



Partitioning of sediment on the shelf offshore of the Columbia River littoral cell

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ABSTRACT

Sediment derived from the Columbia River has been deposited on the continental shelf, along the barriers and beaches, and in the bays of the Oregon and Washington coast during the Holocene. The barrier and beach deposits of this 150-km section of coast comprise approximately 6 km³ of these Holocene sediments (Peterson et al., 2010–this issue) while the fluvial and bay deposits comprise about 104 km³ (Baker et al., 2010–this issue), and the shelf deposit is approximately 79 km³. Seismic-reflection, sidescan sonar, and surface sediment data show that the shelf deposit is not uniform in distribution or composition. The shelf deposit is 15–50 m thick off the beaches of the southern part of the study area but is less than 3 m thick, and, in places, absent from the inner shelf in the northern third of the study area. Surface sediment texture of the shelf deposit varies as well. Pleistocene-age gravel covers parts of the inner shelf in the northern third of the area. To the south, the surface of the Holocene shelf deposit is composed of fine sand near shore that grades offshore to dominantly very fine sand in 25–30 m water depth and muddy sand on the middle and outer shelf (>50 m depth). Although a huge volume of sediment covers the shelf, its uneven distribution indicates that in places only small amounts are available as a potential offshore source to the adjacent beaches, and in other places the finer-grained nature of the shelf deposit indicates that significant winnowing of fine sediment would be necessary to make it compositionally equivalent to sediment on adjacent beaches.

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1. Introduction

Many continental shelves are relict surfaces that have been partially reworked by coastal processes as the shoreface transgressed across the shelf during the Holocene (Curry, 1965; Emery, 1968). Understanding sediment exchange between the shelf and adjacent beaches has been difficult because of uncertainty in determining the degree to which shelf deposition results from modern marine processes or antecedent sediments that have been partially reworked (Swift, 1970; Schwab et al., 1997). The Columbia River littoral cell (CRLC) is one of the few sections of the US coast that is bounded offshore by a shelf that has accumulated a huge volume of sediment during the Holocene sea level rise (Nittrouer, 1978). The mineralogy of the beach sediment (Ballard, 1964) and shelf sediment (Gross et al., 1967) shows that the Columbia River has been the primary sediment source for both, and for this reason, this littoral cell provides an opportunity to study the linkage between a modern shelf and the adjacent accreting beach system. An integrated mapping of the surface and subsurface geology of this inner shelf area had not been available prior to this study. Here we summarize the stratigraphy and surficial geology of the continental shelf part of the CRLC using high-

resolution seismic-reflection profiles, sidescan sonar imagery, surface sediment samples, and bottom photographs.

1.1. Background

The continental shelf off northern Oregon and southern Washington is narrow, with a width of 20–30 km (Fig. 1). The surface is smooth, although incised along the seaward edge with five submarine canyons. Astoria Canyon is the largest of these canyons and indents the shelf about 20 km (Fig. 1).

Interpretation of seismic-reflection data shows that the smooth nature of the shelf surface is partially the result of the thick deposit of Holocene sediment, which covers irregularities in the pre-transgressive substrate (Nittrouer, 1978; Wolf et al., 1997; Twichell and Cross, 2001). This deposit extends northwestward diagonally across the shelf from the mouth of the Columbia River to Quinault Canyon. Seismic profiles on the middle and outer shelf show that it is as much as 50 m thick off the Columbia River, and thins to 15 m near Quinault Canyon (Nittrouer, 1978; Wolf et al., 1997). Short cores suggest that the mid-shelf mud accumulated at rates of 1–2 m/1000 yr (Nittrouer, 1978); whereas vibracores from the inner shelf suggest that recently sedimentation rates have decreased to only 20–30 cm/1000 yr (Kaminsky and Ferland, 2003). Previous geological surveys had focused on the middle and outer shelf. Consequently the shoreward extent and stratigraphy of the inner shelf part of the deposit was poorly defined due to a lack of data.

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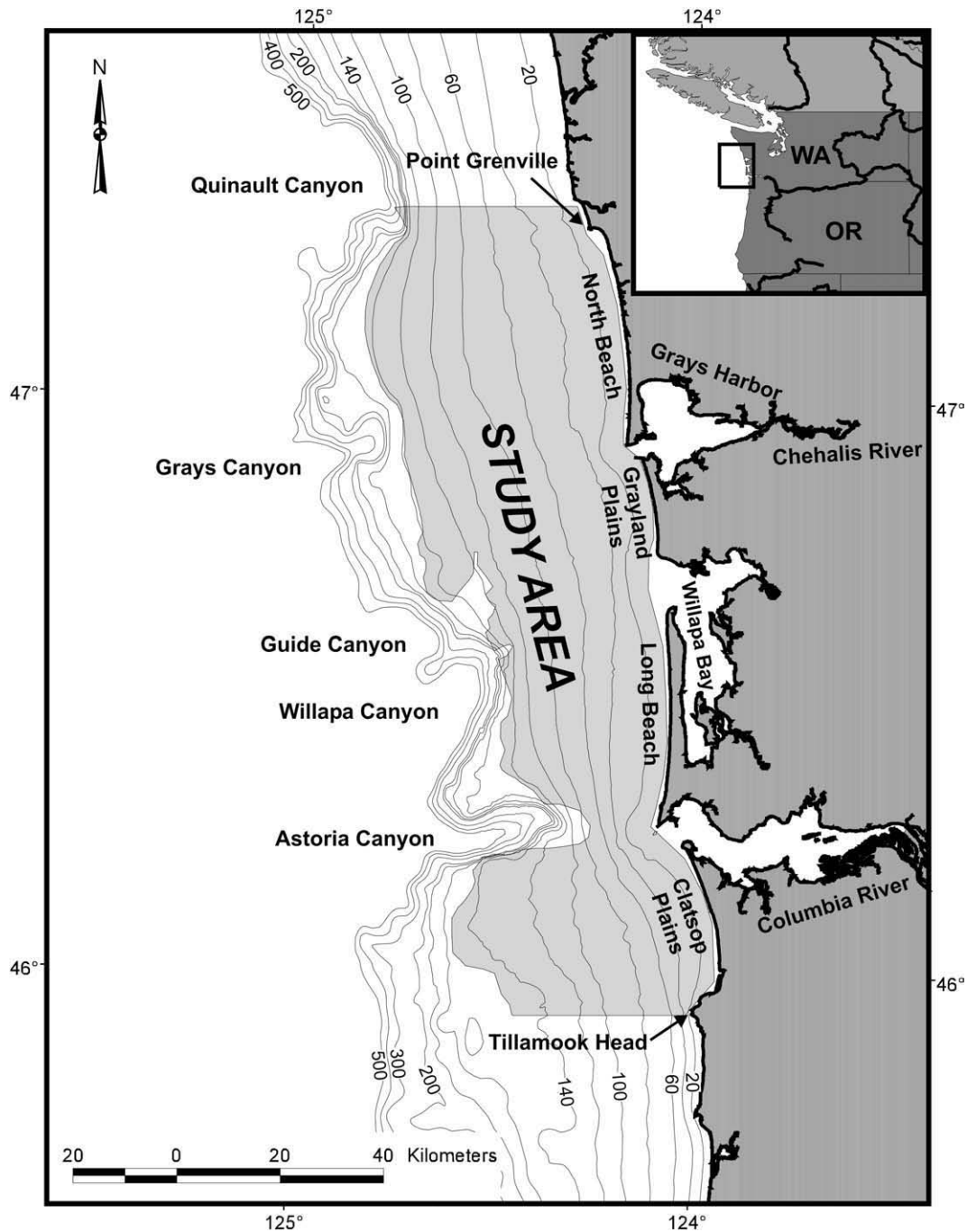


Fig. 1. Location of the study area off the northern Oregon and southern Washington coast. Bathymetric contours are in meters.

Surface sediment samples have been used to map the extent of the mid-shelf deposit (Nittrouer, 1978; Sternberg, 1986) and to identify the geology of the surrounding shelf surface. Patches of gravel of glacial origin occur along the shelf edge (Gross et al., 1967) and also on the inner shelf north of Grays Harbor (Venkatarathnam and McManus, 1973). The mid-shelf deposit is nearly an equal mix of sand and silt off the mouth of the Columbia River. The sand content decreases northwestward becoming almost absent in samples near Quinault Canyon (Nittrouer, 1978; Sternberg, 1986). The mid-shelf deposit becomes sandier towards shore. The inner shelf sediment is fine sand off Clatsop Plains and north of Grays Harbor and very fine sand from the mouth of the Columbia River north to Grays Harbor (Nittrouer, 1978; Sternberg, 1986).

