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BATHYMETRIC CHANGE OFF THE WASHINGTON-OREGON COAST

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Abstract: Historical hydrographic data from the Washington/Oregon shelf are compared for the first time to identify bathymetric change on a regional scale. Offshore data sets exist for four time periods: 1800s, pre-1950s, post-1950s, and 1990s. Data from only two time periods, 1868-87 and 1926-27, cover the entire offshore region between Tillamook Head, Oregon and Grays Harbor, Washington. A confidence interval of +/-1.7m is established for the bathymetric comparison between these two data sets. Wide trackline spacings within the 1868/87 surveys, sounding errors due to horizontal positioning inaccuracies and heavy seas and currents encountered during the surveys, questionable tidal correction methods, and vertical datum inconsistencies, compose most of the uncertainties in this data set. Surveys collected closer to shore, in water depths less than -30m, contain smaller errors and define the sea-floor morphology well. Errors and uncertainties increase with depth and distance offshore. Comparison between these two surveys shows large areas of both accretion and erosion on the shelf between the shoreline and -70m of water, with the greatest change occurring off the mouth of the Columbia River. Quantitative analysis and interpretation of the regional bathymetric changes within the Columbia River Littoral Cell should be approached with caution and with a thorough knowledge of the error distribution and uncertainties associated with the data set.

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INTRODUCTION

The southern Washington and northern Oregon coast has experienced a long history of sediment accretion and high-energy conditions. During the Holocene, large amounts of sediment carried down the Columbia River were deposited on the beaches, the continental shelf, and in flood- and ebb-tidal deltas at the mouths of the rivers and estuaries. During the mid-1800s the region became an important hub of commerce and shipping, and navigation projects such as jetties at the Columbia River Mouth and the entrance to Grays Harbor were established. In the mid-1900s many dams were built across the Columbia River for flood control and generation of hydroelectric power. Within the last decade the trend of sediment accretion on the Washington/Oregon coast has reversed and, in many areas, resulted in severe coastal erosion (Kaminsky *et al.*, 1997). The Southwest Washington Coastal Erosion Study, a Federal/State/Local cooperative, is investigating the regional aspect of these changes within the Columbia River Littoral Cell (CRLC) (Fig. 1). One component of this project is to understand the historical change in regional bathymetry, in order to quantify the large-scale, long-term changes in offshore sediment behavior. This information will help define the role of the inner-shelf within the regional sediment budget, and how changes in nearshore morphology may or may not correlate with changes observed in the position of the coastline. This paper addresses accuracies and errors associated with the historic hydrographic data base and presents preliminary results of bathymetric change observed between 1868 and 1927.

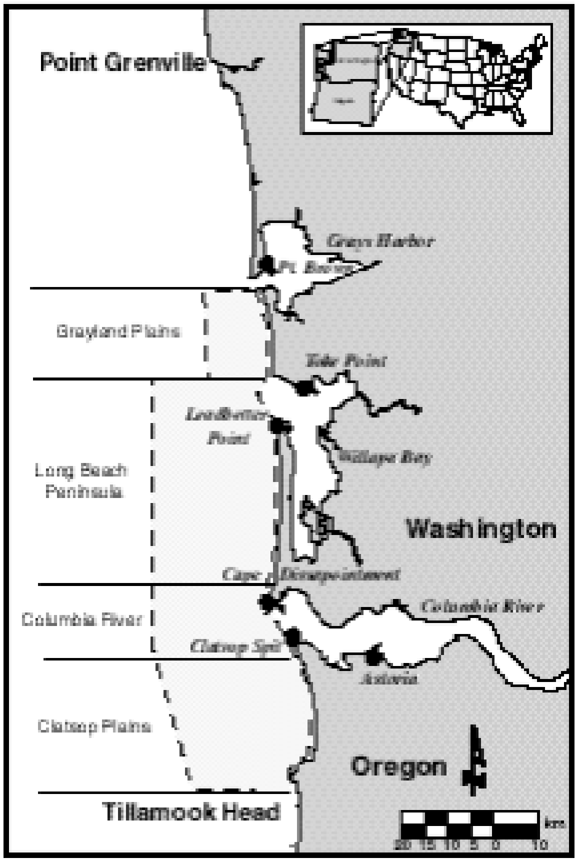


Figure 1. The Columbia River Littoral Cell. Dashed line outlines the boundary of the 1868-1927 bathymetric comparison.

