GREAT EARTHQUAKES, ABUNDANT SAND, AND HIGH WAVE ENERGY IN THE COLUMBIA CELL, USA

Curt D. Peterson[1], Guy R. Gelfenbaum[2], Harry M. Jol[3], Jim B. Phipps[4], Frank Reckendorf[1], Dave C. Twichell[5], Sandy Vanderburg[6], Lorraine Woxell[1].

Abstract: Great earthquakes, abundant sediment supply, and high wave energy in the Columbia cell (165 km long) have conspired to produce alternating conditions of dramatic beach progradation and catastrophic beach retreat. These late-Holocene fluctuations are superimposed on the bidirectional longshore dispersal of sand (several million cubic meters per year) that was pumped through the Columbia River mouth. Beach plains on either side of the Columbia River began to prograde at 5-4 ka. Progradation was delayed until 2-1.5 ka in the two northern subcells located 50-100 km north of the Columbia River. Evidence of alternating rapid progradation and catastrophic retreat is shown respectively, by abandoned linear-dune ridges (maximum of 7 in 4 ka) and buried-linear scarps mapped with ground penetrating radar (GPR). The youngest scarp is correlated to the AD 1700 Cascadia earthquake, and extends at least 120 km longshore. Accretion rates in the subcells are measured for the following intervals: backedge-AD 1700, AD 1700-early historic, and historic (1870-1995). Late-Holocene accretion rates were small (0.5 m yr-1) and relatively uniform within each subcell. By comparison, historic accretion rates were very-large (2-6 m yr-1) and highly asymmetric. Given the past records of sand dispersal and the recent termination of Columbia River sand supply, several outcomes can be predicted. Massive historic accumulations of sand on either side of the Columbia River mouth, and at Grays Harbor, are likely to be redistributed within their respective subcells.

INTRODUCTION

Hotspots of erosion are now occurring in the once sand-glutted barriers of the Columbia littoral cell (Figure 1; Kaminsky et al., this Proceedings). Some of the hotspots reaffirm an end to the rapid beach progradation experienced during the early part of this century (Phipps and Smith, 1978; Phipps, 1990). The factors leading to the diminished sand supply possibly include post-jetty shoreline reconfigurations (early 1900's-present), damming of the Columbia River system (mid 1900's-present), and removal of dredged sand from the littoral system (mid 1900's-present)(Gelfenbaum et al., 1997).

The relative impacts of these anthropogenic effects are difficult to isolate as they overlap in time and are not well documented in early-historic records. Furthermore, the brief historic period, i.e., about 100 years, does not record the system's response to terminated sand supply, or to disequilibria of longshore sand distribution. Framework studies of longer-term depositional records in the Columbia littoral system are underway to address these points. In this paper we present

1) Geology Department, Portland State Univ. Portland, OR 97207
2) Coastal and Marine Geology, U.S.G.S., Menlo Park, CA 94025
3) Geography Department, Univ. of Wisconsin-Eau Claire, WI 54702
4) Grays Harbor College, Aberdeen, WA 98520
5) Marine Geology, U.S.G.S., Woods Hole, MA, 02543
6) Univ. College of Fraser Valley, Abbotsford, B.C. Canada V2S7M9

preliminary estimates of barrier accretion rates from historic, late-prehistoric, and late-Holocene periods. The accretion rates document (1) delayed barrier accretion with increasing separation from the Columbia River mouth in late-Holocene time, and (2) contrasting longshore distributions of littoral sand between the prehistoric- and historic-periods. These study results have implications for the future redistribution of modern beach sand in the four subcells of the Columbia littoral system.

