V6_19_16revised

Accommodation Space Controls On Incised-Valley Sediment Accumulation Rates
During The Holocene Marine Transgression (0–11 ka) In Grays Harbor, A Large
Meso-tidal Estuary, Washington, USA.

Curt D. Peterson, Portland State University, 1825 SW Broadway, Portland, OR 97201
<curt.d.peterson@gmail.com>

James B. Phipps, Grays Harbor College, 1620 Edward P Smith Drive, Aberdeen, WA
98520 <jbhipps@outlook.com >

ABSTRACT

Holocene deposits (0–11 ka) that were drill cored (275 samples from 17 sites) in
the meso-tidal Grays Harbor estuary were analyzed for 1) sediment texture and
source components and 2) calibrated radiocarbon age. These data were used with
basin 10 m-contour interval volumes to establish relations between rates of
increasing basin accommodation space and sediment volume accumulation. Rates of
increasing accommodation space ($0.3\text{--}2.1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) are based interval volumes
and a sea level curve (0–11.5 ka) for the Grays Harbor basin. Total sediment
accumulation rates ($0.41\text{--}1.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) are computed for the same 10 m-depth
intervals (0–60 m depth MSL) and corresponding 10 m-interval sedimentation

26 durations ($0.7-5.0 \times 10^3$ ka) from a sediment level curve. The rates of basin
27 increasing accommodation space and total sediment accumulation are positively
28 correlated ($R^2=0.81$), but sediment accumulation lagged behind increasing
29 accommodation space (23–37 %) during early- and middle-Holocene time (7–10 ka).
30 Slowing rates of sea level rise after 8 ka, permitted combined river and littoral
31 inputs of sediment to reduce basin subtidal water depths (~ 10 m) to intertidal
32 water depths (~ 1 m). The ratios between sand and mud components in the analyzed
33 Holocene deposits are negatively correlated to basin water depth. Shallowing tidal
34 flats promoted the export of river mud out of the estuary and the import of littoral
35 sand into the central estuary areas. Variable rates of increasing basin
36 accommodation space 1) directly controlled the total sediment accumulation rate in
37 the evolving basin and 2) indirectly controlled the relative proportions of mud and
38 littoral sand accumulation, due to changing water depths in the basin. The late-
39 Holocene accumulation of littoral sand (52 % of total sediment volume) is used to
40 compute the net littoral sand sink ($\sim 100 \times 10^6 \text{ m}^3$) in the Grays Harbor basin from a
41 potential 1.0 m rise of future sea level following predicted global warming. The
42 contribution of littoral sand from adjacent barrier sand spits (20 km in length) to fill
43 the increasing accommodation space in the Grays Harbor estuary could result in 0.5-
44 1.0 km of shoreline retreat following a 1.0 m rise in sea level.

46 **1 INTRODUCTION**

Coastal geomorphologists have long recognized the importance of sediment supply, hydrodynamics, and basin bathymetry in controlling the geomorphic development of incised valley estuaries (Dalrymple et al., 1992; Dalrymple, 1994). Geomorphic-stratigraphers have added changing basin accommodation space to the list of geomorphic processes. Accommodation space changes when incised valleys undergo submergence from sea level rise or emergence from net deposition or marine regression (Peterson and Scheidegger, 1984; Dalrymple et al., 1994; Zaitlin et al., 1994; Heap and Nichol, 1997). Though accommodation space is now widely used as a conceptual model in coastal sequence stratigraphic interpretations (Catauneanu, 2007), it has not been adequately quantitatively tested (Peterson et al., 2013) as an important control of deposition in Holocene incised valley systems.

The Grays Harbor estuary (Figure 1) provides an ideal setting to test the importance of changing accommodation space on sediment partitioning, terrestrial sediment throughput and littoral sand sinks in a large meso-tidal incised valley. The modern Grays Harbor estuary displays a simple symmetric geometry, which is very similar to the idealized estuary diagram used by Dalrymple et. al. (1992), except that the central basin in the meso-tidal Grays Harbor estuary has largely ‘filled-up’ to intertidal deposit levels. A test of accommodation space controls was recently conducted in the Columbia River incised valley, a large fluvial-tidal system located 80 km south of the Grays Harbor estuary (Peterson et al., 2013). Large inputs of river sediment into the Columbia River incised valley resulted in sufficiently high sediment accumulation rates to maintain low accommodation space and net export of river bedload to the Columbia River littoral cell (CRLC) during the Holocene

transgression (Peterson et al., 2013; Peterson et al., 2016). It is not known 1) to what extent the relatively smaller rates of river sediment input into the Grays Harbor estuary kept pace with the transgressive submergence of the incised valley and 2) to what extent the meso-tidal Grays Harbor estuary served as a net sink of littoral sand during the Holocene marine transgression.

Work by Scheidegger and Phipps (1976) showed that modern deposits in the Grays Harbor estuary were derived from both river and littoral sand sources, with littoral sand mineralogy reaching at least 11 km inshore from the estuary mouth (Figure 1). Peterson and Phipps (1992) extended the analyses of the Grays Harbor basin to include deposition throughout the Holocene marine transgression (0–11 ka). Sediment accumulation rates were found to positively correspond to rates of sea level rise, but the deposit sample analyses were not divided into different grain size fractions or into fluvial and littoral sand sources. In this article we present detailed analyses of grain size and sand-source mineralogy from 275 core samples recovered from 17 drill core sites in the Grays Harbor basin. These measurements are combined with corresponding sediment isopach volumes and depth-age relations to partition basin accumulation rates on the bases of littoral sand, river sand, mud and gravel components in the Grays Harbor basin. Quantitative relations are established in this article between changes in increasing basin accommodation space and basin averaged rates of sediment accumulation, from littoral sand sources and river sediments.

The relative importance of the Grays Harbor estuary, and of other meso-tidal estuaries, in terms of littoral sand sinks becomes apparent when considered in view

of potential rapid sea level rise from predicted future global warming (Vermeer and Rahmstorf, 2009). If the Grays Harbor estuary served as a major net sink of littoral sand following increases in basin accommodation space during the middle- to late-Holocene transgression then then adjacent beach deposits could serve as sources of sand to future sand sinks in the estuary following predicted global sea-level rise.

2 BACKGROUND

The modern Grays Harbor estuary (290 km² surface area) reaches about 20 km in width and 50 km in channel length from the estuary mouth to the head of tide near the Wynooche River confluence with the Chehalis River (Figure 1). The high-energy estuary-mouth area is dominated by tidal flows (~ 2.5 m s⁻¹ sustained velocities) from a 3.0 m diurnal tidal range (Barrick, 1976). Winter storm ocean swells reach 6–7 m height in the seaward part of the tidal inlet. Locally generated wind-waves (~ 0.5 m height) propagate over tidally-submerged sand flats located landward of the barrier spits. In the central estuary area, the modern intertidal flats are dissected by subtidal channels (3-10 m depth). A narrow shipping channel is maintained to about 15 m depth by channel dredging. The central bay area has largely ‘filled-up’ to intertidal levels (60 % of the estuary surface is intertidal) (Barrick, 1976). Tidal marsh settings are generally limited to lee shores and to tributary tidal creeks and tributary head deltas in the Chehalis, Wishkah, Hoquiam and Humptulips Rivers. Bay cliffs (5–15 m elevation MSL) are cut into Quaternary deposits of glacial outwash, fluvial and/or eolian origins along the northeast and

southeast shorelines of the western estuary area (Walsh et al., 1987; Logan, 2003). Coseismic subsidence events (1–2 m abrupt submergence) resulted in episodic shoreline retreat in the barrier spits (Peterson et al., 2010a) and marsh burial in the Grays Harbor estuary (Atwater, 1992; Barnett, 1997; Peterson et al., 2000). However, interseismic uplift canceled out the coseismic subsidence (~400 year mean recurrence interval for the last 3.2 ka) leaving a very-small net uplift in the convergent margin setting.

Modern sediment sources to the Grays Harbor basin include 1) the Chehalis, Wishkah, Hoquiam, and Humptulips Rivers and 2) the broad beaches and inner-shelf deposits adjacent to the Grays Harbor tidal inlet (Figure 1) (Peterson et al., 2016). The annual river sediment input from all of the Chehalis River tributaries is reported to be 665, 000 t yr⁻¹ (Karlin, 1980; Peterson and Phipps, 1992). We assume that the dominant supply of silt and clay to the Grays Harbor basin has been from the estuary tributaries. Modern sand deposit samples (n=74) from the major tidal channels, accretionary banks and broad tidal flats in the Grays Harbor estuary are predominantly in the fine sand range (0.05–0.5 mm diameter) (Phipps et al., 1976). These grain size ranges could be supplied from the estuary tributaries and/or from the broad littoral zone including the adjacent beaches and inner-shelf, with sand sample mean sizes ranging from 0.25 mm to 0.15mm (Peterson et al., 2010b; Peterson et al., 2016).

Basal gravel deposits in the eastern Grays Harbor basin (30-50 m depth) were supplied by the Chehalis, Wishkah, and Hoquiam Rivers (Figure 1) (Peterson and Phipps, 1992). The overlying mud and sand deposits (1–30 m depth) thin with

landward distance in the Chehalis River valley to gravelly sand bottomed channels near the present head-of-tide at the Wynoochee River confluence. Weathered gravels of Pleistocene age are encountered in basal cutbank deposits of the Chehalis River at the Satsop River confluence, about 10 km above the Wynoochee River confluence. No drill core sampling was performed for this study within the 23 km-long Chehalis River Valley section between the landward-most drill site and the Satsop River confluence. Sand and rare gravel deposits (0–20 m depth) generally overlie muddy sand deposits (30–60 m depth) in the westernmost areas of the Grays Harbor basin, near the tidal inlet. The rare gravel layers that occur under the prograded barrier spits of the Grays Harbor estuary are associated with 1) transgressive ravinement surfaces and/or overlying shoreface deposits (Vanderburgh et al., 2010; Peterson et al., 2016) and 2) underlying tidal inlet deposits (Peterson and Phipps, 1992). Incised valley deposits in the offshore Grays Harbor basin, crossing the present inner-shelf, have been imaged in offshore seismic reflection profiles to 80 m depth (Twichell and Cross, 2001; Twichell et al., 2010) but they have not been sampled by offshore drilling or coring.

The relative proportions of river sand and littoral sand supply to the prehistoric deposits in the western and central areas of the Grays Harbor basin (Figure 1) were not evaluated during the initial studies of the Holocene stratigraphy of the Grays Harbor estuary (Peterson and Phipps, 1992). If the early- and middle-Holocene deposits in the western areas of the Grays Harbor basin are found to contain an abundance of Columbia River littoral sand, as found for the modern deposits in the western area of the Grays Harbor estuary (Scheidegger and Phipps,

1976), then a net-northward alongshore transport from the Columbia River, located 80 km south of Grays Harbor, can be confirmed to have occurred throughout the Holocene transgression (Peterson et al., 2010b; Peterson et al., 2016).

3 METHODS

3.1 Drill Core Site Selection

Seventeen sites in the Grays Harbor basin were drill cored for representative samples of the transgressive Holocene deposits (Figure 2). The general locations of drill core sites were selected on the bases of 1) regional variations in industry borehole logs between the barrier spits and the tributary head deltas, 2) drilling barge access across broad intertidal flats via deeper subtidal channels, 3) approximately equal spacing between drill core sites, and 4) pre-Holocene (ancestral) incised valley morphology. The pre-Holocene incised valley morphologies in the western (seaward) and central areas of the Grays Harbor basin were interpreted from ~300 km of high-resolution seismic reflection profiles, as confirmed by unconsolidated Holocene deposits in the 17 drill core sites (Peterson and Phipps, 1992). The resolution of two-way travel time depth to basin floor reflection is estimated to be ± 0.75 m, based on seismic wave length (Peterson and Phipps, 1992), but the large number of depth measurements (~ 10 m distance spacing) were averaged in 100 m profile sections to reduce potential random errors. Contour crossing depths at seismic lines are shown to the nearest 1 m depth (MSL).