HYDROGRAPHIC DATABASE

Data Sources

Bathymetric data available for comparison within the CRLC include both historical US Coast and Geodetic Survey (C&GS) hydrographic surveys collected between Tillamook Head, Oregon and Point Grenville, Washington, and US Army Corps of Engineers (ACE) surveys collected within the Columbia River, Willapa Bay, and Grays Harbor. The C&GS surveys were acquired in digital format from the National Geophysical Data Center (NGDC 1998) or digitized by the USGS and compiled into an ArcInfo GIS database for gridding and analysis. The C&GS surveys span over 100 years (1851-1958), and are grouped into three time periods based on temporal and regional coverage: 1800s (regional coverage from Tillamook Head, OR to Pt. Brown, WA); pre-1950s (regional coverage from Tillamook Head, OR to Pt. Grenville, WA); and post-1950s (limited to the Columbia River Mouth, Willapa Bay, and Grays Harbor estuaries and their respective tidal-delta complexes) (Fig. 1; Table 1). The ACE has collected surveys in and around the Columbia River, Grays Harbor, and Willapa Bay since the mid-1800s. These agencies continue to collect surveys in areas of local concern to navigation projects. Regional offshore surveys have not been collected since 1927. During the summer of 1998, an area extending approximately 20km north of the Columbia River was surveyed by the Portland District ACE for the SW Washington Coastal Erosion Study.

Data Collection and Processing Techniques

The 1800s and pre-1950s surveys were collected using manual techniques (Shalowitz 1964; USC&GS Hydrographic Survey Descriptive Reports: 1926-1958). Soundings were measured with a graduated pole in depths less than 5m (15 feet); lead lines and Rude-Fisher pressure tubes were used in deeper water. Echo sounding fathometers were employed for the post-1950s and a high precision single-beam fathometer for the 1998 survey. Horizontal positioning for the 1800s surveys was by 1) sextant angles from the ship to shore stations (landmarks); 2) theodolite angles to shore from the survey vessel verified by shore to vessel angles; and 3) estimation of position based on ship's speed and heading (dead reckoning) (Shalowitz 1964**;** Sallenger *et al.* 1975). Later surveys employed both sextant angles to stations and radio acoustic ranging (timed velocity of sound between ship and shore) (C&GS Descriptive Reports). Differential GPS was used for horizontal positioning in the 1998 survey.

The 1800s surveys were some of the first conducted on the West Coast of the United States. They were reconnaissance in nature and, in the offshore region, have the widest trackline spacing (~3000-5000 m) of all the data collected (Fig. 2). The pre-1950s data set is the most comprehensive survey off the coasts of Southern Washington and Northern Oregon and is the most recent bathymetric data set available for this area on a regional scale. Most data were obtained from the National Geophysical Data Center (NGDC) Marine and Geophysical Tracklines CD-ROM (NGDC, 1998), and were referenced to the NAD27 horizontal datum. Several were referenced to either an "unknown" or the Standard North American Datum (NAD13) (Table 1). Surveys with a NAD13 datum were shifted to NAD27 using values provided by NOAA (Steve Baumgardner, written comm.). Surveys with an "unknown" horizontal datum are problematic. Where geographically "fixed" topographic features, such as rocky headlands, are included on the survey sheets (e.g. H1019), a visual "best fit" shift can be performed relative to the shoreline surveys (T-Sheets) of the same time period. Unfortunately, few of these "fixed" features are found in the study area.

Two time periods are considered in this paper: 1868-1887 (referred to as the 1870s) and 1926-1927 (the 1920s). The 1870s and 1920s surveys comprise the regional nearshore/offshore data set and extend from Tillamook Head, OR to Grays Harbor, WA between 0 and -70 m water depth (Fig. 2). After incorporation into a GIS database, data were error checked, edited, and horizontally shifted where necessary. The shoreline of the corresponding time period was assigned a value of z = +2.5m (estimate of the difference between MHW and MLLW) and added to the data set. The point data (xyz) were then gridded using a uniform grid cell spacing (varying from 250-1000m), using two techniques: Inverse Distance Weighting (IDW), and a 2-D Minimum Tension gridding algorithm (EarthVision, Dynamic Graphics). Results presented in this paper use the EarthVision technique with a 750m grid cell spacing, linearly interpolated to the shoreline.