BACKGROUND

The Columbia littoral cell experiences interseismic uplift and coseismic subsidence (1-2 m) associated with great Cascadia earthquakes (Atwater, 1987). Episodic coseismic subsidence is recorded in numerous tidal-marsh deposits throughout the study area (Barnett, 1997). The buried marsh records demonstrate earthquake recurrence intervals of 500±300 (Atwater, and Hemphill-Haley, 1996). Based on Bruun's rule, an abrupt tectonic subsidence of 1.5 m could result in 200-400 m of catastrophic beach retreat throughout the littoral cell (Doyle, 1996). Between the earthquakes rapid shoreline progradation resulted from rebound-uplift, an abundant sand supply, and effective longshore dispersal of the available sand. Net accretion of the barrier-beaches preserves the geologic record of episodic progradation forced by the tectonic strain cycles (Meyers et al., 1996). The Columbia River is thought to have delivered several million cubic meters of bedload annually to the coast, prior to dam regulation (Gates, 1994; Gelfenbaum et al., this Proceedings). The distinctive volcanic-arc mineralogy of the Columbia River sand has been traced across the shelf (White, 1967) and northward to Grays Harbor (Scheidegger and Phipps, 1976). The sand mobility derives from winter high-wave energy with peak significant-wave heights (H1/3) in excess of 7 m (Tillotson and Komar, 1997). Due to the low gradient of the inner-shelf, e.g., mean gradient 0.004 (Doyle, 1996) the largest waves shoal more than a kilometer offshore. The abundant supply of fine-sand (mean diameter 0.2 mm) yields dissipative beach slopes (mean slope 0.02) throughout the Columbia cell (Peterson et al., 1994). Deep-water wave angle varies seasonally but, large winter surf out of the southwest yields a slight net-northward littoral drift (Gelfenbaum et al., this Proceedings).

STUDY AREA

The longshore dispersal of Columbia River sand has produced wide beaches between Point Grenville and Tillamook Head (Ballard, 1964). The upper-shoreface of the cell (160 km in length) is divided into four subcells by tidal inlets of the Columbia River estuary, Willapa Bay and Grays Harbor (Figure 1). Holocene tidal-basin filling has been investigated in Grays Harbor (Peterson and Phipps, 1992) and the lower Columbia River valley (Gates, 1994). Results of those preliminary studies indicate 2-4 fold decreases in basin fill rates following the declining rates of sea-level rise after 7 ka. Holocene total-sediment thickness on the inner-continental shelf decreases from offshore of the Columbia River mouth (40 m thick) to offshore of the adjacent subcells (20 m thick) to offshore of the northernmost subcell (0-5 m thick) (Figure 2). The decrease in inner-shelf sediment thickness is largely attributed to decreasing accommodation space to the north. Tectonic uplift, since the 83 ka eustatic high-stand, increases from 10-15 m at the southern end of the cell (Mulder, 1992) to 30-35 m at the northern end of the cell (West and McCrumb, 1988). Incisions of the shelf platform by the antecedent Columbia River and lateral tributaries during the last glacial interval (20-15 ka) further lowered the topography prior to the Holocene transgression (Cross et al., 1998). The NNW inflection of the shoreline at the northern end of the cell reflects the greater tectonic uplift, and retarded retreat of the northernmost coastline. The cell bounding headlands, e.g., Tillamook Head, Cape Disappointment, and Point Grenville (Figure 1) all derive from erosion-resistant basalt, locally faulted or emplaced into surounding Tertiray mudtones. Remnant Pleistocene deposits are exposed in bay- and sea-cliffs (Clifton et al., 1989) that rim the Columbia cell embayment. In summary, much of the cell's geomorphology arises from its inherited structural elements. These elements include resistant basalt headlands, antecedent river-valleys, and regional tectonic warping in an active-margin setting.