Modern sediment movement on this shelf presumably is similar to sediment movement on the northern California shelf off the Eel River

or on the neighboring Oregon shelf. Instrumentation on the Eel River shelf recorded active remobilization of sediment in 60 m of water associated with periods of significant wave activity, tidal currents, and river discharge (Ogston and Sternberg, 1999; Cacchione et al., 1999). The presence of ripples in water as deep as 200 m on the Oregon shelf indicates continued reworking of this shelf surface by winter storms (Komar et al., 1972). On the Washington shelf, maximum significant wave heights reach 8 m at a buoy near Grays Harbor moored in 40 m water depth (Gelfenbaum et al., 2003). Tides, which have a range of 2–4 m, generate currents that are around 10 cm/s on the middle shelf, but stronger at inlet entrances (Sternberg, 1986). Further support for dynamic movement of sediment on this shelf comes from historical bathymetric surveys, which show changes in seabed elevation between the 1920s and the 1990s that exceed 4 m near estuary

mouths, and reach 2 m in localized areas of the inner shelf removed from inlets (Buijsman et al., 2003).

2. Methods

High-resolution seismic-reflection profiles, sidescan sonar imagery, sediment samples and bottom photographs were collected from the shelf part of the Columbia River littoral cell during 1997 and 1998 (Cross et al., 1999a,b; Twichell et al., 2000). Single-channel seismic-reflection profiles and sidescan sonar imagery were collected from the inner and middle shelf along lines spaced approximately 5 km apart (Fig. 2). A Geopulse boomer or sparker was the sound source and an ITI or Benthos hydrophone was the receiver for the seismic-reflection data. A detailed summary of the seismic systems and the digital data processing are given in Cross et al. (1999a,b) and Twichell and Cross (2001). Sidescan sonar imagery was collected simultaneously along most of the seismic lines using an EdgeTech DF-1000 sidescan sonar system. These data were logged with a Triton Elics Isis data logging system. Twichell et al. (2000) provide a detailed summary of the sidescan processing procedures.

Sediment samples were recovered from 95 locations shown in Fig. 2. Samples were collected with a VanVeen grab sampler in a frame, which also held a video camera and 35-mm Benthos still camera (Blackwood and Parolski, 2001). Bottom photographs and video were acquired at most sample stations. Differential GPS or P-Code GPS receivers were used for navigation of the seismic and sidescan sonar data and to locate sample sites, providing location precision to approximately 10 m.

In the laboratory, samples were washed to remove the salt and then were sieved using a 62.5- μm sieve to separate the silt and clay fraction from the sand and gravel fraction. The silt and clay fractions were analyzed by Coulter counter (Shideler, 1976). The sand and gravel fractions were sieved at 1/4 phi intervals, and the results were recorded as percentages by weight. Size classifications are based on the method and nomenclature proposed by Wentworth (1929) and Krumbein (1934). Laboratory procedures have been described in detail by Poppe et al. (1985).

Sediment samples collected by Roberts (1974), Nittrouer (1978), and Smith et al. (1980) compliment the samples collected during this study (Fig. 2). These samples were not processed the same way as in this study, and comparison of these historical results with our results could only be done as percentages of gravel, sand, and silt plus clay.

3. Results

Three stratigraphic units are differentiated on the seismic profiles (Figs. 3, 4), and the surficial geology shows the distribution of exposures of each of these units on the present shelf surface (Fig. 5). The oldest unit is undifferentiated Tertiary-age strata, which include Eocene-age volcanic rocks offshore of Tillamook Head (Walker and McLeod, 1991), Tertiary marine sediments that underlie much of the study area (Twichell et al., 2000; McCrory et al., 2002), and localized intrusive features off Grayland Plains and North Beach (Figs. 3B, 4B). The Tertiary strata are commonly folded, and the unconformity that separates these strata from the overlying Holocene deposit is clearly identified on the seismic profiles (Fig. 3). Broad exposures of folded Tertiary strata are present on the inner and middle shelf north of Grays Harbor, and this part of the shelf is virtually free of Holocene-age sediment (Fig. 3A).

The second unit is gravel, which is exposed in patches on the inner shelf north of Willapa Bay (Figs. 4A, 5, 6) and discontinuously along the shelf edge (Venkatarathnam and McManus, 1973). The gravel is well rounded (Fig. 6A), has a provenance from the Olympic Mountains, and is interpreted to be Pleistocene-age glacio-fluvial deposits (Gross et al., 1967; Venkatarathnam and McManus, 1973). The sidescan imagery shows that the gravel is exposed on the sea floor in discontinuous

patches off Grayland Plains and the North Beach areas (Figs. 4, 6). Some of the gravel patches are irregular in shape while others are extended in an E–W orientation (Fig. 6A). Many of them are surrounded by fine sand, have abrupt edges, and occupy the floors of shallow depressions. Multibeam bathymetry shows that these depressions have about 1 m relief (Flood et al., 1999). These patches are most common off the Grayland Plains. Grain size analyses show that the gravel is mostly 2-mm to 2-cm in diameter (Twichell et al., 2000).

An unconformity separates Holocene deposits from Tertiary and Pleistocene strata (Fig. 3). This unconformity has been drilled on land (Baker et al., 2010-this issue; Vanderburgh et al., 2010-this issue, Peterson et al., 2010-this issue), and radiocarbon dates indicate that it was cut, or at least was most recently modified, during and since the last sea level lowstand. This lowstand unconformity shows two well-developed valleys extending offshore from the Columbia River and Grays Harbor (Figs. 6B, 7A, 8C). The paleo-Columbia River valley extends to the head of Astoria Canyon. The smaller Chehalis River valley, due to limited seismic coverage, can only be traced from the mouth of Grays Harbor to the middle shelf. No valley is present off Willapa Bay either because the valley was so small it was not preserved or because it drained northward into the Chehalis River system shoreward of the shelf survey lines. The lowstand unconformity away from the two valleys is overprinted by a younger unconformity. This surface has a smooth seaward gradient under the shelf, but shows a shallow embayment underlying the present middle shelf south of the mouth to Willapa Bay (Fig. 7A).

The deposit overlying this lowstand unconformity is Holocene in age. Seismic profiles and wells (Peterson and Phipps, 1992; Baker et al., 2010-this issue) show that it can be broken into two units: (1) fluvial and bay deposits that fill paleo-river valleys and (2) an overlying shelf deposit with a much broader aerial extent (Fig. 7C). The sandy nature of these deposits probably explains why the fill is acoustically featureless on most of the seismic profiles (Figs. 6B, 8C). The fluvial and bay deposits exceed 50 m in thickness under the inner shelf in the paleo-Columbia River valley and 40 m in the paleo-Chehalis River valley. The total volume of fluvial and bay sediment in Willapa Bay and Grays Harbor and their offshore extensions is approximately 25 km³ (Peterson and Phipps, 1992; Twichell and Cross, 2001). The volume of Holocene sediment contained in the Columbia River basin exceeds 79 km³ (Baker et al., 2010-this issue), and because of the narrow shelf, only 6 km³ of this deposit lies offshore of the present shoreline. The total volume of fluvial and bay sediment is approximately 104 km³.

The second Holocene unit, the shelf deposit, overlies the fluvial and bay deposits. The two units are separated by an unconformity that was cut during the Holocene marine transgression (Fig. 7B). The marine transgressive unconformity and the lowstand unconformity are separate surfaces only in the paleo-river valleys, while on the interfluvial the two unconformities merge (Fig. 8C). The flatness of the marine transgressive unconformity where it cuts the fluvial and bay deposits indicates that these valleys were filled with sediment before the shoreface crossed them (Figs. 7B, 8C). The shelf deposit is of greater lateral extent than the fluvial and bay deposits. Where it is not underlain by fluvial and bay deposits it overlies Pleistocene or Tertiary strata (Figs. 3, 4).