186

187 Ages of the Holocene deposits in the drill core sites were established by radiocarbon
188 dating of peat, wood and shell materials (1–11 ka in age) (Peterson and Phipps,
189 1992). Ancestral valley morphologies under the barrier spits are based 1)
190 extrapolations between inshore- and offshore- seismic reflection profiles (Peterson
191 et al., 1992) and 2) confirmations of the depths and descriptions of Holocene
192 deposits under the barrier spits from industry boreholes (Herb, 2000) and drill core
193 sites (Table 1). The ancestral river valley morphology in the eastern basin area is
194 based on 70 geotechnical boreholes (unpublished geotechnical reports) where thick
195 basal gravel deposits attenuated seismic penetration. The deepest drill core sections
196 in the Grays Harbor basin (sites 1, 2, 3, 8, 15, 16) were locally positioned to recover
197 maximum thicknesses of the Holocene fill (40–60 m depth MSL) in the ancestral
198 valley axes. Mean sea level is about +1 m relative to the 0 m NAVD88 elevation
199 datum in the study area. All drill sites were surveyed into registered benchmarks or
200 to measured daily tidal cycles, calibrated to local registered benchmarks, to
201 establish elevations to the nearest ± 0.1 m MSL. Digitization of ancestral river-valley
202 depth contours was performed on a 1:40,000 scale Mercator projection base map
203 (NOAA, 1977) with ArcView Geographic Information System (GIS). The digitized
204 areas were calibrated to square kilometers directly from the map scale (0.1 km scale
205 resolution). Each area was measured three times and averaged for a mean estimated
206 area. The measured areas were rounded to the nearest 100,000 square meters (0.1
207 km²), i.e., the resolution of digitizing at the 1:40,000 scale.

208

3.2 Sediment Composition Analyses

A total of 275 core samples (25–75 cm in length) were recovered at 1.5 or 3.0 m depth intervals downhole from the 17 drill core sites in the Grays Harbor basin (Figure 2). Channel samples (2.5 cm in width) were taken along the entire lengths of recovered cores, yielding sample weights of 100–200 g each. The channel samples were wet sieved into >2.000 mm, 0.062–2.000 mm, and <0.062 mm screen sizes, respectively, to separate gravel, sand, and silt-clay (mud) fractions. Gravel-rich samples from the western drill core sites contained minor abundances of shell fragments. The larger shell fragments (>0.25 cm diameter) were removed from the samples prior to size fraction measurements. The relative dry weight abundances of the three size fractions (gravel, sand and mud) were measured to the nearest 0.1 g, and are reported to the nearest one percent. Sand-size fractions in samples from drill core sites 1, 2, 8, and 15 were analyzed for grain size frequency distributions. The sand fractions of these samples were mechanically sieved at 0.5 phi size classes to establish sand mean grain size (Folk 1980).

All sample sand fractions from the 17 drill core sites were sieved to yield fine sand fractions (0.062 –0.250 mm) for petrographic analysis of heavy minerals that are diagnostic of beach and river sand sources (Phipps and Scheidegger, 1976). The heavy- and light-mineral fractions were separated by centrifuge in Na-polytungstate (specific gravity of 2.95). The heavy-minerals were grain mounted in piccolyte™ for identification of at least 200 colored pyroxene grains (hypersthene and augite) per sample under petrographic microscopy at 250x. The restriction of pyroxene grain

counts to colored pyroxene grains improves the discrimination of hypersthene grains in Columbia River derived sand (Baker et al., 2010), as found in beach and barrier spit deposits in the CRLC system (Peterson et al., 2010b). This method slightly decreases hypersthene to augite ratios, relative to analyses reported by Scheidegger and Phipps (1976).

The hypersthene:augite ratios in fine sand samples from Grays Harbor drill core sites 15 and 1, respectively (Figure 2), were analyzed to calibrate the pyroxene mineral-pair proxy relative to river and beach sand end-member sources. Hypersthene to augite ratios of the two end-member sources of fine sand (0.06–0.25 mm) to the Grays Harbor basin, including the local rivers and adjacent beach/inner-shelf, respectively, are calibrated with shallow downhole samples from drill core sites 15 and 1 (Table 2). Five samples (≥ 74 wt % sand fraction) from drill core site 15 (6.5–18.5 m depth MSL) average 0.057 hypersthene:augite. For this study we define the river end-member mineralogy in the Grays Harbor basin as 0.06 hypersthene:augite. Five samples (≥ 96 wt % sand fraction) from drill core site 1 (2.0–8.5 m depth MSL) averaged 0.83 hypersthene:augite, so we define the littoral end-member mineralogy in the Grays Harbor basin as 0.83 hypersthene:augite. Sample analyses are averaged over 10-m depth intervals in each drill core site for basin analyses of sediment accumulation rates (Appendix 1 in Supplemental Materials).

3.3 Sedimentary Structures In Drill Core Samples

Undisturbed samples, which were recovered by hydraulic-ram coring from representative drill hole sites (1, 2, 3, 4, 6, 8, 15, 17) (Figure 2), were cut into slabs (25x7.5x1 cm) for X-radiography using Kodack X-Omat XTL-5 low-density high-contrast film. The x-radiographs were viewed on a light table with a 1.0-cm grid overlay to estimate relative abundances of sedimentary structures. Sedimentary structures are divided into four categories including: (1) lag deposits of gravel, wood, and/or shell-hash, (2) cross-bedded sand, (3) laminated mud, and (4) burrows and/or loss of primary bedding. The last category is designated as bioturbation, however, other factors, such as coseismic liquefaction (Atwater, 1994), might have contributed to the loss of primary structures in some sand-rich cores in the Grays Harbor basin. The relative abundance of the sedimentary structures (100 grid cells counted per core) are reported semi-quantitatively: 0=absent (0 %), 1=rare (1–24 %), 2=common (25–49 %), 3=abundant (50–74 %) and 4=dominant (75–100 %) for the analyzed samples.

3.4 Invertebrate Shell Fragment Assemblages

Shell fragments (1.0–5.0 cm diameter) in samples from drill core sites 1, 2 and 3 (Figure 2) were analyzed for invertebrate species occurrences. A total of 21 species were identified in downhole samples from the three drill core sections (Table 3). The listed species (16 in number) are grouped into three faunal assemblages on the basis of measured frequencies of mutual occurrence. Assemblage 1 includes thick-shelled infaunal pelecypods that inhabit unstable

coarse grained substrates found near or in estuary mouths (Ricketts and Calvin, 1968; Hancock et al., 1979; Mooris et al., 1980). Assemblage 2 includes thin-shelled suspension and deposit feeding, infaunal pelecypods that thrive in hypoxic sand and mud flats (Dunnill and Elis, 1969; Coan, 1971; Hancock et al., 1979). Assemblage 3 includes epibenthic invertebrates whose adaptations for variable salinities and high turbidity ensure success in estuarine brackish tidal-channel environments (Shelford et al., 1935; Hopkins, 1937; Harger, 1972). Specimens in nearly all shell-rich samples were transported. However, consistent faunal-habitat groupings and strong spatial gradients in assemblage distributions indicated limited mixing relative to the broad sampling intervals used in this study.

4 RESULTS

In this section we present the downhole compositions of recovered samples from the 17 drill core sites in the Grays Harbor basin (Figure 2). The sources of the sediments are discriminated between river and beach sources, as based on grain size and mineralogy. Sedimentary structures and invertebrate shell fragments are analyzed from selected drill core sites to aid with interpretation of changing estuary geomorphology and depositional processes during the period of basin filling. An isopach map of the Holocene deposits is divided into 10 m depth intervals and seven strip sectors to yield 38 cells. Deposit compositions are averaged for each cell based on the downhole sample compositions in the corresponding drill core sites in the seven sectors. Previously reported radiocarbon dates are recalibrated and

combined with new radiocarbon dates to establish basin sediment accumulation rates in the Grays Harbor basin throughout the Holocene marine transgression (0–11 ka).

4.1 Vertical and Horizontal Trends in Sediment Composition

Core samples (275 in number) from 17 drill core sites in the Grays Harbor estuary (Figure 2) are analyzed for gravel, sand, mud, and sand source compositions to yield to 1,100 bulk sample compositional analyses (Appendix 1 in Supplemental Materials). Relative abundances of the gravel, sand, and mud components in recovered samples are plotted downhole for west-east drill core sites (1, 3, 10, and 15) (Figure 3), and for north-south drill core sites (4, 6, 2 and 8) (Figure 4). The westernmost drill core site (1), located adjacent to the modern tidal inlet, contains sand and minor beds of gravelly sand or muddy sand from 0 to 57 m depth MSL. In the western area of the estuary the deeper drill core sites (2, 3, 6, 8) are dominated by sand in the upper 20 m of the basin fill and by alternating beds of sand and mud in the lower 30–60 m of the basin fill. The deeper eastern core sites, as represented by drill core site 15, contain alternating sand and mud in the upper 30 m of basin fill and sandy gravel deposits in the lower 30–50 m of the basin fill.

Sand size fractions (0.06–2.00 mm diameter) in samples from drill core sites 1, 2, 8 and 15 were analyzed for mean grain size (Figure 5). The ranges of the grain size means are 0.11–1.88 mm (site 1), 0.12–1.45 mm (site 2), 0.1–0.98 mm (site 8) and 0.01–2.00 mm (site 15). Samples with substantial gravel abundances (>20 %

weight gravel) in the western core sites (1, 2, 8) contained abundant shell fragments in the coarsest sand-size fractions. Excluding all samples with greater than 20 percent gravel, and corresponding coarse-sand sized shell fragments, the drill core site averages of the sand sample means are 0.25 mm for site 1 (sample number n=36), 0.19 mm for site 2 (n=35), 0.22 mm for site 8 (n=12) and 0.19 mm for site 15 (n=25). The averages of the mean sand sizes (0.19–0.25 mm) in all four drill core sites are well within the grain size ranges of both the river and littoral sand sources (Phipps et al., 1976).

Fine sand fractions (0.06–0.25 mm diameter) from all of the samples in drill core sites 1–17 were analyzed for relative abundances of littoral and river sand source components (Figures 6, 7). The sand fractions in the westernmost drill core sites (1, 2, 3) are dominated by the littoral sand component at all depths (1–60 m depth MSL). Drill core sites from the central bay areas (6, 8, 10, 11, 12) show the littoral sand component in the uppermost deposits transitioning to the river component in the lower deposits. The easternmost drill core sites (15, 16, 17) contain only the river sand component at all depths.

4.2 Sedimentary Structures And Invertebrate Shell Assemblages

Selected drill core sites (1, 2, 3, 4, 6, 8, 15, 17) (Figure 2) were sampled by hydraulic/ram coring to yield undisturbed samples for x-radiographic analyses of apparent sedimentary structures. The sedimentary structure types, including 1) erosional lag deposits of gravel, shell-hash, and/or wood, 2) cross-bedded sand, and

3) laminated mud, reflecting, in order, decreasing energies of deposition. A fourth sedimentary structure type identified as an absence of apparent primary structures in the x-radiographs could represent primary structure disturbance from bioturbation or coseismic liquefaction (Appendix 1 in Supplemental Materials). The relative abundances of the structure types (1–3) are plotted downhole in west-east drill core sites 1, 3, 15, and 17 (Figure 8) and in north-south drill core sites 4, 6, 2 and 8 (Figure 9). The west-east basin trends in sedimentary structure types generally follow those of sediment grain size, with cross-bedded sand structures in the westernmost drill core site 1 transitioning to alternating cross-bedded sand and laminated mud in drill core sites 3, 8 and 15 in the central and eastern areas of the basin. Vertical trends include 1) a predominance of cross-bedded sand transitioning downhole to a predominance of laminated mud in western drill core sites 1, 4, and 2, and 2) alternating cross-bedded sand and laminated mud transitioning downhole to basal-gravel lag deposits in the eastern drill core sites 15 and 17.