METHODS

This paper focuses on barrier beach-plain accretion in the Ocean Shores, Grayland, Long Beach and Clatsop subcells (Figure 2). Barrier width decreases from 2-3 km near the Columbia River mouth to less than 0.3 km in the northern beaches. The detailed records of tectonically-influenced barrier accretion in the Long Beach subcell (Meyers et al., 1996) are now extended to the other three subcells. These geologic records of episodic accretion are documented with (1) airphoto-mossaics of linear beach ridges, after Cooper (1958) and Rankin (1983), and (2) ground penetrating radar (GPR) profiles of subsurface erosion scarps (Jol et al., 1999). Groundtruthing of the airphoto and GPR records is accomplished by vibracoring and sand-augering of shallow (3-10 m) stratigraphic sections (Woxell, 1998). Three time scales of barrier accretion records are of interest including (1) a historic record to verify process modeling, (2) a prehistoric record of several centuries to document pre-anthropogenic trends or cycles, and (3) a millennial scale record to establish beach response to evolving cell morphology. Rates of historic accretion (AD 1870-1995) are estimated from historic shoreline positions analyzed by the Washington Department of Ecology (Kaminsky et al., this Proceedings). Latest-prehistoric accretion records (AD 1700-1880) are based on a paleoshoreline correlated to the last great Cascadia earthquake (Meyers et. al., 1996; Woxell, 1998). Late-Holocene accretion rates (4-0.3 ka) are based on reported radiocarbon dates from the backedges of the beach plains (Rankin, 1983; Peterson and Phipps, 1992; Meyers et. al., 1996; Woxell, 1998).

RESULTS

Estimated Ages of Beach Accretion

The ages of initial beach accretion in the Columbia subcells are estimated from compilations of sample C14 ages taken from the backedges of the barrier beach plains (Figure 2). The samples include (1) drift wood in beach sand deposits, and (2) basal peat in freshwater bogs between dune ridges (Table 1). The peat develops well after beach progradation in response to rising water table and valley flooding. Comparisons of beach wood- and basal peat-C14 dates (Woxell, 1998) show that the basal peat deposits post-date the onset of beach plain progradation by at least 0.5-1 ka.

Table 1. West and East C14 Dates From The Columbia Cell Barriers

Reference	UTM	Lab #	C14 Age*	Material
(1) COPA1	5218308-410710	Beta 109952	680+-50 BP	Shell
(1) RAIN5	5206942-412764	Beta 116545	720+-40 BP	Wood
(2) Site#4-1	5203970-413320	Beta 20293	830+-60 BP	Peat
(1) COUN2	5182660-417743	Beta 116541	990+-60 BP	Peat/Wood
(1) NSMI5	5177358-418772	Beta 116542	910+-40 BP	Peat

(3) BIGD	5176100-417000	Beta 22386	230+-70 BP	Wood
(4) SMITH	5175820-418605	Beta 108535	3550+-40 BP	Wood
(5) SANDR	5151230-421383	TO 4831	4250+-70 BP	Wood
(5) 1WLOM	5143155-419105	Beta 79506	300+-70 BP	Wood
(6) BRIS	5137190-419095	Beta 111641	470+-60 BP	Peat
(1) SEVE1	5133033-418826	Beta 109955	130+-40 BP	Wood
(1) SECO1	5109242-426819	Beta 116546	180+-60 BP	Paleosol
(1) PERK	5108572-429006	Beta 116544	3110+-70 BP	Peat/Wood
(7) #4	5101270-430850	UW 602	4050+-70 BP	Wood
(7) #7	5101080-430655	UW 605	3070+-65 BP	Peat
(1) PAUL1	5100555-428370	Beta 109954	160+-50 BP	Paleosol
(8) PALMR	5091600-428490	Beta 28852	3650+-100 BP	Charcoal

References: (bold=eastern backedge sample, nonbold=westernmost scarp, pond or paleosol sample); (1) Woxell, 1998, (2) Peterson and Phipps,1992, (3) Phipps et al., 1997, (4) Bender, 1998, (5) Meyers et al., 1996, (6) Schlicting and Peterson, unpublished data, 1998, (7) Rankin, 1983, (8), Connolly, 1995.
* Conventional C14 Age +-1 standard deviation, in radiocarbon years (BP)

Estimates of initial progradation in the subcells are as follows: Long Beach (5 ka), Clatsop (4 ka), Grayland (2 ka), and Ocean Shores (1.5 ka). In the Ocean Shores subcell the beach plain pinches-out north of Copalis River, leaving only the active beach to front the recently eroded sea-cliffs. Progradation of the northern beaches is not addressed in this report but, probably began following rebound from the last coseismic subsidence event (0.3 ka)

