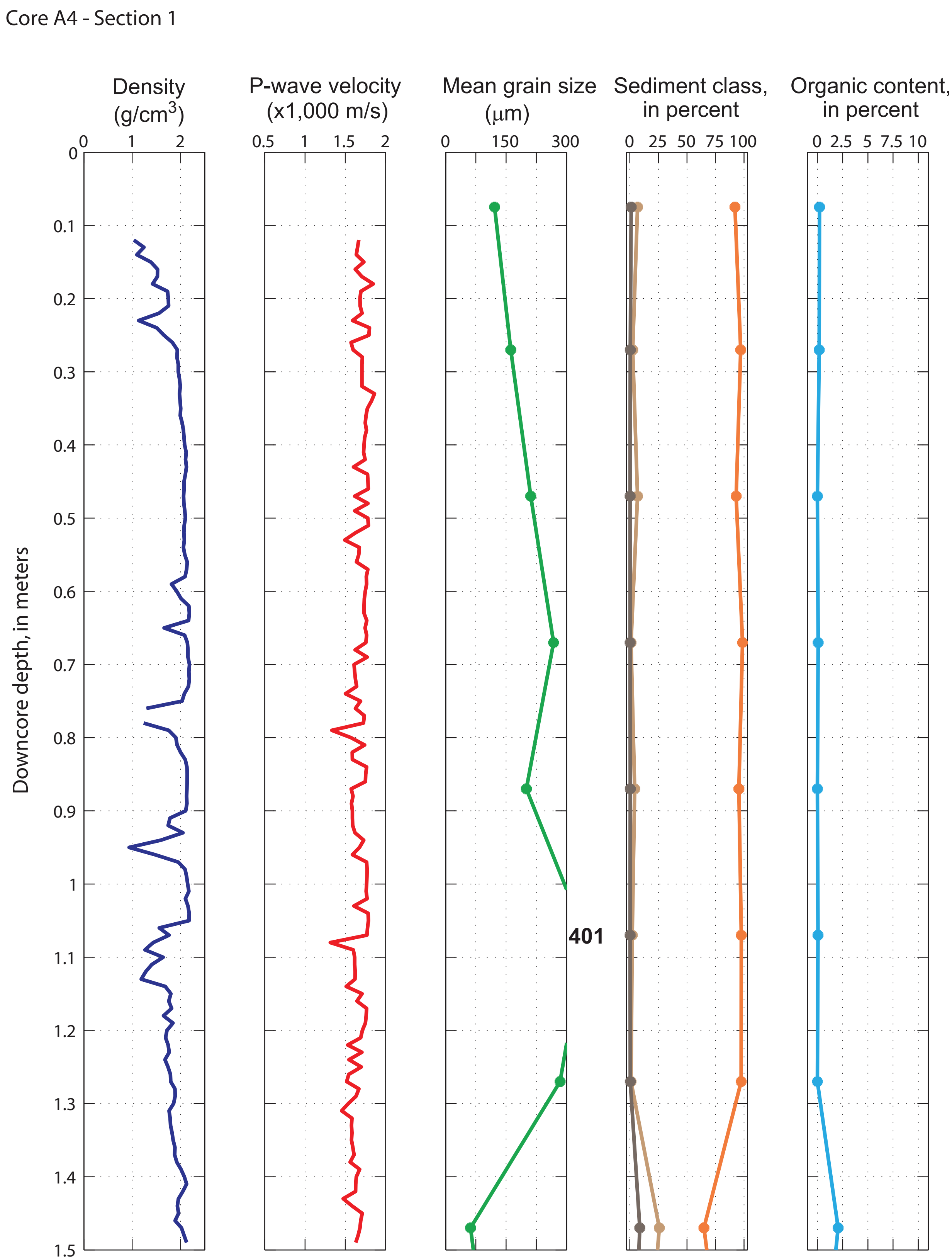

Figure A.1.5. Diagram of physical properties and lithology of sediments from Core A4, Skagit River Delta, Washington.

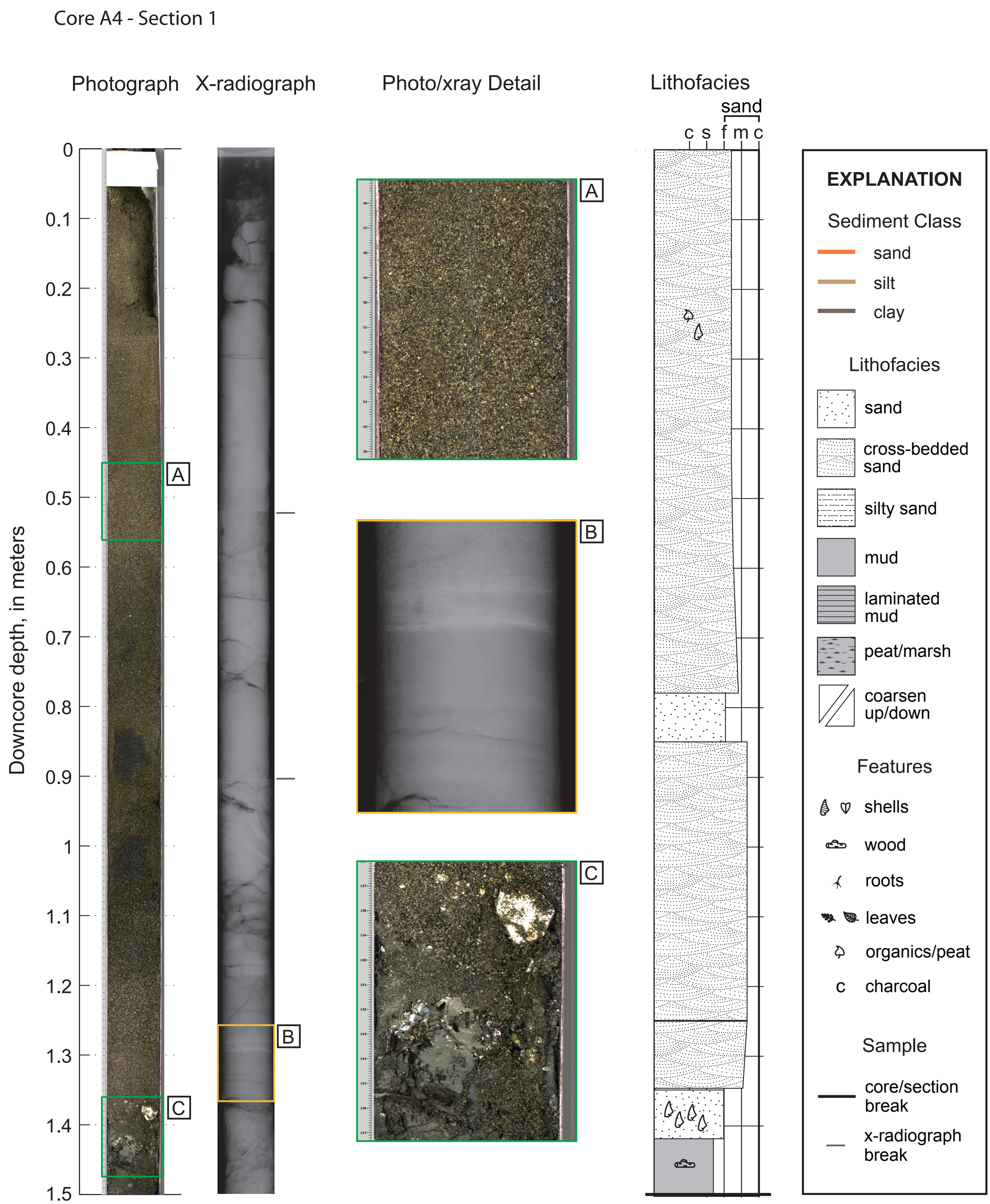

Figure A.1.5, cont.

Core A4 - Section 2

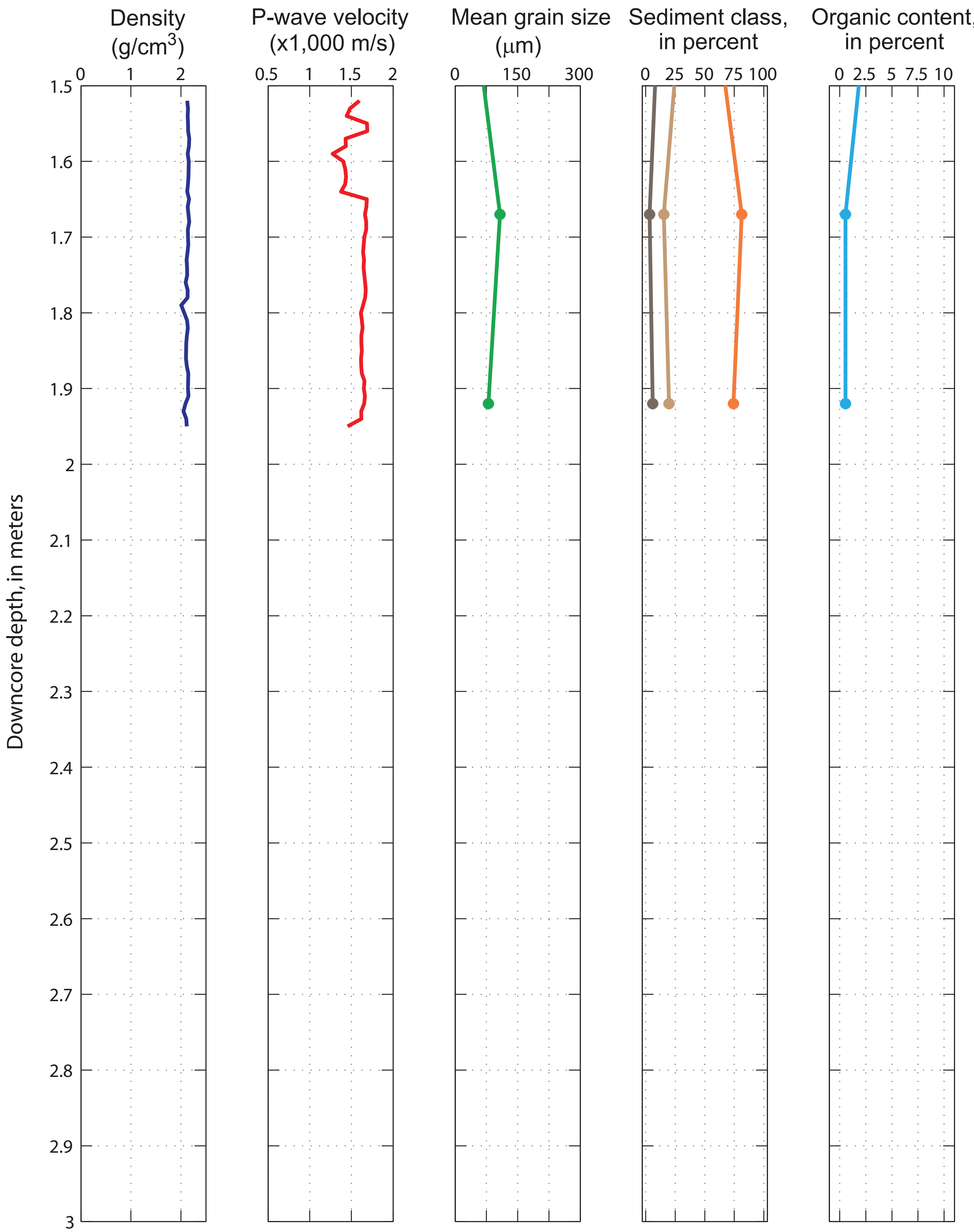

Figure A.1.5, cont.

Core A4 - Section 2

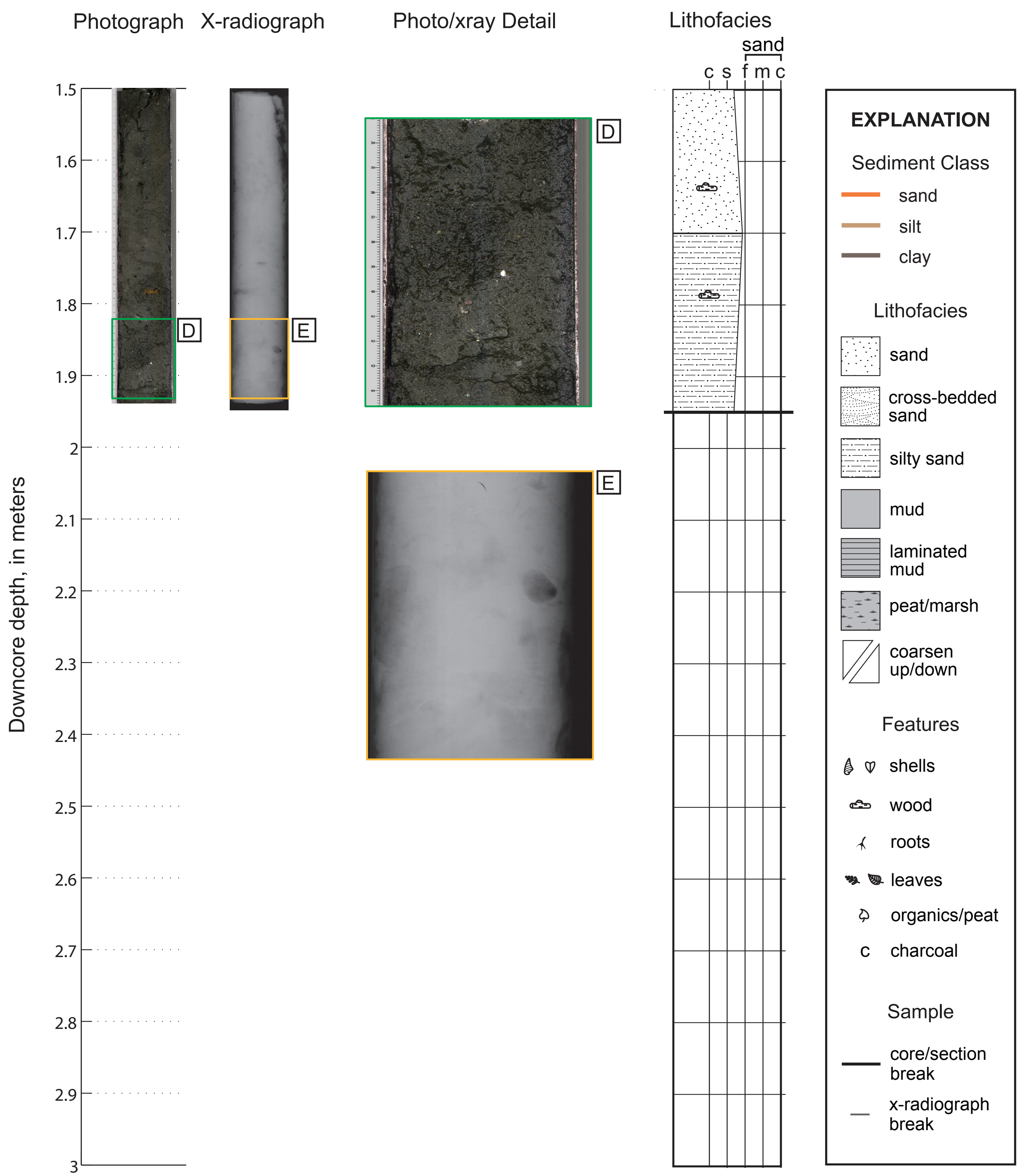

Figure A.1.5, cont.

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Core A5

This core was collected at the delta front, offshore of the North Fork Skagit River at a depth of -2.41 m (mllw) and is 3.81 m long. The upper section, between 0 and 0.9 m, is dominated by cross-bedded sands interfingered with 10-cm-thick units of massive sand, peat-marsh, and mud. The section between 0.9 and 1.8 m is characterized by silty sand and mud with more organic debris, including two layers of wood pieces and one layer of shells. The bulk density ranges from 1.16 to 2.11 g/cm^3 with large decreases at 0.70–0.90 m and 2.22–2.26 m and fluctuations below 3.00 m. A mean of 1.81±0.20 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 896 to 1,562 m/s and has a mean of 1,378±112 m/s and consistent fluctuations downcore. Velocity increases were observed at the same depths as the decreases in density. A decrease in grain size was observed between 0.7 and 0.80 m (in the same section as the decrease in density), but in general, there are two regimes in mean grain size—coarser than 150 µm in the top 1.0 m and finer (~65–80 µm) for the lower portion of the core. The sand fraction dominates for most of the core, but the silt, and to a lesser degree the clay fractions, increase notably with depth downcore, beginning at 1.0 m. The digital photographs and x-radiograph images show brown and tan sand with occasional cross-bedding in the upper 1.1 m, gray mud and layers of peaty material at 0.73–0.84 m (fig. A.1.6, insets A and B) and shell hash common between 1.2 and 1.6 m. The imagery also helps show wood at 2.2 m and peaty-marsh material between 2.48 and 2.61 m (fig. A.1.6, insets C and D), 3.12 to 3.24 m (fig. A.1.6, insets E and F) and 3.48 to 3.59 m (fig. A.1.6, inset G). The x-radiograph images show clearly the cross-bedded sands in the upper core and the laminated silt and mud layers and peaty-marsh in the lower core.

Core A5 - Section 1

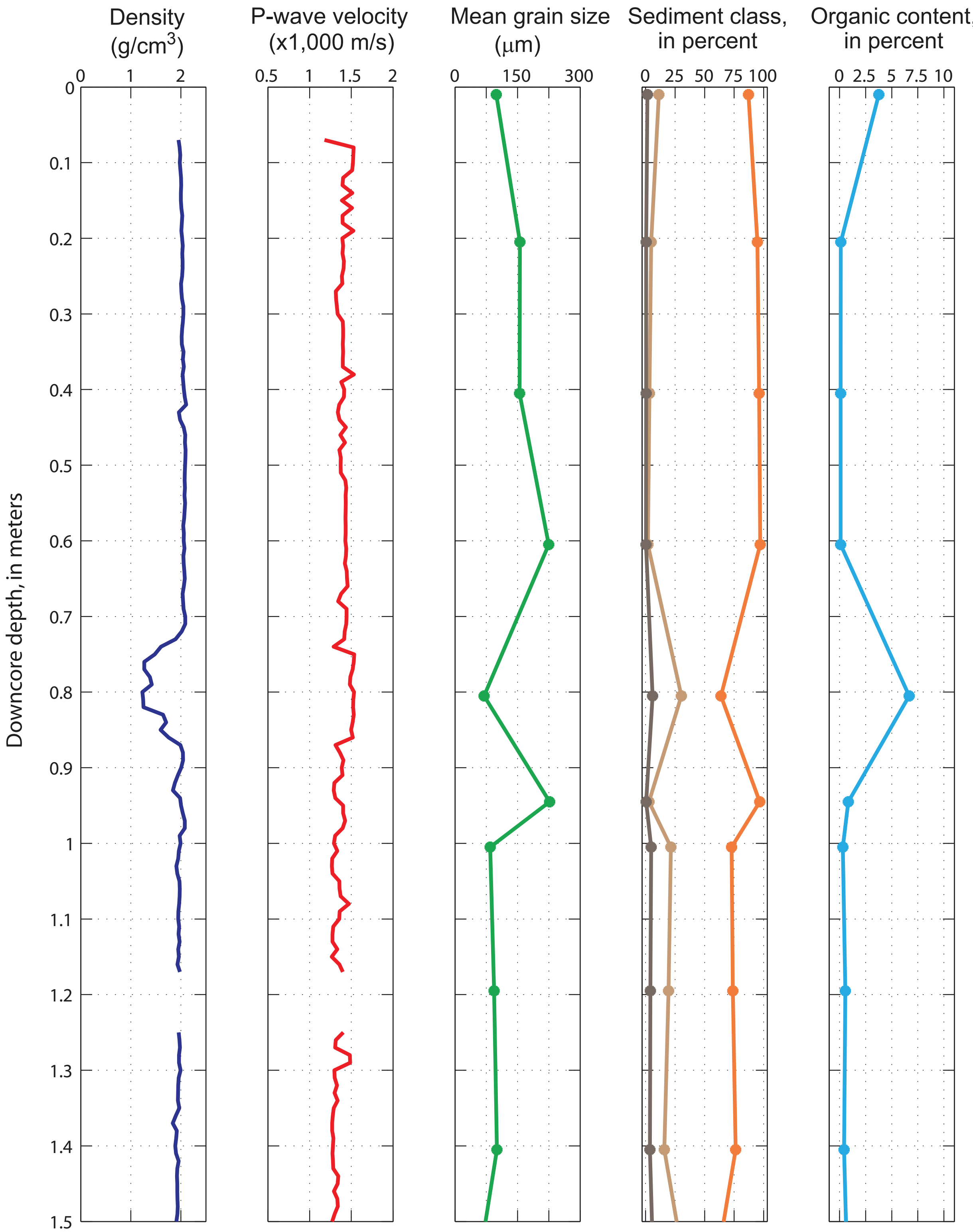

Figure A.1.6. Diagram of physical properties and lithology of sediments from Core A5, Skagit River Delta, Washington.

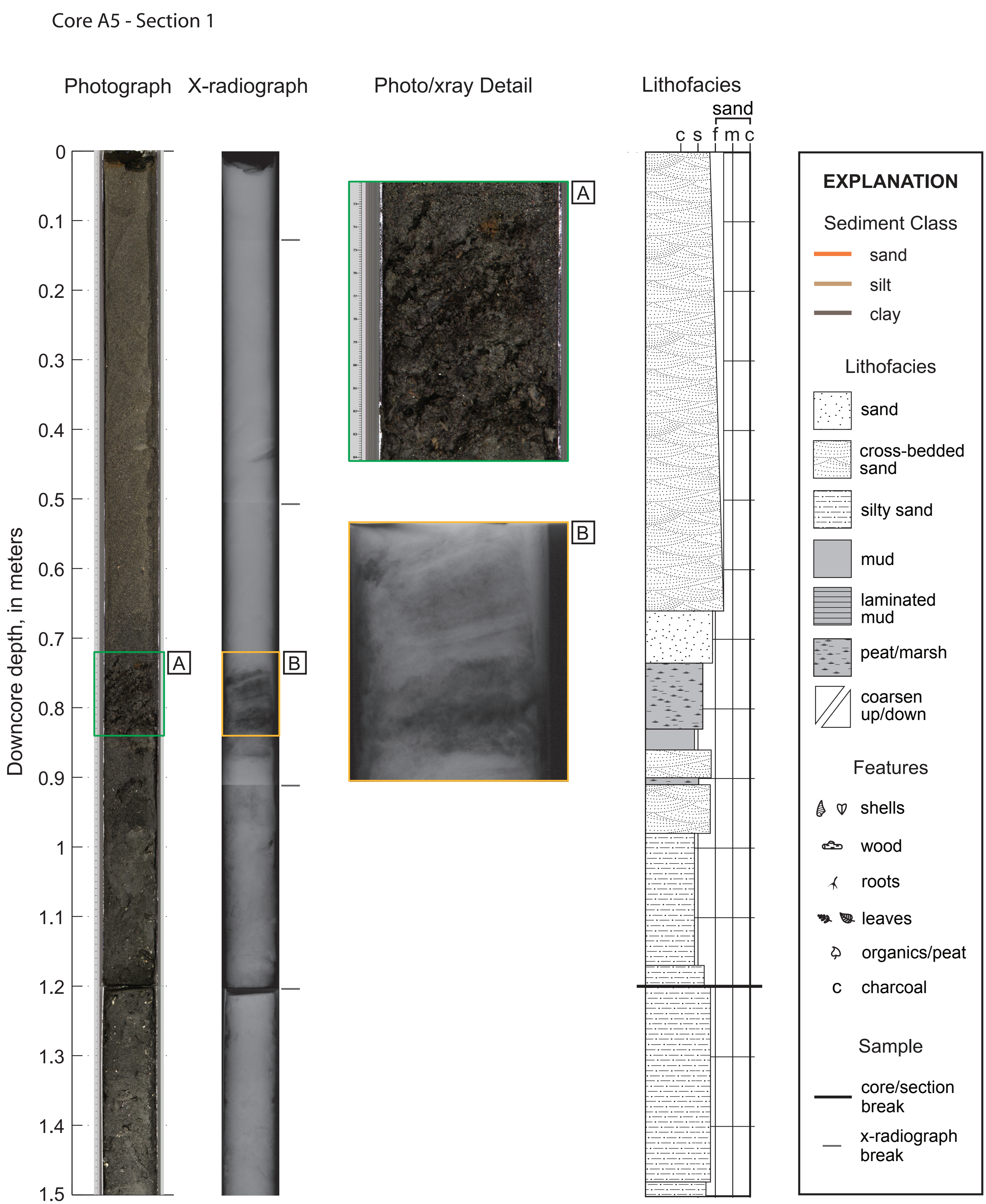

Figure A.1.6, cont.

Core A5 - Section 2

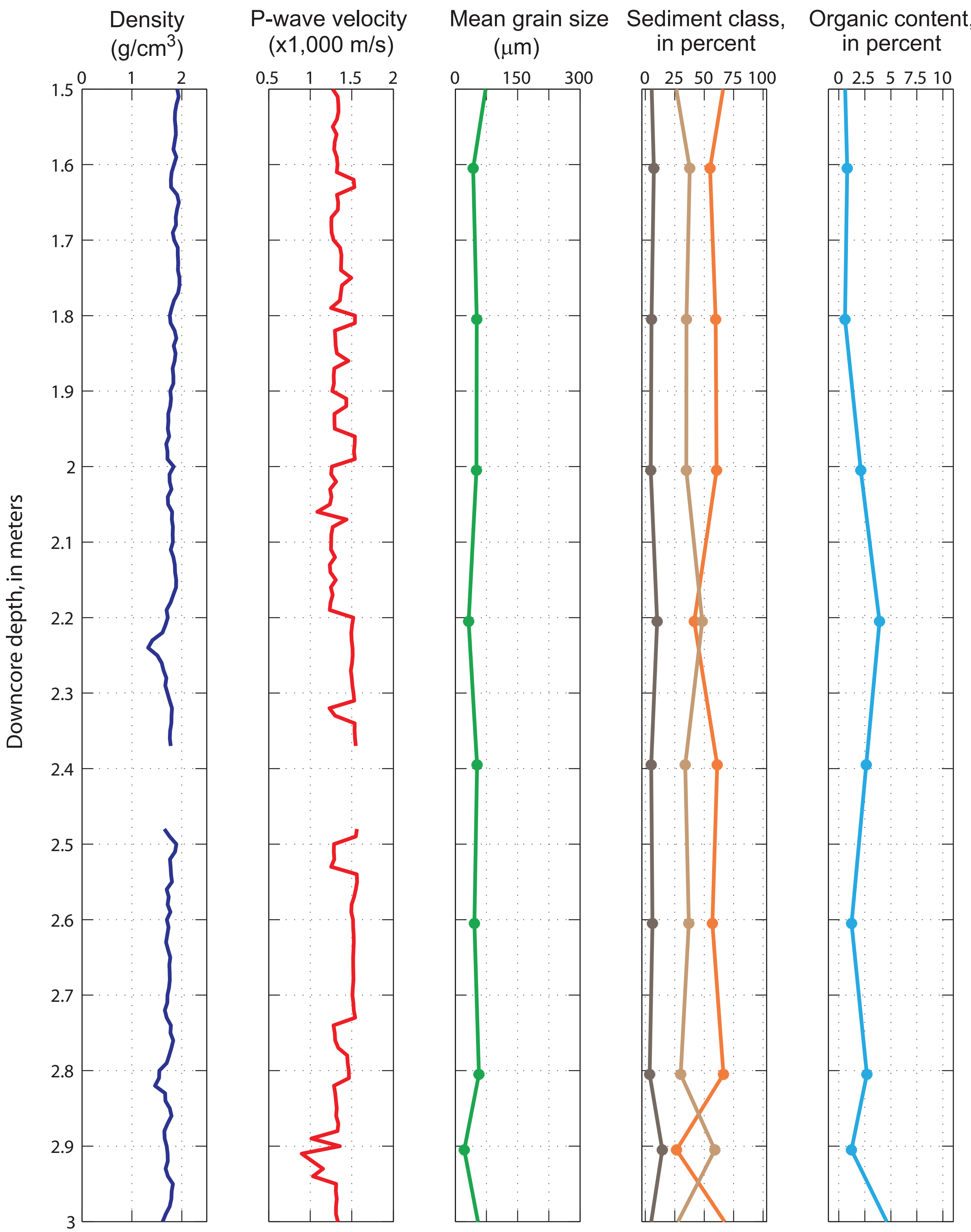

Figure A.1.6, cont.