Downhole abundance plots of three invertebrate species assemblages (Table 3) are shown for three westernmost drill core sites (1, 2, 3) in the Grays Harbor basin (Figure 10). The faunal assemblage changes reflect the physical evolution of the seawardmost Grays Harbor basin during the Holocene transgression. In drill core sites 1 and 2 the most recent assemblage–1 species (estuarine mouth) are replaced downhole by assemblage–2 species (hypoxic mud/sand flat) and assemblage–3 species (estuarine channel) below 25–35m depth MSL. The predominance of assemblage–3 species (estuarine channel) at 50–55 m depth in drill core site 1 establishes the presence of an estuarine setting located seaward of

the present barrier-spit positions during the earliest period of basin filling. The uphole shift in habitats at drill core site 1, from protected estuarine channels and tidal flats (Assemblages 2 and 3) to exposed estuarine mouth (Assemblage 1), reflects the landward retreat of the protected estuarine facies during the Holocene transgression. The predominance of assemblage-2 and assemblage-3 species from 10 to 55 m depth in drill core site 3 indicates the presence of protected estuarine environments located landward of the modern barrier-spit positions throughout the Holocene transgression. The minor occurrence of assemblage-1 species from 10-30 m depth in drill core site 3 indicates that the high-energy tidal inlet was likely situated at or near its present location throughout late-Holocene time.

4.3 Basin Sector Area And Cell Volume Measurements

Measurements of basin Holocene fill volumes in Grays Harbor are based on 1) previously published morphology of the western- and central-basin areas, as established by seismic reflection profiling and 17 drill core sites (Peterson and Phipps, 1992), 2) 70 industry borehole logs from the easternmost basin area and eight industry boreholes from the barrier spits and bay flats adjacent to the sand spits (Table 1; Figure 11), 3) modern bay bathymetry from navigation charts, 1:40,000 scale (NOAA, 1977), and (4) interpreted transgressive ravinement surfaces under the prograded barrier spits (Vanderburgh et al., 2010; Peterson et al., 2010a,b). The data sets from the deposit isopach-volume analyses are combined with sample compositional analyses to yield average sediment compositions for

393 corresponding basin sectors (A-G). The strip sectors (~5 km in width) are arranged
394 west-east to trend perpendicular to the maximum gradients in reported basin
395 deposit compositions (Scheidegger and Phipps, 1976; Peterson and Phipps, 1992).
396 The use of broad sectors averages random analytical errors in the isoopach
397 mapping, thereby reducing relative uncertainties in the large surface area estimates.
398 The positions of the sector boundaries are placed to include at least two drill core
399 sites in each of the bay sectors (B-G). A narrow sector (A) covers the western halves
400 of the bay spits, and is represented by one drill core site 1 near the present tidal
401 inlet. Sample compositions from drill core site 1 are used to represent the upper 30–
402 40 m of deposits in the north spit and southern part of the south spit based on their
403 similarities with reported deposit compositions in industry boreholes OS1 and OS2
404 in the north spit and GW23 in the south spit (Table 1).
405 The seven basin area sectors are divided into 10-m depth intervals (0–60 m depth
406 MSL) yielding a total of 38 cells (Figure 11). The 60-m depth contour does not
407 extend into sectors F and G. Digitization of cell-bounding surface areas (upper and
408 lower surfaces) was performed on a 1:40,000 scale Mercator projection base map
409 (NOAA, 1977) with ArcView™ GIS. The digitized surface areas were calibrated to
410 square kilometers directly from the map scale (0.1 km scale resolution). Modern
411 channel bathymetry areas were measured for the shallowest depth contours (-1 m
412 and -10 m depths MSL) and were then subtracted from corresponding cell surface
413 areas in the 0–10 m depth interval to yield adjusted cell surface areas. Mid-point cell
414 surface areas are taken from differences between upper and lower adjusted cell
415 surface areas. The mid-point surface areas of the cells are multiplied by the cell

depth (10 m) to yield cell volume ($\times 10^6 \text{m}^3$) in the 38 cells (Table 4). The shallowest cells (0–10 m depth interval) in the westernmost sectors (A, B) were adjusted by removing prograded shoreface volumes (1–10 m depth wedge) from under the prograded spit areas. The depths to the transgressive ravinement surfaces under the prograded shoreface deposits were previously established in the north and south barrier spits by ground penetrating radar (GPR) and borehole drilling (Peterson et al., 2010b; Vanderburgh et al., 2010). Cell volumes are reported to the nearest one million cubic meters ($1 \times 10^6 \text{m}^3$).

4.4 Basin Deposit Radiocarbon Ages

Deposits of mud and/or sand and peat were dated by bulk and AMS radiocarbon analyses of wood, marine shell, plant detritus and peat (Table 5). Brackish-water peaty deposits, defined on the bases of 1) $\geq 10\%$ in-situ plant and root remains and 2) presence of brackish/marine-water diatoms, occur in intertidal marsh settings (1 ± 0.5 m MSL) in the Grays Harbor estuary (Peterson et al., 2000). The brackish-water peaty samples ($n=14$) establish a sea level curve (0 to -43 m MSL; 0–10.3 ka) in the Grays Harbor basin (Figure 12). One peaty mud sample (CR W73) from the nearby Columbia River estuary (Baker et al., 2010) is used to extend the local sea level curve back to -71 m MSL at 11.5 ka. Radiocarbon samples from organic materials in deposits of mud and/or sand ($n=25$) establish a sediment level curve (0 to -60 m MSL; 0–11.1 ka) in the Grays Harbor basin. Deposit dates that occur at least 10 m depth below the sea level of corresponding age are assumed to

represent deeper channel cut-and-fill sequences. The anomalous 'young' radiocarbon samples are generally associated with the uppermost ~10 m of basin fill in the Grays Harbor basin. They are not included in the basin-averaged sediment level curve. Two radiocarbon samples yielded dates that placed them above the sea level curve. Those two samples are assumed to represent remobilized 'older' radiocarbon materials, so they are not included in the sediment level curve.

The computed rates of sea level rise range from 20 m ka⁻¹ in the 50–60 m depth interval to 1.7 m ka⁻¹ in the 0–10 m depth interval in the study area (Table 6). The depth averaged sedimentation rates in the Grays Harbor basin range from 14.3 m ka⁻¹ in the 50–60 m depth interval to 2.0 m ka⁻¹ in the 0–10 m depth interval. The depth averaged sedimentation rate in the Grays Harbor basin fell behind the rate of sea level rise (62 %) in the 40–50 m depth interval but slightly exceeded sea level rise (111 %) in the 10–20 m depth interval and (117 %) in the 0–10 m depth interval. A very-deep central basin never developed in the estuary (Figure 12). However, the sediment level curve fell significantly below the sea level curve for most of the early and middle Holocene transgression (6–10 ka). The maximum vertical offset (10 m depth) between the basin-averaged sediment level curve and the overlying sea level curve occurred at about -30 m MSL, corresponding to a middle Holocene age of ~8 ka. By late-Holocene time (0–5 ka) the offset between the basin-averaged sediment level and sea level curves had dropped to only 1–4 m. As previously noted, the modern sediment surface in the Grays Harbor estuary is about 60 % intertidal (Barrick 1976), which is to say that at least 60% of the sediment surface is less than 1.5 m depth below MSL. In this article we use the

differences between the sea level curve and the sediment level curve as a proxy for water depth in the evolving Grays Harbor basin.

5 DISCUSSION

In this section we demonstrate the relations between 1) transgressive submergence, depositional filling, and geomorphic development of the Grays Harbor estuary (Figures 1, 2) and 2) increasing basin accommodation space and basin sediment accumulation rates throughout the Holocene transgression. These relations are based on sediment composition data (Figures 3–7), basin sediment isopach data (Figure 11; Table 4), and deposit radiocarbon age data (Table 5; Figure 12). Unlike some proxies for accommodation space, such as channel gradient and base profile (Blum and Törnqvist, 2000; Quirk, 2012) we utilize a direct measure of the rate of increasing accommodation space, as based on basin-wide submergence volumes in 10 m-depth intervals (Figure 11) and corresponding ages of submergence from a local sea level curve (Figure 12). This approach requires depth contouring of the incised valley geometry but it provides a fully integrated measure of basin submergence (Peterson et al., 2013). The relations between accommodation space and basin sediment volume accumulation rates, which are established in the tidally dominated Grays Harbor basin, are contrasted with those from the nearby fluvial-tidal Lower Columbia River Valley. They are also used to estimate potential littoral sand sinks in the Grays Harbor basin from future sea level rises that are predicted to result from global warming.

5.1 Evolution of the Grays Harbor Basin During the Holocene Marine Transgression

The onset of flooding in the ancestral Grays Harbor basin occurred near the present bay mouth (-70 m depth MSL) at ~11.5 ka (Figures 11, 12, 13). By the time that net deposition had reached the -60 m sediment depth level (11 ka) littoral sand had been transported into the submerged lowermost reaches of the Chehalis River valley at drill core site 3 (Figure 6). Meanwhile, the transgressive flooding surface had reached borehole BH62 in the upper Chehalis valley at -60 m depth (Figure 2; Table 1). Littoral sand did not reach the central-eastern drill core sites 12 and 13 located adjacent to BH62 until the -20 m depth at about 7 ka. Tidal inlet(s) reached the present estuary mouth area in the Grays Harbor basin by ~9.5 ka based on the first occurrences of invertebrate assemblage-1 fauna (estuarine mouth affinities) at -40 m depth in the westernmost drill core site 1 (Figure 10). Rare gravelly sand deposits at 30–40 m depth in OS1 (Table 1; Figure 2) substantiate high-energy conditions in the vicinity of the present tidal inlet at ~9 ka.

Channel cut-and-fill sequences in the central areas of the Grays Harbor basin, as imaged in seismic reflection profiles (Peterson and Phipps, 1992), were largely developed above -30 m depth MSL. Channel bottom lag deposits of wood, shell and/or rock fragments are rare or absent between -30 and -50 m depths in analyzed drill core sites from the central and western areas of the Grays Harbor basin. Channel lag deposits were infrequently deposited above -20 m depth (after 7 ka) in drill core sites 2, 3, 4, and 8 (Figures 8, 9). The narrow tidal channels that dissect the

modern intertidal flats of the Grays Harbor estuary (Figure 2) are recent features in the Grays Harbor basin. Their localized occurrence throughout the basin during late-Holocene time is based on the relative abundances of 1) channel lag structures in the 5–20 m depth interval and 2) the anomalous ‘young’ radiocarbon samples (1–5 ka in age) that are hosted in the 5–15 m depth interval (Figure 12).

The western area of the Grays Harbor basin was protected from high-energy storm surf throughout the Holocene transgression, as shown by 1) invertebrate assemblage-2 fauna (hypoxic mud/sand flat affinities) from -55 to -10 m depth in drill core sites 2 and 3 (Figure 10) and 2) preserved mud beds from -55 to -10 m depth in drill core sites 3, 4, and 8 (Figures 3, 4). The transgressive ravinement surface in the westernmost area of the Grays Harbor basin was cut into gravelly sand deposits from tidal-inlets, barrier shoals, and/or retreating barrier beaches at -1 to -10 m depth MSL (4–8 ka), located under the barrier spits (Figure 13) (Herb, 2000; Vanderburgh et al., 2010). Net progradation of the north and south barrier spits began at ~3.0 ka (Peterson et al., 2010a; 2010b) corresponding to a sediment level depth of -5 m MSL in the Grays Harbor estuary (Figure 12). The broader aspects of barrier, beach plain, and shoreface progradation at Grays Harbor and the adjacent shorelines in the Columbia River littoral cell are addressed separately (Peterson et al., 2010a,b; Peterson et al., 2016).

5.2 Averaged Sediment Compositions

The sediment size fraction and sand source data from the 275 drill core samples (Appendix 1 in Supplemental Materials) are averaged to yield sediment compositions for the 10 m-depth interval cells in each of the six sectors A–G. Averaged sediment compositions in the 38 cells range widely: average gravel size fraction 0–50 %, average total sand size fraction 8–98 % and average mud size fraction 0–91 % (Table 7). The fine sand size fraction is divided into two components including littoral sand source and river sand source, as based on heavy mineral analyses (Table 2). The littoral sand component ranges from 0 % to 100 % relative abundance in the fine sand size fraction.