The episodic nature of barrier accretion is demonstrated by shore-parallel dune ridges that occur in each of the barrier beach plains. The very-linear nature of the prehistoric shorelines possibly reflects uniform energy dissapation across the low-gradient shoreface (see Background and Study Area). Across-barrier profiles from each subcell (Figure 2) demonstrate a reduction in the number of linear ridges from Long Beach (5-8) and Clastop (5-7) to Grayland (2-4) and Ocean Shores (1-2) (Cooper, 1958; Rankin, 1983; Meyers et al., 1996). The reduction in the number of subcell dune ridges roughly corrresponds to the decrease in age of subcell backedges. Work is now underway to correlate the dune ridges between the subcells. However, the youngest ridge has been correlated between the subcells on the bases of continuity (Phipps et al., 1997), radiocarbon dates (Table 1), and buried scarp signatures (Jol et al., 1999). Buried erosion scarps are identified in across-barrier GPR records taken at 5 km intervals in the subcells (Figure 2). Paired scarps are commonly identified on the western flank of the latest-prehistoric dune ridge (Figure 3). Auger and vibracoring logs (1-10 m depth) demonstrate that the buried scarps are backfilled with heavy-mineral placers, i.e., magnetite- and ilmenite-bearing black sand (Woxell, 1998). The two scarps represent two catastrophic events of beach retreat, resulting from coseismic subsidence. The paired scarps are associated with young paleosols in the dune ridge, indicating reactivation of dune-ridge accretion. The burial of vegetated dune soils by reactivated dune-ridge accretion occurs after the catastrophic retreat, but before dune ridge abadonment by rapid beach progradation (Figure 3). The timing of dune ridge formation is limited, but not well constrained. By comparison, the westernmost prehistoric-scarp age is well constrained, i.e., the last great Cascadia earthquake at AD 1700 (Satake et al., 1996) thereby representing the shoreline position very-close to that time.

Estimates of Accretion Rates

Accretion rates for the Columbia cell beaches are based on four shoreline positions (time lines) established for each subcell. The dated shoreline positions include: (1) backedge or onset of accretion, (2) AD 1700 retreat scarp, (3) 1870-1885 early-historic shoreline (Washington Department of Ecology), and (4) the 1995 modern shoreline (Washington Department of Ecology). The backedges of the barriers are irregular due to bay-side erosion or to gullying and slumping of the paleosea-cliffs. For these reasons either the oldest continuous dune ridge or a straight-line at the foot of the paleosea-cliff is used for the back-edge shoreline. In the case of Long Beach, a 4.2 ka dune-ridge is used for the backedge shoreline.

Figure 3: Diagram of paired coseismic-retreat scarps (two dashed lines) terminating seaward dipping shoreface strata (1-2° dip) produced by beach progradation between great earthquakes. The dunal paleosol indicates reactivation of the latest-prehistoric dune ridge (Big Dune) after shoreline retreat from the last Cascadia earthquake (AD 1700). Figure from Woxell (1998).

The AD 1700 scarp is typically 10's of meters in width so, the landward edge of the buried scarp is mapped from the GPR record. The position of the AD 1700 scarp is extrapolated between GPR profiles, taken at 5 km intervals, or mapped at the seaward flank of the latest-prehistoric dune ridge (Woxell, 1998). Distances between the mapped shorelines are measured east-west from 1:6000 orthophoto base maps. Shoreline position errors are estimated to be ± 10 m. The backedge ages have assumed uncertainties of ± 500 years, based on ranges of radiocarbon dates (Woxell, 1998).

The accretion rates for the three time intervals are plotted together with corresponding error estimates with respect to distance alongshore (Figure 4). The net geologic accretion rates, i.e., backedge to AD 1700 scarp, from all four subcells are on the order of 0.5-1 m yr-1. These rates are based on the interval during which each subcell prograded. Alternatively, the younger subcells, Grayland (2 ka) and Ocean Shores (1.5 ka), show about half the accretion rates of the older subcells, Long Beach and Clatsop, when compared to a common starting time, i.e., 4 ka. The longshore trend of the accretion rate is relatively flat for each subcell, demonstrating a uniform, net accretion within each subcell over the corresponding geologic period of progradation.