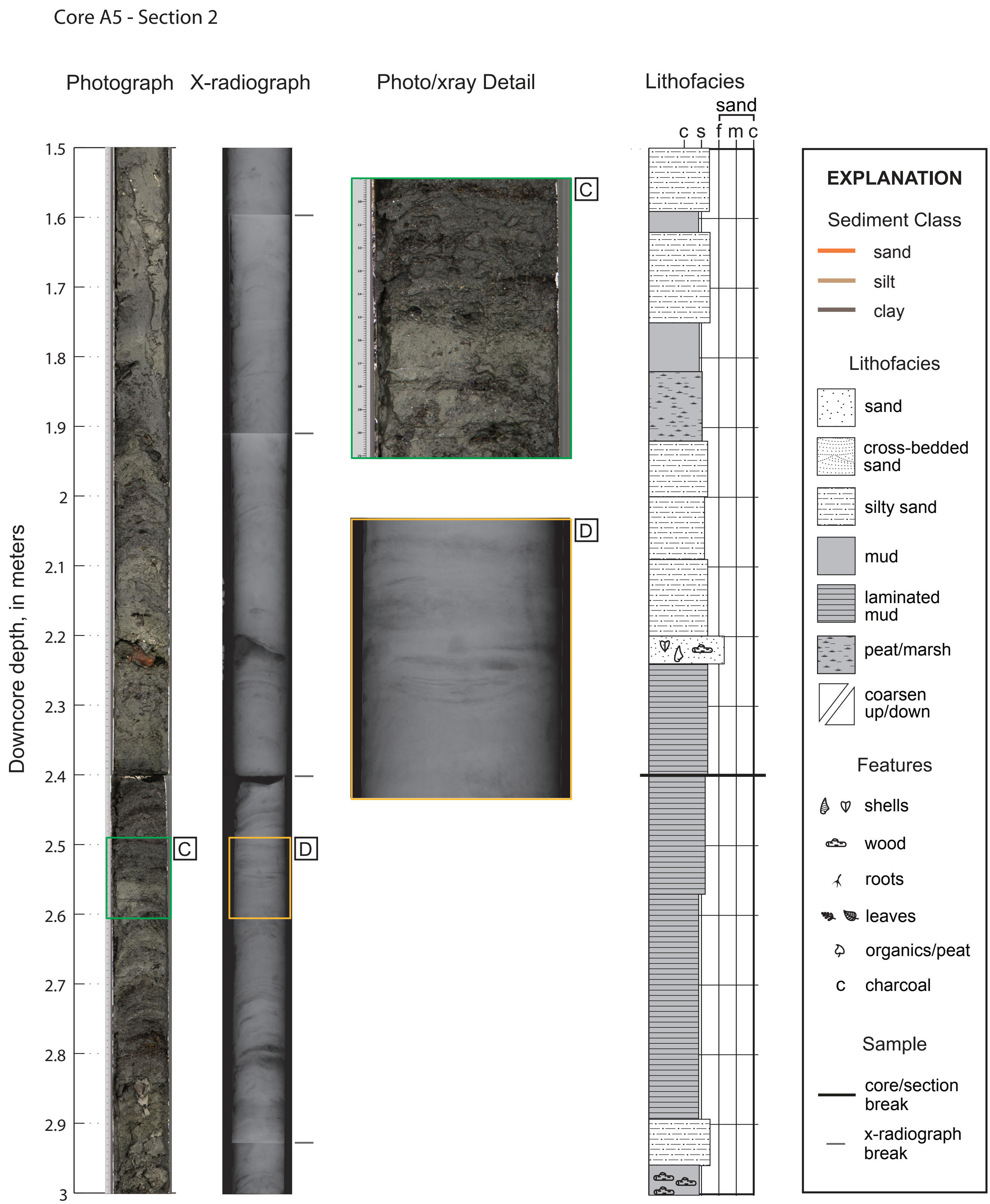

Figure A.1.6, cont.

Core A5 - Section 3

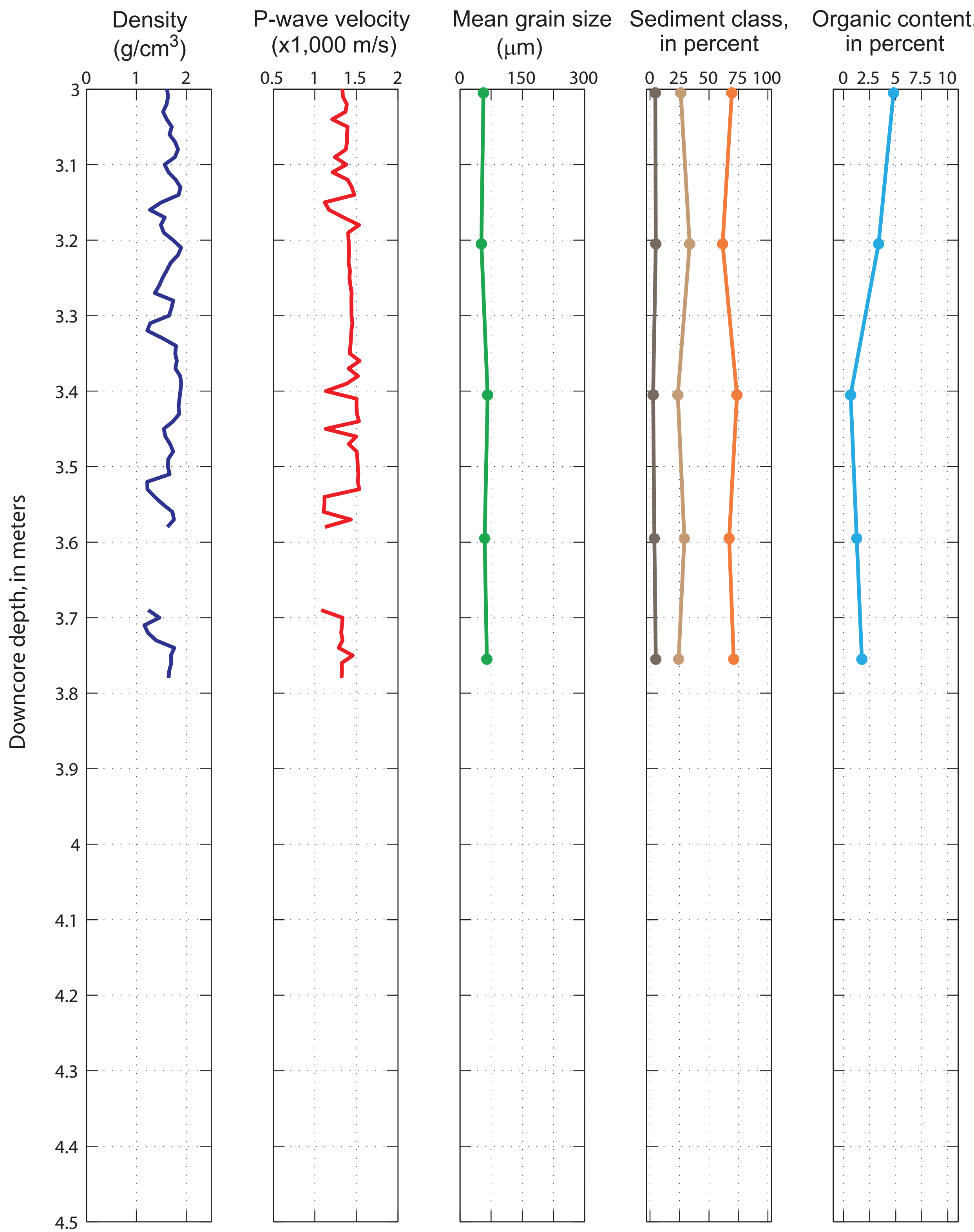

Figure A.1.6, cont.

Core A5 - Section 3

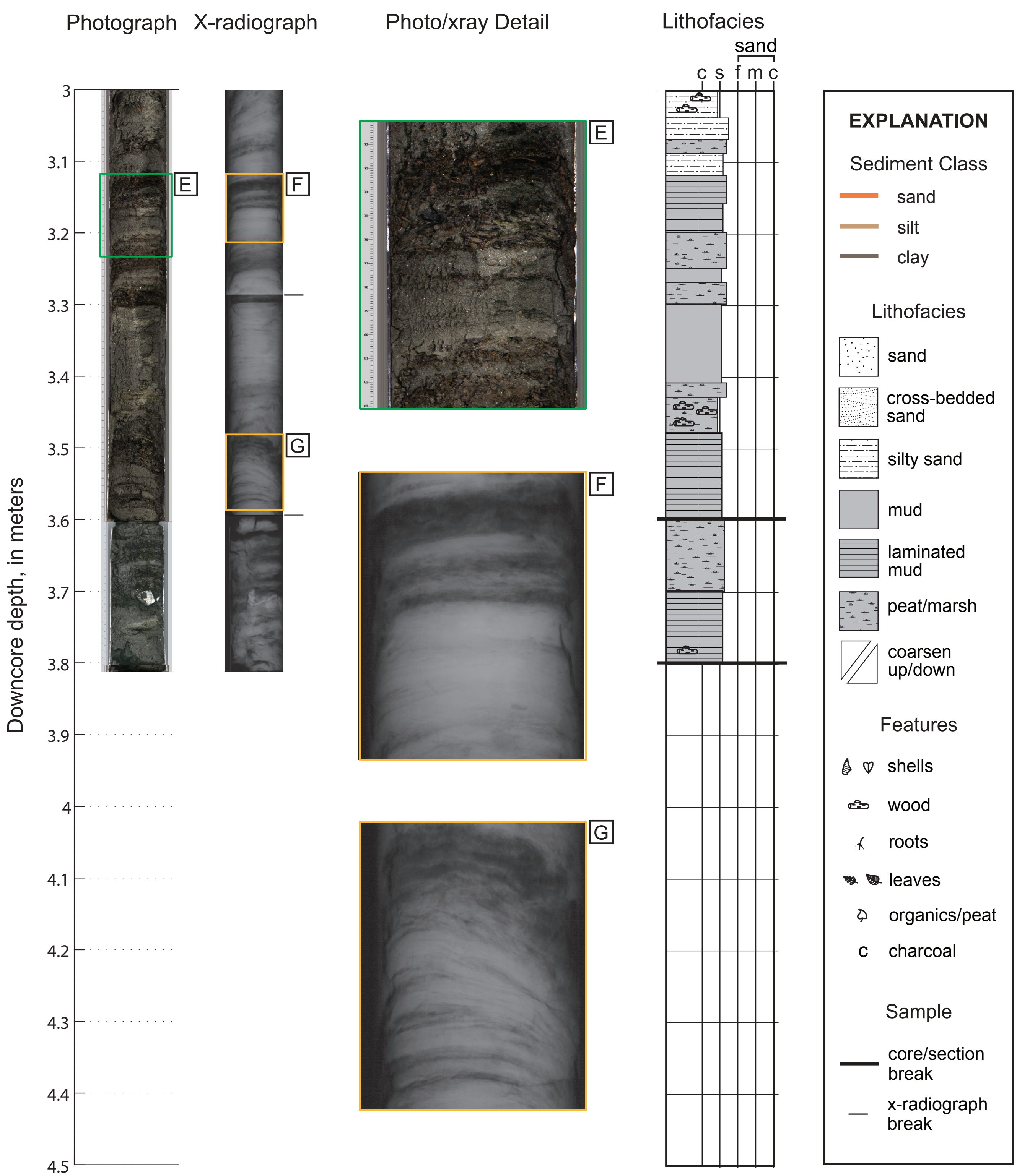

Figure A.1.6, cont.

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Core B1

This core was collected near Hall Slough at an elevation of 3.12 m (mllw) and is 2.15 m long. Three major facies were identified: peat/marsh in the top 0.38 m, sand from 0.38–0.78 m, and muds with three interfingered sand and silt units in the lower portion of the core. Roots are found in the peaty section, wood pieces are found in the sand section, and various fragments of fine organic debris are found in the deepest mud section. The bulk density ranged from 0.95 to 1.72 g/cm^3, with more variability in the top 0.3 m and a mean of 1.41±0.12 g/cm^3. The P-wave compression velocity ranges from 1,011to 1,541 m/s and has a mean of 1,412±107 m/s. Sharp fluctuations in velocity were observed at 0.55 m and below 1.45 m. Mean grain size ranges less than 30 µm for most of the core, with a slight coarsening to 45 µm at the base. Silt dominates the core, generally comprising more than 50 percent of the sediment composition. The digital photographs and x-radiograph images show the upper peaty section as being a brown unit, thick with roots (fig. A.1.7, inset A), and laminated mud units at 1.35 to 1.47 m (fig. A.1.7, insets B and C) and 1.94 to 2.5 m (fig. A.1.7, insets D and E).

Core B1 - Section 1

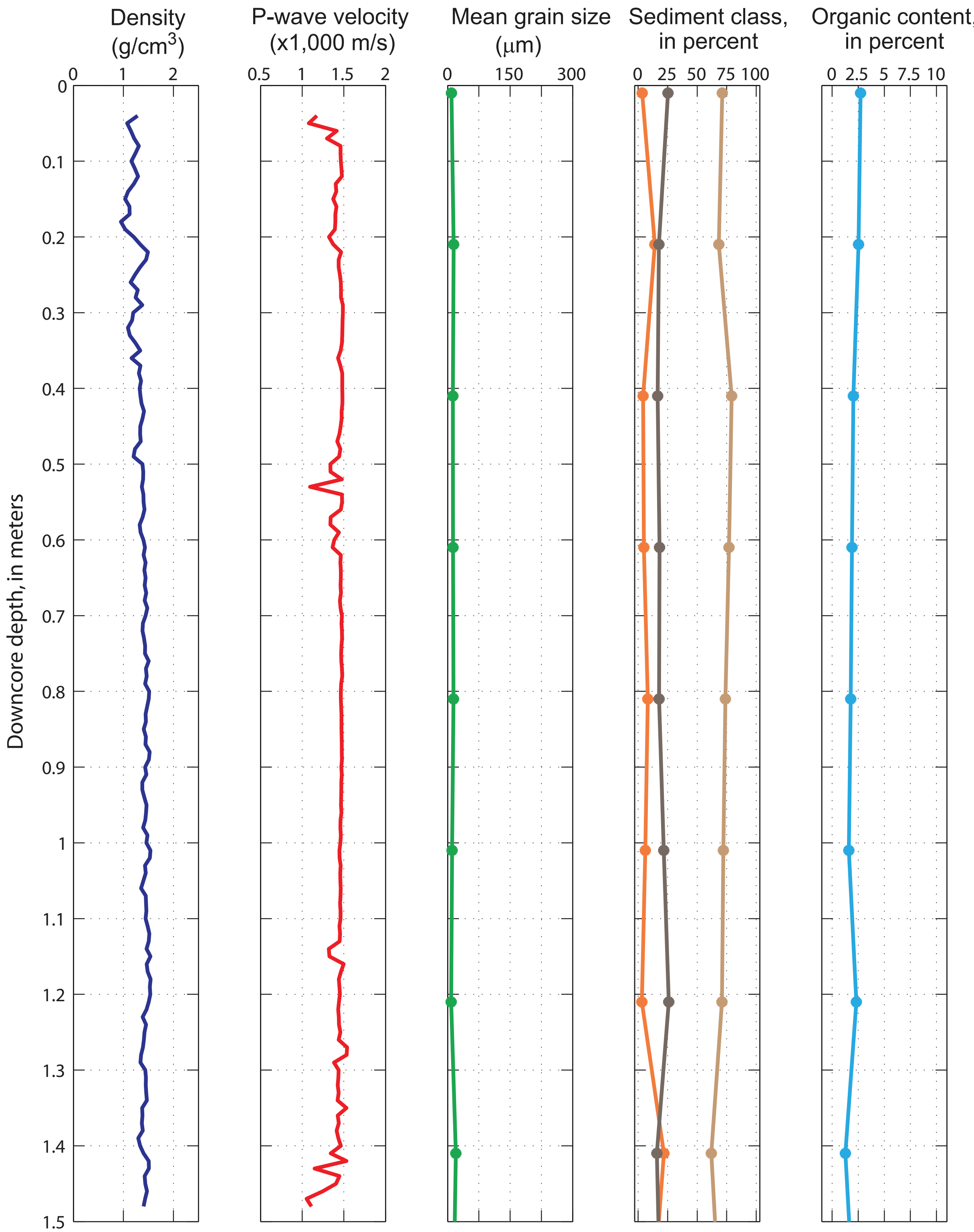

Figure A.1.7. Diagram of physical properties and lithology of sediments from Core B1, Skagit River Delta, Washington.

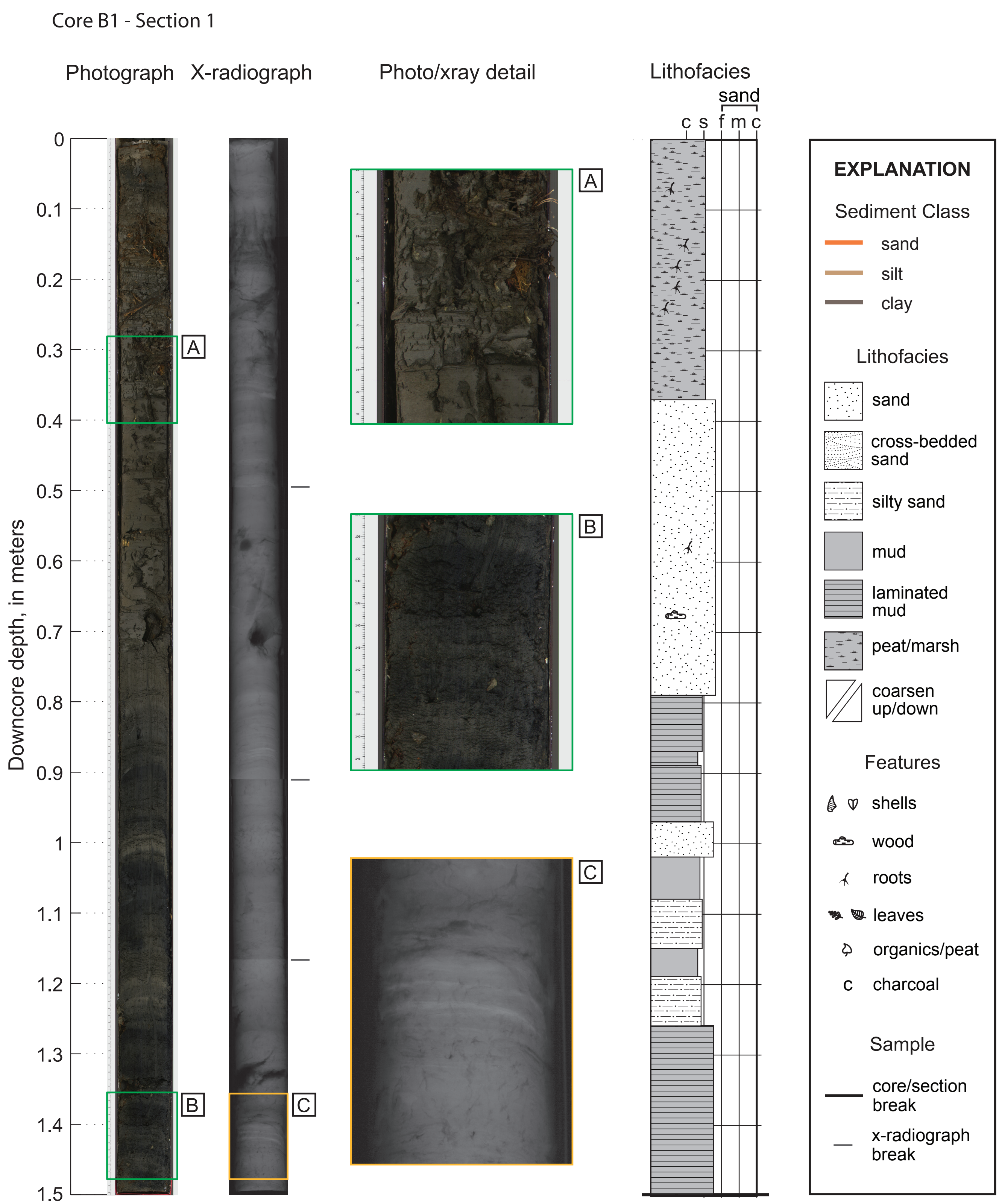

Figure A.1.7, cont.

Core B1 - Section 2

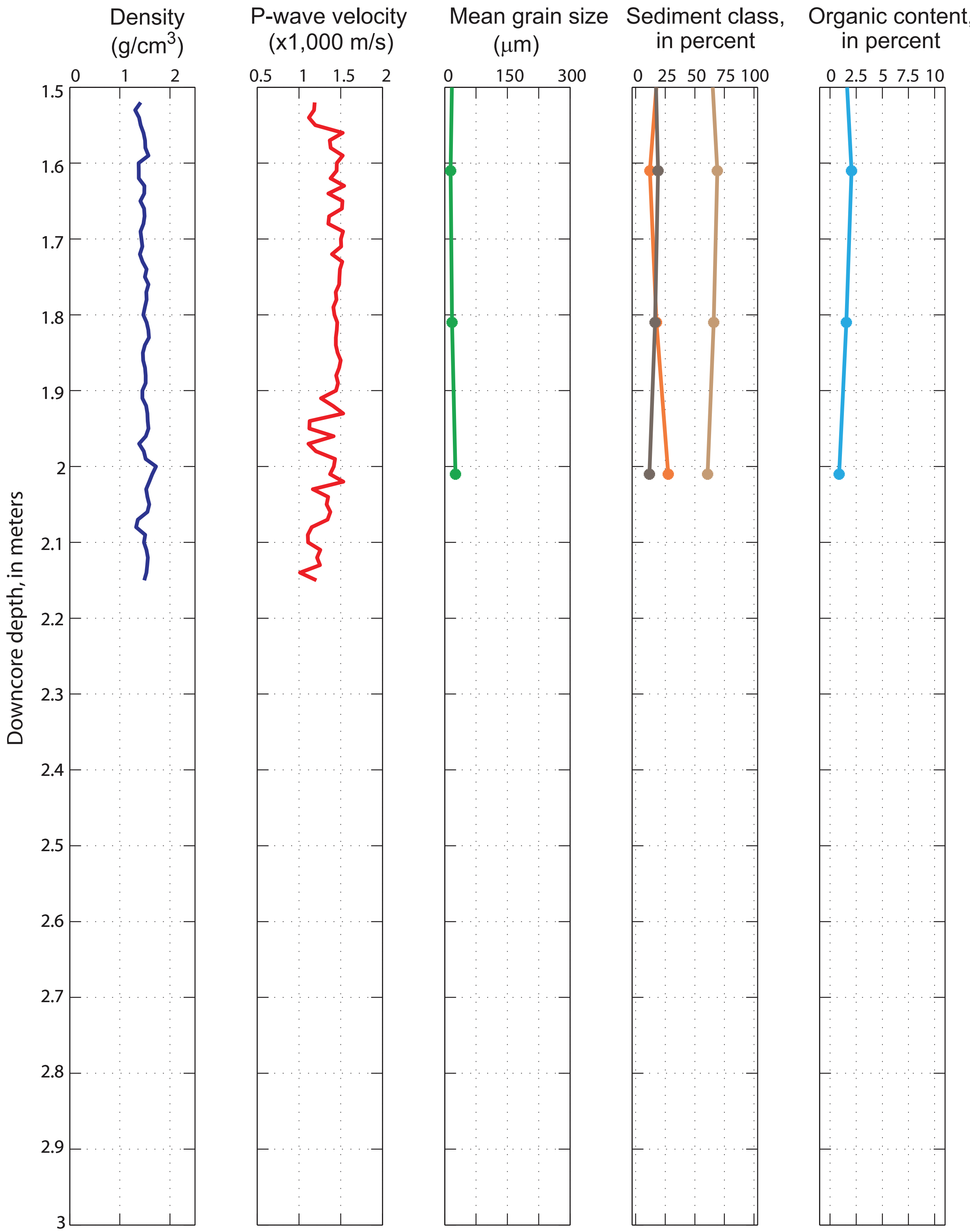

Figure A.1.7, cont.

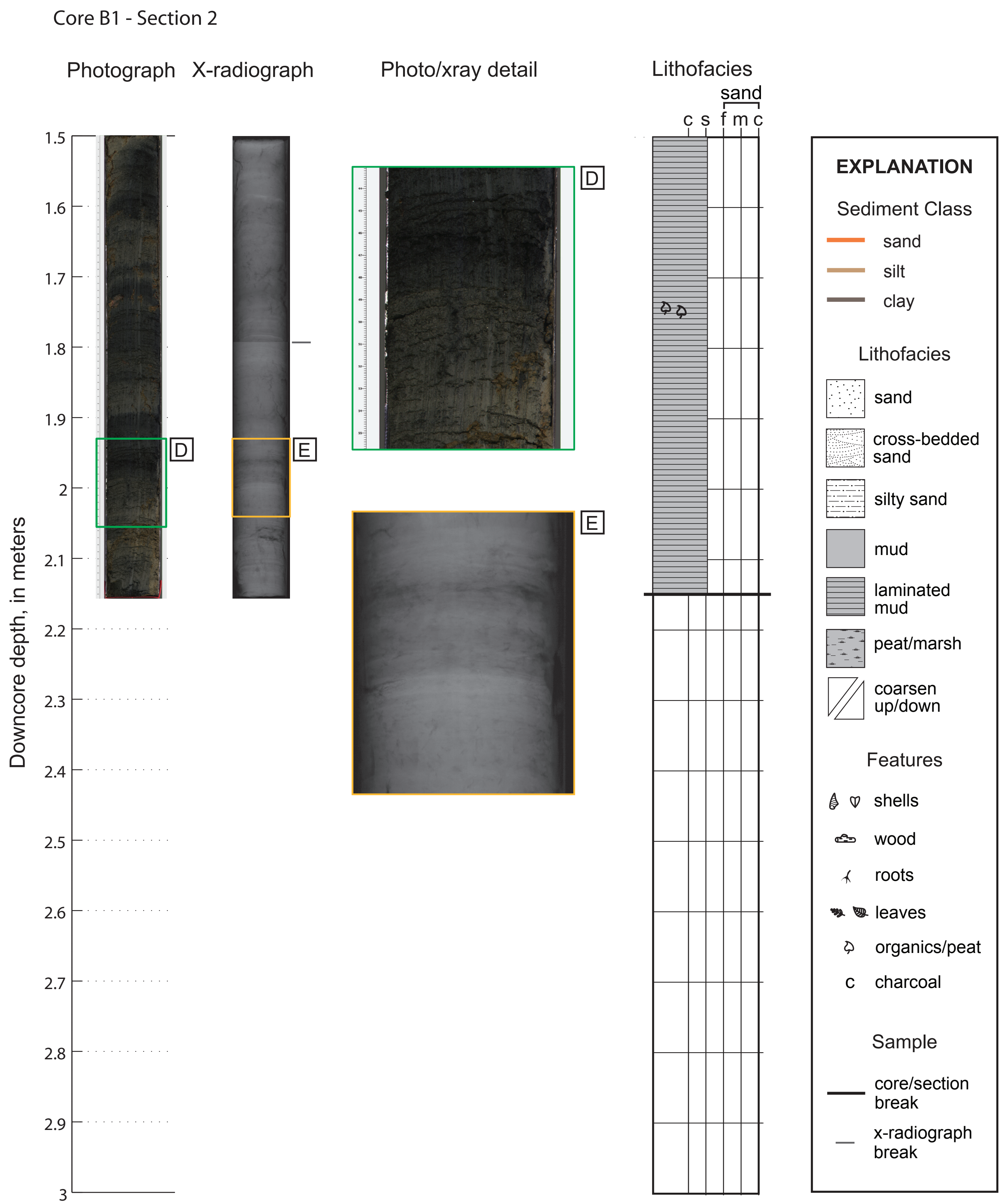

Figure A.1.7, cont.