The Holocene shelf deposit is as much as 50 m thick on the middle shelf off the mouth of the Columbia River, and has a thick axis that trends northwestward diagonally across the middle and outer shelf (Fig. 7C). This deposit pinches out along its offshore side near the shelf edge. Its southern limit is somewhat south of Tillamook Head, while it extends northward past the limit of the study area to Quinalt Canyon (Nittrouer, 1978; Sternberg, 1986; Wolf et al., 1997). On the innermost shelf the sediment above the marine transgressive unconformity is 20–30 m thick off Clatsop Plains and Long Beach (Fig. 3C, E). This deposit thins abruptly north of the mouth of Willapa Bay, where the underlying Tertiary strata shoal abruptly to within 2–

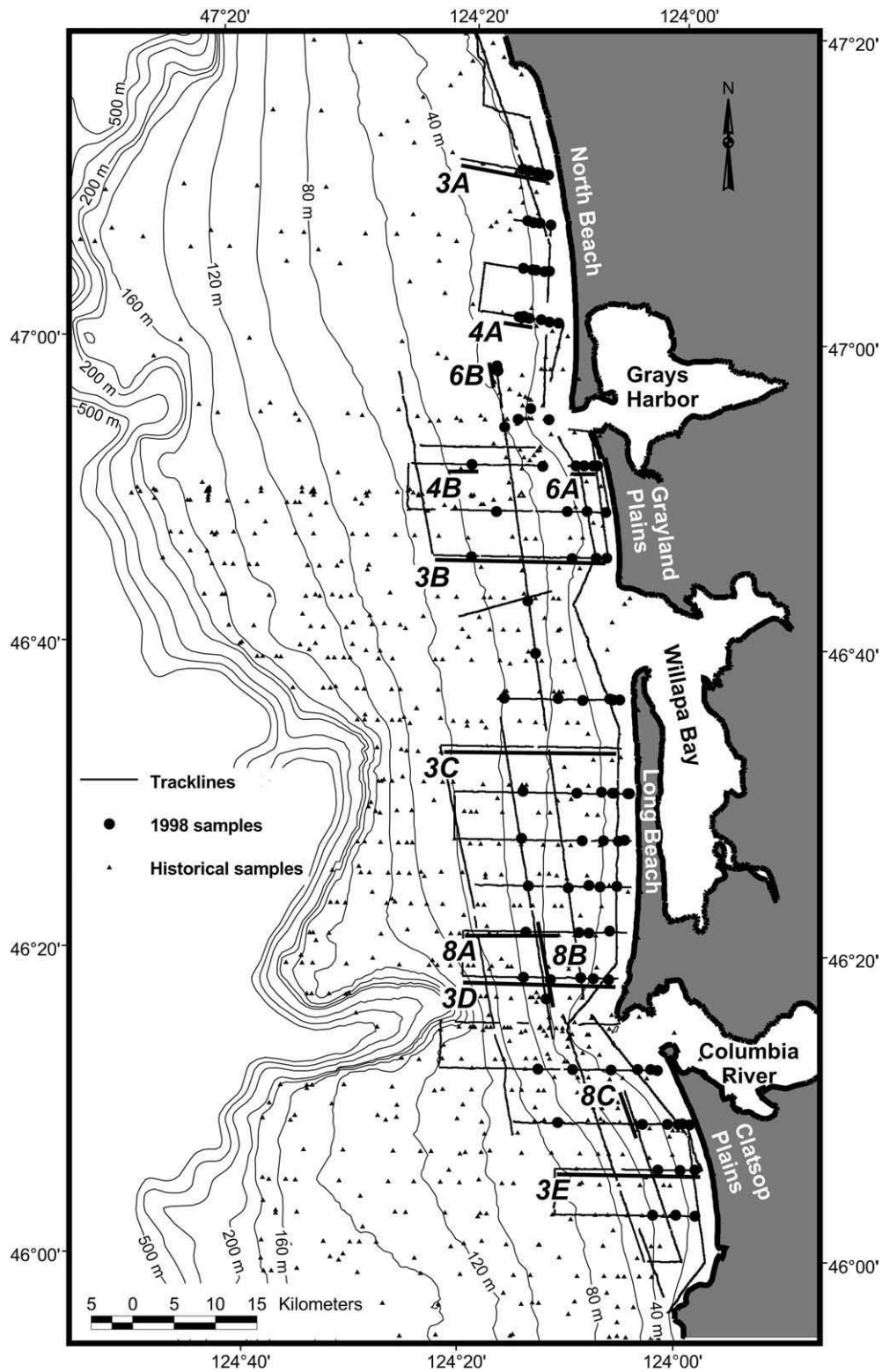


Fig. 2. Summary of the data used for this study. High-resolution seismic data were collected along all the track lines, and sidescan sonar imagery along most of the same lines. Sediment samples and/or bottom photographs were collected at the 1998 sample sites on the inner and middle shelf. Historical samples complemented new samples (Roberts, 1974; Nittrouer, 1978; Smith et al., 1980). Heavy, numbered line segments show locations of other figures. Bathymetric contours are in meters.

5 m of the seafloor (Figs. 3B, 7C). North of Grays Harbor this deposit is absent except on the very innermost part of the shelf (Fig. 3A). This area, as was first inferred by Gross et al. (1967) based on sediment samples, is a relict shelf surface. Drill holes on the barriers shoreward of many of the seismic profiles penetrated barrier and shelf sands that overlie a gravel lag which commonly rests on Pleistocene or Tertiary

strata (Herb, 2000; Vanderburgh et al., 2010-this issue). The base of the Holocene deposit in the boreholes is at a depth comparable with the onshore projection of the marine transgressive unconformity seen in the seismic data (Vanderburgh et al., 2010-this issue).

The part of the shelf deposit within the study area outlined in Fig. 1 contains approximately 79 km³ of sediment. The shelf deposit appears

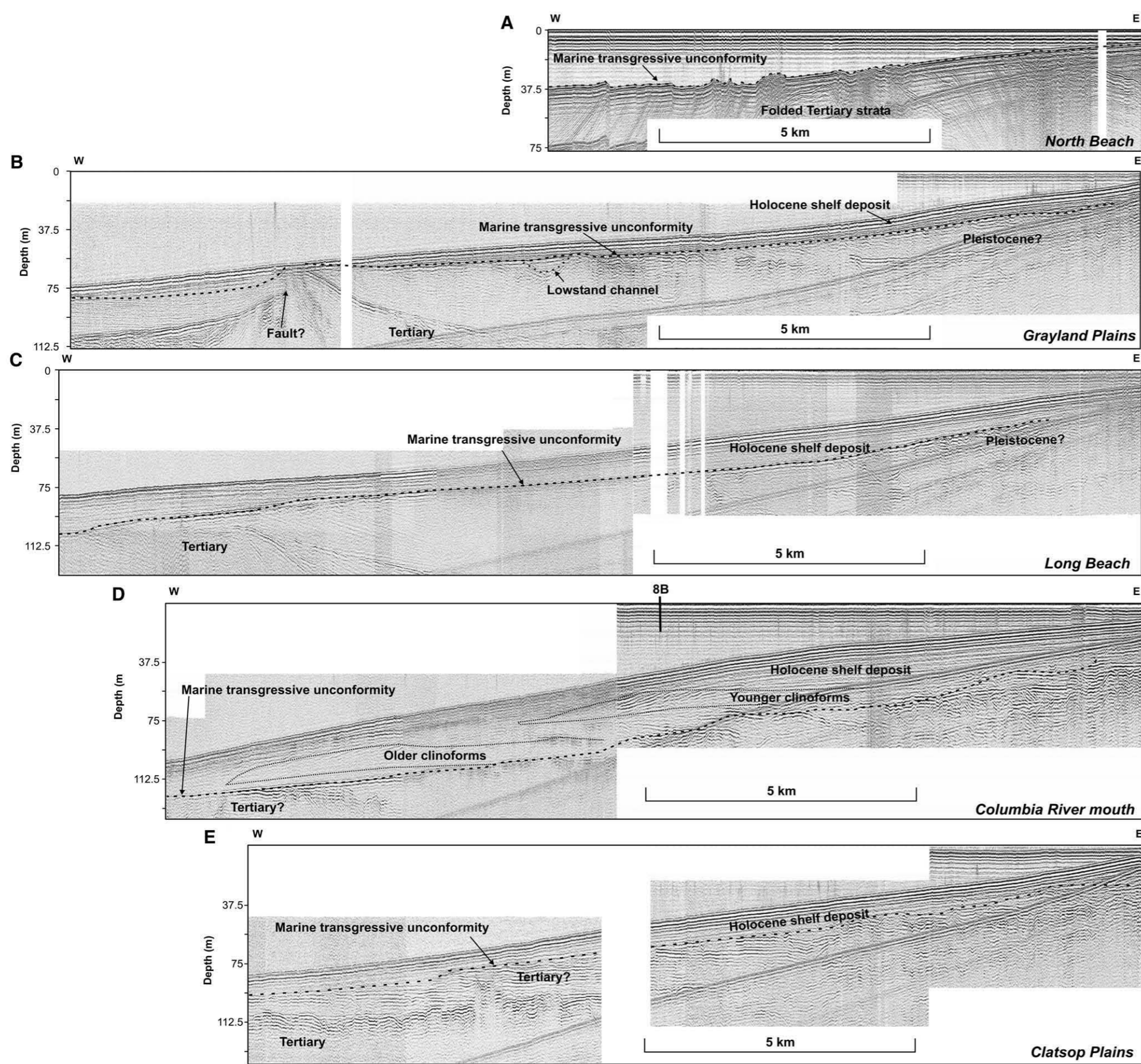


Fig. 3. Seismic profiles (Uniboom) across the inner and middle shelf showing variations in the shelf stratigraphy along the length of the CRLC. (A) Folded Tertiary strata outcrop on the seafloor off North Beach, (B) a thin Holocene shelf deposit covers Tertiary and Pleistocene strata off Grayland Plains, (C) a thicker Holocene shelf deposit buries Tertiary and Pleistocene strata off Long Beach, (D) the Holocene shelf deposit is thickest immediately north of the mouth of the Columbia River with the acoustic uniformity of this deposit interrupted by two intervals containing clineforms, and (E) a thinner Holocene shelf deposit off Clatsop Plains. Profile locations shown in Fig. 2.