5.3 Sediment Volumes In Cell And Basin 10-m Depth Intervals

The isopach cell volume data (Table 4) are rearranged by the six 10-m depth intervals for each sector (A–G). The cell volume data are reported to the nearest 1 million cubic meters. The 10 m-depth interval data are then summed to yield basin volumes for each 10- m depth interval. Calculated basin 10-m depth interval volumes range from $514 \times 10^6 \text{ m}^3$ in the 50–60 m depth interval to $2,344 \times 10^6 \text{ m}^3$ in the 10–20 m depth interval (Table 8). The shallowest depth interval (0–10 m depth) is slightly reduced in sediment volume ($2060 \times 10^6 \text{ m}^3$) relative to the 10–20 m depth interval due to 1) the subtracted channel bathymetric volumes in the western/central basin area and 2) the subtracted prograded shoreface volumes under the sand spits. The total sediment volumes are then divided into size fraction and sand source volumes, based on the sediment composition data in Table 7. The

basin gravel volumes range from $46 \times 10^6 \text{ m}^3$ in the 0–10 m depth interval to $214 \times 10^6 \text{ m}^3$ in the 40–50 m depth interval (Figure 14). The basin littoral sand volumes range from $270 \times 10^6 \text{ m}^3$ in the 50–60 m depth interval to $1349 \times 10^6 \text{ m}^3$ in 10–20 m depth interval. The basin river sand volumes range from $110 \times 10^6 \text{ m}^3$ in the 50–60 m depth interval to $522 \times 10^6 \text{ m}^3$ in 0–10 m depth interval. The basin mud volumes range from $68 \times 10^6 \text{ m}^3$ in the 50–60 m depth interval to $548 \times 10^6 \text{ m}^3$ in 20–30 m depth interval.

5.4 Changing Rates of Accommodation Space and Sediment Accumulation

The six 10-m depth interval volumes ($\times 10^6 \text{ m}^3$) in the ancestral Grays Harbor basin (Tables 4, 8) are divided by corresponding age duration ($\times 10^3 \text{ yr}$) of sea level rise from the sea level curve (Figure 12; Table 6) to compute the rate of increasing basin accommodation space ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$) for each 10-m depth interval (Table 9). Combined analytical errors are estimated to less than $\pm 5 \%$, therefore rates of increasing accommodation space and volume fill are reported to one significant figure (0.X) in millions of cubic meters per year ($\text{X.X} \times 10^6 \text{ m}^3 \text{ yr}^{-1}$). Two significant figures (0.XX) are shown in Table 9 for computational purposes. The rates of increasing basin accommodation space range from $0.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 0–10 m depth interval to $2.1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 20–30 m depth interval. The rates of increasing accommodation space are controlled both by the ancestral basin geometry and by the rate of sea level rise. The upwards widening of the Grays Harbor ancestral valley (Figure 11) is accompanied by upward decreasing rates of

sea level rise (Figure 12), leading to maximum rates of increasing accommodation space between the -20 m and -50 m depths MSL. The six 10 m-depth interval volumes are divided by the corresponding duration of sedimentation ($\times 10^3$ yr) from the sediment level curve to derive the total sediment volume accumulation rates in the Grays Harbor basin (Figure 15). Total sediment accumulation rates range from $0.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 0–10 m depth interval to $1.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 20–30 m depth interval. There is a positive correlation ($R^2=0.81$) between the rates of increasing accommodation space and total sediment accumulation in the Grays Harbor basin (Figure 16). The positive correlation is not unexpected because the sediment level curve only slightly deviated from the sea level curve during the middle part of the marine transgression (5–9 ka).

5.5 Basin Sediment Accumulation And Increasing Accommodation Space

Basin accumulation rates of gravel, littoral sand, river sand and mud in the Grays Harbor basin are computed from sediment component volumes in the 10-m depth intervals (Table 8) and the durations or age spans of the depth intervals (Table 6). Littoral sand accumulation rates range from $0.2 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 0–10 m depth interval to $0.7 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 20–30 m depth interval (Table 10; Figure 17). River sand accumulation rates are about one half of the littoral sand accumulation rates in the corresponding depth intervals in the Grays Harbor basin. However, additional river sand deposition in the uppermost reaches of the Lower Chehalis River Valley, between the Wishkah and Wynoochee Rivers (Figure 1), is not

accounted for in this study. Mud accumulation rates range from $0.1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 0–10 m depth interval to $0.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 20–30 m depth interval. Gravel accumulation rates range from $0.01 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ to $0.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the sampled basin area.

The basin volume accumulation rates of river sand stayed relatively constant ($\sim 0.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) between the 40–50 m depth interval and the 20–30 m depth interval in the Grays Harbor basin (Table 10). These similar accumulation rates suggest a constant input and effective retention of river sand in the estuary between 7 and 10 ka. A decrease in river sand accumulation rate in the upper 0–20 m depth interval is attributed to deposition in the uppermost reaches of the lower Chehalis River Valley (20–25 km distance), between the Wishkah and Satsop Rivers (Figure 1) which were not sampled in this study. Whereas little to no river sand was transported into the western areas of the estuary in late Holocene time (Figure 6) the modern mud input rates ($0.665 \times 10^6 \text{ t yr}^{-1}$ or $0.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) substantially exceed estimated mud accumulation rates ($0.1 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) in the Grays Harbor basin during late Holocene time. As much as ~85 % of the tributary mud supply could have been exported out of the Grays Harbor basin during late-Holocene time.

The basin volume accumulation rates of sand and mud vary widely throughout the period of marine transgression in the Grays Harbor basin (Table 10; Figure 17). For example, the littoral sand accumulation rates increase 224 % between the 30–40 m depth interval ($0.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) and the 20–30 m depth intervals ($0.7 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$). The mud accumulation rates decrease 55 % from $0.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 20–30 m depth interval to $0.2 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ in the 10–20 m

depth interval. A downhole plot of the ratios between the rates of littoral sand accumulation and mud accumulation is shown in Figure 18. Processes that could cause the apparent opposing trends of mud and littoral sand accumulation rates in the Grays Harbor basin are discussed below.

Changes in the accumulate rate ratios of the total sand:mud are negatively correlated to estimated water depth in the Grays Harbor basin (Figure 19), as based on the elevation differences in the sea level and sediment level curves for corresponding ages (Figure 12; Table 6). Estimated water depths ranged from 1 to 8 m in the six 10-m depth intervals in the Grays Harbor basin. Maximum mud accumulation rates occurred in the 20–30 m depth interval (Table 10) when estimated average water depth reached 8 m. Minimum mud accumulation rates occurred in the 50-60 m and 0-10 m depth intervals when basin averaged water depths approached 1 m depth. Wind-waves and/or constricted tidal flow resuspension of sediments in the shallowing tidal flats likely enhanced mud export out of the estuary and littoral sand migration into the central estuary areas after 8 ka.

The substantial decreases in the basin accumulation rates of mud and littoral in the Grays Harbor basin, during late Holocene time (Table 10; Figure 17), are directly linked to the very-low rate of increasing accommodation space ($0.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) during the 0–6 ka time period (Table 9). It is likely that the smaller decreases in river sand and gravel accumulations rates, above 20 m depth, resulted from some deposition of those components in the uppermost reaches of the Lower Chehalis River Valley, between the Wishkah and Satsop Rivers (20–25 km in length) (Figure

1), which were not investigated in this study. In addition to the large decreases in mud and total sand accumulation rates in the Grays Harbor basin after ~8 ka there are substantial shifts in the relative proportions of sand and mud, which correlate to shallowing water depths in the basin (Figure 19). The shallowing water depths are the result of decreasing rates of increasing accommodation space relative to sediment input. Therefore, both the total sediment accumulation rate and the ratios of the sand and mud size fraction components in the Grays Harbor basin were controlled by the relative rates of increasing accommodation space in the evolving estuary during the middle- to late-Holocene marine transgression.

5.6 Comparison Of Accommodation Space Controls In Two Estuaries Of Different Hydrographies and River Sediment Inputs

The Grays Harbor estuary and Columbia River estuary (Figure 1) experience similar modern conditions of onshore high-wind-energy and nearshore high-wave-energy, but differ greatly in hydrography and relative rates of river sediment input (Sherwood et al., 1990; Peterson and Phipps, 1992; Peterson et al., 2013; Peterson et al., 2016). The Grays Harbor estuary has a modern tidal:fluvial hydrographic ratio (H_r) of 86:1, based on mean tidal prism discharge divided by mean annual fluvial discharge, as normalized to a six hour tidal cycle (Peterson et al., 1984). The large Columbia River estuary has a modern H_r value of 5:1, with early-historic (pre-impoundment) river floods having displaced the salt water wedge out of the estuary during periods of maximum fluvial-ebb discharge (Peterson et al., 2014). The

Columbia River system is now regulated for flow by many tributary impoundments (Sherwood et al., 1990), but the Chehalis River system is much less regulated.

The estuary hydrographic ratios (H_r) would have varied in each estuary during Holocene transgressive submergence. However, the modern values likely characterized the relative importance of tidal and fluvial flows in the two estuaries during the late-Holocene, during which time the basin geometries and sedimentation rates differed least from modern conditions (Tables 4, 6; Figure 11). We use historic or pre-impoundment sediment input rates as proxies for late-Holocene sediment supply rates when modeled paleoclimate conditions differed least from pre-industrial conditions (Bartlein et al., 1998). The reported modern rates of river sediment input are compared against early- or middle-Holocene rates of maximum river sediment accumulation in the two estuaries.

The annual rate of total river sediment input to the Lower Columbia River Valley in pre-industrial time is reported to have been $14 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ (Sherwood et al., 1990). The maximum estimated rate of sediment accumulation in the Lower Columbia River Valley ($13.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) occurred in the 40–50 m depth interval (9.9–10.5 ka) (Peterson et al., 2013). This value does not account for sediment that was bypassed through the estuary to the marine side. The ratios of pre-impoundment river sediment supply rates to increasing accommodation space rates in the Lower Columbia River Valley are 6.4 (0–10 m depth interval), 1.6 (10–20 m depth interval) and 1.4 (20–30 m depth interval) (Table 11). A river sediment supply rate of $14 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ would have exceeded increasing basin accommodation in the 0–30 m depth interval in the Lower Columbia River Valley. The high rates of

river sediment supply resulted in a 1:1 correspondence between the rates of increasing basin accommodation space and total sediment accumulation (Peterson et al., 2013). Together with seasonally high fluvial-discharge rates the relatively high rates of river sediment supply in the Lower Columbia River Valley resulted in 1) the export of some river sand out of the estuary, 2) a predominance of sandy channel cut-and-fill sequences in basin deposits, and 3) a lack of littoral sand sink(s) in the estuary

The modern annual river suspended load input into the Grays Harbor estuary is reported to be $0.665 \times 10^6 \text{ t yr}^{-1}$ (Karlin, 1980). Assuming a bedload supply of 20% of total sediment, or 25 % of suspended load, the estimated volume of total river sediment input is $0.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$, using a mass to volume conversion factor of 0.54. The maximum estimated rate of total river sediment accumulation in the Grays Harbor basin ($0.7 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) occurred in the 20-30 m depth interval (7.0–8.3 ka) (Table 10). The ratios of modern river sediment supply rates to increasing accommodation space rates in the Grays Harbor basin are 1.3 (0–10 m depth interval), 0.4 (10–20 m depth interval) and 0.2 (20–30 m depth interval) (Table 11). Neither the modern river sediment supply rate nor the highest prehistoric accumulation rate of river sediments ($0.8 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) would have been sufficient to fill the increasing accommodation space in the 10–30 m depth intervals. The relatively small rates of river sediment supply contributed to the subtidal water depths in the Grays Harbor basin during middle Holocene time (Figure 12). However, the combined inputs of river sediment and littoral sand were sufficient to reduce water depths in the 10–20 depth interval and to potentially over-fill

increasing accommodation space in the 0–10 m depth interval. The efficient export of river mud out of the shallowing estuarine tidal flats permitted accommodation space for continued littoral sand accumulation in the 0–10 m depth interval during late-Holocene time (0–5 ka). Littoral sand was delivered to the Grays Harbor basin throughout the Holocene marine transgression by northward alongshore transport from the Columbia River sand source (Peterson et al., 2016). In summary, the relatively low rates of river sediment supply and relatively small fluvial discharge rates in the meso-tidal Grays Harbor basin permitted 1) retention of river sand in the estuary, 2) a predominance of mud/sand flat sequences in basin deposits, and 3) substantial sink(s) for littoral sand in the estuary.