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Core B2

This core was collected on a shallow portion of the tidal flats at an elevation of 1.51 m (mllw) and is 1.84 m long. Fine to medium sand dominates this core, with wood pieces, shells and organics found above 1.1 m. The bulk density ranged from 0.91 to 2.19 g/cm^3, but the minima could be related to gaps in the sediment recovery; a mean of 1.92±0.20 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranged from 1,179 to 1,825 m/s and has a mean of 1,680±115 m/s. The mean grain size and sediment classes confirmed the sand-dominated observations for the core, with the smallest grain size of 250 µm and sand comprising 97 percent of the sediment. No x-radiograph image was collected, but the digital photographs show the massive unit of brown sand and evidence of a slightly coarser unit near the top (fig. A.1.8, inset A) relative to the mid-section between 1.30 and 1.43 m (fig. A.1.8, inset B). Between 1.67 and 1.81 m a slight fining near the base of the core is evident (fig. A.1.8, inset C).

Core B2 - Section 1

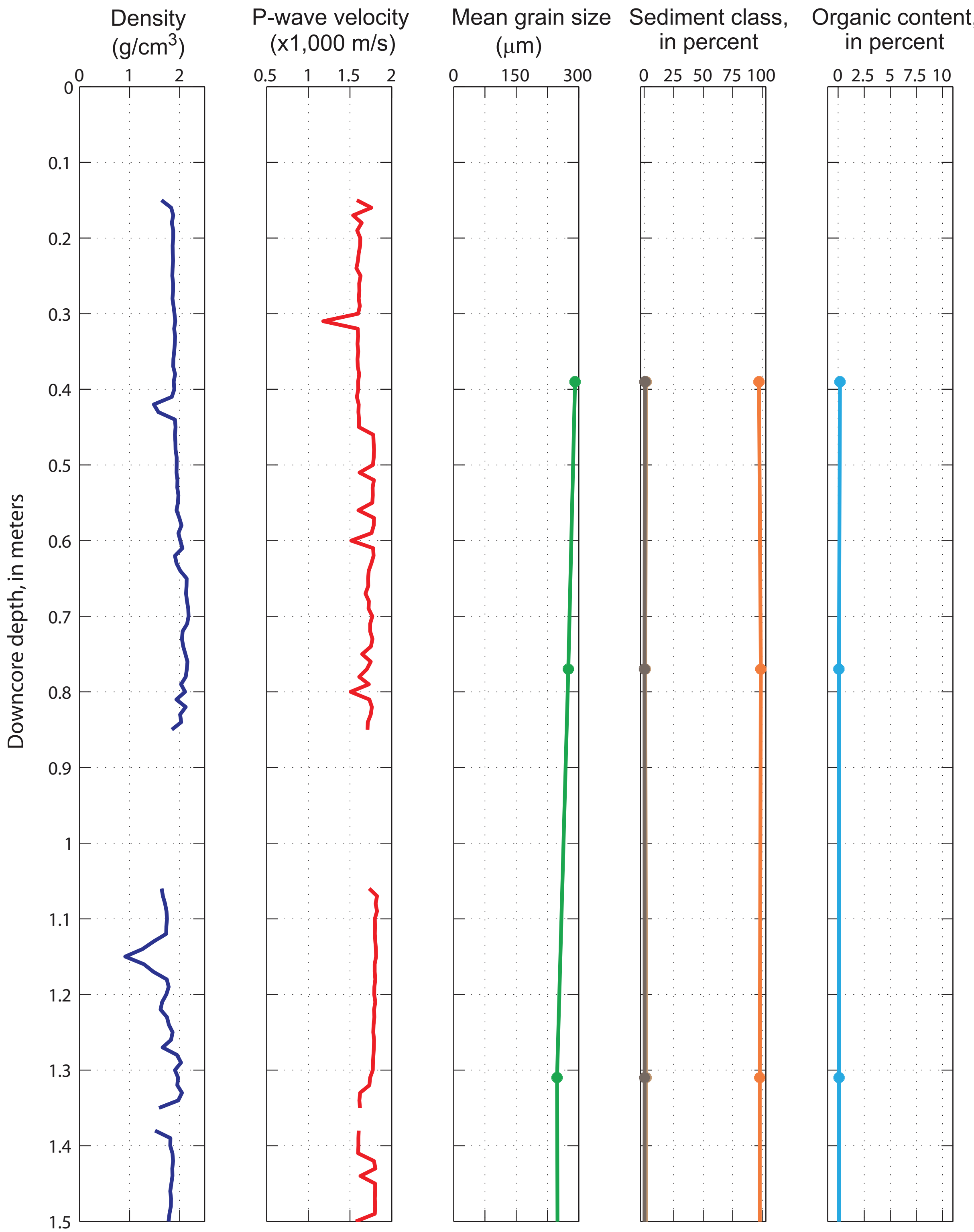

Figure A.1.8. Diagram of physical properties and lithology of sediments from Core B2, Skagit River Delta, Washington.

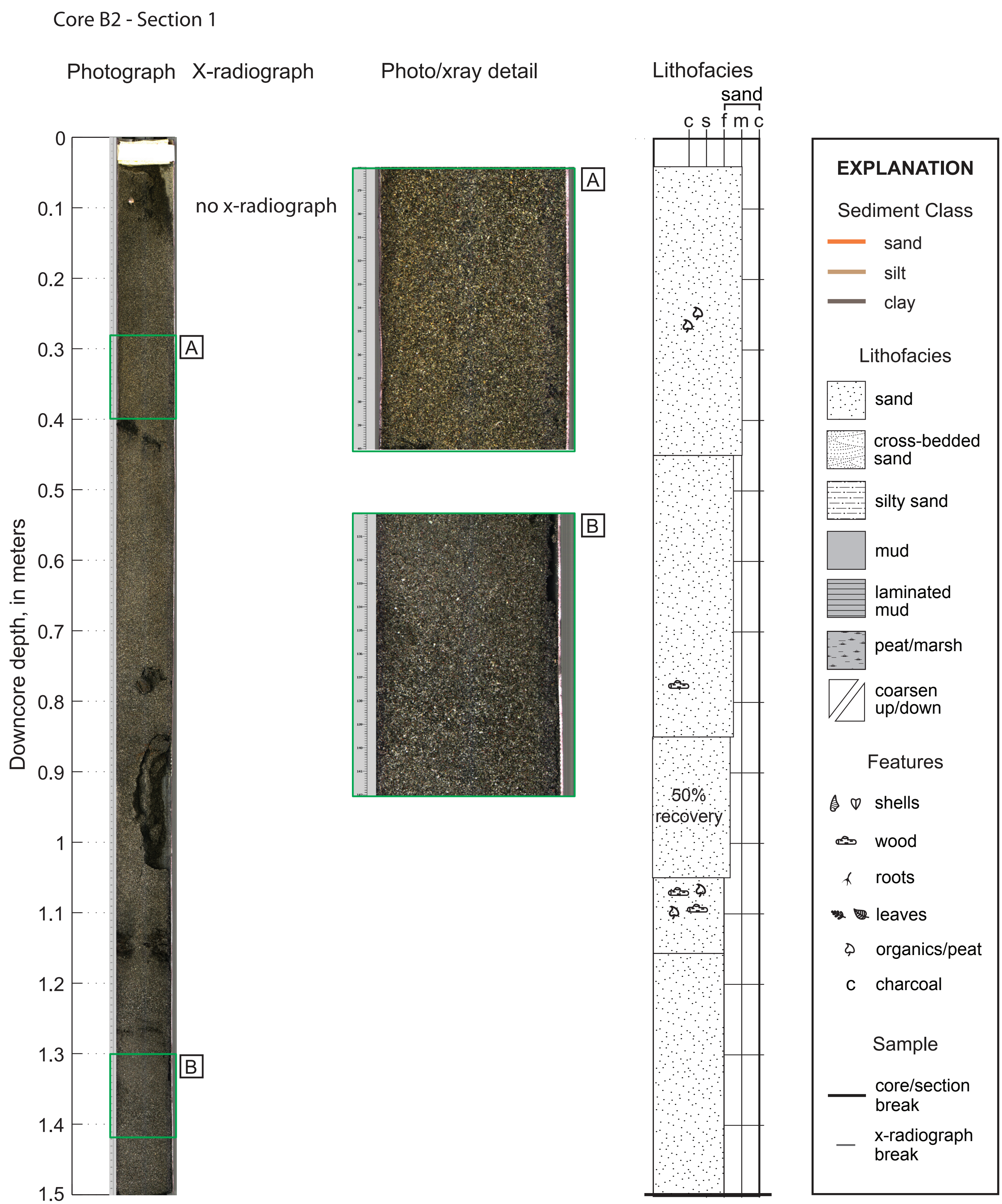

Figure A.1.8, cont.

Core B2 - Section 2

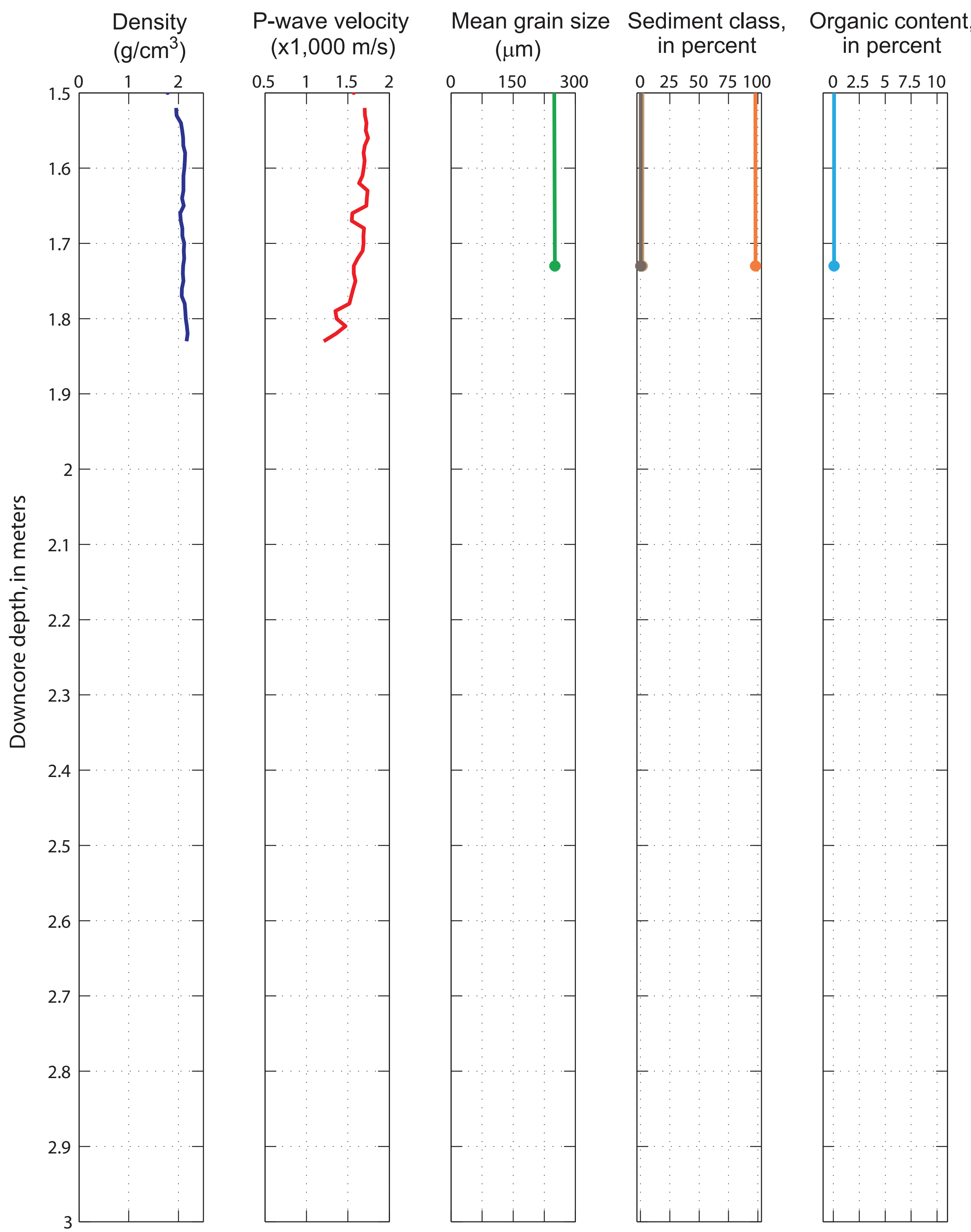

Figure A.1.8, cont.

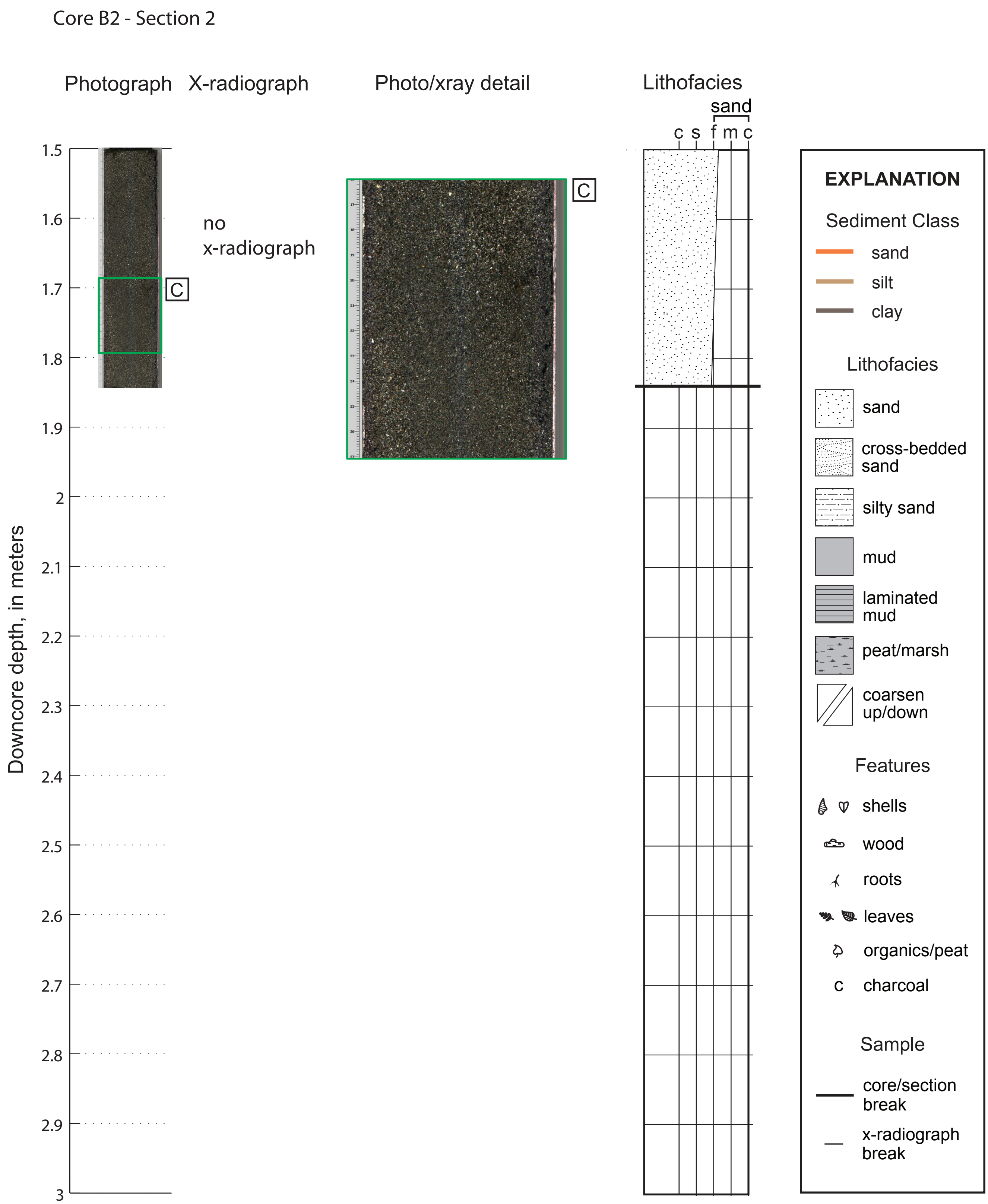

Figure A.1.8, cont.

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Core B3

This core was collected on the delta front at an elevation of -1.23 m (mllw) and is 3.6 m long. Very fine to medium sand dominates the upper portion of core, and very fine sand and silt compose the bottom, with individual units at 3.0 m, 3.1, and 3.5 m showing lamination. A 5-cm-thick layer of peat and a 5-cm-thick layer of silt were observed at 1.0 m and 2.8 m, respectively. Shells, charcoal, and wood pieces are scattered below 1.0 m. The bulk density increased from 1.45 g/cm^3 to approximately 2 g/cm^3 in the top 0.12 m and remained steady for the remainder of the core; a mean of 1.98±0.11 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 928 to 1,855 m/s and has a mean of 1,546±165 m/s and large fluctuations throughout the core. The mean grain size and sediment classes indicates a notable coarsening upward sequence with the deepest units near 3.6 m composed of the finest sediment (20 µm). The basal section contains considerably more silt (55 percent) than the upper portions of the core. The digital photographs and x-radiograph images show the brown and brownish-gray sand of the upper 0.6 m (fig. A.1.9, inset A) overlying cross-bedded sands between 0.60 and 0.95 m. A 0.13-m-thick mud unit (fig. A.1.9, insets B and C) was observed within the cross-bedded sands between 1.05 and 1.18 m. Contacts between overlying cross-bedded sand and underlying muds also are evident between 1.90 and 2.04 m (fig. A.1.9, insets D and E) and between 2.72 and 2.83 m (fig. A.1.9, inset F). The general fining downward to silty mud is comparable between the inset photographs listed above and the unit shown between 3.03 and 3.17 m (fig. A.1.9, insets G and H).

Core B3 - Section 1

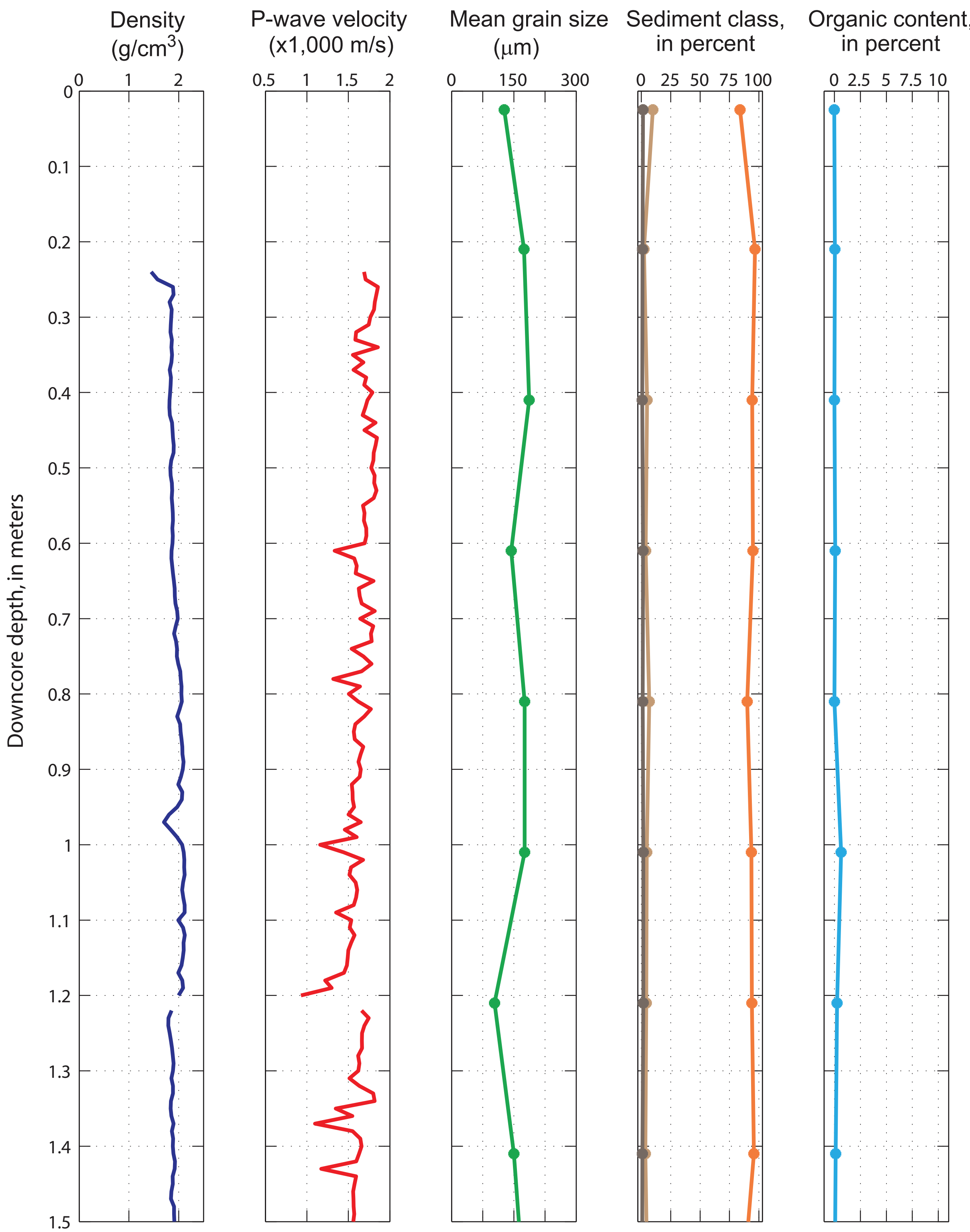

Figure A.1.9. Diagram of physical properties and lithology of sediments from Core B3, Skagit River Delta, Washington.

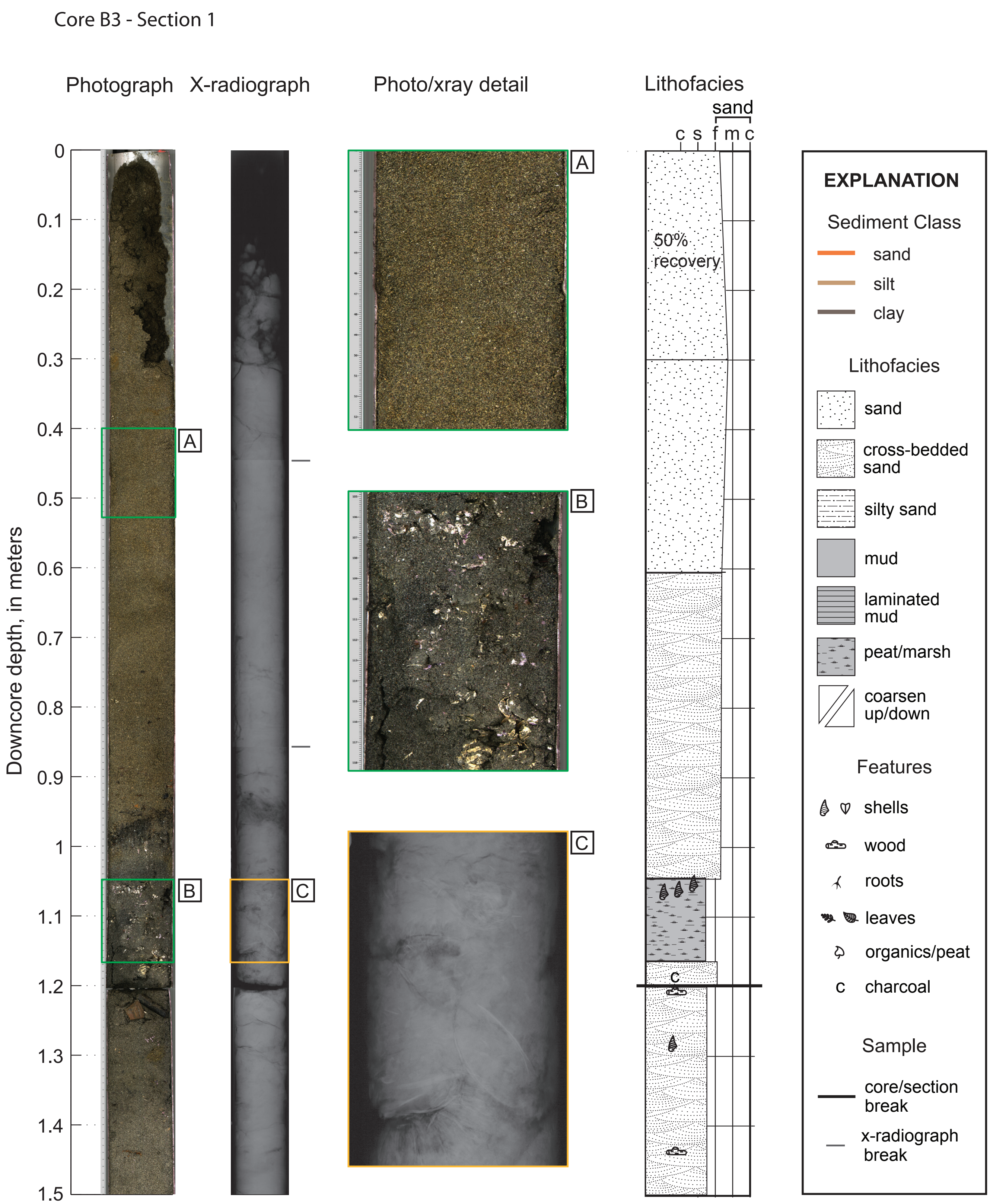

Figure A.1.9, cont.