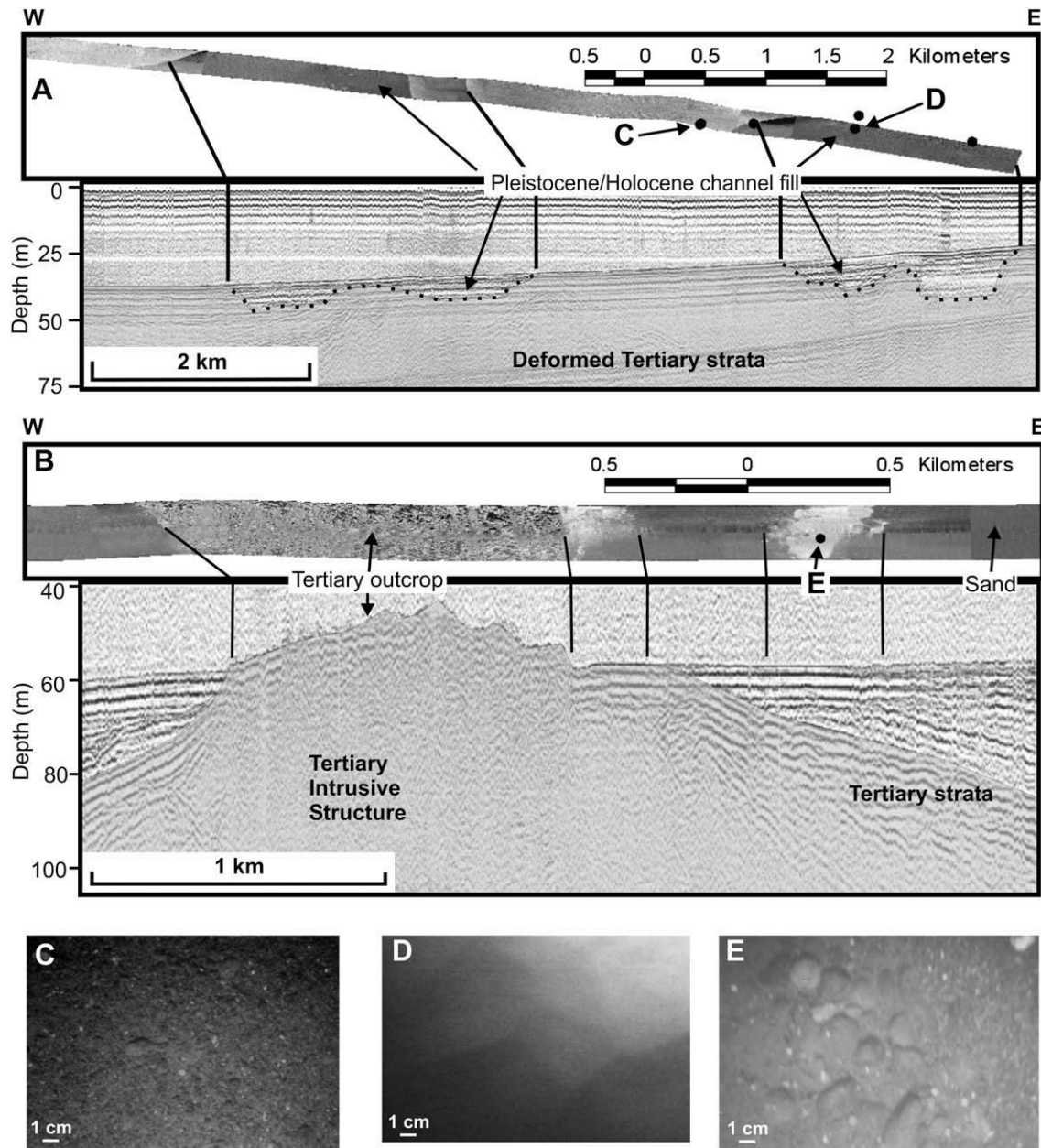


Fig. 4. Sidescan sonar image (top panel) and seismic profile (bottom panel) along the same line showing that (A) areas of high backscatter on the sidescan image off North Beach coincide with areas where Pleistocene glacial gravel is exposed on the sea floor, and areas of low backscatter are areas where finer-grained Holocene sands cover the sea floor; and (B) the two data types on a line over a Tertiary intrusive structure offshore of Grayland Plains. The locations of the photos C, D, and E are shown on the sidescan images. Profile locations shown in Fig. 2.

to extend under some of the barrier beaches (Peterson et al., 2010-this issue), but its volume is small. The total volume of sediment that has accumulated above the marine transgressive surface, which includes both the shelf and barrier deposits, is 87 km³. Thus, the amount contained in the barriers and under the very innermost shelf (shoreward of the area outlined in Fig. 1) is only about 6 km³.

Although much of the shelf deposit is acoustically uniform, two intervals containing clinoforms interrupt the acoustically transparent nature of the deposit around the mouth of the Columbia River (Figs. 3D, 7C, 8B). The deeper of the two sets of clinoforms is as much as 18 m thick, 12 km wide, and extends northward from the paleo-Columbia River approximately 21 km (Fig. 7A, C). The northern part of this clinoform unit rests directly on the marine transgressive unconformity, and the acoustically uniform shelf deposit underlies the southern part (Figs. 3D, 8A). The beds within this deposit dip offshore (Figs. 3D, 8A) except near its southern end where one profile

shows an apparent southward dip (Fig. 8B). The tops of the clinoforms are truncated indicating some erosion subsequent to their formation (Fig. 8A). The depth where the shoreward side of this clinoform deposit pinches out against the marine transgressive unconformity is 65–70 m. The second interval containing clinoforms forms an arcuate band around the mouth of the Columbia River (Fig. 7C). This deposit is less than 12 m thick, and its arcuate shape suggests it is an older ebb-tidal delta of the Columbia River that is broader in extent than the present delta. The top of this interval occurs in 42–55-m water.

The remainder of the shelf deposit is acoustically uniform (Fig. 3B, C, and E). Although high-resolution seismic profiles collected by Nittrouer (1978) on the outer shelf did show a shallow reflector that was interpreted to represent the base of the modern mid-shelf mud belt, this horizon was not identified on the profiles collected during this study. The reasons for its absence may be because it could not be

resolved by the lower frequency seismic system used in this study, or that Nittrouer (1978) identified this reflector on profiles north of our study area in a part of this shelf deposit where the sediment is finer.

The surface sediment texture, like the Holocene sediment thickness, is not uniform across the study area. Instead, the deposit fines with increasing water depth except around inlet mouths (Fig. 5). Fine sand comprises more than 80% of samples in water depths less than 15 m, 30–40% in water depths of 20–35 m, and less than 20% in most samples deeper than 40 m (Fig. 9). The very fine sand and silt plus clay fractions both show the inverse trend, being low near shore and increasing offshore. Medium sand and coarser material is less

than 10% of all shelf samples within the bounds of the Holocene shelf deposit south of Grays Harbor, except for one sample on the innermost shelf off Long Beach and five samples off the mouth of the Columbia River. In the northern part of the study area, where the seismic data show Holocene sediment to be absent, the surface sediment is coarser. Medium sand and coarser material is found at all water depths off North Beach rather than being limited only to the innermost 20 m on the shelf as is the case south of Grays Harbor (Fig. 9).