5.7 Projected Increases In Basin Accommodation Space And Littoral Sand Sinks Following Future Sea Level Rise

The onset of beach and barrier net progradation at ~3.0–4.0 ka in the Grays Harbor area (Peterson et al., 2010a) were delayed until after the filling of available accommodation space for littoral sand in the inner-shelf and in the Grays Harbor estuary (Tables 9, 10), and not from transgressive ravinement and shoreward transport of pre-Holocene shelf sand deposits. The inner-shelf likely contained greater accommodation space relative to the large tidally dominated estuaries, Grays Harbor and Willapa Bay (Figure 1) in the Columbia River Littoral Cell system during the Holocene transgression (Twichell et al., 2010). However, the decreasing rates of littoral sand accumulation in the Grays Harbor basin, after 5 ka, likely

influenced barrier shoal consolidation and eventual barrier spit progradation in the Grays Harbor estuary area during late Holocene time. How might changes in littoral sand accommodation space in the Grays Harbor estuary impact barrier shoreline dynamics in the future?

In the event of possible sea level rise of 1.0 m following predicted global warming during the next century (Vermeer Rahmstorf, 2009) the rate of increasing basin accommodation space in the Grays Harbor estuary could increase by 10-fold relative to the rate that occurred in latest Holocene time (Table 6). A sea level increase of 1.0 m would increase basin accommodation space by $\sim 200 \times 10^6 \text{ m}^3$ in the Grays Harbor estuary, based on 0.1 multiplied by the total sediment volume ($2060 \times 10^6 \text{ m}^3$) in the 0–10 m depth interval (Table 9). Assuming that the relative proportions of littoral sand, river sand and mud, remain the same (52% littoral sand component) as occurred during the last 0–5 ka (0–10 m depth interval in Table 7), then the increased accommodation space in Grays Harbor estuary could host $\sim 100 \times 10^6 \text{ m}^3$ of littoral sand. Discounting along-shore sand transport from future Columbia River discharge (Peterson et al., 2013), which could be lost to increases in inner-shelf accommodation space (Twichell et al., 2010; Peterson et al., 2016), the predicted littoral sand sink in the Grays Harbor basin could be filled by littoral sand that currently exists in adjacent barrier beaches. If all of the littoral sand that fills the estuary sand sink is supplied by shoreline retreat of the adjacent barriers (20 km in length), and assuming average vertical beach profile depths of 5–10 m, then net shoreward erosion distances of 500–1000 m of the current shoreline could

occur in the study area from a potential 1.0 m submergence of the Grays Harbor basin.

6 CONCLUSIONS

Changing rates of sediment accumulation in the Grays Harbor basin that occurred during the Holocene marine transgression are related to increasing accommodation space, water depth, and the tidal:fluvial discharge ratio (H_r) in the estuary. Total sediment accumulation rates are positively correlated ($R^2=0.81$) to increasing accommodation space, which is itself a function of incised valley geometry and rate of sea level rise. The relative proportions of sand and mud, as averaged throughout the basin in 10 m depth intervals, are correlated to the difference between sea level and sediment level curves, a proxy for water depth in the estuary, which is itself related to relative rates of increasing accommodation space and sediment accumulation in the basin. The relative proportions of littoral sand to river sand are related to tidal:fluvial discharge in the estuary, based on comparisons of the Grays Harbor basin ($H_r=86:1$) and the nearby Lower Columbia River Valley ($H_r=5:1$). Littoral sand is dominant in late-Holocene sand-size deposits from the seaward and central areas of the meso-tidal Grays Harbor basin, but only river sand is present in the sand-size deposits in the fluvial-tidal Columbia River estuary. Significant volumes of littoral sand (average $\sim 0.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) were supplied to the early Holocene deposits, 30–60 m depth (8.3–11.1 ka) in the Grays Harbor basin, arguing for northward along-shore sand transport (80 km distance) of

Columbia River bedload that was discharged to the littoral zone since early-Holocene time. Using late-Holocene proportions of littoral sand in the Grays Harbor basin (52 % of total sediment accumulation) and total sediment accumulation volume in the most recent 0–10 m depth interval (0–5 ka in age) a prediction is made for a net littoral sand sink in the Grays Harbor estuary following a 1.0 m rise in future sea level. Sand loss from adjacent barrier-beach shorelines to fill the littoral sand sink in the Grays Harbor estuary could equal 0.5–1.0 km of shoreline retreat over an alongshore distance of 20 km from a 1.0 m rise in sea level.

Acknowledgements

Larry Sloss provided early encouragement for this study. The US Geological Survey, Pacific Marine Branch, and the US Army Corps of Engineers, Seattle District, assisted with seismic profiling and navigation in the Grays Harbor estuary and adjacent inner-shelf. Don Kenner of Kenner Drilling Inc. performed the rotary mud drilling in the Grays Harbor basin. Tom DeVries performed the invertebrate shell analysis and corresponding invertebrate assemblage habitat analyses. Mark Hower performed the sediment grain size analyses. Margaret Mumford performed the core X-radiography analyses. Kennett Peterson provided editing assistance with early versions of this article. Unpublished industry borehole logs were provided by the Cities of Aberdeen, Westport and Ocean Shores. Drilling and radiocarbon dating support for this study was provided by the National Science Foundation under grant OCE-8403295 and by the College of Research, Oregon State University. Core-sample

archival in the COAS Core Lab at Oregon State University is supported under ongoing extensions of NSF grant OCE-8800548. Support for the petrographic heavy-mineral analyses in this study was provided by the U.S. Geological Survey, Coastal and Marine Geology Program, under the South West Washington Coastal Erosion Project, Co-op #1434-HQ-96-AG-01612 from 1996-2001.

References

- Atwater, B. F., 1992. Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington. Radiocarbon dates in Appendix as Supplement, Journal of Geophysical Research 97, 1901–1919.
- Atwater, B. F., 1994. Geology of Holocene Liquefaction Features along the Lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace Islands Oregon and Washington. U.S. Geological Survey Open-File Report 94-209, Seattle, Washington.
- Baker, D., Peterson, C., Hemphill-Haley, E., and Twichel, D., 2010. Holocene Sedimentation in the Columbia River Estuary, Marine Geology 27, 83-95.
- Barnett, E. T., 1997. Potential for coastal flooding due to coseismic subsidence in the central Cascadia margin. M.S. Thesis, Portland State University, 144 p.
- Barrick, R. C., 1976. Hydrodynamics of Grays Harbor estuary, Washington. Appendix

828 A: In Knott, N.P., and Barrick, R.C., (eds), Maintenance dredging and the
829 environment of Grays Harbor, Washington. U.S. Army Corps of Engineers,
830 Seattle District., 16 p.

831

832 Bartlein, P. J., Anderson, K. H., Anderson, P. M., Edwards, M. E., Mock, C. J., Thompson,
833 R. S., Webb, R. S., Webb III, T., and Whitlock, C., 1998. Paleoclimate
834 simulations for North America over the past 21,000 years: Features of the
835 Simulated Climate and Comparisons with Paleoenvironmental Data.
836 Quaternary Science Reviews 17, 549-585.

837

838 Blum, M.D., and Törnqvist, T.E., 2000. Fluvial response to climate and sea-level
839 change: a review and look forward. Sedimentology 47, 2-48.

840

841 Coan, E. V., 1971. The northwest American Tellinidae. Veliger, supplement 14, 1-63.

842

843 Catuneanu, O., 2007. Principals of Sequence Stratigraphy. Elsevier, Amsterdam, p.
844 375.

845

846 Dalrymple, R. W., Zaitlin, B. A., and Boyd, R., 1992. Estuarine facies models:
847 conceptual basis and stratigraphic implications. Journal of Sedimentary
848 Petrology 62, 1130-1146.

849

850 Dalrymple, R. W., Boyd, R., and Zaitlin, B. A., 1994. Incised-valley systems: Origins

851 and Sedimentary Sequences. SEPM Society for Sedimentary Geology. Special
852 publication No. 51.
853
854 Dunnill, R. M., and Elis, D. V., 1969. Recent species of the genus *Macoma*
855 (Pleceypoda) in British Columbia. Natural History Museum of Canada
856 Historical Papers 451-34.
857
858 Folk, R. L., 1980. Petrology of Sedimentary Rocks: Hemphill Publishing Company,
859 Austin Texas, 182 p.
860
861 Hancock, D. R., Gaumer, R. F., Willeke, G. B., Robert, G. P., and Flynn, J., 1979. Subtidal
862 clam populations: Distribution, abundance and ecology. Oregon State
863 University Sea Grant College Program, Corvallis, Oregon, 242 pp.
864
865 Harger, J. R. E., 1972. Competitive co-existence. Maintenance of interacting
866 associations of the sea mussels *Mytilus edulis* and *Mytilus californianus*.
867 Verliger 14, 387-410.
868
869 Heap, A. D., and Nichol, S. L., 1997. The influence of limited accommodation space on
870 the stratigraphy of an incised-valley succession: Weiti River estuary, New
871 Zealand. Marine Geology 144, 229-252.
872
873 Herb, A. A., 2000. Holocene stratigraphy and sediment volumes for the

874 Columbia River littoral cell, Pacific Northwest, USA. M.S. Thesis, Portland
 875 State University, Portland, Oregon, 186 p.
 876

877 Hopkins, A. E., 1937. Experimental observations on spawning, larval development
 878 and settling in the Olympia oyster, *Ostrea lurida*. Bulletin of the Bureau of
 879 Fisheries 48, 439-450.
 880

881 Karlin, R., 1980. Sediment sources and clay mineral distributions off the Oregon
 882 coast. Journal of Sedimentary Petrology 50, 543-560.
 883

884 Logan, R. L., 2003. Geologic map of the Copalis Beach 1:100,000 Quadrangle,
 885 Washington. Washington Division of Geology and Earth Resources Open-File
 886 Report 2003-16. Map 1:100,000 scale and geologic unit key.
 887

888 Mooris, R. H., Abbott, D. P., and Haderlie, E. C., 1980. Intertidal invertebrates of
 889 California. Stanford University Press, Stanford California, 690 pp.
 890

891 NOAA, 1977. Grays Harbor, Washington Chart 18502. National Oceanic and
 892 Atmospheric Administration, Washington D.C. Bathymetric chart 1:40,000
 893 scale.
 894

895 Peterson, C. D., Doyle, D. L., and Barnett, E. T., 2000. Coastal flooding and beach

896 retreat from coseismic subsidence in the central Cascadia margin, USA.
 897 Environmental and Engineering Geology 6, 255-269.
 898
 899 Peterson, C. D., Gates, E. B., Minor, R., and Baker, D. L., 2013. Accommodation space
 900 controls on the latest Pleistocene and Holocene (16-0 ka) sediment size and
 901 bypassing in the Lower Columbia River Valley: A large fluvial-tidal system in
 902 Oregon and Washington, USA. Journal of Coastal Research 29, 1191-1211.
 903
 904 Peterson, C. D., Jol, H. M., Vanderburgh, S., Phipps, J.B., Percy, D., and Gelfenbaum, G.,
 905 2010a. Dating of late-Holocene shoreline positions by regional correlation of
 906 coseismic retreat events in the Columbia River littoral cell. Marine Geology
 907 273, 44-61.
 908
 909 Peterson, C. D., and Phipps, J. B., 1992. Holocene sedimentary framework of Grays
 910 Harbor basin, Washington, USA. Quaternary Coastal Systems of the United
 911 States, Marine and Lacustrine Systems: SEPM Society for Sedimentary
 912 Research, Special Publication No. 48, 273-285 pp.
 913
 914 Peterson, C. D., and Scheidegger, K. F., 1984. Holocene depositional evolution in a
 915 small active- margin estuary of the northwestern United States. Marine
 916 Geology 59, 51-83.
 917
 918 Peterson, C. D., Scheidegger, K. F., Niem, W., and Komar, P.D., 1984. Sediment