Core B3 - Section 2

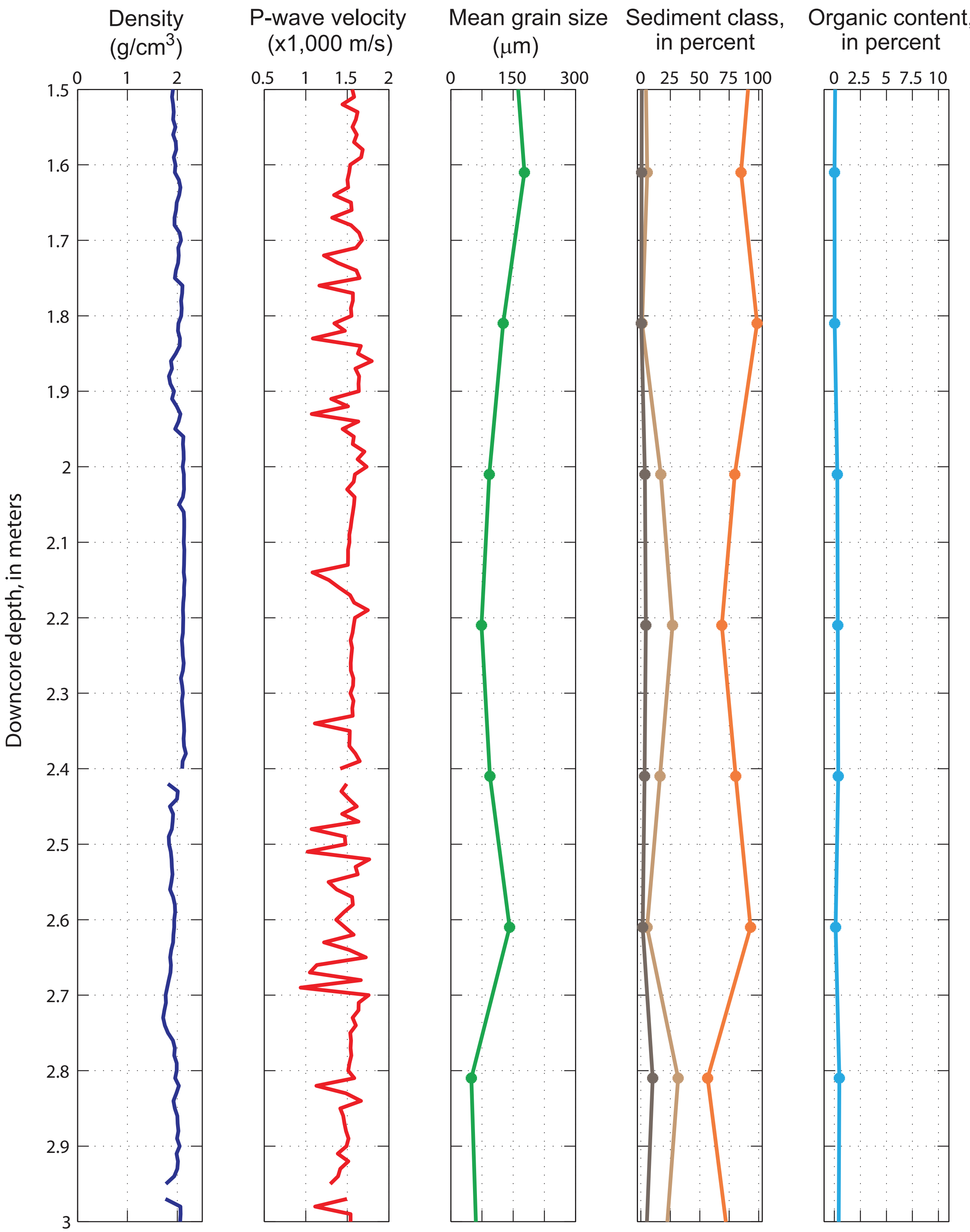

Figure A.1.9, cont.

Core B3 - Section 2

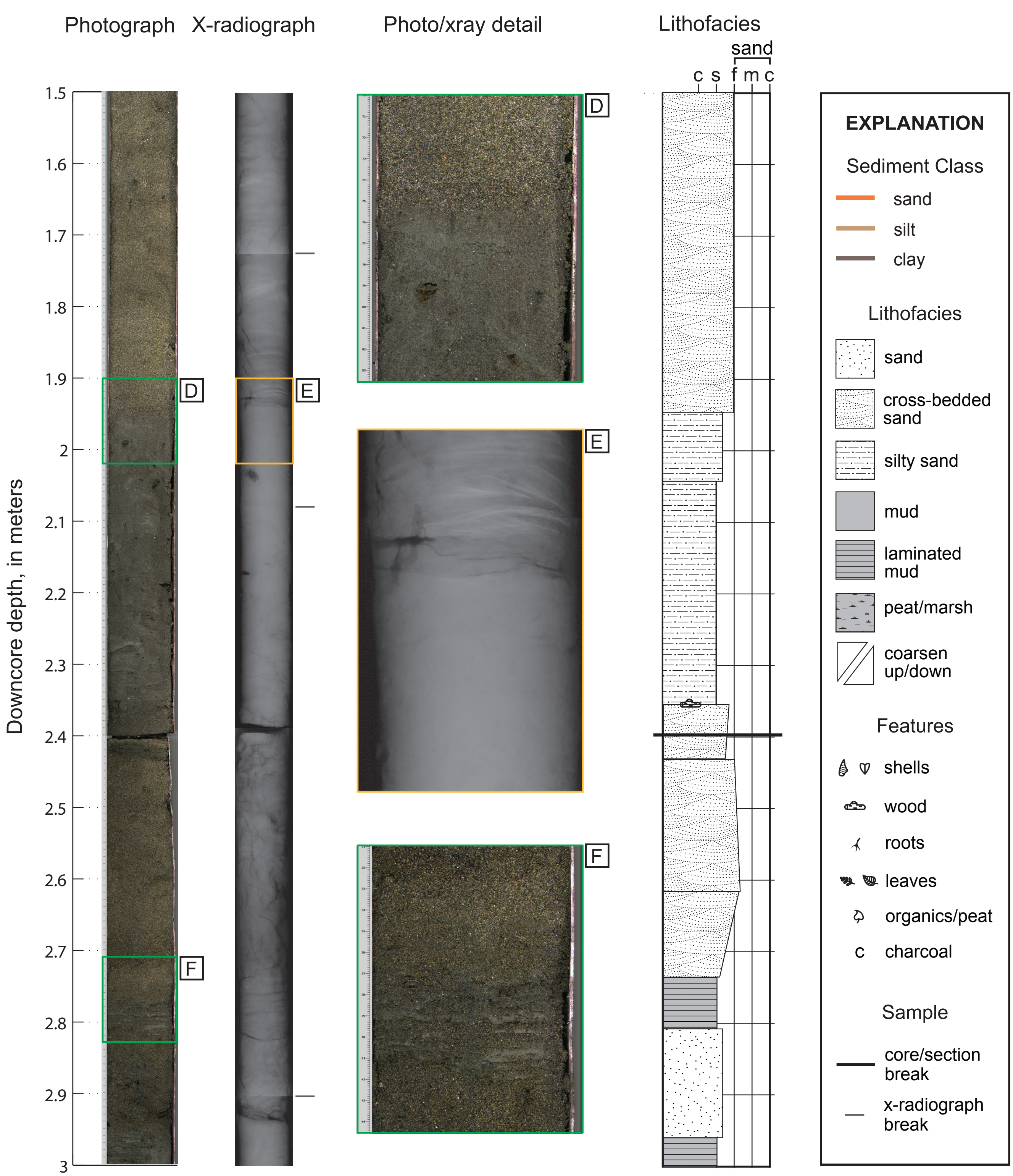

Figure A.1.9, cont.

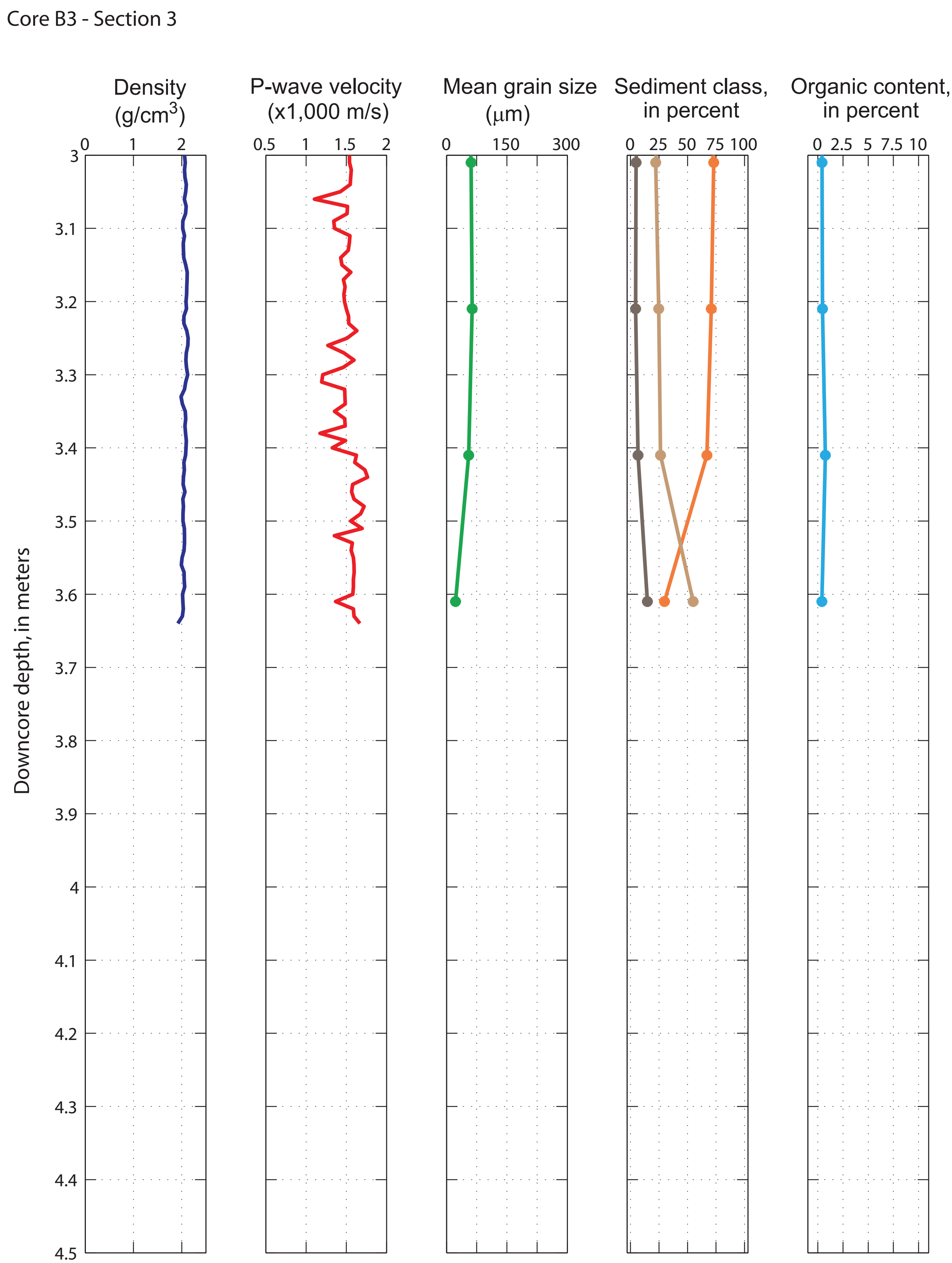

Figure A.1.9, cont.

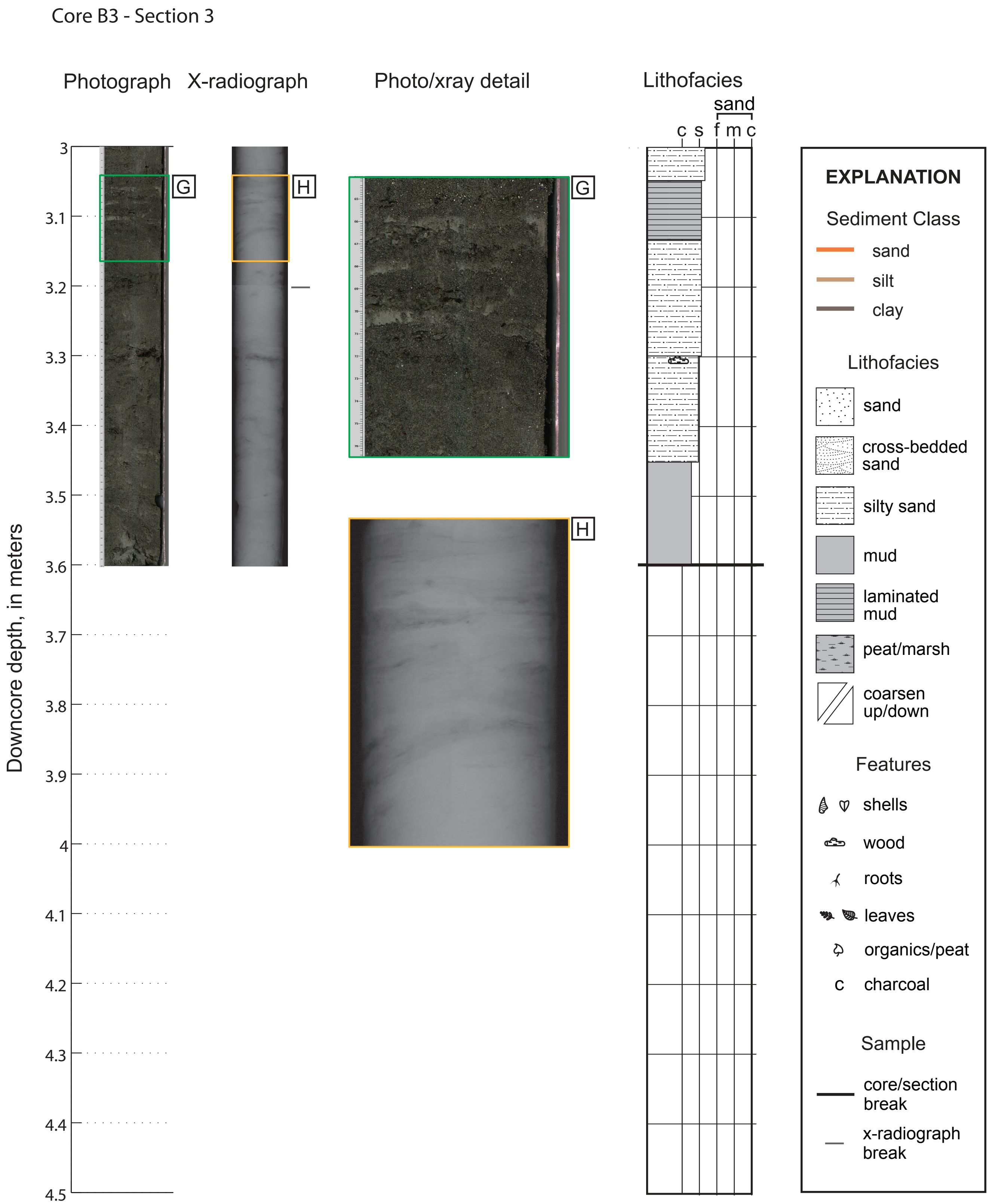

Figure A.1.9, cont.

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Core B4

This core also was collected on the delta front, close to Core B3, at an elevation of -1.53 m (mllw) and is 4.5 m long, the longest core recovered. Sand dominated the top 1.8 m, followed by mud from 1.8 to 3.0 m. The remaining 1.5 m alternates between sand and mud. Shells and organics were identified in the top 1.5 m, followed by mud clasts from 1.70 to 1.75 m and organics below 3.6 m. The bulk density remains almost constant for the core, ranging from 1.32 to 1.53 and having a mean of 1.40±0.02 g/cm^3 for the entire core. The P-wave compression velocity, however, fluctuates. It ranges from 727 to 1,185 m/s and has a mean of 983±78 m/s. The mean grain size reflected the major lithofacies with coarser grain sizes in the top 1.5 m, finer grain sizes in the middle 1.5 m section, and variable sizes ranging between mud and sand in the bottom 1.5 m. Likewise, the sediment fractions shift from sand-dominated to mud-dominated and then alternate between the two lithologies as downcore depth increase. The digital photographs and x-radiograph images show brown sand in the top 1.7 m (for close up fig. A.1.10, inset A) and a contact between cross-bedded sands and laminated silts at 1.26–1.38 m (fig. A.1.10, insets B and C). Between 1.7 and 3.7 m, the muds show lamina (fig. A.1.10, insets D and E). Between 3.15 and 3.25 m (fig A.1.10, insets F and G), laminated mud show fine layers of organic material; and peaty layers were observed at 3.27 to 3.32 m.

Core B4 - Section 1

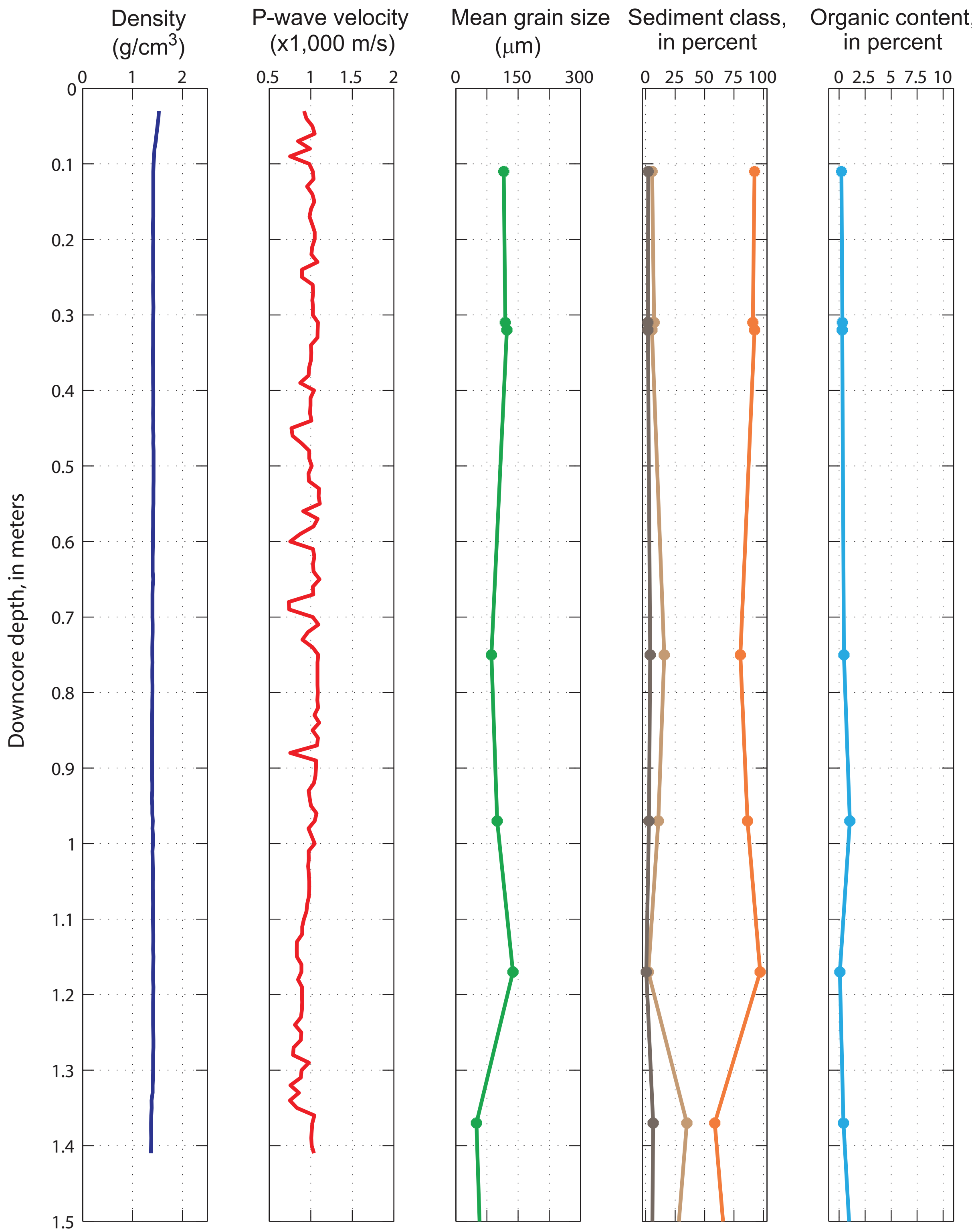

Figure A.1.10. Diagram of physical properties and lithology of sediments from Core B4, Skagit River Delta, Washington.

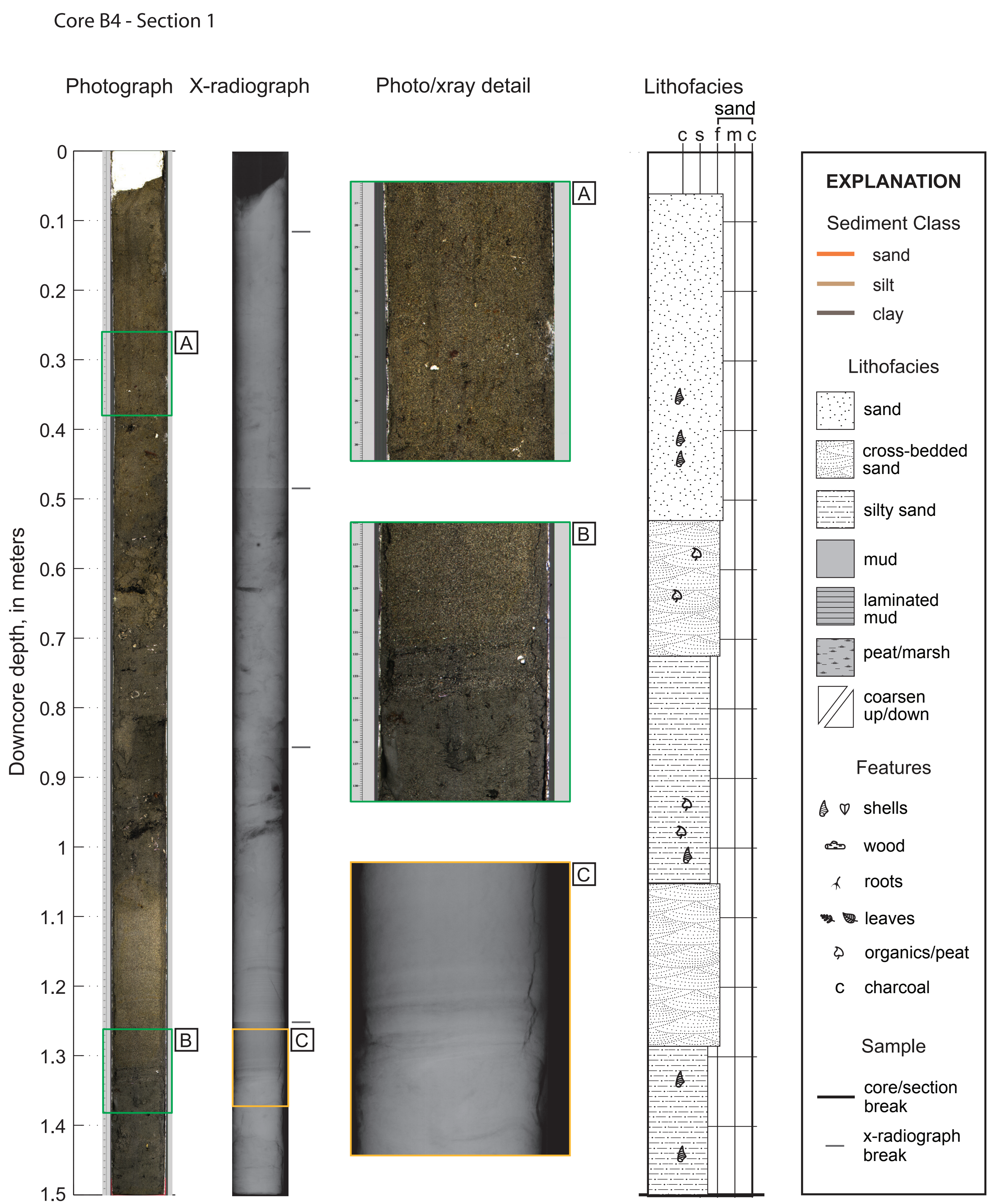

Figure A.1.10, cont.

Core B4 - Section 2

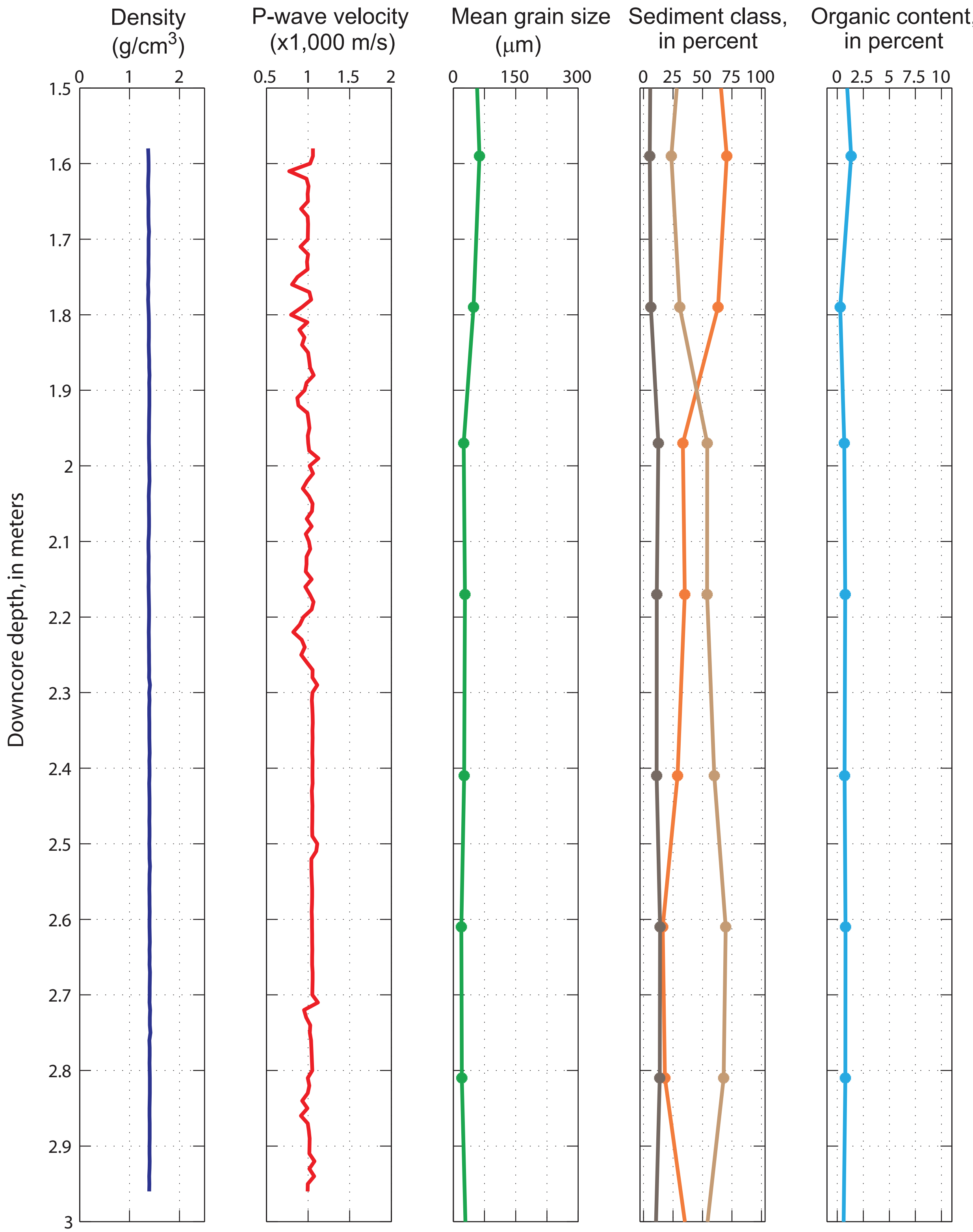

Figure A.1.10, cont.