The trend of offshore fining of surface sediment is interrupted off the mouth of the Columbia River. Here samples show that the surface

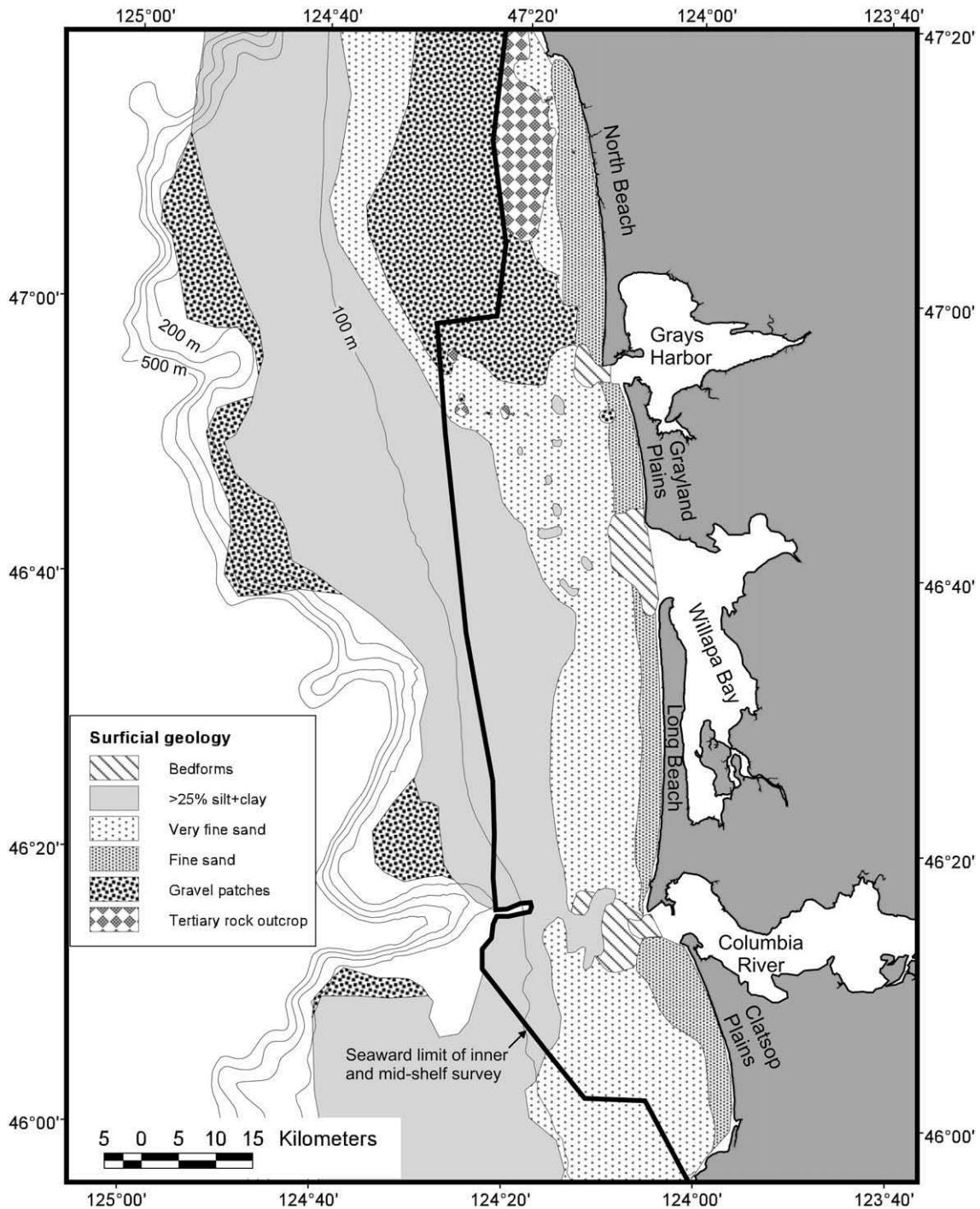


Fig. 5. Surficial geology of the continental shelf offshore of the Columbia River littoral cell. The heavy black line outlines the part based on data collected for this study. Surficial geology of the outer shelf is based on historical surface sediment samples (Roberts, 1974; Nittrouer, 1978).

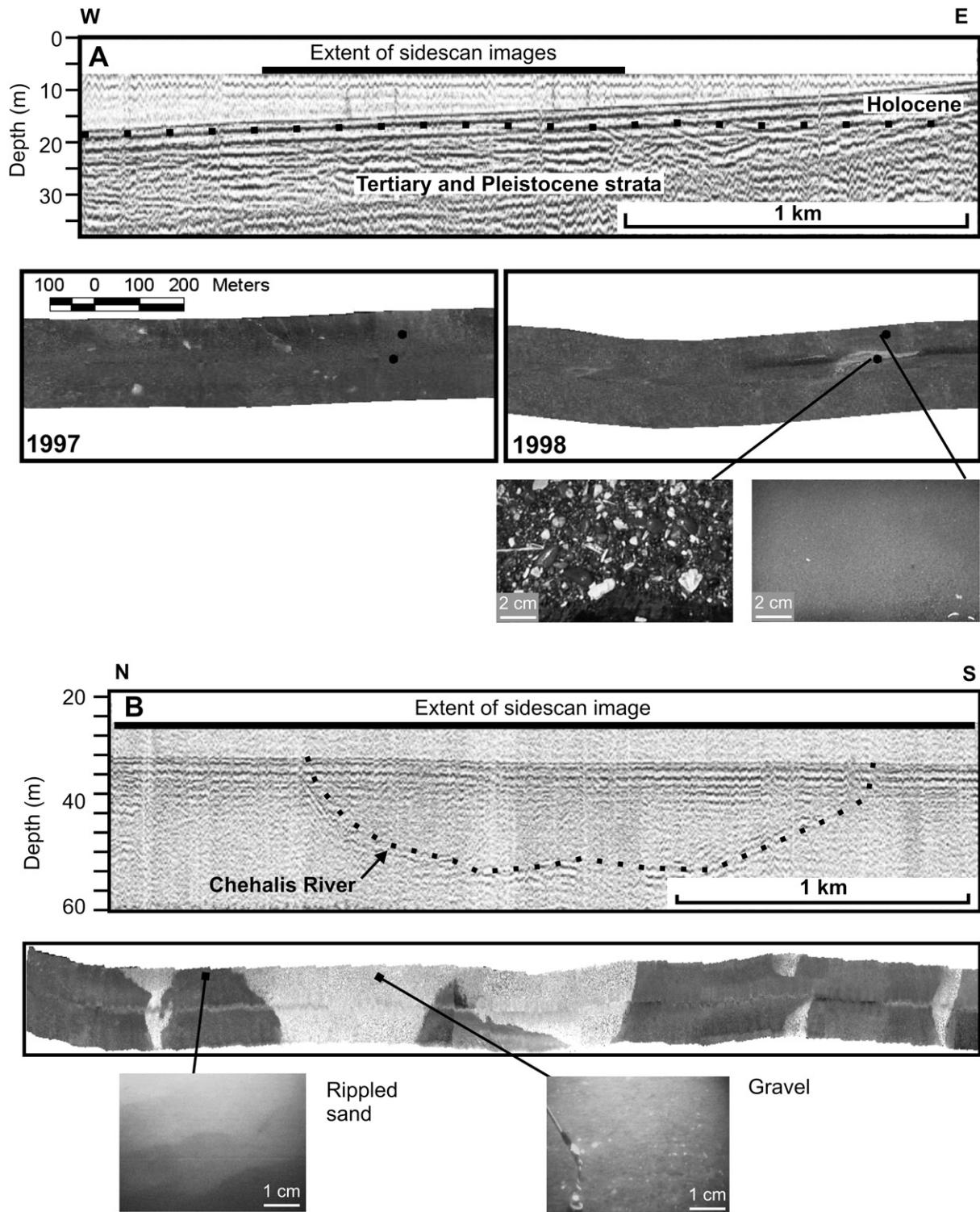


Fig. 6. Seismic profile, sidescan sonar image, and bottom photographs of two areas where Pleistocene glacial gravel is partially exposed on the sea floor. (A) a seismic profile off Grayland Plains shows thin Holocene cover, and sidescan image collected in 1998 shows a patch where the underlying gravel is exposed that was covered in 1997. The 1998 sediment sample locations are included on the 1997 image for correlation purposes. (B) gravel patches surrounding and covering the paleo-Chehalis River valley. Photographs show direct observations of the different sediment types. Profile locations shown in Fig. 2.

sediment is slightly coarser than to the north or south, and the sidescan imagery shows alternating bands of high and low backscatter radiating away from the inlet mouth. Megaripples are seen near the mouths of all three inlets, but the sediment off Willapa Bay and Grays Harbor was not found to be coarser than the surrounding shelf, and the sand ribbon-like features were not observed off the northern two inlets (Twichell et al., 2000).