919 composition and hydrography in six high-gradient estuaries of the
 920 northwestern United States. *Journal of Sedimentary Petrology* 54, 86-97.
 921
 922 Peterson, C. D., Twichell, D.C. Roberts, M. D., Vanderburgh, S. and Hostetler, S. W.,
 923 2016. Accommodation space in high-wave-energy inner-shelf during the
 924 Holocene marine transgression: Correlation of onshore and offshore inner-
 925 shelf deposits (0-12 ka) in the Columbia River littoral system, Washington
 926 and Oregon, USA. *Marine Geology* 379, 140-156.
 927
 928 Peterson, C. D., Vanderburgh, S., and Roberts, M., 2014. Late Holocene
 929 Geomorphology of the Columbia River Estuary, Oregon and Washington, USA.
 930 *Journal of Geography and Geology* 6, 1-27.
 931
 932 Peterson, C. D., Vanderburgh, S., Roberts M.C., Jol, H.M., Phipps, J.P., and Twichell,
 933 D.C. 2010b. Composition, age, and depositional rates of Holocene shoreface
 934 deposits under barriers and beach plains of the Columbia River littoral cell,
 935 USA. *Marine Geology* 273, 62-82.
 936
 937 Phipps, J. B., Gage, B., and Caryl, J., 1976. Grain size analyses of some Grays Harbor
 938 sediment samples, Appendix C. In Knott, N.P., and Barrick, R.C., (eds)
 939 Maintenance dredging and the environment of Grays Harbor, Washington.
 940 U.S. Army Corps of Engineers, Seattle District, 16 p.
 941

942 Phipps, J. B., Hemphill-Haley, E., and Atwater, B. F., 201., Chance findings about early
 943 Holocene tidal marshes of Grays Harbor, Washington, in relation to rapidly
 944 rising seas and great subduction earthquakes: U.S. Geological Survey
 945 Scientific Investigations Report 2015-5063, 36 p.,
 946 <http://dx.doi.org/10.3133/sir20155063>. Accessed January 10, 2016.
 947
 948 Quirk, D.G.,1996. Base profile: a unifying concept in alluvial sequence stratigraphy.
 949 Geological Society, London, Special Publications 1996, 104, 37-39.
 950
 951 Ricketts, E. F., and Calvin, J., 1968. Between the Pacific Tides. Fourth Ed. Stanford
 952 University Press, Stanford, California, 614 pp.
 953
 954 Scheidegger, K. F., and J. B. Phipps, 1976. Dispersal patterns of sands in Grays
 955 Harbor, estuary, Washington. Journal of Sedimentary Petrology 46, 163-166.
 956
 957 Shelford, V. E., 1935. Some marine biotic communities of the Pacific coast of North
 958 America. Ecological Monographs 5, 251-345.
 959
 960 Sherwood, C. R., Jay, D. A., Harvey R. B., Hamilton, P., and Simenstad, C. A., 1990.
 961 Historical changes in the Columbia River estuary. Progress In Oceanography
 962 25, 299-352.
 963
 964 Twichell, D. C., and Cross, V. A., 2001. Holocene evolution of the southern

965 Washington and northern Oregon shelf and coast: Geologic discussion and
 966 GIS data release, U.S. Geological Survey, Open File Report 01-076, 27 p., and
 967 CD Rom disk.
 968
 969 Twichell, D. C., Cross, V. A., Peterson, C. D., 2010. Partitioning of sediment on the
 970 shelf offshore of the Columbia River littoral cell. *Marine Geology* 273, 11–31.
 971
 972 Vanderburgh, S., Roberts, M. C., Peterson, C. D., Phipps, J. B., and Herb, A., 2010.
 973 Holocene transgressive and regressive deposits of the Columbia River littoral
 974 cell barriers and beach plains. *Marine Geology* 273, 32-43.
 975
 976 Vermeer M., and Rahmstorf, S., 2009. Global sea level linked to global temperature.
 977 *Proceedings of the National Academy of Sciences* 106, 21527-21532.
 978
 979 Walsh, T. J., Korosec, M. A., Phellips, W. M., Logan, R. L., Schasse. H. W., 1987.
 980 Geologic Map of Washington-Southwest Quadrant. Washington Division of
 981 Geology and Earth Resources Geologic Map GM-34 10p. and map 1:250,000
 982 scale
 983 [http://wadnr.s3.amazonaws.com/Publications/ger_gm34_geol_map_sw_wa_](http://wadnr.s3.amazonaws.com/Publications/ger_gm34_geol_map_sw_wa_250k.pdf)
 984 [250k.pdf](http://wadnr.s3.amazonaws.com/Publications/ger_gm34_geol_map_sw_wa_250k.pdf) Accessed September 17, 2015.
 985
 986 Zaitlin, B. A.; Dalrymple, R. W., and Boyd, R., 1994. The stratigraphic organization of

incised–valley systems associated with relative sea–level change. SEPM
Society for Sedimentary Geology, special Publication No. 51, 45–60.

Figure Captions

Figure 1: Location map of the study region including Grays Harbor, Willapa Bay and the Columbia River estuaries in the Columbia River littoral cell (CRLC), extending from Tillamook Head, Oregon (OR), north to Point Grenville, Washington (WA). Shelf bathymetric contours (lines) are in 20 m intervals relative to the mean sea level (MSL) datum. Tributaries entering the Chehalis River and the Grays Harbor basin directly are named. Drill core sites (17 solid squares) provide constraints on the compositions and ages of Holocene transgressive deposits in the Grays Harbor basin. Map coordinates are in degrees Lat and Long (°) and in UTM-10N kilometers, northing (N) and easting (E).

Figure 2: Grays Harbor ancestral valley sides near high-tide line (bold line), barrier sand spits (shaded), Chehalis, Wishkah, Hoquiam and Humptulips tributaries (named), tidal inlet > 10 m depth contour (dashed line), modern tidal channels > 1 m depth contour (dotted line), selected industry boreholes (open squares) and 17 drill core sites (solid squares). Map coordinates are in UTM-10N kilometers, northing (N) and easting (E).

Figure 3: Downhole compositions of weight percent gravel, sand and mud in drill core sites 1, 3, 10, 15 in the Grays Harbor basin (Figure 2). Data are from Appendix 1 in Supplemental Materials.

1011

1012 Figure 4: Downhole compositions of weight percent gravel, sand and mud in drill core sites
1013 5, 6, 8, 9 in the Grays Harbor basin (Figure 2). Data are from Appendix 1 in Supplemental
1014 Materials.

1015

1016 Figure 5: Downhole plots of mean grain size (mm) of the sand size fraction (0.06–2.00 mm
1017 grain diameter) in samples from drill core sites 1, 2, 8, 15 in the Grays Harbor basin (Figure
1018 2). Data are from Appendix 1 in Supplemental Materials.

1019

1020 Figure 6: Downhole plots of percent littoral sand component (%) in the fine sand fractions
1021 (0.06–0.25 mm diameter) of samples from drill core sites 1–9 in the Grays Harbor basin
1022 (Figure 2). The balance of the sand fraction composition is from estuary tributary sources
1023 (Table 2). Data are from Appendix 1 in Supplemental Materials.

1024

1025 Figure 7: Downhole plots of percent littoral sand component in the fine sand fractions
1026 (0.06–0.25 mm diameter) of samples from drill core sites 10–17 in the Grays Harbor basin
1027 (Figure 2). The balance of the sand fraction composition is from estuary tributary sources
1028 (Table 2). Data are from Appendix 1 in Supplemental Materials.

1029

1030 Figure 8: Downhole plots of the relative abundances of three sedimentary structure types in
1031 the Grays Harbor basin including 1) lag deposits of gravel, wood and/or shell fragments
1032 (Lag %), 2) cross-bedded sand (Xbed %) and 3) laminated mud (Lam %) in west-east drill
1033 core sites 1, 3, 15, 17 (Figure 2). The relative lack of apparent primary sedimentary

structures, via bioturbation or coseismic liquefaction, is not plotted downhole in Figure 8 but it is presented for all analyzed samples in Appendix 1 in Supplemental Materials.

Figure 9: Downhole plots of the relative abundances of three sedimentary structure types in the Grays Harbor basin including 1) lag deposits of gravel, wood and/or shell fragments (Lag %), 2) cross-bedded sand (Xbed %) and 3) laminated mud (Lam %) in north-south drill core sites 4, 6, 2, 8 (Figure 2). The relative lack of apparent primary sedimentary structures, via bioturbation or liquefaction, is not plotted downhole in Figure 9 but it is presented for all analyzed samples in Appendix 1 in Supplemental Materials.

Figure 10: Downhole plots of invertebrate assemblages (1, 2, 3) in drill core sites 1, 2, 3 in the westernmost area of the Grays Harbor basin (Figure 2). Species lists for each assemblage are listed in Table 3. Assemblages include estuarine mouth fauna (assemblage-1), hypoxic mud/sand flat fauna (assemblage-2), and estuarine channel fauna (assemblage-3). Assemblage abundances are based on shell fragment counts.

Figure 11: Isopach map of Holocene fill (10 m depth contours) in the defined Grays Harbor basin includes sand spit barriers (shaded), seismic profile lines (lines), drill holes (squares), industry borehole sites (circles), and sectors (dashed lines) lettered A–G. Map coordinates are in UTM-10N kilometers, northing (N) and easting (E).

Figure 12: Comparison plots of calibrated sediment ages from sand/mud deposits (open symbols) used to establish a sediment level curve (dashed line) and from intertidal peat deposits (solid symbols) used to establish a sea level curve (solid line) in Grays Harbor. Radiocarbon samples are from the western drill core sites 1–10 (squares) and the eastern

drill core sites 11–17 and boreholes A and H (circles) (Figure 2). One intertidal peat sample (CR W-73), from the Columbia River estuary (Columbia River), is added to the Grays Harbor plot to extend the sea level curve back ~11.5 ka at -71 m depth MS (Peterson et al., 2010b). Sediment deposit dates that occur at least ~10 m depth below the sea level curve are assumed to represent deeper channel cut-and-fill sequences. Two sediment deposit dates that are positioned above the sea level curve are attributed to remobilized ‘older’ radiocarbon materials. Data are from Table 5. Analytical errors for the sea level curve are estimated to be 1-3%, which fall within the symbol sizes used for sample dates and positions.

Figure 13: Three stages of basin filling at (A) -40 m (9.5 ka), (B) -20 m (7 ka), (C) -10 m (5 ka) in the Grays Harbor basin.

Figure 14: Plot of basin sediment volumes of gravel, littoral sand, river sand and mud components for six depth intervals (0-60 m depth MSL) that occurred during the Holocene transgression (0-11 ka) in the Grays Harbor basin. The shallowest depth interval (0–10 m depth MSL) is slightly reduced in volume due to subtracted channel bathymetry volume and subtracted prograded-shoreface volume (Table 4). Data are from Table 8.

Figure 15: Plot of total sediment volume accumulation rate ($\text{m}^3 \times 10^6 \text{ yr}^{-1}$) versus depth/time in the Grays Harbor basin. Data are from Table 9. Estimated analytical error (bars) are $\pm 0.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$.

Figure 16: Plot of total sediment volume accumulation rate versus increasing accommodation space rate in the Grays Harbor basin, as based on 10-m depth intervals

during the Holocene transgression (0–11 ka). A least-squares linear regression analysis (n=6 samples) yields a positive correlation ($R^2=0.81$). Data are from Table 9. Estimated analytical errors (bars) are $\pm 0.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$.

Figure 17: Plots of sediment component volume accumulation rates for six depth intervals (0–60 m depth MSL.) that occurred during the Holocene transgression (0–11 ka) in the Grays Harbor basin. Data are from Table 10. Estimated analytical error (bar) is $\pm 0.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$.