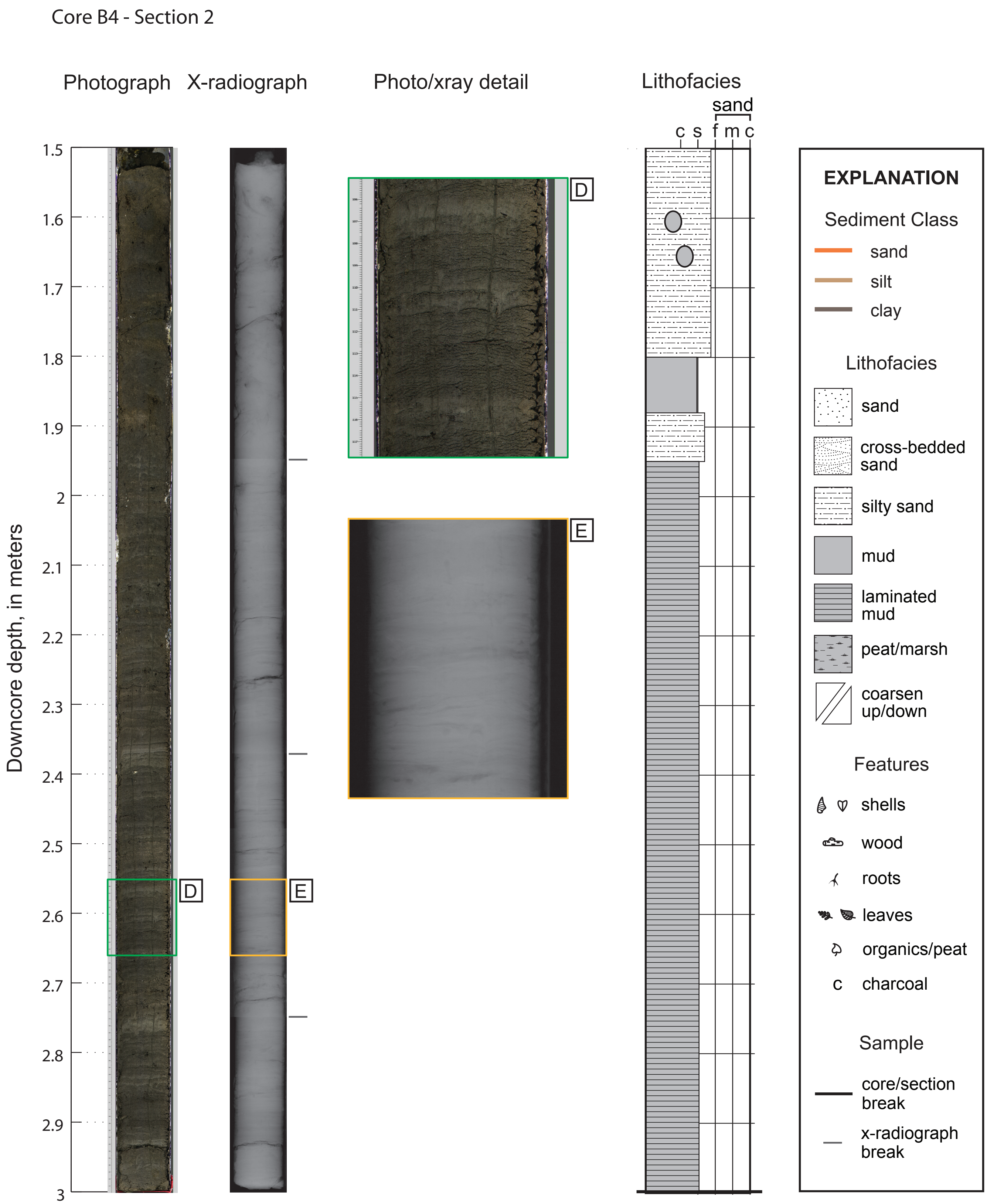

Figure A.1.10, cont.

Core B4 - Section 3

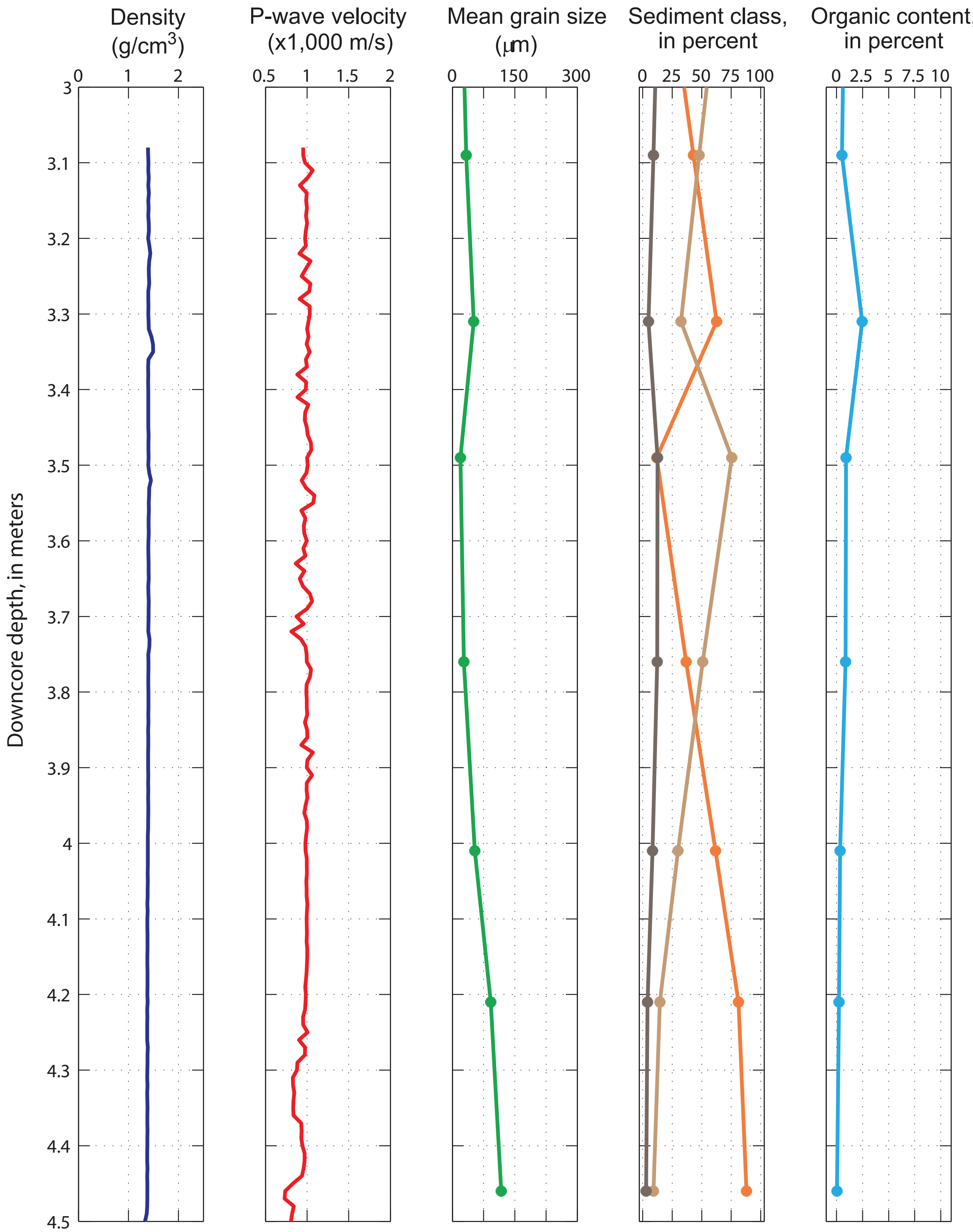

Figure A.1.10, cont.

Core B4 - Section 3

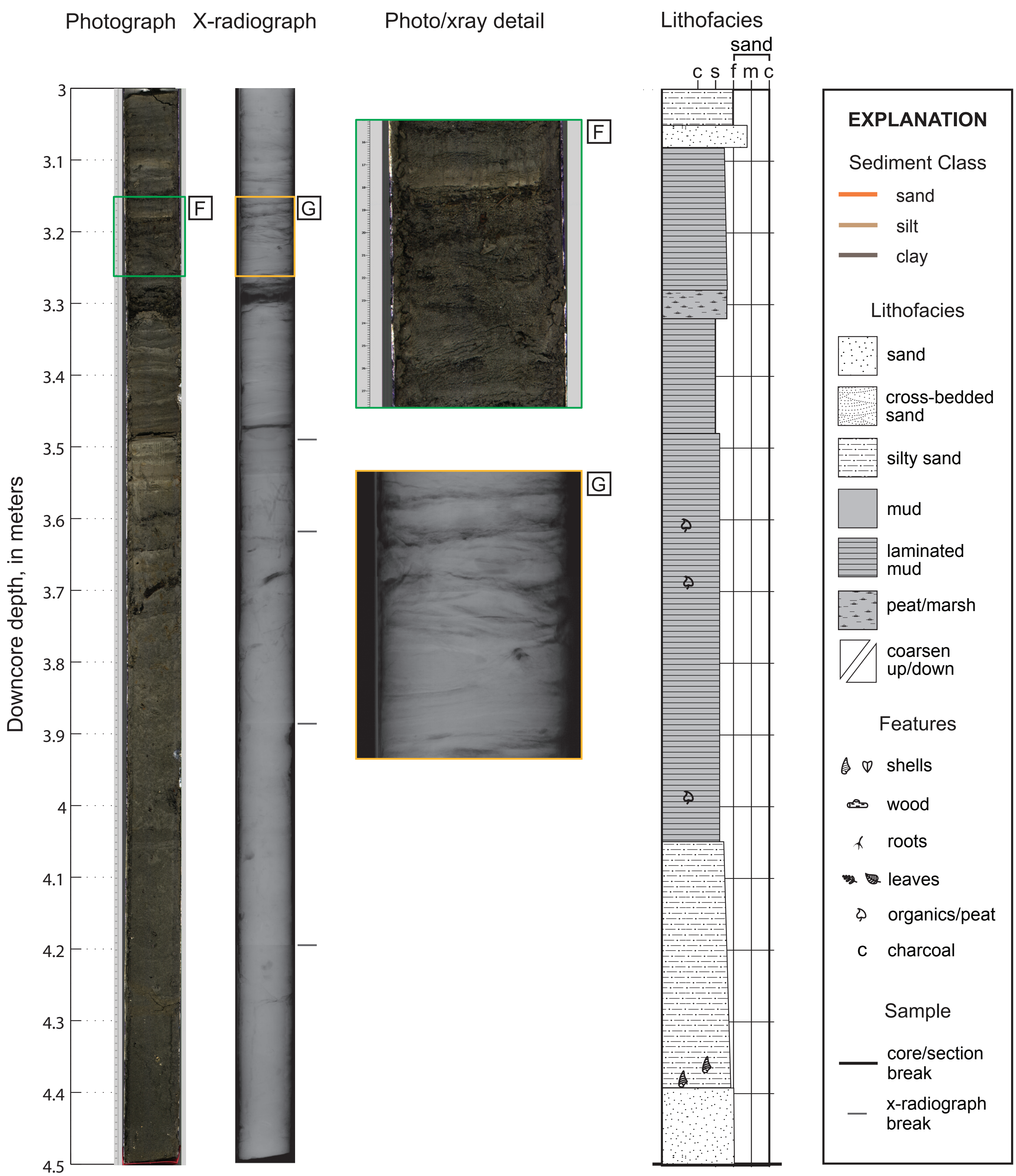

Figure A.1.10, cont.

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Core C1

This core was collected near Big Ditch at an elevation of 3.1 m (mllw) and is 1.91 m long. The entire core was muddy, has some very fine sand, and contains roots, organics, and shells. Slight coarsening downward was observed from 1.00 to 1.50 m. The bulk density is fairly uniform, ranging from 1.31 to 1.61 g/cm^3 and having a mean of 1.42±0.04 g/cm^3. The P-wave compression velocity ranges from 672 to 1,191 m/s and has a mean of 933±105 m/s. Consistent fluctuations in velocity were observed throughout the core. The mean grain size generally is less than 60 µm, except from 1.10 to 1.50 m where the sediment is coarser (~75 µm). Similarly, the silt fraction remains above 50 percent for most of the core, except from 1.10 to 1.50 m, where very fine sand comprises up to 70 percent of the sediment. Below 1.5 m, silt increases again to upwards of 55 percent of sediment. The digital photographs show brown and gray-brown muds with roots common in the upper half of the core. Fine laminae and layered peat are evident throughout the core, as observed between 0.7 and 0.83 m in photographs and x-radiograph images (fig. A.1.11, insets A and B).

Core C1 - Section 1

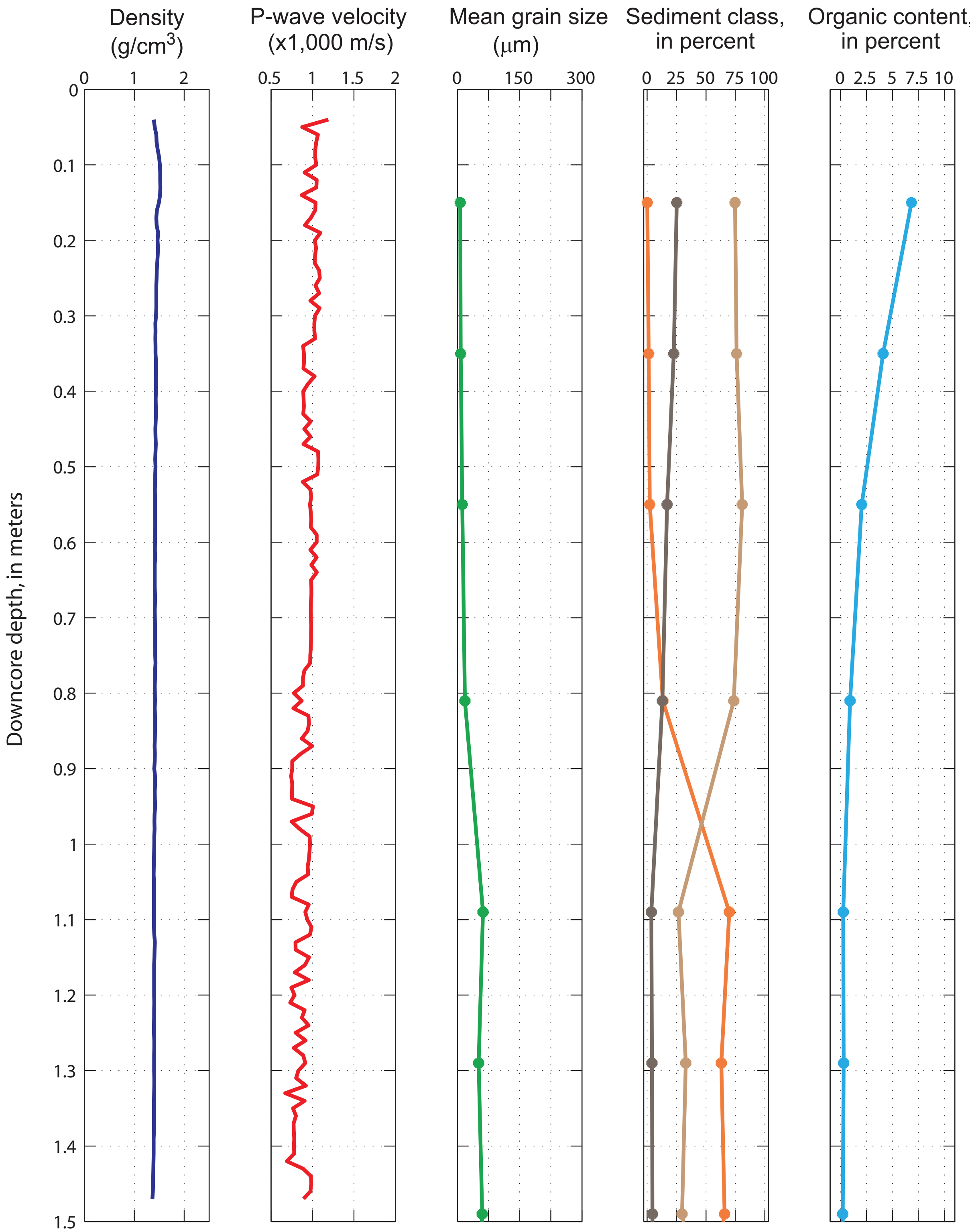

Figure A.1.11. Diagram of physical properties and lithology of sediments from Core C1, Skagit River Delta, Washington.

Core C1 - Section 1

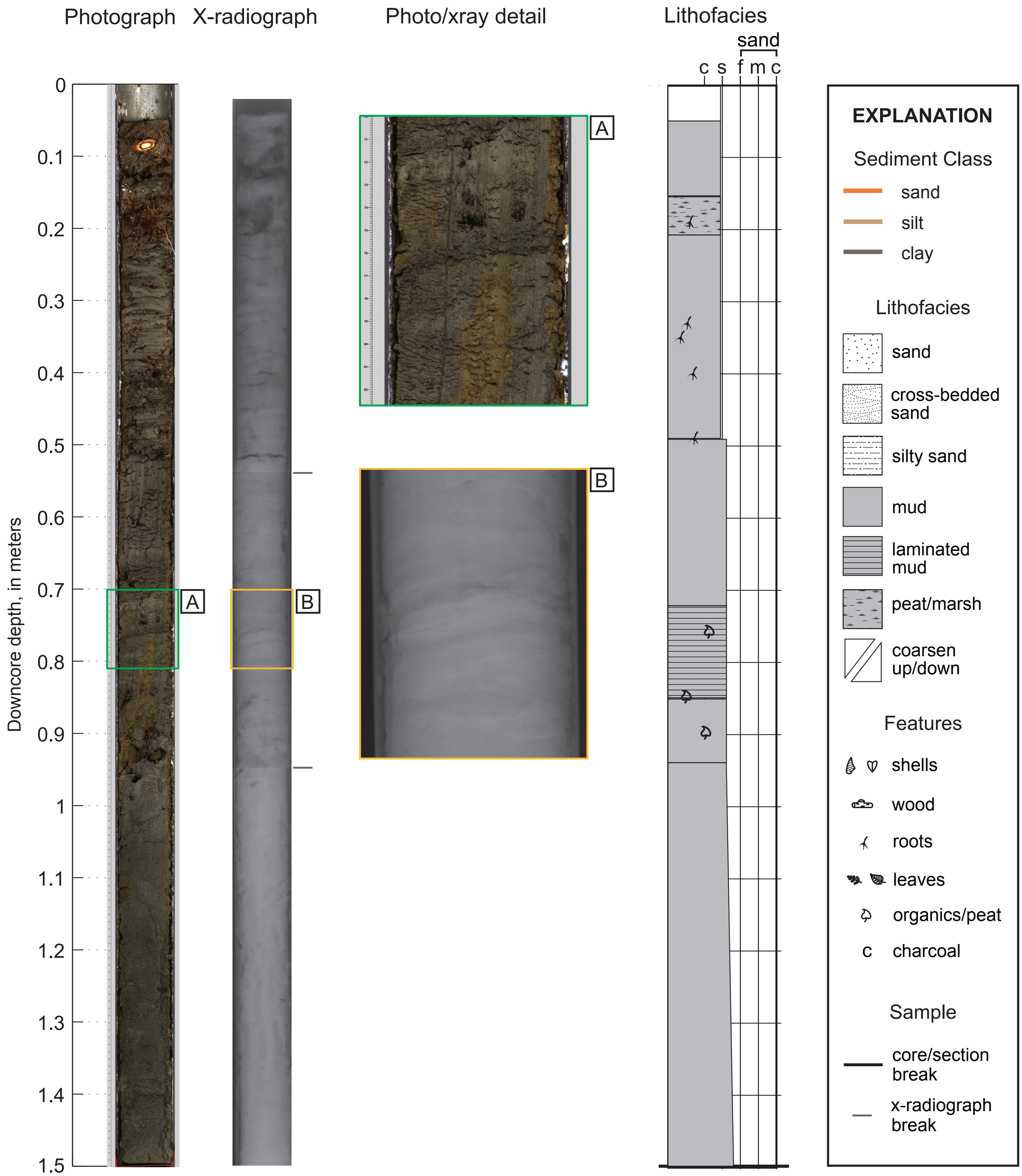

Figure A.1.11, cont.

Core C1 - Section 2

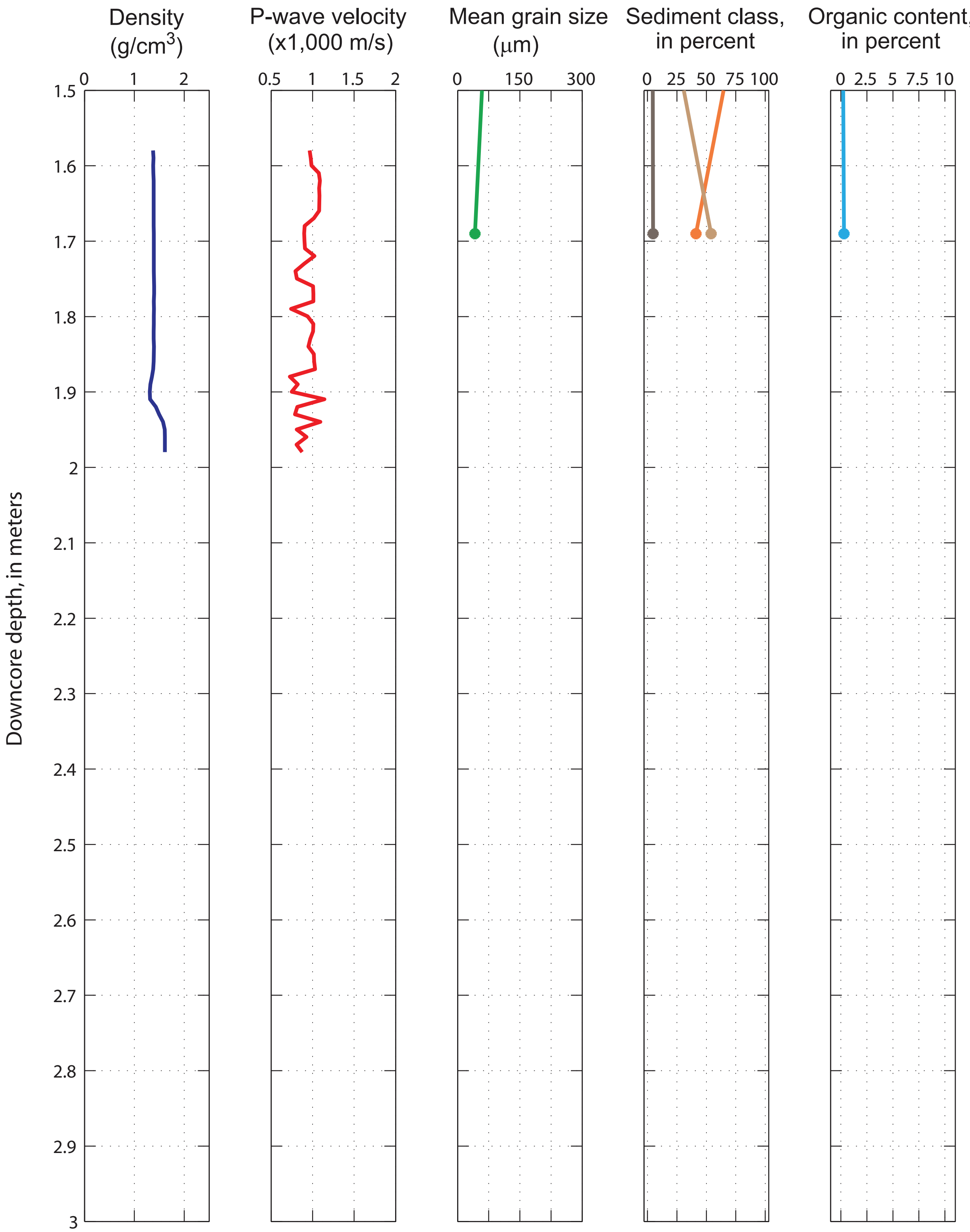

Figure A.1.11, cont.

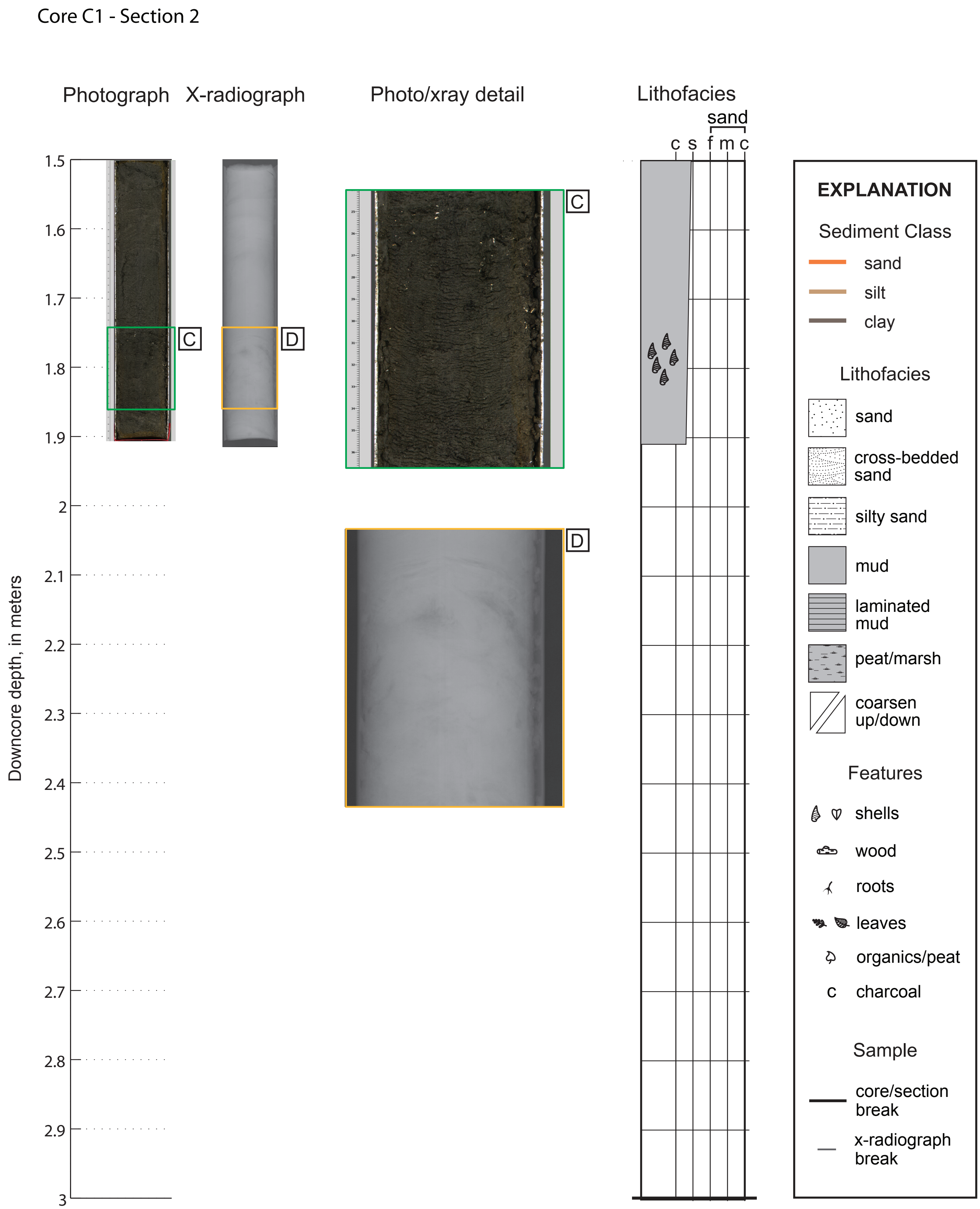

Figure A.1.11, cont.