4. Discussion

The barriers and beaches of the CRLC have accreted during the last 1000–5000 years, and the growth of these beaches has been attributed to the large sediment contribution of the Columbia River during the latest Holocene (Woxell, 1998; Peterson et al., 1999, 2010-this issue). In addition to supplying sediment to these actively

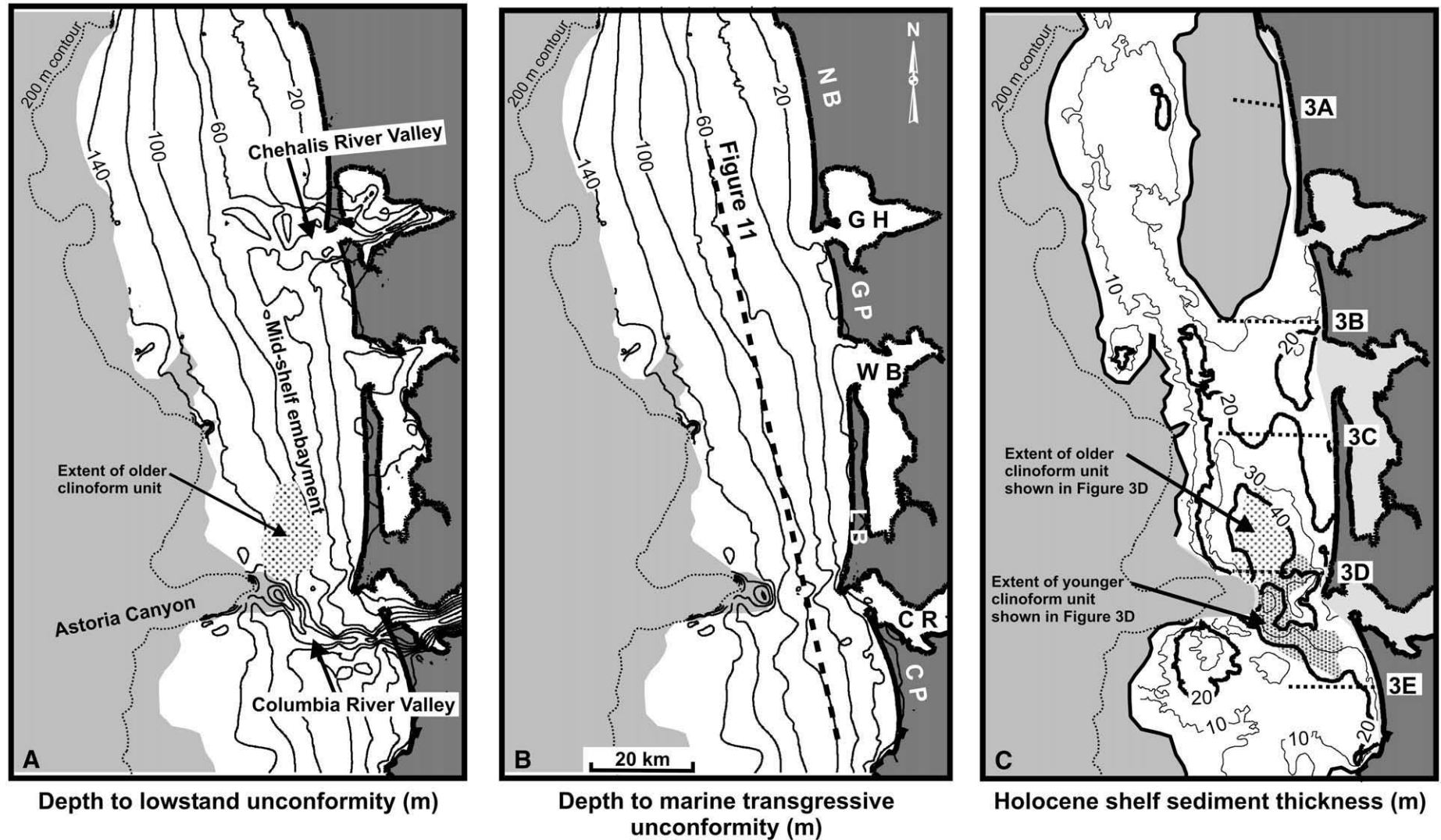


Fig. 7. Summary maps derived from the seismic data showing (A) depth to the lowstand unconformity, (B) depth to the marine transgressive unconformity, and (C) thickness of the Holocene shelf deposit that rests on the marine transgressive unconformity. The location of the older clinoform interval at an abrupt bend in the paleo-Columbia River is shown in (A), and the extent of both clinoform intervals is shown in (C). Location of Fig. 11 shown in (B). Abbreviations refer to the following locations: North Beach (NB), Grays Harbor (GH), Grayland Plains (GP), Willapa Bay (WB), Long Beach (LB), Columbia River (CR), and Clatsop Plains (CP).

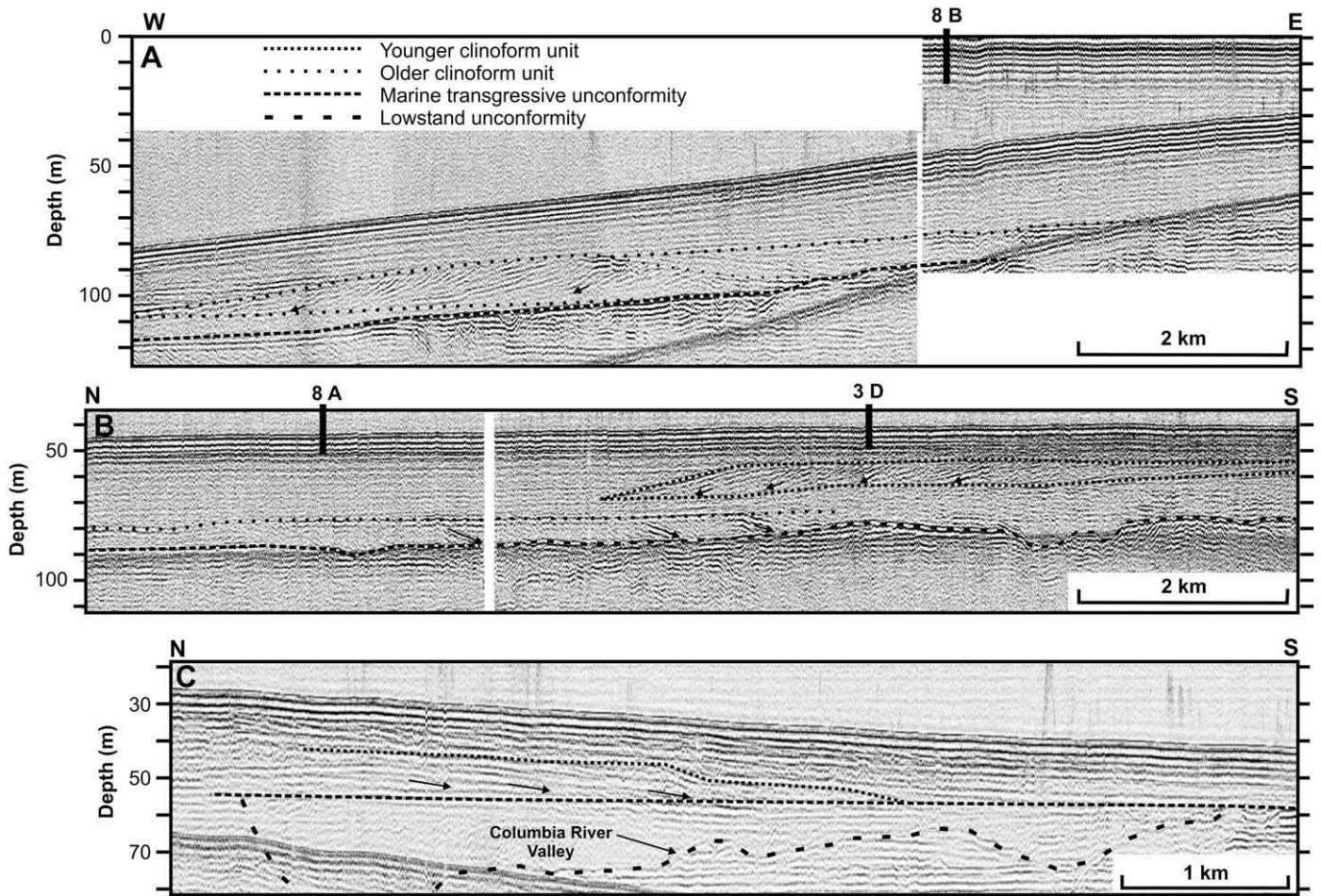


Fig. 8. Seismic profiles off the mouth of the Columbia River showing the two clinoform intervals and the paleo-Columbia River valley. Note the surface of the older set of clinoforms is truncated (A), and that these internal reflections dip southward (B). In the offshore area, the younger set of clinoforms was deposited on top of acoustically transparent shelf deposits (B) while farther shoreward and to the south it rests directly on the marine transgressive surface (C). Profile locations shown in Fig. 2.

accreting barriers, the river also supplied a huge volume of sediment to the adjacent continental shelf (Figs. 7C, 10). It has been unclear whether beach accretion took place by along-shore transport of Columbia River input or by onshore transport from the shelf (Peterson et al., 2010-this issue). Here, we discuss the effect of pre-existing stratigraphy and the long-term response of the shelf to the processes recorded in the present surface and shallow subsurface sediments of the inner and middle shelf off the CRLC. The discussion will focus on four points: (1) the stratigraphy of the Holocene deposits suggest sediment accumulation on the shelf has not been constant through the Holocene, (2) Holocene sediments are not uniformly distributed along the length of the CRLC, (3) the modern shelf deposit continues to be actively reworked by modern processes, and (4) much of the shelf surface is finer-grained than the adjacent beaches and therefore would appear to be a sink to, or only a minor source of beach sand.