Figure 4: Retreate rates for Ocean Shores subcell (upper) and Grayland subcell (lower)

Figure 4: Retreat rates for Long Beach subcell (upper) and Clatsop subcell (lower).

The last tectonic-cycle of accretion in each subcell is represented by the AD 1700 scarp-historic shoreline (1870-1885). Accretion rates from this interval range from 0.5 to 3 m yr-1. The longshore trends of accretion rates are variable both within and between the cells (Figure 4). For example, high rates of accretion (2-3 m yr-1) at the southern end of Ocean Shores subcell fall off to very-low rates (0-0.5 m yr-1) at its northern end. The AD 1700 scarp-historic interval in the Long Beach subcell shows accretion rates below 0.5 m yr-1 for all but the northern tip. The accretion rates for this interval are low and uniform for the Clatsop subcell (about 0.5 m yr-1) but, show upturns at the opposite ends of the Grayland subcell (reaching 2 m yr-1). Although not shown in these data, the increase in post-1700 AD scarp accretion near the northern ends of the Long Beach and Grayland subcells appear to be associated with northward spit elongation.

By comparison to the small and relatively uniform rates of prehistoric accretion (above) the historic accretion rates are quite large (2-6 m yr-1) and strongly asymmetric (Figure 4). For example, historic accretion rates (1870-1995) exceed 5 m yr-1 at the southern ends of the Ocean Shores, Grayland, and Long Beach subcells. The opposite trend for this historic interval (1885-1995) occurs in the Clatsop subcell where accretion rates exceed 5 m yr-1 at its northern end. Neither the large rates of historic accretion nor the obvious asymmetry of historic sand distribution within the subcells are displayed by the prehistoric accretion intervals.

DISCUSSION

Net beach accretion preserves a geologic record of cyclic beach-plain progradation in the Columbia cell during late-Holocene time. The earliest westward accretion of the intact Long Beach barrier at 4-5 ka (Table 2) follows on the heals of declining rate of eustatic sea-level rise (7 ka) and increased bypassing of bedload through the Columbia River tidal basin (see Background and Study Area). However, the barrier plains accretion is delayed by several thousand years with increasing distance north from the Columbia River mouth. The delayed onsets of subcell progradation are consistent with a decrease in the number of linear-dune ridges with distance north of the Columbia River (Table 2). The northward lag in subcell response to Columbia River sand supply argues for sequential filling of available 'accommodation' space within the littoral system. The beaches and inner-shelf provided accomodation space for littoral sand (see Background and Study Area). However, the backedge time gaps on either side of Willapa Bay and Grays Harbor (Table 2) attest to the importance of these tidal basins as sand sinks between 5 ka and 1.5 ka. The lack of a synchronous onset of progradation throughout the Columbia cell argues against an across-shelf supply of littoral sand to the barriers in late-Holocene time.

Measured accretion rates between and within the Columbia subcells establish the shoreline response to both regional and local sand supply. The accretion rates are

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Tabel 2. Summary of Subcell Late-Holocene Progradation

Subcell Name	Mid-distance From Columbia R. (km)	Ridges Maximum Number	Onset 'Backedge' C14 Dates (ka)	Prehistoric Averag Width (km)
Ocean Shores**	90	2	1.5	770
Grayland	70	4	2	1100
Long Beach	20	8	4-5	1690
Clatsop	15	7	4	2470

Distance= Subcell midpoint distance from the Columbia River mouth.
Ridge Number= Maximum number of linear ridges in subcell.
Onset 'Backedge' Dates= Thousand years (ka) before present from C14 analyses.
Prehistoric Width=Average barrier-plains width from back-edge to AD 1700 scarp.
** Subcell north to the Copalis River