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Core C2

This core was collected on the shallow tidal flats of the South Fork at an elevation of 0.3 m (mllw) and is 1.82 m long. Fine to medium sand dominates the core with two thin mud-dominated units at 0.67–0.71 m and 0.98–1.03 m. Wood pieces and charcoal also are observed along with a wood-rich layer at 1.4 m and mud clasts at 0.95 m, 1.20 m, and 1.75 m. Several contacts were seen in the lithofacies, including the sand to mud sections noted above and a 3-4-cm-thick peat layer just above 1 m in the core. The bulk density is fairly uniform and has a noticeable decrease at the depth of the peat layer. Density ranges from 1.54 to 2.18 g/cm^3; a mean of 1.95±0.14 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 1,176 to 1,861 m/s and has a mean of 1,628±105 m/s, and fluctuates consistently throughout the core. The mean grain size ranges from 120 to 290 µm, with the coarsest samples observed immediately above the peat layer and at the base of the core. The sand fraction remained above 80 percent for the entire core. The digital photographs show brown and black sand (fig. A.1.12, inset A) and some identifiable contacts between sand and mud layers (fig. A.1.12, insets B and C) as well as medium to coarse nature of sands at the base (fig. A.1.12, inset D) . No x-radiograph images were collected and, as a result, the sand facies are characterized as massive; however they likely contain cross-bedding similar to the upper sand units of the middle and outer tidal-flat cores of transects A and B.

Core C2 - Section 1

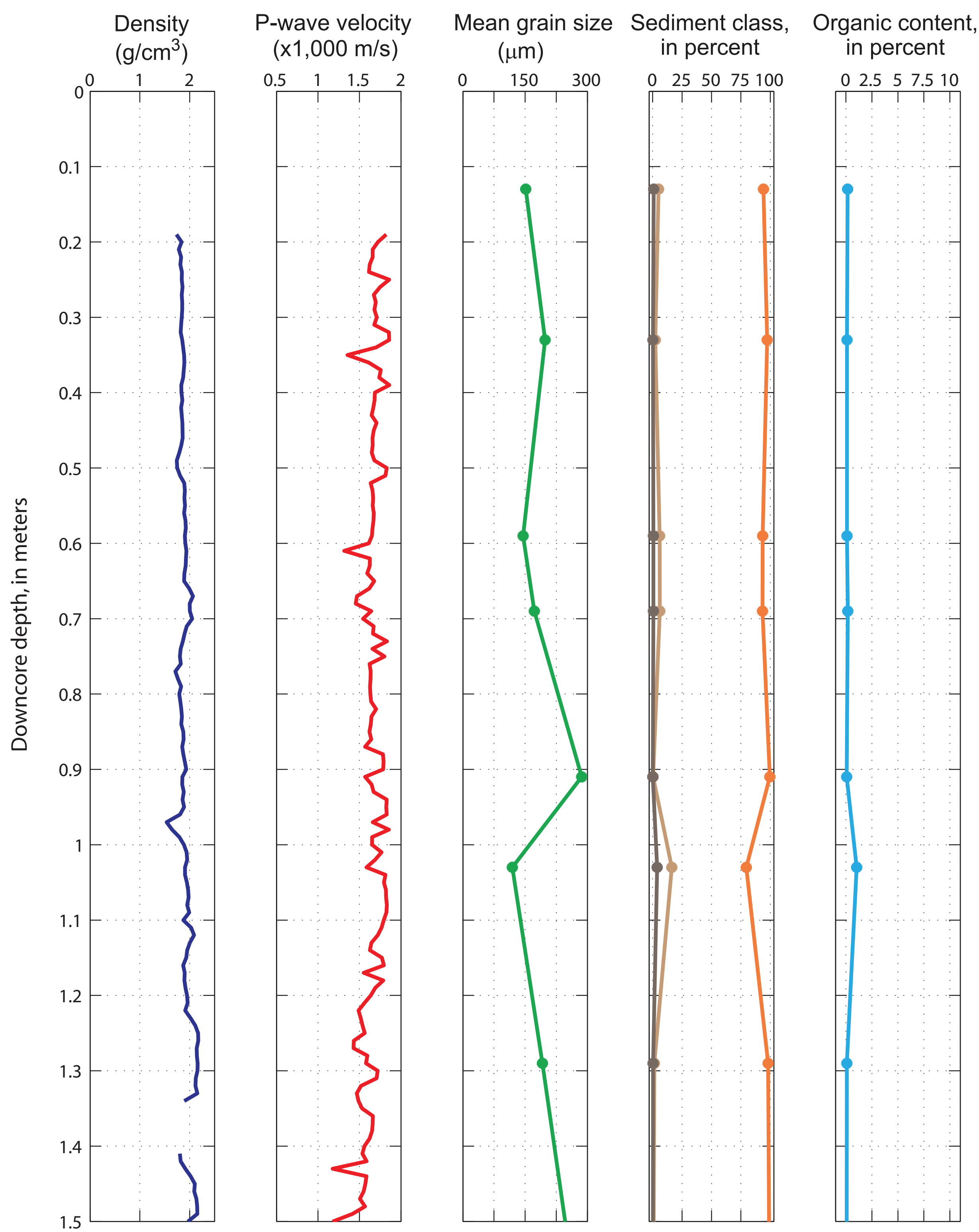

Figure A.1.12. Diagram of physical properties and lithology of sediments from Core C2, Skagit River Delta, Washington.

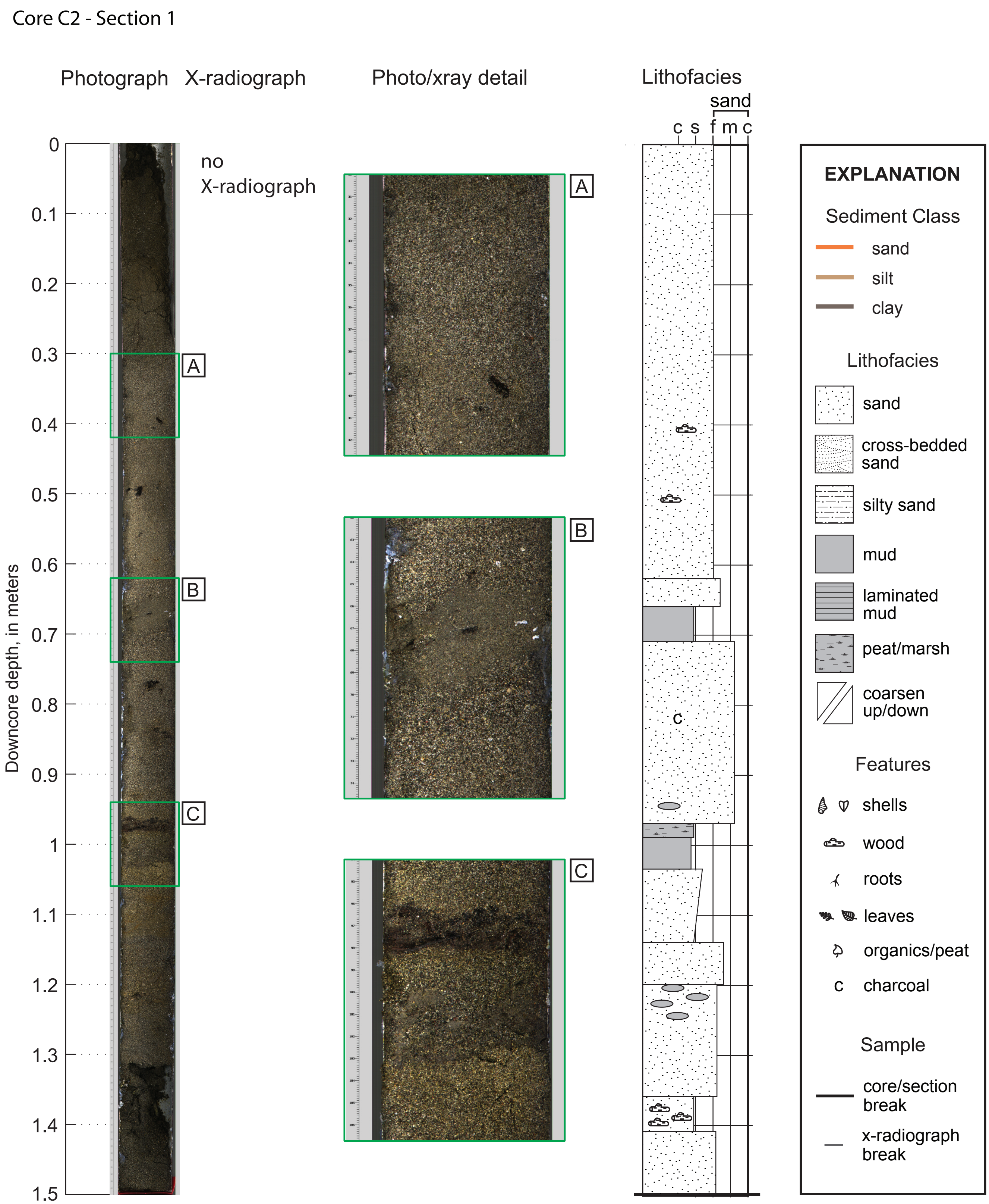

Figure A.1.12, cont.

Core C2 - Section 2

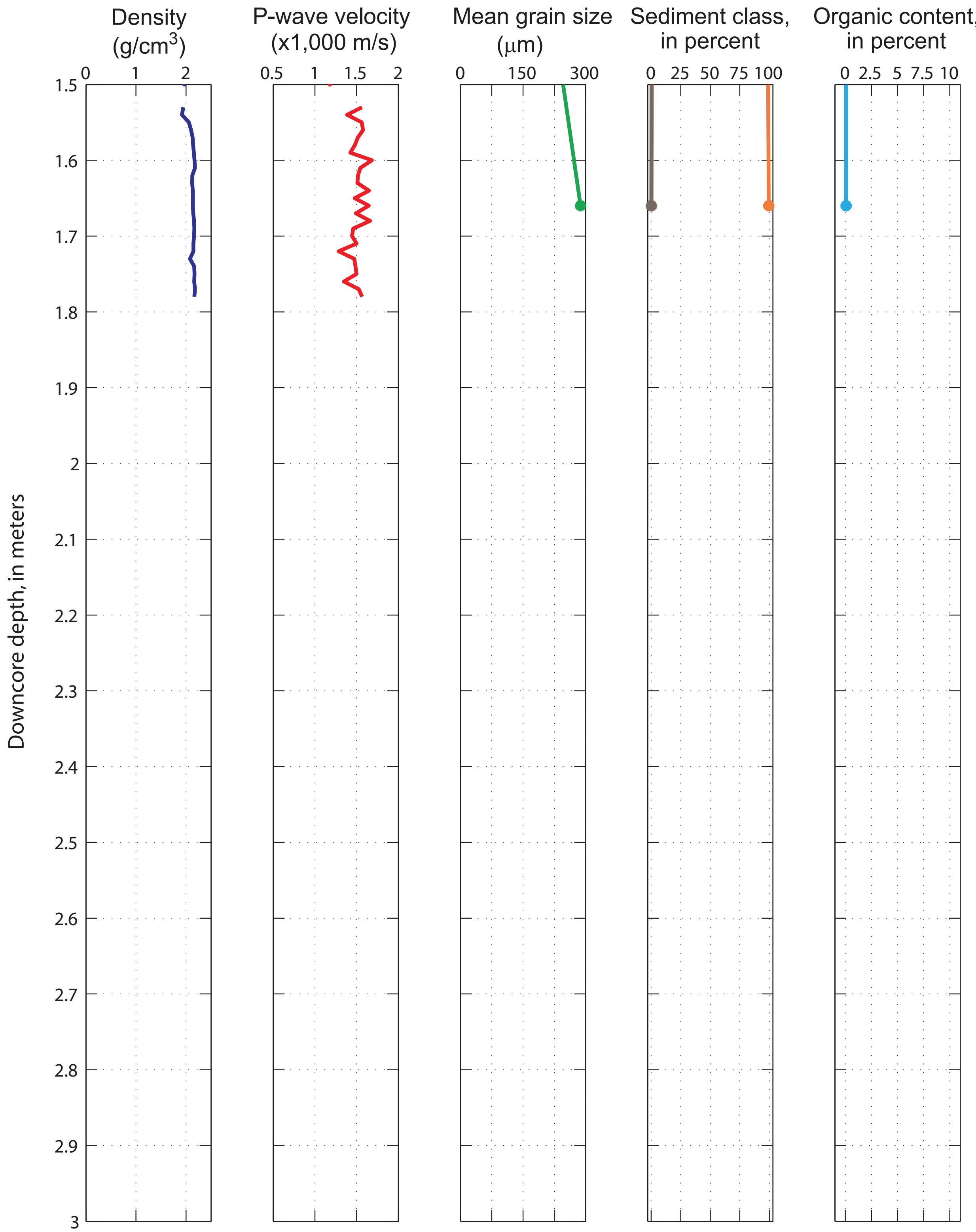

Figure A.1.12, cont.

Core C2 - Section 2

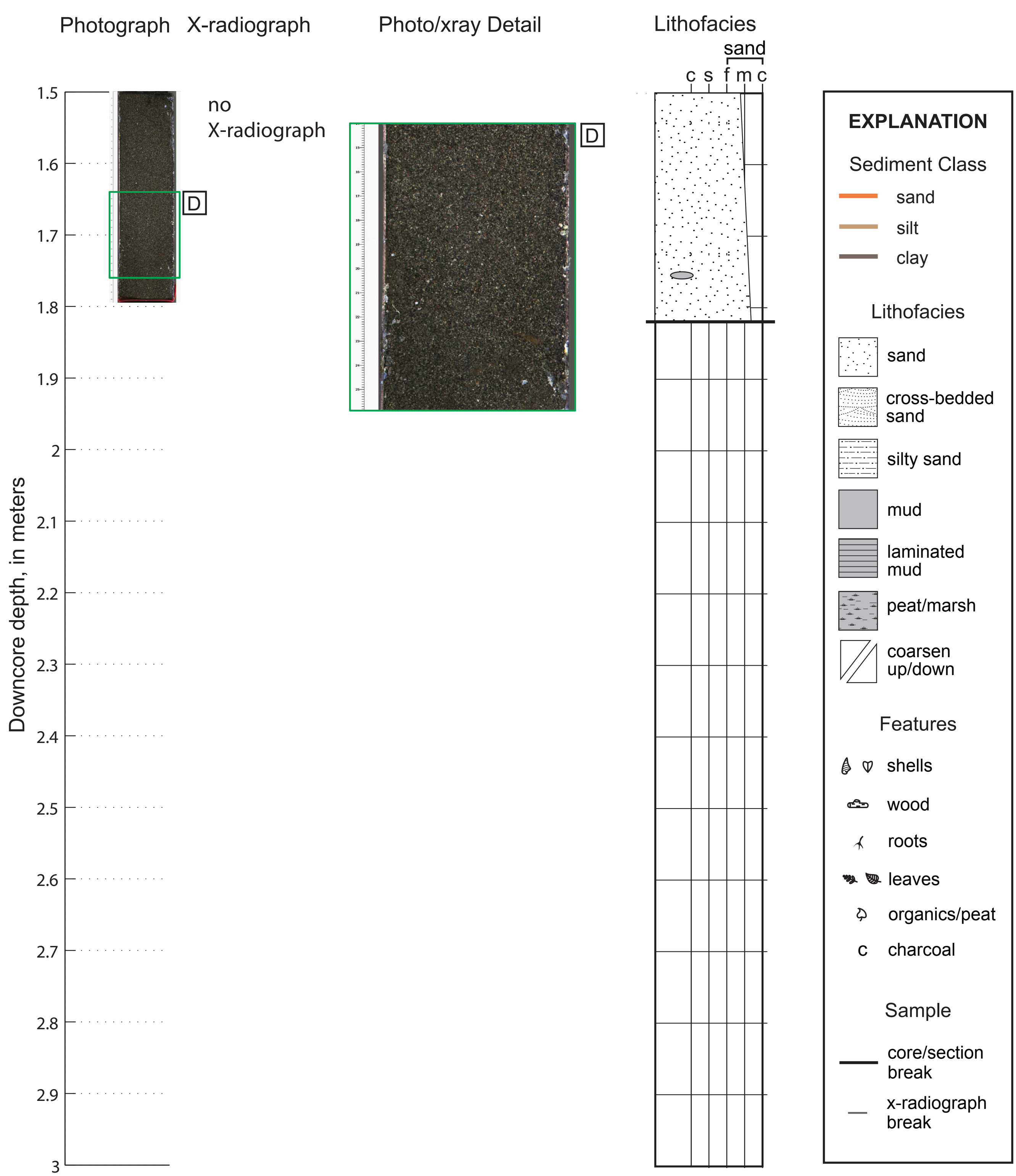

Figure A.1.12, cont.

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Core C3

This core was collected on the southern delta front at an elevation of -0.62 m (mllw) and is 3.95 m long. Sand dominates the core, with three 5-cm layers of peat (~1.10 m, ~1.85 m, and ~1.90 m) and an 8-cm layer of mud (1.62 – 1.70 m). Shells, charcoal, organics, and wood pieces are scattered throughout the core. Bulk density and P-wave compression-velocity data were lost for Core C3 owing to computer-hardware problems. The mean grain size is characterized mostly by very fine to fine sand sizes, with the exception of two samples at 1.65 m and 1.83 m, where the mean size decreases to silt where the mud (combined silt and clay) percentage is larger than 75 percent. The remainder of the core is sand dominated. Even in the sandy sections though, a slight upward coarsening of the sediment was observed. The digital photographs show mostly tan, brown, and brownish-gray sand (fig. A.1.13, insets A and B) and scattered organic detrital material is clear in x-radiograph images (fig. A.1.13, inset C). The sharp contact observed between sand and mud at 1.62–1.70 m is clear in the photographs (fig. A.1.13, inset D), and cross-bedding within the sands between 2.44 and 2.57 m is evident in both photographs and x-radiograph images (fig. A.1.13, insets E and F). The silt-rich, very fine sand of the basal unit lack bedding and appear to be structureless (fig. A.1.13, insets G and H).

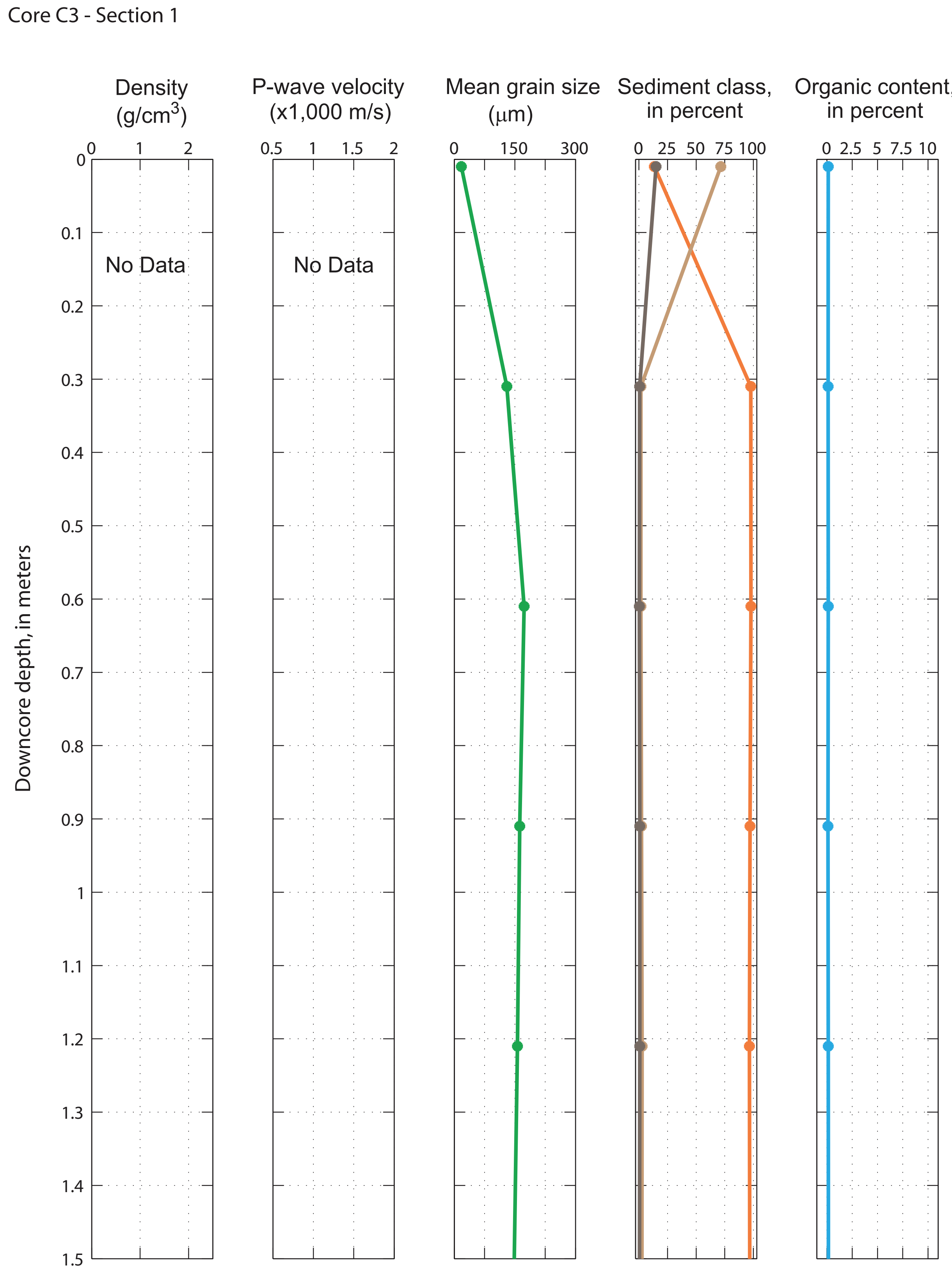

Figure A.1.13. Diagram of physical properties and lithology of sediments from Core C3, Skagit River Delta, Washington.

Core C3 - Section 1

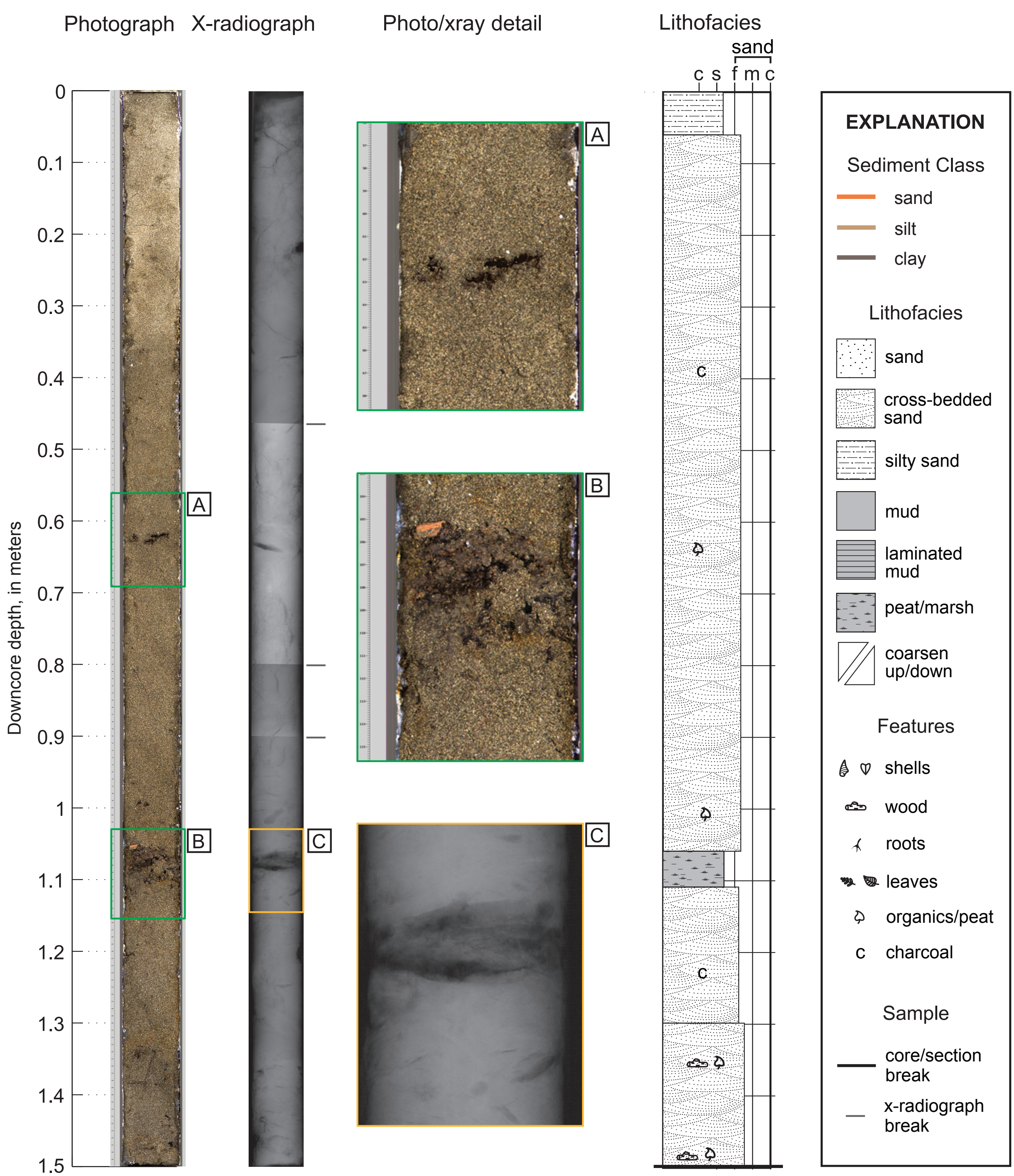

Figure A.1.13, cont.