A variety of terms are in use that describe the transition between the beach and the shelf, and for clarification we define our terminology here. The shoreward extent of the study area is on the lower shoreface, and the study area extends across the inner shelf to the middle and outer shelf, which we lump together. We base the transitions between these three zones on facies changes. The boundaries are gradational, and we have arbitrarily defined them such that the lower shoreface coincides with areas having mean grain size of surface samples coarser than fine sand (125 μm). The inner shelf occupies the area where the mean grain size is finer than 125 μm but the mud content is less than 25%. The middle and outer shelf is where the mud content exceeds 25%. By these definitions, the

transition from lower shoreface to shelf normally is in 15–25 m water depths, and the transition from inner to middle shelf is in approximately 55-m water depth.

4.1. Evidence for varied sedimentation rates through the Holocene

The seismic-reflection profiles show that the Holocene deposit on the shelf can be broken into two parts, which are separated by the marine transgressive unconformity (Fig. 11). Below this unconformity are fluvial and bay sediment filling the paleo-river valleys of the Columbia and Chehalis Rivers (Peterson and Phipps, 1992; Baker et al., 2010-this issue). The Columbia River is the deeper of the two valleys and sediment started accumulating at the borehole site about 16,000 yr BP (Baker et al., 2010-this issue). Boreholes into the Chehalis and Columbia River valleys recovered only fluvial and shallow estuarine deposits, which indicate that sedimentation in these valleys kept pace with the Holocene rise in sea level, even during the early Holocene when sea level rose rapidly (Peterson and Phipps, 1992; Baker et al., 2010-this issue).

Within the modern shelf deposit, which overlies the marine transgressive unconformity, sediment accumulation rates decreased through time. Nittrouer (1978) estimated average sedimentation rates of 1–2 m/1000 years based on ^{210}Pb measurements. ^{14}C dates from vibracores suggest that recent sediment accumulation rates are only 10–70 cm/1000 years (Kaminsky and Ferland, 2003). In both cases, the amount of sediment on the shelf at the sample sites exceeds

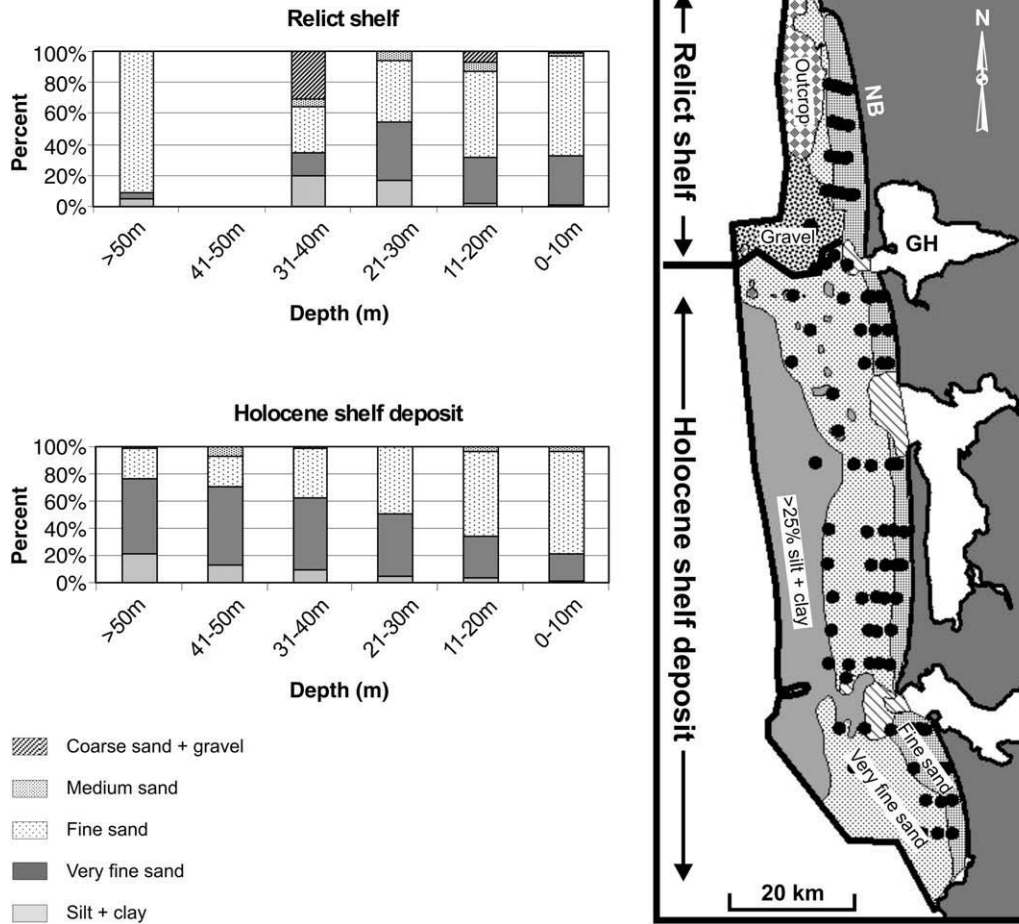


Fig. 9. Map showing the surficial geology from Fig. 5, and the distribution of relict and Holocene shelf surfaces. Graphs show variations in the grain size, based on averages for all samples within each depth interval, for both the modern and relict parts of the shelf. Map abbreviations refer to North Beach (NB) and Grays Harbor (GH).

what would have been deposited if these were average accumulation rates throughout the Holocene.

Much of the shelf deposit is acoustically uniform, but the two intervals containing clinoforms off the mouth of the Columbia River suggest pulses of rapid sediment input during the early phase of deposition. The older interval of clinoforms, whose top is as shallow as 65–70 m, occupies part of an embayment on the middle shelf north of a point where the paleo-Columbia River makes abrupt turns first to the north and then back to the west (Fig. 7A). The regional sea level curve compiled by Peterson and Phipps (1992) and modified by Baker et al. (2010-this issue) shows that the sea level was 70 m lower than the present 11,500 years BP. This age coincides with the final stages of the Missoula floods in the Columbia River Basin (Mullineaux et al., 1978; Waitt, 1985), and the deeper clinoforms may have been deposited during these floods. Baker et al. (2010-this issue) attribute the lower 45 m of the borehole drilled at the mouth of the Columbia River to deposition from these floods. Drilling in the Escanaba Trough, 800 km from the present mouth of the Columbia River recovered Missoula flood deposits as well (Brunner et al., 1999). Thus we suggest that the deeper clinoform unit is the shelf record of these floods. The origin of this deposit could be similar to sediment lobes on the outer shelf off the Hudson River that are attributed to the catastrophic drainage of glacial lakes (Uchupi et al., 2001). Alternatively, it could represent a barrier beach similar to those preserved on the Australian shelf that resulted from reworking of flood deposits by coastal processes (Roy et al., 1994).

The arcuate shape of the shallower interval of clinoforms suggests it is an ebb-tidal delta. The top of this deposit is in about 50 m of water

and may be associated with the period of greatest sediment accumulation at the Warrenton site 9000 BP (Baker et al., 2010-this issue). Regardless of the origin of these clinoforms, their formation when sea level was rising rapidly suggests periods of rapid sediment input. The eroded surface of the deeper of these deposits suggests sediment input diminished abruptly allowing erosion by marine processes to have removed part of its surface (Fig. 8A).

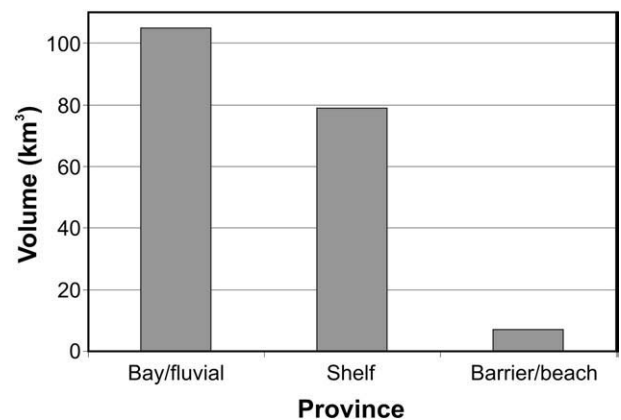


Fig. 10. The volume of sediment contained in each of the three provinces. The volume of fluvial and bay deposits is the sum of Columbia River fill reported by Baker et al. (2010-this issue) and the amount in other bays and underlying the shelf (Twichell and Cross, 2001).

The time lines in the modern shelf deposit on Fig. 11 draw on the inferred ages of the clinoforms as well as age dates from vibracores collected by Kaminsky and Ferland (2003) and Phillips and Dunhill (1999). Sedimentation rates during the last 4000 years are lower than earlier in the Holocene (Kaminsky and Ferland, 2003). Continued high sedimentation rates on the middle shelf are limited to the area off the mouth of the Columbia River (Fig. 11). Although the Missoula floods were spectacular, the volume deposited on the shelf was modest in comparison to the total shelf volume. At this time large volumes of sediment bypassed the shelf and were deposited in the deep sea (Brunner et al., 1999) probably due to limited accommodation space on the shelf. Prior to 4000 yr BP, shelf sedimentation appears to have been highest during the middle part of the Holocene; whether it is tied to the period of increased sediment accumulation rates in the lower Columbia River estuary or a period of increased sediment bypass through the lower estuary (Baker et al., 2010-this issue) will await a drill hole on the shelf.