averaged along the length of each subcell (Table 3) to compare regional sand distribution between the Columbia subcells. Average accretion rates for the 4 ka-AD 1700 interval demonstrate decreasing accretion rates from 0.5-0.6 m yr-1 for the southern two subcells to 0.2-0.3 m yr-1 for the northern two subcells. The average accretion rates for the backedge date-AD 1700 interval show little variation (0.5-0.6 m yr-1) between the subcell barrier-beach plains. Significant amounts of sand must have bypassed the Long Beach subcell to have supplied the rapidy accreting northern subcells after 1.5-2 ka. The AD 1700-historic interval represents prehistoric accretion after the last Cascadia earthquake. Average accretion rates from this interval show a dramatic increase from 0.3-0.5 m yr-1 in the southern subcells to 1.2-1.8 m yr-1 in the northern subcells. These results demonstrate substantial bypassing of sand from the southern subcells to the northern subcells during the period of shoreline recovery from the last event of catastrophic retreat. Prehistoric tidal inlets at Willapa Bay and Grays Harbor were not effective in blocking northward sand transport during the latest prehistoric interval.

By comparison to any of the averaged prehistoric-accretion rates, the averaged historic rates (late 1800's-1995) are very-large indeed (3.2-3.4 m yr-1)(Table 3). The averaged historic-accretion rates are five-fold larger than corresponding prehistoric rates in the Clatsop and Long Beach subcells. The source(s) of sand producing these anomalous accretion rates during the historic interval are derived, in large part, from degrading ebb-tide deltas at the mouth of the Columbia River (Phipps, 1990) and Grays Harbor (Gelfenbaum et al., this Proceedings). The great asymmetries of historic sand distribution next to the harbor mouth jetties (Figure 4) confirm the ebb-tide deltas as the immediate sources of historic beach-sand accretion. However, the ultimate source of sand that produced the ebb-tide deltas was the Columbia River. In the absence of any new sand supply from the impounded Columbia River system, the existing shorelines will realign to long-term 'geologic' equlibrium conditions. For example, prehistoric shorelines extending north of paleoheadlands serve as proxies for future shorelines extending north of the large jetties in the Columbia cell. The Long Beach subcell prograded to the seaward extent of Cape Dissapointment (2 km) under the influence of abundant sand supply from the Columbia River (Figures 1 and 2). By comparison, beach sand in the Clatsop subcell never did reach the base of Tillamook Head (3-4 km projection) where cobble beaches existed until early-historic time (Fiedorowicz, 1997). The prehistoric Clatsop subcell owed its sustained beach progradation to Columbia River sand trapped south of Cape Disappointment. With no bounding headlands to the north, and no continuing sand supply from the south, the large historic-sand volumes that accumulated just north of the Columbia River and Grays Harbor will be gradually redistributed within the cell system.

Table 3. Summary of Subcell Accretion Rates

Subcell Name	4 ka Accretion Rate (m yr-1)	Onset Accretion Rate (m yr-1)	AD 1700 Accretion Rate (m yr-1)	Historic* Accretion Rate (m yr-1)
Ocean Shores**	0.2	0.6	1.8	3.4
Grayland	0.3	0.6	1.2	3.4
Long Beach	0.5	0.5	0.3	3.2

Clatsop	0.6	0.6	0.5	3.3

4 ka Accretion Rate= Barrier accretion rates from 4 ka to AD 1700
Onset Accretion Rate= Accretion rates from backedge date to AD 1700
Historic Accretion= Accretion rates from AD 1700 to 1870-1885
*Data from Washington Department of Ecology.
** Subcell north to the Copalis River.

CONCLUSIONS

The late-Holocene history of net beach accretion in the Columbia River littoral cell demonstrates episodic progradation and catastrophic retreat, corresponding to multi-century tectonic-strain cycles. The episodic accretion is superimposed on a millennial time-scale record of sand dispersal from the Columbia River mouth. The sequential filling of accomodation space in beach, shelf, and bay settings delayed the onset of subcell progradation by several thousand years with increasing distance from the Columbia River source. However, bypassing of sediment to the northern subcells became increasingly efficient during the last several strain cycles. The shore-parallel development of alternating beach-dune ridges and linear erosion scarps demonstrates the subcell's rapid response to episodes of sediment supply and starvation. Both long-term and short-term accretion rates are small and relatively uniform within each subcell. By contrast the historic period is characterized by large, asymmetric accumulations of sand near harbor mouth jetties. The modern shoreline geometry appears to be in disequilibria, when compared to prehistoric records of sand distribution within the Columbia littoral cell.

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