Core C3 - Section 2

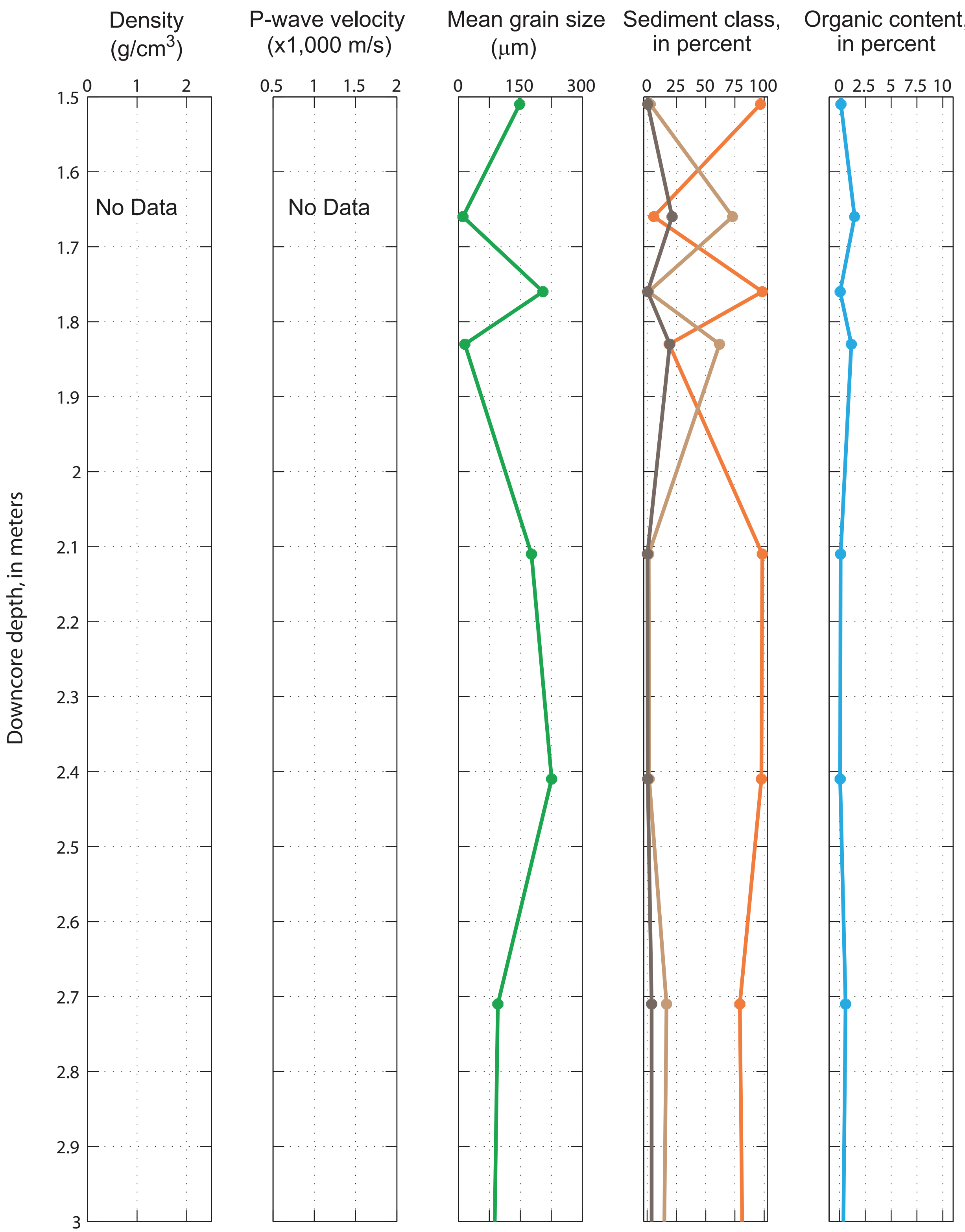

Figure A.1.13, cont.

Core C3 - Section 2

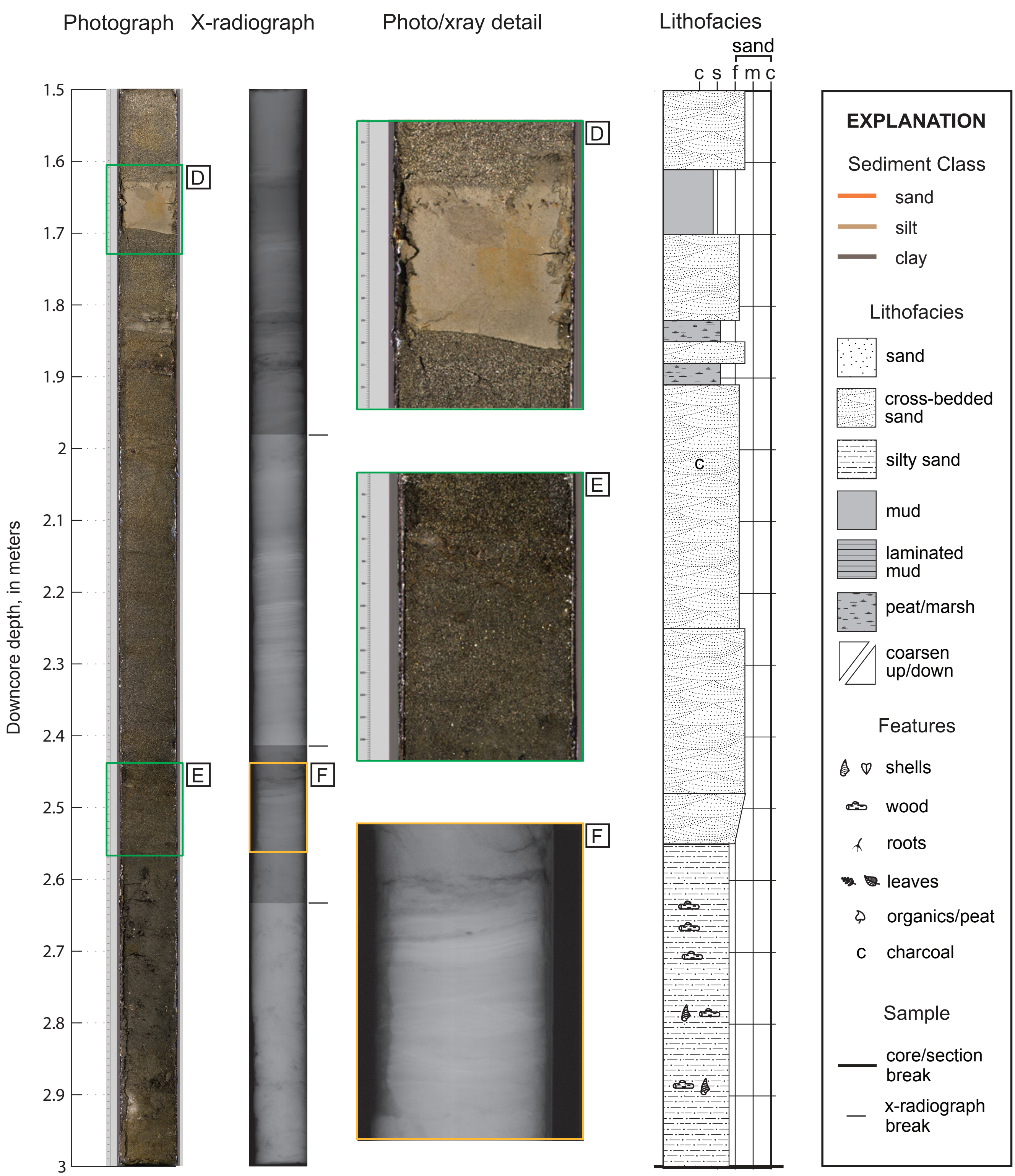

Figure A.1.13, cont.

Core C3 - Section 3

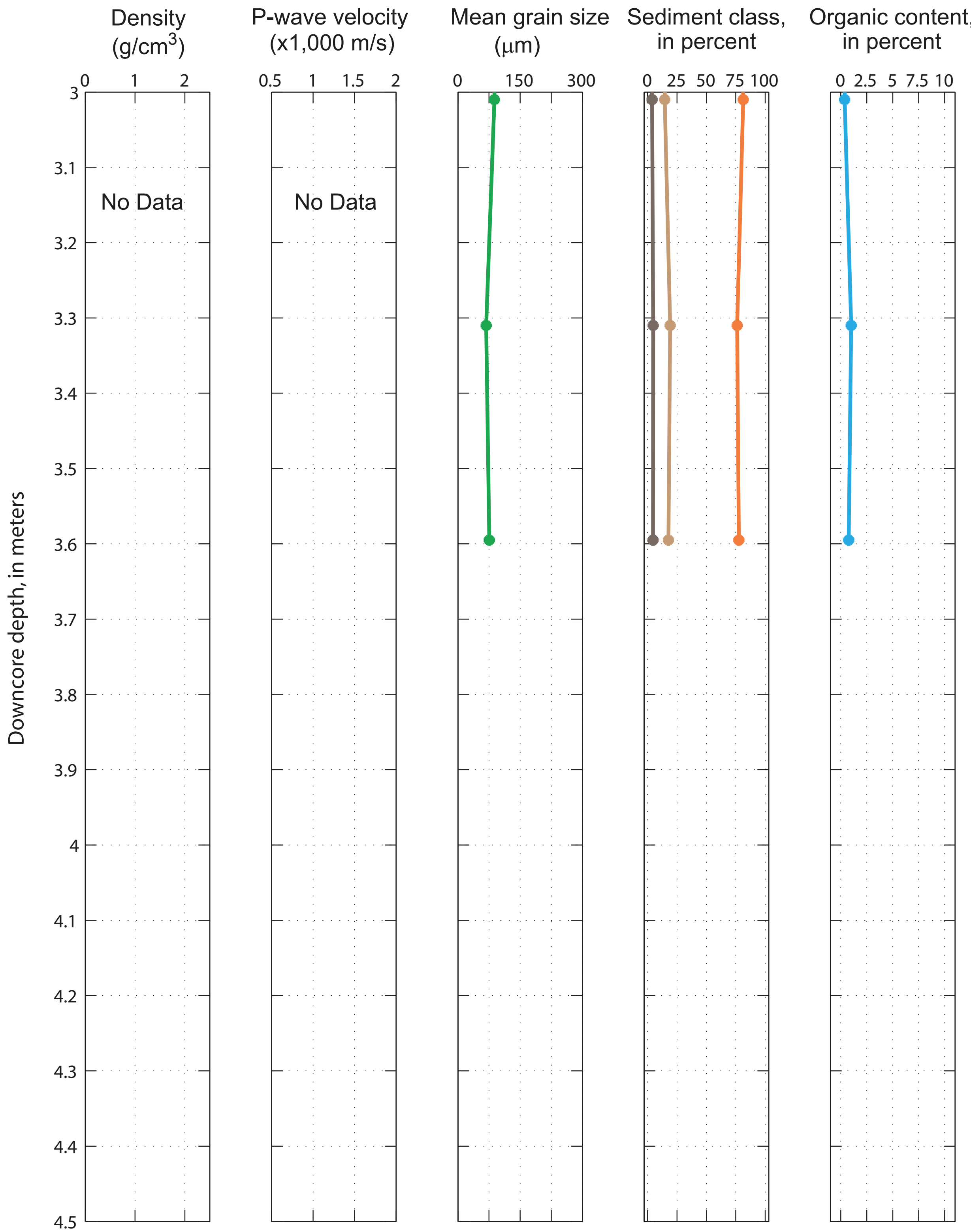

Figure A.1.13, cont.

Core C3 - Section 3

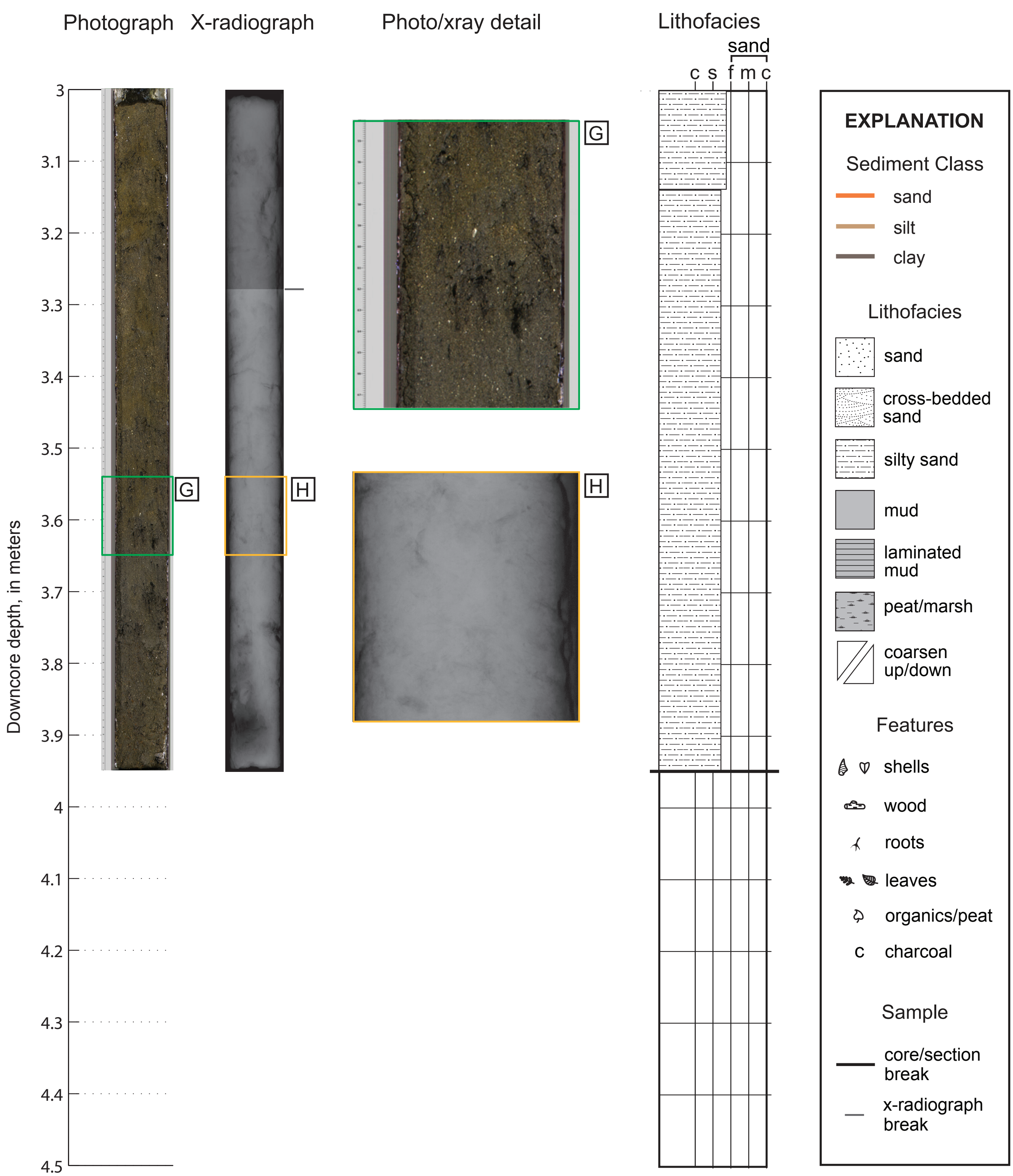

Figure A.1.13, cont.

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Transect C Augers

The tree augers collected within the Wiley Slough area were obtained from an elevation of +2.1 m (mllw), and they each penetrated 9.6 m (figs. 2 and 9). The lithofacies in each of the augers are similar to each other and characterized by an upper unit consisting of 0.30–0.45 m thick sod, representative of the modern grasses grown in the area diked for agriculture and grazing. Below this a silt to silty sand layer with scattered organic material, including small rootlets, extending to 1.0–1.5 m depth above a thick basal unit of sands. The sands of the underlying units generally coarsens downward from very fine sand with silt to the base, characterized by fine to medium sands. Organic matter, dominated by larger fragments of wood (2–4 cm long, 1–2 cm diameter), are scattered throughout the intervals sampled, but are more common near the base of the augers.

Core D1

This core was collected closer to shore at an elevation of -0.19 m (mllw) and is 3.0 m long. The core is dominated by silt, with a significant proportion of clay (10–20 percent) throughout the core, except for a short (10–15 cm) section at 1.4 m and between 1.5 and 2.2 m, where very fine sand and fine sand increase up to 55 percent and 75 percent, respectively. A transitional area between fine sand and underlying mud, between 1.8 and 2.2 m, includes an interesting vertical contact of mud within the sand. Shells, charcoal, wood pieces, and organics are found above the transition zone. The bulk density ranges from 1.52 to 2.12 g/cm^3 and is mostly uniform with increasing downcore depth; a mean of 1.78±0.12 g/cm^3 was calculated for the entire core. The P-wave compression velocity ranges from 991 to 1,557 m/s and has a mean of 1,427±109 m/s. Periodic fluctuations in velocity were observed in the top 0.7 m, followed by more random fluctuations within the remainder of the core. The mean grain size ranges from 20 to 75 µm for most of the core, with the exception of one sample at 2.03 m that measures 180 µm. The sand and silt fractions are evenly balanced for most of the core, although a sand-dominated region was observed from 1.5 to 2.2 m. The digital photographs and x-radiograph images show gray and black sediment throughout the core and the dominance of dark mud at the top of the core (fig. A.1.14, inset A), relative to the siltier, sandier fractions below that show cross-bedding (fig. A.1.14, insets B and C). Near the mud transition to sand between 1.5 and 2.2 m, mud is observed interfingered with dark fine sands (fig. A.1.14, inset D) and contacting the sands vertically (fig. A.1.14, insets E and F).

Core D1 - Section 1

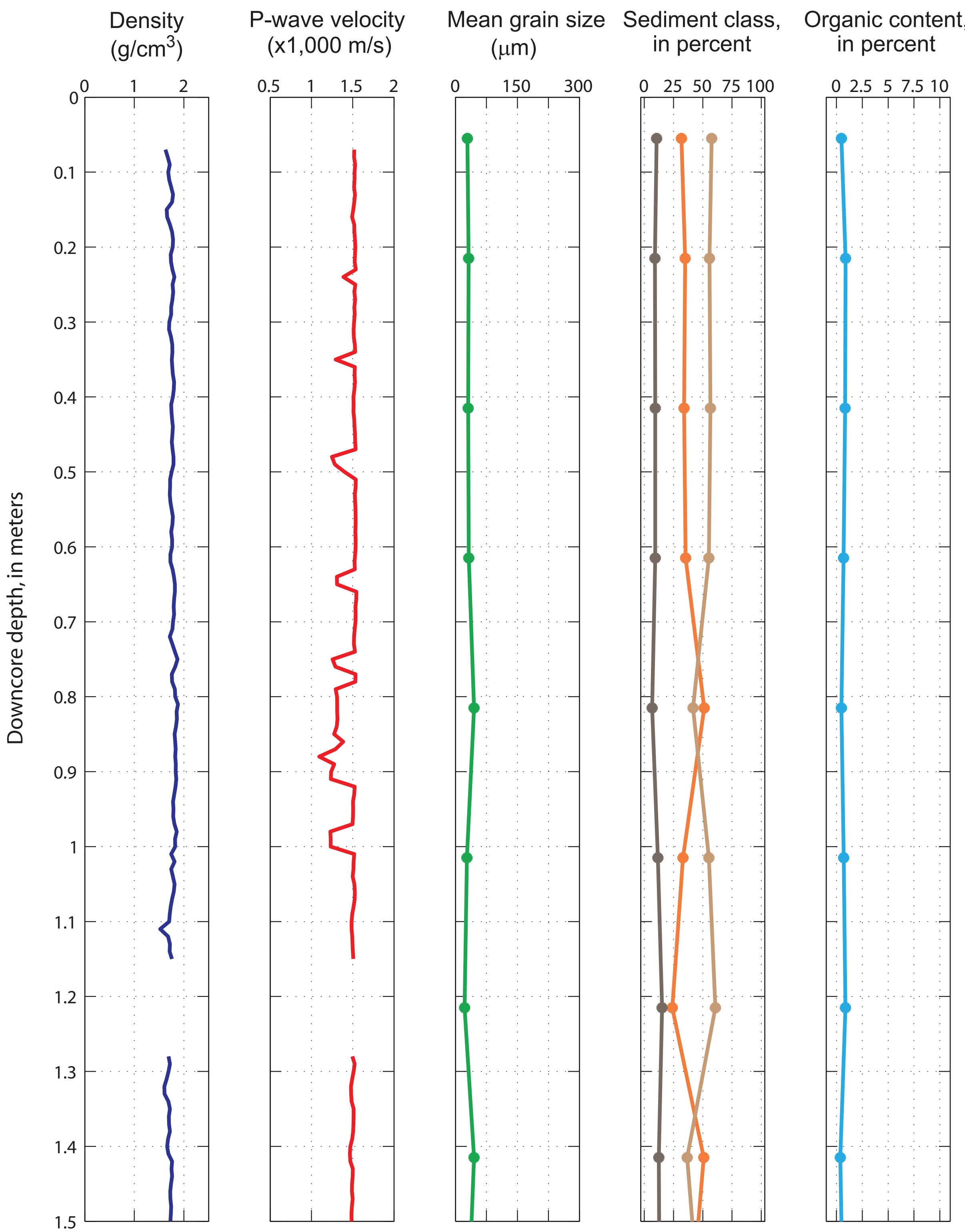

Figure A.1.14. Diagram of physical properties and lithology of sediments from Core D1, Skagit River Delta, Washington.

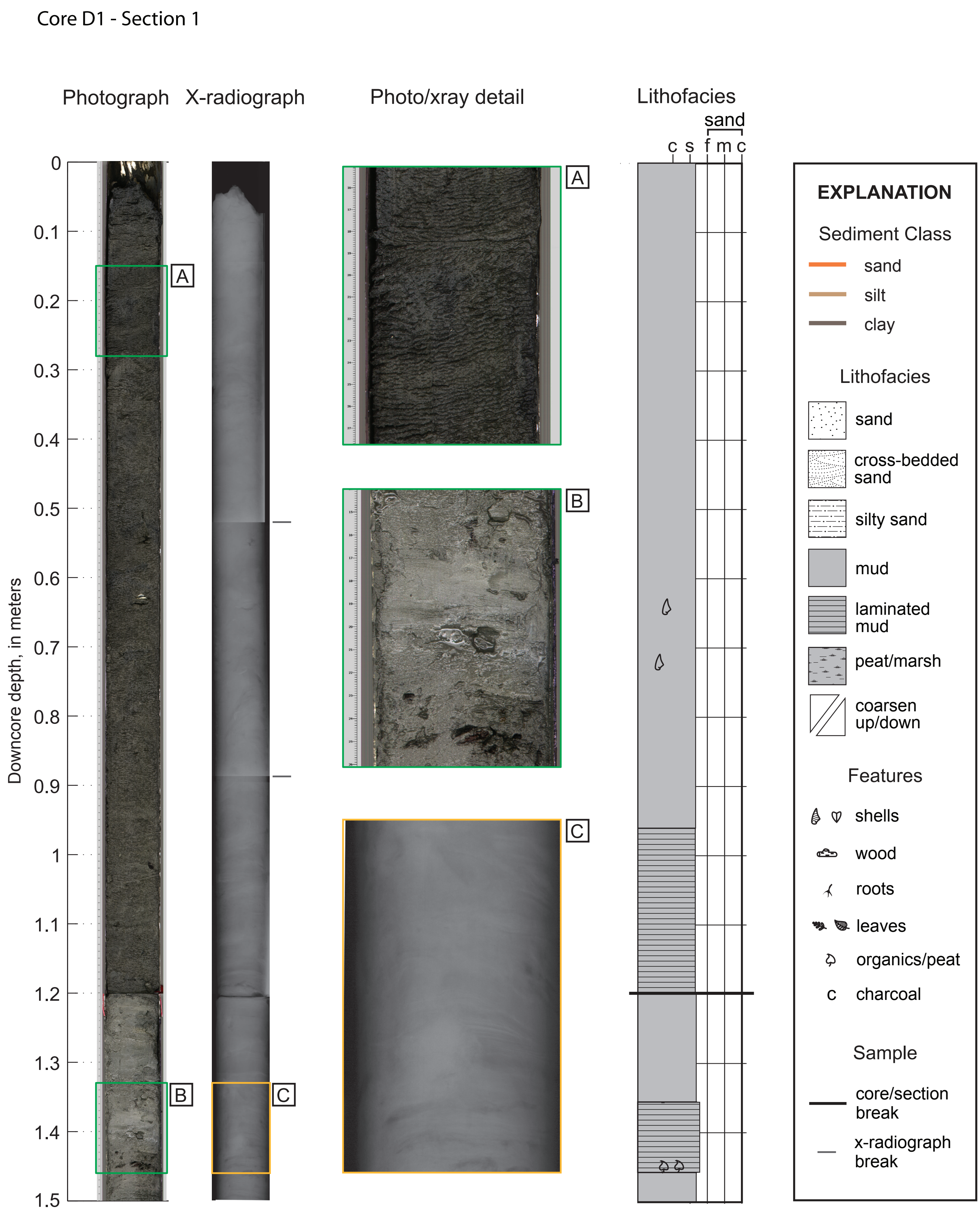

Figure A.1.14, cont.