Figure 18: Plot of ratio between littoral sand volume accumulation rate and mud volume accumulation rate versus depth/time in the Grays harbor basin.

Figure 19: Ratios of total sand to mud accumulation rates versus estimated water depth (m) in the Grays Harbor basin. Sediment component accumulation rates for the six depth intervals are from Table 10. Water depths for the six depth intervals are taken from the differences of mid-point depths between the sea level curve and sediment level curve for corresponding ages (Figure 12).

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

KEY

- Drill core sites
- Sand spit positions
- Sandy mud
- Muddy sand
- Gravelly sand
- Ravinement surface
- 0 m contour MSL

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Table 1: Drill core sites and selected industry borehole logs in Grays Harbor.

Site #	UTMe	UTMn	Deposit depth and (type)/ basal deposit depth and relative age (H or P). Depth in meters (m) below MSL.
Industry			
OS1	411000	5204000	0–30 m (S), 30–35 m (MS), 35–40 m (GS)/ 40 m (H)
OS2	411000	5204000	0–22 m (S), 22–29 m (GS), 29–30 m (SM)/ 31 m (P)
OS3	411000	5209000	0–10 m (S), 10–20 m (SG, GS)/ ~15 m (P)
GW23	417000	5189700	0–22 m (S), 22–23 m (M), 23–39 (S)/ 39 m (H)
BH62	431000	5203000	0–35 m (SM), 35–45 m (MS), 45–56 (SG)/ 56 m (H)
H3	432500	5202500	0–28 m (MS), 28–40 m (Pt), 40–42 m (G)/ 42 m (H)
BH21	435000	5202000	0–40 m (SM), 40–50 m (GS), 50–62 m (G)/ 62 m (P)
BH35	436000	5201000	0–25 m (MS), 25–30 m (GS), 30–40 (SG)/ 40 m (P)
A3	436700	5201500	3–28 m (SM), 28–34 m (Pt), 34–37 (S), 38 (G)/ 38 (H)
BH60	440000	5202000	0–25 m (SM), 25–35 (MS), 35–45 (SG)/ 45 m (H)
BH25	442000	5201000	0–25 m (SM), 25–30 m (GS), 30–42 (G)/ 42 m (H)
Drill Core			
1	414300	5193200	0–61.5 m (H)/62 m (P)
2	416500	5193500	0.5–58.5 m (H)/59 m (P)
3	415400	5199500	6–61.5 m (H)/ 62 m (P)
4	413200	5205200	1–29.5 m (H)/ 30 m (P)
5	417800	5209800	1.5–5.5 m (H)/ 6 m (P)
6	418100	5203700	0.5–45 m (H)/ 45 m (H)
7	422100	5204800	1.5–5 m (H)/ 6 m (P)
8	422000	5197500	9.5–49.5 m (H)/ 49.5 m (H)
9	419800	5194000	1.5–6 m (H)/ 7 m (P)
10	424800	5199800	5–32.5 m (H)/ 32.5 m (H)
11	426000	5201000	6–37 m (H)/ 37 m (H)
12	428600	5201000	6–33.5 m (H)/ 33.5 (H)
13	429400	5198600	5.5–20.5 m (H)/ 21 m (P)
14	431500	5199300	4.5–13.5 m (H)/ 14 m (P)
15	434600	5201900	0.4–42.5 m (H)/ 42.5 m (H)
16	438500	5202400	11.5–46.5 m (H)/ 46.5 m (H)
17	440500	5202300	0–35 m (H)/ 35 m (H)

Notes: North spit boreholes OS1 (17/12-3R1), OS2 (17/12-3R2), OS3 (18/12-34C1) data are from the City of Ocean Shores. South spit borehole GW23 (GH-4962) data are from Herb (2000). Selected eastern basin boreholes include BH62 (ITN79-1/ITT Rainier), BH21 (IT-TR-24-5 ITT Rainier), BH35 (PA-CD18 Port of Aberdeen), BH60 (Dock Well Weyerhaeuser), BH25 (WPB17 Weyerhaeuser), H3 and A3 (Phipps et al., 2015). Deposit depths in meters and compositions: peat (Pt), mud (M), sand (S), gravel (G), and mixed compositions, for example: sandy gravel (SG). Drill core sites 1–17 include depths in meters of Holocene (H) deposits. Data are from Peterson and Phipps (1992). Basal deposits for all boreholes and drill core sites (designated by /) include depth in meters and relative age; unconsolidated Holocene (H) and weathered Pleistocene (P).

Table 2: Diagnostic heavy-mineral indicators of sand sources to the Grays Harbor basin.

River sand sources	Hypersthene: augite (ratio)	Littoral sand sources	Hypersthene: augite (ratio)
Chehalis-1	0.10	Ocean Shore beach	0.8
Chehalis-2	0.08	Vbwes01-surf zone	0.8
Chelhalis-3	0.06	DHwest1-7.5 m	0.8
Wishkah	0.02	Drill core site 1, n=5	0.83
Hoquiam	0.05		
Humptulips	0.02		
Drill core site 15, n=5	0.06		

Notes: Chehalis-1 is at the Montesano River confluence. Chehalis-2 is at the Satsop River confluence. Chehalis-3 is at Cosmopolis, WA. Wishkah is at the Wishkah River tributary head. Hoquiam is at the Hoquiam River tributary head. Humptulips is at the HW109 crossing. Drill core site 15 is in Grays Harbor estuary (Figure 2). Ocean Shore beach is at the modern beach backshore in the north spit. Vbwes01 is in the surf zone in the south spit. DHwest1 is located at drill core site 1 in the south spit at -7.5 m NAVD88 (Peterson et al., 2010b). The sample hypersthene:augite ratio is adjusted by subtracting the river end-member value (0.06) and then multiplied by the end-member range (0.77) to yield the littoral end-member component, as reported to the nearest 10 percent littoral sand contribution (Appendix 1 in Supplemental Materials). The combined river source(s) are represented by the balance of the sample sand composition, $\{(100\% - \text{littoral sand } \%) = \text{river sand } \%\}$.

Table 3: Invertebrate species list and assemblages.

Assemblage 1	Assemblage 2	Assemblage 3
<i>Clinocardium nuttalli</i> (Conrad)	<i>Macoma balthica</i> (Linne)	<i>Mytilus edulis</i> (Linne)
<i>Tresus capax</i> (Gould)	<i>Macoma inquinata</i> (Deshayes)	<i>Ostrea lurida</i> (Carpenter)
<i>Protothaca staminea</i> (Conrad)	<i>Macoma nasuta</i> (Conrad)	<i>Balanas glandula</i> (Darwin)
<i>Saxidomus giganteus</i> (Deshayes)	<i>Transenella tantilla</i> (Gould)	
<i>Nucella lamellose</i> (Gmelin)	<i>Solen siarius</i> (Gould)	
	<i>Cryptomya californica</i> (Conrad)	
	<i>Zifaea pilsbryi</i> (Lowe)	
	<i>Nassarius fossatus</i> (Gould)	

Notes: Species identified but not assigned to an assemblage: *Gari californica*, *Acmaeid* sp., *Odostomia* (Evalea) sp., *Odostomia* (Chrysallida) sp., crab fragments.

Table 4: Basin sediment volumes from 10-m depth intervals in seven basin sectors.

Cell depth interval (-m MSL)	Cell volume ($\times 10^6 \text{m}^3$)	Cell depth interval (-m MSL)	Cell volume ($\times 10^6 \text{m}^3$)
A:0-10	0	D:20-30	179
A:10-20	235	D:30-40	117
A:20-30	302	D:40-50	81
A:30-40	261	D:50-60	45
A:40-50	221	E:0-10	227
A:50-60	174	E:10-20	218
B:0-10	473	E:20-30	176
B:10-20	627	E:30-40	144
B:20-30	505	E:40-50	107
B:30-40	394	E:50-60	53
B:40-50	307	F:0-10	172
B:50-60	182	F:10-20	144
C:0-10	755	F:20-30	117
C:10-20	720	F:30-40	98
C:20-30	461	F:40-50	76
C:30-40	234	G:0-10	138
C:40-50	119	G:10-20	126
C:50-60	60	G:20-30	109
D:0-10	295	G:30-40	91
D:10-20	274	G:40-50	69

Notes: Seven east-west sectors (A–G) are divided into five or six 10-m depth intervals (0–60 m depth MSL) to form 38 cells in the Grays Harbor basin (Figure 11). Digitized surface areas (km^2) of the 0–10 m depth cells in the sectors A–C are adjusted by removing major channel bathymetry areas. The mid-point surface areas of the cells are multiplied by the cell depth (10 m) to yield cell volume ($\times 10^6 \text{m}^3$). Prograded shoreface volumes are removed from the cells in the 0–10 m depth range in the westernmost sectors (A, B).

Table 5: Calibrated radiocarbon dates from Grays Harbor drill cores and boreholes.

Site-sample	Lab ID#	Depth (m) MSL	Material	Adjusted date RCYBP	Cal $\pm 2\sigma$ date RCYBP	Median prob. RCYBP
04-01	20293	1.0	peat	830 $\pm$ 60	671-907	753
07-01	20308	1.5	detritus	620 $\pm$ 70	523-677	603
15-03	20296	2.0	wood	330 $\pm$ 100	255-540*	376
17-05	20529	4.5	peat	4120 $\pm$ 80	4438-4488	4651
02-04	20279	5.0	shell	1360 $\pm$ 70	737-1057	903
05-06	20309	5.0	detritus	3380 $\pm$ 80	3449-3835	3628
15-06	20297	6.5	wood	3190 $\pm$ 230	2809-3973	3403
A2-10.7	263291	8.0	wood	1130 $\pm$ 40	960-1174	1035
A5-9.7	263295	8.0	wood	1660 $\pm$ 40	1416-1694	1565
A4-12.8	264293	9.9	wood	1000 $\pm$ 40	796-975	919
A1-13.2	263290	10.0	detritus	4950 $\pm$ 40	5597-5842	5677
01-08	20283	10.0	shell	4760 $\pm$ 120	4704-5329	5035
17-07	20530	11.0	peat	5540 $\pm$ 80	6185-6495	6342
01-09	20957	11.5	shell	4020 $\pm$ 120	3718-4380	4042
08-02	20301	12.5	shell	4740 $\pm$ 100	4789-5285	5008
06-03	20528	12.5	shell	5080 $\pm$ 90	5246-5625	5434
15-10	20527	12.5	peat	5770 $\pm$ 140	6293-6893	6579
15-14	20299	13.5	detritus	7340 $\pm$ 140	7877-8409	8159
03-11	20287	14.5	shell	3570 $\pm$ 80	3268-3669	3466
03-14	20288	19.0	wood	6170 $\pm$ 80	6859-7261	7068
17-12	20531	20.0	peat	7350 $\pm$ 80	8009-8343	8166
06-06	20306	21.0	shell	6440 $\pm$ 110	6664-7187	6931
03-16	20291	22.0	shell	7320 $\pm$ 390	6973-8613	7806
A2-28.4	NOSAMS	25.9	peat	7960 $\pm$ 45	8649-8990	8834
A4-30.7	263294	27.9	peat	7710 $\pm$ 50	8413-8585	8493
H2-31.1	263297	28.0	peat	7720 $\pm$ 50	8417-8589	8499
H4-30.7	263300	28.5	peat	7690 $\pm$ 50	8401-8579	8480
17-16	20532	29.0	peat	7930 $\pm$ 120	8454-9086	8788
03-21	20289	29.5	shell	7350 $\pm$ 110	7589-8013	7811
02-20	20280	29.5	shell	7990 $\pm$ 90	8269-8683	8456
H1-32.9	263296	29.6	peat	7780 $\pm$ 50	8428-8641	8556
01-22	20284	31.0	shell	6040 $\pm$ 90	6276-6660	6464
15-24	20300	34.0	peat	8050 $\pm$ 110	8607-9259	8922
02-25	20281	37.0	shell	8940 $\pm$ 100	9407-9925	9627
A3-39.3	263292	37.4	peat	8860 $\pm$ 50	9744-10,172	9989
03-30	20290	43.0	shell	8730 $\pm$ 100	9116-9578	9386
H3-43.5	263299	43.5	peat	9150 $\pm$ 50	10,225-10,485	10,317
08-14	20304	47.5	shell	10,110 $\pm$ 270	10,420-12,027	11,141
02-35	20282	52.5	shell	9700 $\pm$ 130	10,248-10,958	10,600
03-41	20959	60.0	detritus	9710 $\pm$ 460	9915-12,555	11,154

CRw73*	131805	71.0	peat	11,550±80	11,550
--------	--------	------	------	-----------	--------

Notes: A and H borehole samples are from Phipps et. al., (2015); all other samples are from drill core sites 1–17, as reported in Peterson and Phipps (1992), but are recalibrated here using CALIB v7.1html (2015) <http://calib.qub.ac.uk/calib>. Accessed Dec. 4, 2015.