4.2. Varied Holocene sediment distribution on the shelf-structural control and sediment supply

The surficial geology of the shelf varies along the length of the CRLC. North of Grays Harbor much of the inner and middle shelf is a relict surface where Tertiary and Pleistocene strata are still exposed on the sea floor (Fig. 9). Off Grayland Plains, the modern shelf deposit is thin and patchy (Figs. 5, 7C), and then abruptly thickens south of the mouth of Willapa Bay (Fig. 11). Boreholes show that the barriers shoreward of the relict shelf are only 1–11 m thick while those shoreward of the modern shelf deposit are 20–36 m thick (Herb, 2000; Vanderburgh et al., 2010-this issue).

The distribution and thickness of the shelf deposit is partially controlled by the original geometry of the surface upon which it was deposited. Figs. 7B and 11 show that the surface underlying the shelf deposit shoals abruptly just north of the entrance to Willapa Bay. The abrupt shoaling may mark the offshore transition between two crustal blocks that have been identified on land (McCroly, 1996; McCroly

et al., 2002), and would indicate that antecedent structures partially control the location of the depocenter for the Holocene shelf deposit. South of the mouth of Willapa Bay there was more accommodation space to be filled, particularly on the middle shelf, before deposition on the shelf could spread farther north.

Although the accommodation space determined by earlier structures on the shelf partially explains the location of the Holocene depocenter, the thickest part of the deposit is off the mouth of the Columbia River (Fig. 7C). The increased thickness here is not due to a depression in the original surface, but instead is due to a mounding of the deposit at this location (Fig. 11). The mounding of the surface of the deposit indicates that sediment dispersal processes from the Columbia River source also control its geometry.

4.3. Modern processes actively rework shelf surface sediment at all depths

The surface of much of the modern shelf deposit is uniform and featureless on the sidescan sonar images (Twichell et al., 2000); yet other evidence indicates that much of shelf's surface continues to be actively reworked by modern marine processes. Certainly, results from the STRATAFORM program on the Eel River shelf indicate active reworking of a similar modern shelf deposit (Cacchione et al., 1999; Ogston and Sternberg, 1999). The presence of ripples in 55-m water depth in the summer (Twichell et al., 2000), documentation of ripples at all depths on the Oregon shelf during the winter (Komar et al., 1972), and measurable bathymetric changes between surveys in the 1920s and 1990s (Buijsman et al., 2003) all support the continued reworking of this shelf surface. Off Grayland Plains, where the Holocene shelf deposit is thin, there is further evidence of ongoing reworking of the shelf deposit. Here, a patch of gravel was exposed between the two sidescan surveys conducted in 1997 and 1998 (Fig. 6A). The origin of this linear gravel patch appears similar to rippled-scour depressions observed on other shelves (Cacchione et al., 1984; Schwab et al., 1997). Similar depressions may have formed farther south where the shelf deposit is thick, but because of the lack of textural variability they

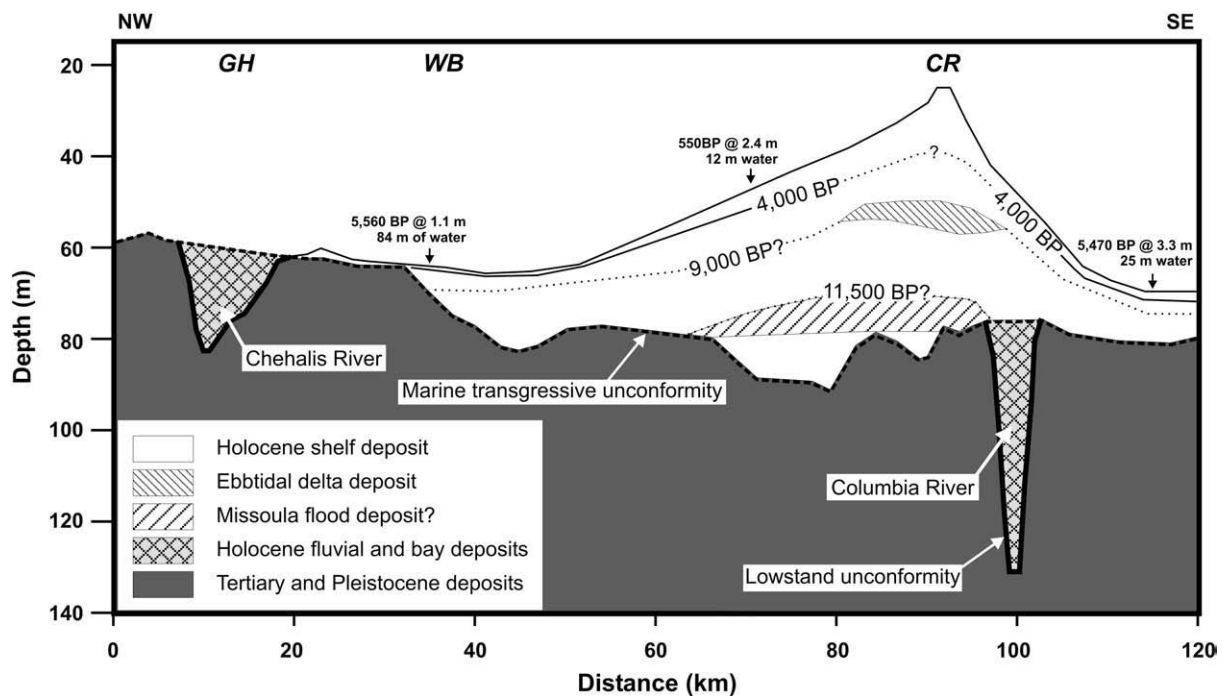


Fig. 11. Shore parallel profile extending along the CRLC summarizing the stratigraphy of the shelf (location shown in Fig. 7B). The profile extends from the relict shelf surface off North Beach nearly to Tillamook Head. The locations of the three inlets are shown at the top of the figure; Grays Harbor (GH), Willapa Bay (WB), and the Columbia River (CR). Note the abrupt shoaling of the pre-Holocene strata north of the mouth of Willapa Bay. Time lines are inferred from results summarized in the text.

were not apparent. Because these depressions are preserved only where the Holocene cover is less than 1–2 m thick, variable sediment types appear to be necessary for the formation or preservation of these features. These gravel floored depressions may be a valuable marker of relict shelf surfaces in other modern shelf environments as well as in the stratigraphic record.

4.4. Offshore fining of surface sediment is inconsistent with present shelf being a source for beach sand

The redistribution of the Holocene shelf deposit is dynamic and ongoing, but the long-term result has been a net offshore fining of the surface sediment (Fig. 9). Whether the inner shelf is a source or sink for beach sediment had been unclear; however the fine-grained nature of inner shelf samples suggests that this area is not a major source of beach sand. Sediment samples collected on the beach show the median grain size to be 125–225 μm along the entire length of this littoral cell except for some gravel on the beaches of Grayland Plains and North Beach (Ruggiero et al., 1999; Ruggiero and Voigt, 2000). By contrast, the median grain size of shelf sediment in water less than 10 m ranges from 177 to 210 μm , while samples in water depths greater than 25 m all are finer than 125 μm (Twichell et al., 2000). Fig. 9 shows changes in partitioning of sediment by size ranges across the shelf. The fraction of sediment that is fine sand and coarser material (coarser than 125 μm) comprises most of the beach material (Ruggiero and Voigt, 2000). This size range comprises 79% of samples collected from water depths less than 10 m. This coarse fraction decreases to 45% in water depths of 21–30 m and is only 22% of samples in 51–60 m depths. If the shelf were a major source of sediment for the beaches, a substantial volume of very fine sand and mud would have to be winnowed from the shelf to provide sediment of the proper composition to the beaches.

5. Summary

A huge volume of Holocene-age sediment is stored on the shelf compared to the barriers (Fig. 10). The evolution of the shelf deposit suggests slow accumulation during the early Holocene due to limited accommodation space, rapid accumulation during the middle Holocene and slower accumulation during the latest Holocene (Fig. 11). This speculation is supported both by the drill hole at the mouth of the Columbia River (Baker et al., 2010–this issue) and vibracores collected on the shelf (Kaminsky and Ferland, 2003). The shelf stratigraphy suggests large volumes of sediment were introduced to the system during very short events. Modern processes actively rework the present shelf surface, and surface sediment becomes progressively finer offshore. Only the lower shoreface is texturally similar to the subaerial beach, so only a small part of this large shelf deposit could serve as a supply of sand for the beaches.

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