Core D1 - Section 2

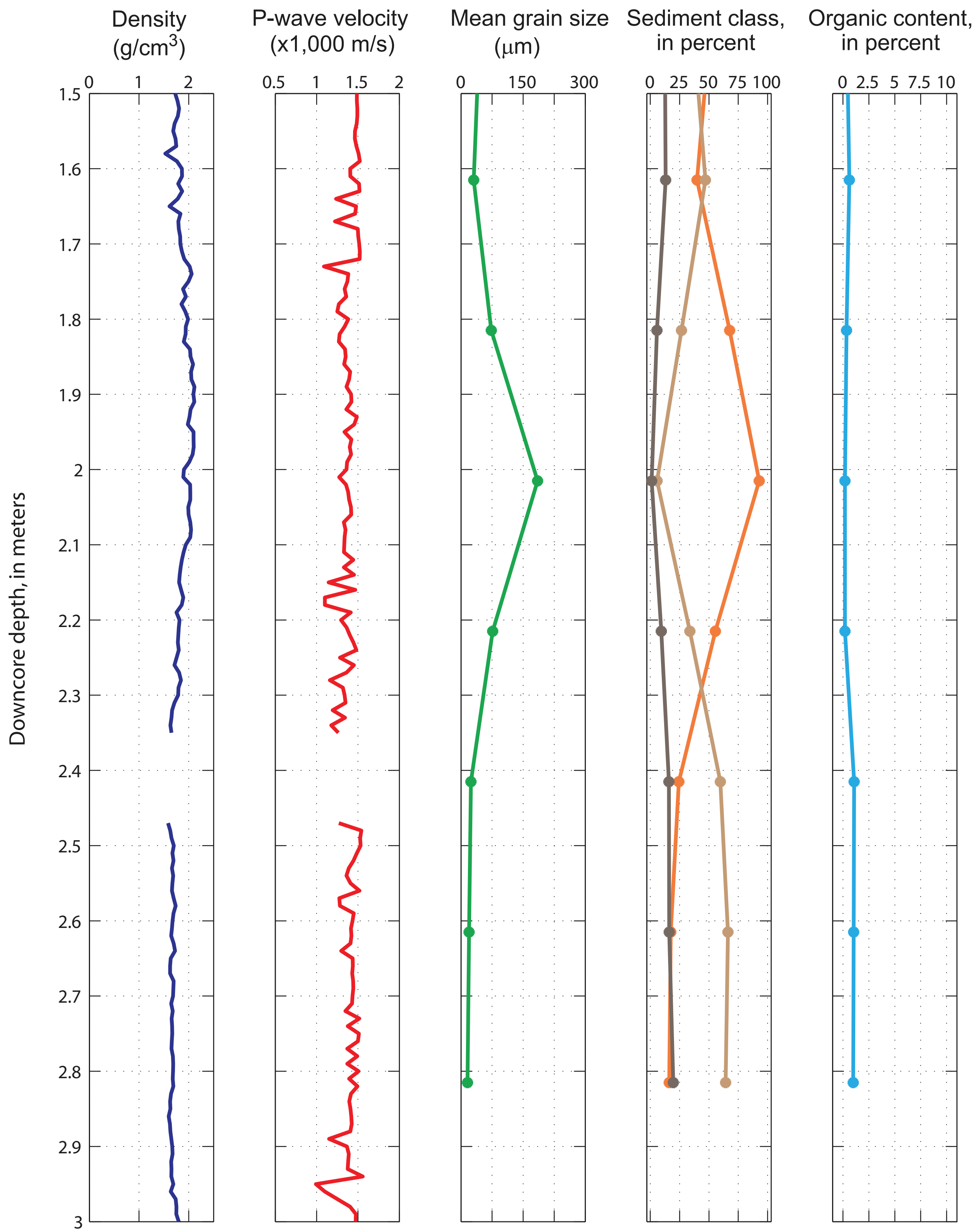

Figure A.1.14, cont.

Core D1 - Section 2

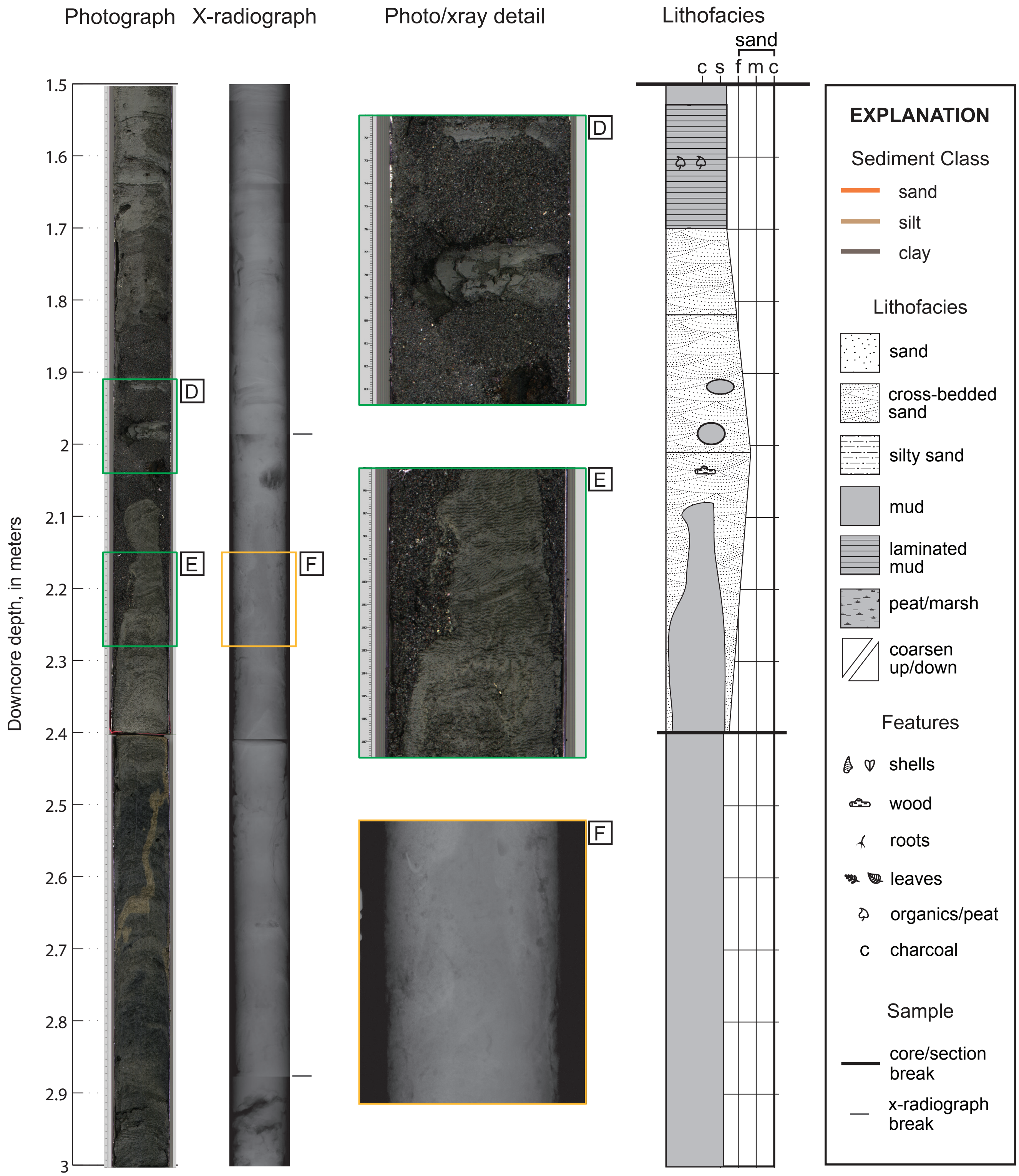

Figure A.1.14, cont.

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Core D2

This core was collected seaward of D1 at an elevation of -0.92 m (mllw) and is 2.4 m long. The core is mostly silty sand and has very fine sand in the top 1.6 m. Below 1.6 m, the sediment composition is more variable, ranging from mud and silt to medium sands. Shells and charcoal were found above 1.3 m, and large amounts of wood pieces occur in the bottom section of the core. The bulk density ranges from 0.50 to 2.14 g/cm^3 and has a mean of 1.80±0.21 g/cm^3. P-wave compression velocity ranges from 1,021 to 1,552 m/s and has a mean of 1,413±123 m/s. The density and velocity both fluctuated more in the bottom 1.2 m than in the top 1.2 m. Mean grain size ranged from silt and very fine sand (30–75 µm) in the top 1.6 m to fine and medium sand (130–210 µm) below 1.6 m. The sand and silt fractions are evenly balanced in the top 1.6 m, while the remainder of the core is sand-dominated. The digital photographs and x-radiograph images show gray and black sediment throughout the core (fig A.1.15, inset A) and interfingered mud and fine cross-bedded sands in the lower core, similar to Core D1 (fig. A.1.15, insets B and C). The contact between muds and sands at 1.6 m is sharp (fig. A.1.15, inset D), and buried wood and other detrital materials in the sands likely produce the variable bulk density and p-wave velocities evident in both photographs and x-radiograph images (fig. A.1.15, insets E and F).

Core D2 - Section 1

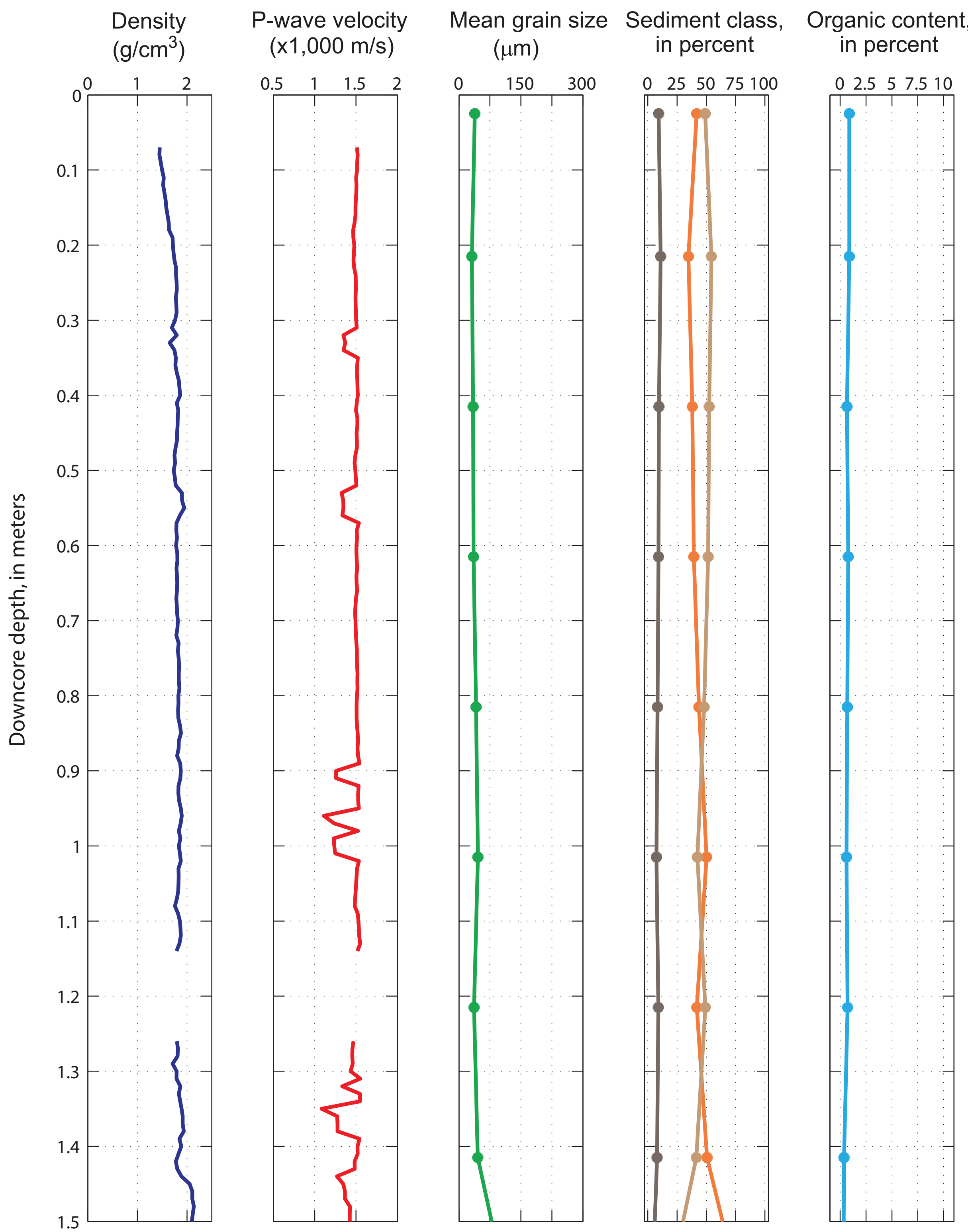

Figure A.1.15. Diagram of physical properties and lithology of sediments from Core D2, Skagit River Delta, Washington.

Core D2 - Section 1

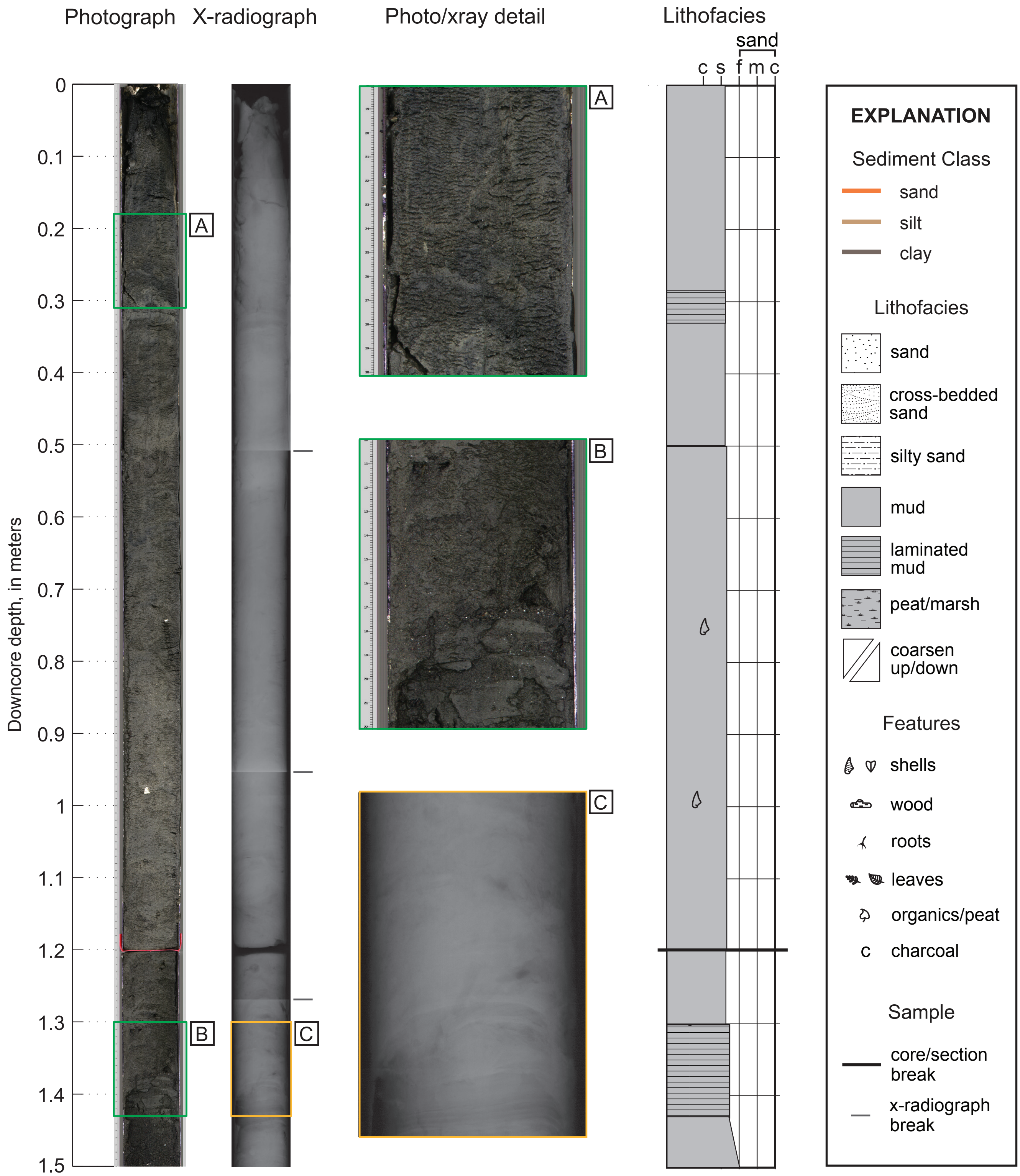

Figure A.1.15, cont.

Core D2 - Section 2

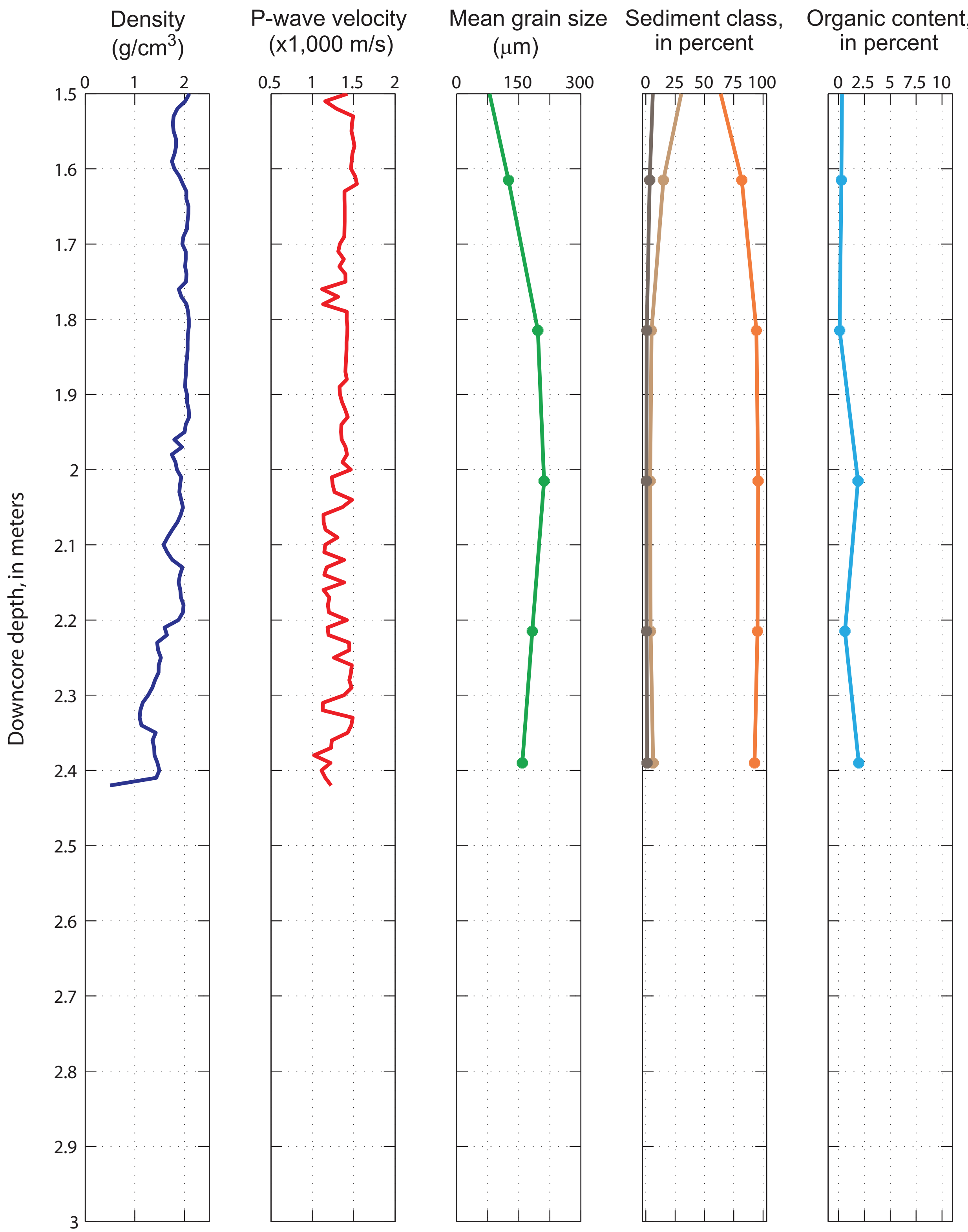

Figure A.1.15, cont.

Core D2 - Section 2

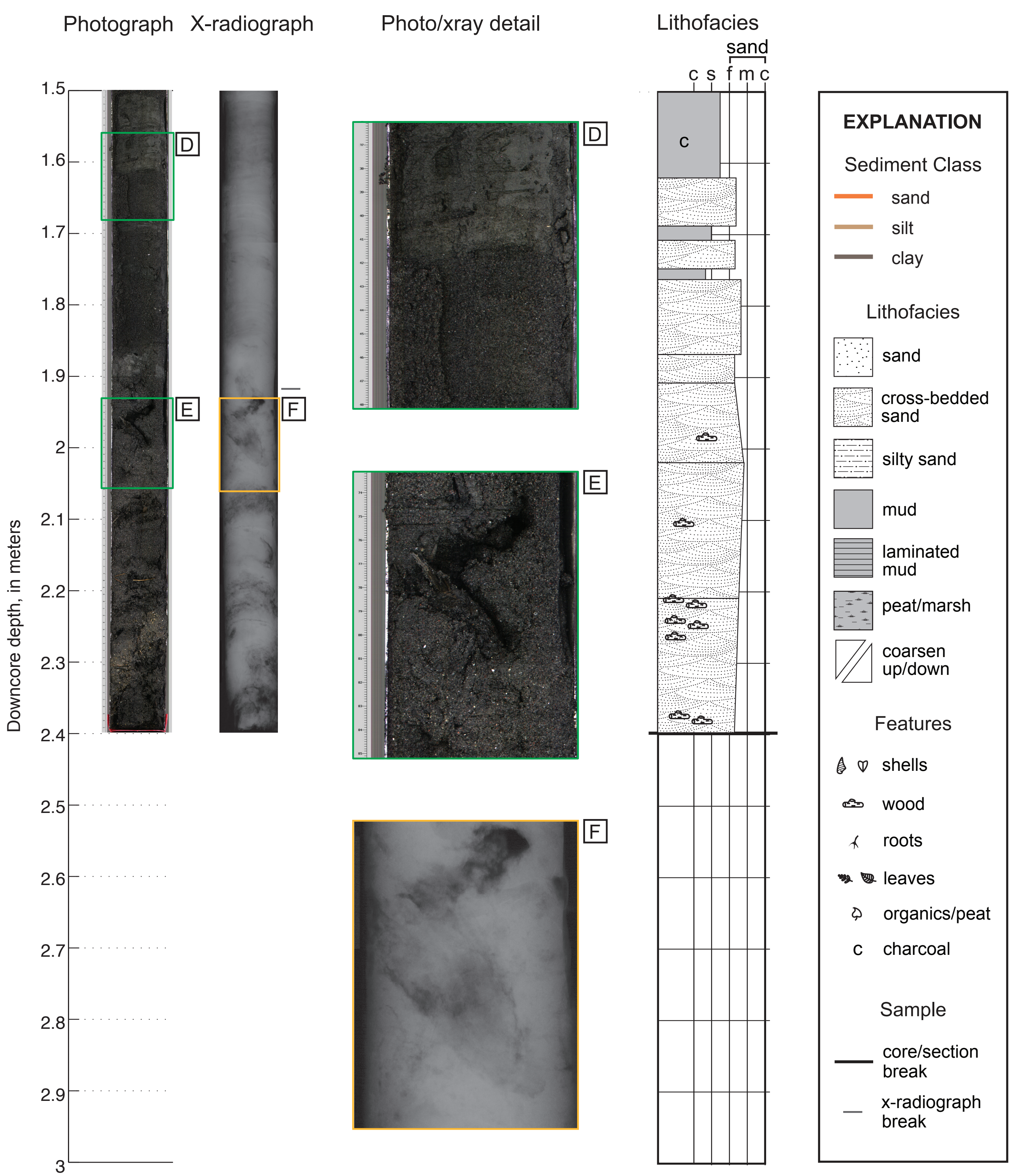

Figure A.1.15, cont.

Transect D Push Cores

Three push cores were collected across the inner tidal flats of Transect D at elevations ranging from -0.2 to 0.75 m (mllw). These push cores penetrated 0.4–0.7 m depth, although recovery was limited to 0.4–0.5 m. Each of these push cores is composed of fluffy mud extending down 0.4–0.5 m (figs. 2–4, and 10). The upper portions of the cores generally are characterized by a thin, 1–4-cm-thick brown mud unit overlying an approximately 10–20-cm-thick black mud unit.

Appendix 2. Statistics of Physical Properties of Vibracores including Density, P-wave Velocity, Sediment Grain Size, Percent Sand, Percent Silt, and Percent Clay.

	Density				P-wave velocity, in meters per second				Grain size, in millimeters			
Core ID	mean	min	max	std	mean	min	max	std	mean	min	max	std
A1-A	1.69	1.11	2.06	0.19	1536.87	1100.00	2060.00	207.19	0.07	0.01	0.22	0.07
A1-B	1.81	1.38	2.22	0.17	1560.82	1360.00	1810.00	100.78	0.12	0.01	0.46	0.15
A2	1.60	0.19	2.09	0.28	1225.21	814.97	1443.71	113.42	0.08	0.01	0.24	0.09
A3	2.01	0.96	2.16	0.20	1672.04	1205.71	1870.83	115.98	0.24	0.15	0.37	0.08
A4	1.94	0.94	2.19	0.27	1651.46	1274.42	1862.58	103.89	0.18	0.06	0.35	0.09
A5	1.81	1.16	2.11	0.20	1378.05	896.16	1562.70	111.93	0.08	0.02	0.23	0.06
B1	1.41	0.95	1.72	0.12	1412.41	1011.61	1541.38	107.08	0.01	0.01	0.03	0.01
B2	1.92	0.91	2.19	0.20	1679.83	1179.31	1825.37	115.85	0.27	0.25	0.29	0.02
B3	1.98	1.45	2.17	0.11	1546.75	928.74	1855.96	165.08	0.12	0.02	0.19	0.05
B4	1.40	1.32	1.53	0.02	983.54	727.92	1185.94	78.47	0.06	0.02	0.14	0.04
C1	1.42	1.31	1.61	0.04	933.00	672.21	1191.29	105.85	0.03	0.01	0.06	0.02
C2	1.95	1.54	2.18	0.14	1628.81	1175.90	1860.53	130.54	0.19	0.12	0.29	0.06
C3	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	0.12	0.01	0.23	0.07
D1	1.78	1.52	2.12	0.12	1427.07	991.83	1557.71	109.23	0.05	0.02	0.18	0.04
D2	1.80	0.50	2.14	0.21	1413.72	1021.26	1552.07	123.75	0.09	0.03	0.21	0.07

	Sand (%)				Silt (%)				Clay (%)			
Core ID	mean	min	max	std	mean	min	max	std	mean	min	max	std
A1-A	51.51	5.82	95.97	33.44	39.24	3.44	74.57	26.12	9.25	0.59	20.50	7.55
A1-B	52.18	12.23	98.58	30.13	38.86	1.04	68.39	24.20	8.97	0.28	23.73	6.51
A2	46.51	0.00	99.65	43.05	42.77	0.28	80.62	33.82	10.72	0.04	22.32	9.45
A3	96.18	89.88	99.09	3.29	3.04	0.74	7.90	2.54	0.78	0.17	2.22	0.75
A4	89.22	64.91	98.76	11.68	8.52	1.04	25.82	8.74	2.10	0.20	8.74	2.98
A5	69.50	26.48	97.06	17.75	25.63	2.01	59.05	14.87	4.50	0.34	14.47	3.26
B1	11.19	3.11	27.54	8.26	70.06	60.80	79.26	5.71	18.73	11.66	25.95	4.19
B2	98.01	97.29	98.80	0.63	1.46	0.88	1.68	0.39	0.37	0.20	0.69	0.23
B3	81.41	29.80	98.63	17.41	14.27	1.00	54.91	13.97	3.40	0.37	14.85	3.71
B4	59.50	11.92	97.22	28.30	33.42	2.27	75.46	23.94	7.01	0.51	14.02	4.51
C1	32.14	0.12	69.84	31.20	56.06	26.67	80.81	23.21	11.80	3.49	25.10	8.91
C2	94.42	79.66	99.60	6.50	4.71	0.31	16.32	5.24	0.84	0.09	3.80	1.22
C3	75.52	5.69	98.45	33.67	19.30	1.19	72.94	26.56	5.13	0.29	21.37	7.23
D1	40.63	16.20	92.87	20.38	48.22	5.84	66.26	16.54	11.02	1.21	19.53	4.65
D2	61.55	34.76	95.78	25.62	32.45	3.67	54.30	21.61	6.00	0.54	10.95	4.03