Sample A2-28.4 lab ID is NOSAMS-88068; all other sample lab IDs are from Beta Analytic Inc.

*Sample CRw73 is from the Columbia River estuary (Baker et al., 2010).

The sample 15-03 calibrated age is based on 0.863 relative area under the probability distribution, due its young age.

All shell material samples (shell) are calibrated under the MARINE13 ($\pm 2\sigma$) curve which includes a 400 yr (younger) Delta R; all other samples are calibrated under the IntCal13 ($\pm 2\sigma$) curve in radiocarbon years before present (RCYBP).

The median probability (Median prob.) values are presented from the calibrated probability distribution ($\pm 2\sigma$) curves derived from CALIB v7.1html (2015). Radiocarbon analytical uncertainties are on the order of 1-3 % for the majority of samples. Brackish peat deposits in Grays Harbor are restricted to 0.5–1.5 m mean tidal level (MTL) (Peterson et al., 2000) yielding a ± 0.75 m elevation analytical error, which corresponds to a 1.5% error at 50 m depth.

Table 6: Rates of sea level rise and sedimentation for 10 m-depth intervals.

Depth Interval -m (MSL)	Start sea level age (ka)	End sea level age (ka)	Sea level rise rate (m ka ⁻¹)	Start Sediment age (ka)	End Sediment age (ka)	Sedimentation rate (m ka ⁻¹)
0-10	6.0	0	1.7	5.0	0	2.0
10-20	8.2	6.0	4.5	7.0	5.0	5.0
20-30	9.1	8.2	11.1	8.3	7.0	7.7
30-40	10.1	9.1	10.0	9.6	8.3	7.7
40-50	10.6	10.1	20.0	10.4	9.6	12.5
50-60	11.1	10.6	20.0	11.1	10.4	14.3

Notes: Start and end ages (ka) for sea level and sedimentation at each 10 m-depth interval (-m MSL) in the Grays Harbor basin are taken from Figure 12. Rates of sea level rise and sedimentation (m ka⁻¹) are computed from the 10 m-depth intervals, as divided by corresponding age intervals. Based on analytical errors, as presented in Methods and outlined in Table 5, the rates of sea level rise and sedimentation are reported to 0.1 m ka⁻¹ accuracy.

Table 7: Averaged sediment compositions from 10-m depth interval cells in Grays Harbor

Cell ID, by sector: depth (-m MSL)	Average gravel (%)	Average total sand (%)	Average mud (%)	Average littoral sand (%)
A Ave: 0-10	0	98	2	100
B Ave: 0-10	7	91	2	100
C Ave: 0-10	2	78	20	63
D Ave: 0-10	0	85	15	63
E Ave: 0-10	0	87	13	48
F Ave: 0-10	0	63	37	15
G Ave: 0-10	0	9	91	0
A Ave: 10-20	9	88	3	100
B Ave: 10-20	8	69	23	91
C Ave: 10-20	0	78	22	98
D Ave: 10-20	0	77	23	50
E Ave: 10-20	4	85	11	38
F Ave: 10-20	0	85	15	18
A Ave: 20-30	6	92	2	100
B Ave: 20-30	4	78	18	88
C Ave: 20-30	9	48	43	74
D Ave: 20-30	0	70	30	32
E Ave: 20-30	0	71	29	13
F Ave: 20-30	0	24	76	0
A Ave: 30-40	10	87	3	100
B Ave: 30-40	1	40	59	75
C Ave: 30-40	3	30	67	20
D Ave: 30-40	4	76	20	15
E Ave: 30-40	8	72	20	0
F Ave: 30-40	22	49	29	0
G Ave: 30-40	33	42	25	0
A Ave: 40-50	0	88	12	99
B Ave: 40-50	0	66	34	88
C Ave: 40-50	41	35	24	5
D Ave: 40-50*	25	75	0	0
E Ave: 40-50*	25	75	0	0
F Ave: 40-50	92	8	0	0
G Ave: 40-50	71	25	4	0
A Ave: 50-60	0	93	7	97
B Ave: 50-60	1	68	31	88
C Ave: 50-60*	25	75	0	0
D Ave: 50-60*	50	50	0	0
E Ave: 50-60*	50	50	0	0

Notes: Averaged sediment sample depths (-m MSL) and sample compositions are shown for each 10-m depth interval cell in each sector (A–G), based on sediment sample data from the 17 drill core sites in the Grays Harbor basin (Appendix 1 in Supplemental Materials). Averaged gravel (%), sand (%), and mud (%) fractions are based on measured weight fractions. Some cells in the eastern basin sectors C–E (*) at 40–60 m depths were not adequately sampled due to poor sample recovery (Appendix 1 in Supplemental Materials). Averaged compositions in these cells were based on the few samples that were recovered or from nearby cells at equivalent depths. Sector boundaries are shown in Figure 11.

Table 8: Cell and basin depth interval volumes of sediment components.

Cell ID: by sector: depth interval (-m MSL)	Gravel volume ($\times 10^6 \text{ m}^3$)	Littoral sand volume ($\times 10^6 \text{ m}^3$)	River Sand volume ($\times 10^6 \text{ m}^3$)	Mud volume ($\times 10^6 \text{ m}^3$)
A: 0-10	0	0	0	0
B: 0-10	31	432	0	10
C: 0-10	15	367	220	152
D: 0-10	0	157	94	44
E: 0-10	0	93	103	30
F: 0-10	0	16	92	63
G: 0-10	0	0	12	126
Sum: 0-10	46	1066	522	425
A: 10-20	21	207	0	7
B: 10-20	48	395	39	146
C: 10-20	0	549	9	160
D: 10-20	0	106	106	62
E: 10-20	8	71	115	24
F: 10-20	0	21	100	22
G: 10-20	1	0	90	35
Sum: 10-20	78	1349	458	456
A: 20-30	18	278	0	6
B: 20-30	19	349	46	91
C: 20-30	41	162	59	197
D: 20-30	0	40	86	54
E: 20-30	0	17	108	52
F: 20-30	0	0	28	89
G: 20-30	1	0	48	60
Sum: 20-30	79	846	375	548
A: 30-40	26	227	0	8
B: 30-40	4	118	39	234
C: 30-40	7	14	57	156
D: 30-40	5	13	76	23
E: 30-40	12	0	104	28
F: 30-40	21	0	48	28
G: 30-40	30	0	39	22
Sum: 30-40	105	373	362	500
A: 40-50	0	192	2	26
B: 40-50	0	179	24	104
C: 40-50	49	2	39	28
D: 40-50*	20	0	61	0
E: 40-50*	27	0	80	0
F: 40-50	70	0	6	0
G: 40-50	49	0	17	3
Sum: 40-50	214	373	230	161
A: 50-60 [#]	0	160	2	12

B: 50-60 [#]	2	110	14	56
C: 50-60 [*]	15	0	45	0
D: 50-60 [*]	22	0	22	0
E: 50-60 [*]	27	0	27	0
Sum: 50-60	66	270	110	68

Notes: Cell sediment volume data ($\times 10^6 \text{ m}^3$) from Table 4 are arranged by 10-m depth intervals for each sector (A–G) and are then summed (Sum) to yield basin volume ($\times 10^6 \text{ m}^3$) for each 10 m-depth interval in the Grays Harbor basin. The cell volume data are multiplied by averaged size fraction and sand source composition data (Table 7) to yield cell sediment component volumes ($\times 10^6 \text{ m}^3$) for gravel, littoral sand, river sand and mud. The cell sediment component volumes are summed for each 10-m depth interval to yield basin sediment component volumes ($\times 10^6 \text{ m}^3$).

Table 9: Rates of increasing basin accommodation space and basin total sediment volume accumulation.

Depth interval (-m MSL)	Ancestral basin volume ($\times 10^6 \text{ m}^3$)	Sea level age interval ($\times 10^3 \text{ yr}$)	Interval duration $\times 10^3 \text{ yr}$	Accommodation space increase rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)
0-10	2060	0-6.0	6.0	0.34
10-20	2344	6.0-8.2	2.2	1.07
20-30	1849	8.2-9.1	0.9	2.05
30-40	1340	9.1-10.1	1.0	1.34
40-50	979	10.1-10.6	0.5	1.96
50-60	514	10.6-11.1	0.5	1.03
Depth Interval (-m MSL)	Basin sediment volume ($\times 10^6 \text{ m}^3$)	Sediment level age interval ($\times 10^3 \text{ yr}$)		Basin sediment volume accumulation rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)
0-10	2060	0-5.0	5.0	0.41
10-20	2344	5.0-7.0	2.0	1.17
20-30	1849	7.0-8.3	1.3	1.42
30-40	1340	8.3-9.6	1.3	1.03
40-50	979	9.6-10.4	0.8	1.22
50-60	514	10.4-11.1	0.7	0.73

Notes: Rates of sea level rise and corresponding rates of increasing basin accommodation space in the Gays Harbor basin are based on volumes and age spans of the 10-m depth intervals (-m MSL). The ancestral basin volume data ($\times 10^6 \text{ m}^3$) are from Table 4 and the sea level age intervals ($\times 10^3 \text{ yr}$) are from Table 6. The 10-m depth interval volumes are divided by the sea level age intervals to yield the rates of increasing basin accommodation space ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$). Sediment level age intervals ($\times 10^3 \text{ yr}$) are from Table 6 and the basin sediment volume fill data are from Table 8. The 10-m depth interval sediment volumes are divided by the sediment level age intervals to yield the rates of basin sediment volume accumulation ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$).

Table 10: Basin accumulation rates of gravel, littoral sand, river sand and mud.

Depth interval (-m MSL)	Interval duration ($\times 10^3$ yr)	Gravel accumulation rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Littoral sand accumulation rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	River sand accumulation rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Mud accumulation rate ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)
0-10	5.0	0.01	0.21	0.10	0.08
10-20	2.0	0.04	0.67	0.23	0.23
20-30	1.3	0.06	0.65	0.29	0.42
30-40	1.3	0.08	0.29	0.28	0.38
40-50	0.8	0.27	0.47	0.29	0.20
50-60	0.7	0.09	0.38	0.16	0.10

Notes: Sediment component volume accumulation rates ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$) are computed for gravel, littoral sand, river sand and mud in the Grays Harbor basin. Depth interval time spans are from the sediment level data in Table 6. Sediment component volumes for the six 10-m depth intervals (0–60 m depth MSL) are from Table 8.

Table 11: Ratios of modern river sediment input to basin increasing accommodation space.

Estuary/ depth interval (-m)	Modern river sediment input ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Basin increasing accommodation space ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Ratio of modern river sediment input to increasing accommodation space
Columbia R.V.	14		
0–10		0.7	6.4
10–20		2.9	1.6
20–30		3.4	1.4
Grays Harbor	0.45		
0–10		0.34	1.3
10–20		1.07	0.4
20–30		2.05	0.2

Notes: Average modern sediment supply rate in the Lower Columbia River Valley (Columbia R.V.) is estimated to be $9.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. Basin increasing accommodation space data shown for the lower Columbia River Valley (Peterson et al., 2013) and Grays Harbor (Table 9).