Table 1. Columbia River Littoral Cell C&GS Hydrographic Database

Time Period	Survey Year: Survey ID*	Scale	Area Covered	Average Data Density
1800s	*1851: H273*	1:20,000	Tillamook Head,	**Trackline separation**
	1852: H335	1:20,000	OR	offshore: 500-5000 m
	1862: H809	1:20,000	to	nearshore: 100-200 m
	1868: H1019	1:20,000	Pt. Brown, WA	**Along tracklines**
	1877: H1378; H1379	1:40,000		offshore: 200-1500 m
	1887: H1800	1:40,000		nearshore: 100- 200 m
	1891: H1589a	1:20,000		Dist. offshore: 200-500 m
Pre-1950s	*1911: H3297*	1:20,000	Tillamook Head	**Trackline separation**
	1924: H4363	1:20,000	OR	offshore: 800 m
	1926: H4611, H4612	1:20,000	to	midshore: 400 m
	***H4618*, H4619**	1:20,000	Pt. Grenville, WA	nearshore: 150-200 m
	H4620, H4621	1:20,000		**Along tracklines**
	H4635	1:40,000		offshore: 300 m
	H4636	1:80,000		midshore: 250 m
	H4633a	1:120,000		nearshore: 50-150 m
	1927: H4634	1:40,000		Dist.offshore: 100-300 m
	H4658	1:15,000		
	H4710, H4715	1:20,000		
	H4716	1:20,000		
	H4728, H4729	1:40,000		
	H4735	1:80,000		
	1939: H6519, H6520	1:10,000		
	H6521	1:10,000		
	1940; H6646, H6647	1:10,000		
	1941: H6665	1:10,000		
Post-1950s	1951: H7940	1:10,000	Columbia River,	**Trackline separation**
	1954: H8136, H8137	1:10,000	OR	offshore: 50-500 m
	H8138	1:15,000	Willapa Bay, WA	estuary: 20-150 m
	1955: H8252	1:20,000	Grays Harbor, WA	**Along tracklines**
	1956: H8250, H8251	1:10,000	and	offshore: 50-200 m
	H8292, H8293	1:10,000	ebb-tidal deltas	estuary: 10-100 m
	H8423	1:10,000		Dist. offshore: 200-400 m
	1958: *H8416, H8417*	1:20,000		
	H8419, H8420	1:20,000		

*Surveys in bold type are included in the 1868-1927 bathymetric comparison. Surveys in Italics were digitized by the USGS. Other surveys were obtained from NGDC. All data area originally from NOAA, National Ocean Surveys (formerly US Coast and Geodetic Survey). H273, H335, and H1019 have unknown horizontal datums. H1379, H3297, and H4363 are referenced to the Standard North American Datum (NAD13). All other surveys referenced to NAD27. H1019 was manually shifted (~1067m NW) to coincide with the 1870s shoreline.

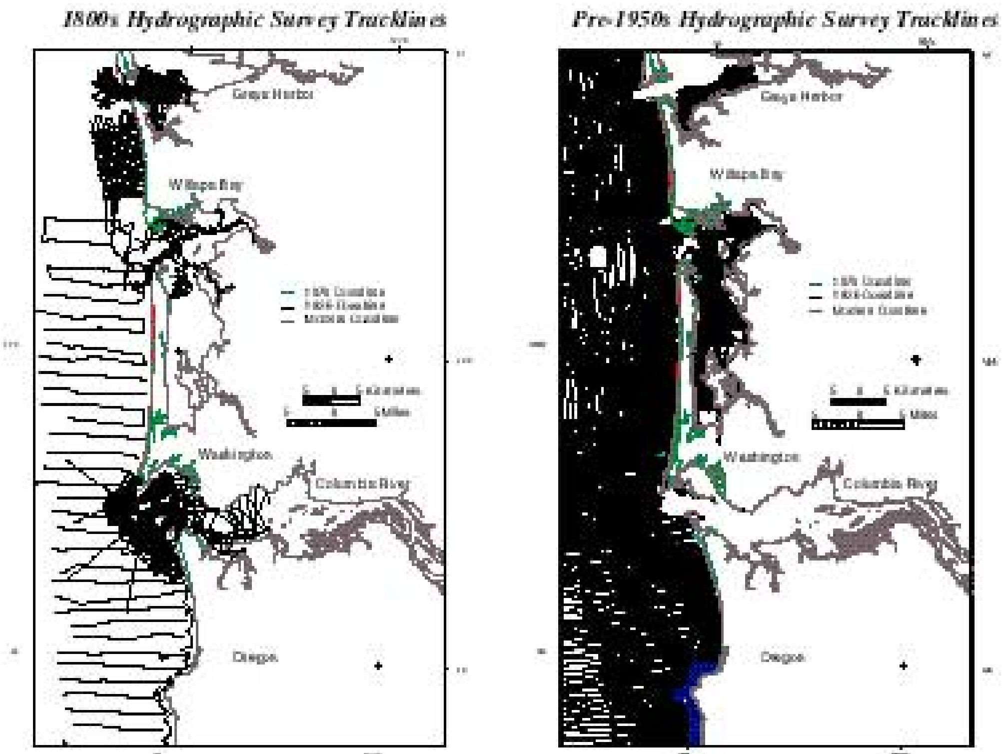


Figure 2. US Coast and Geodetic Surveys from the 1800s and pre1950s. Note the variation in trackline spacing both between and within the different time periods.

ERRORS AND ACCURACY

Defining the accuracy and total error associated with bathymetric change analysis is difficult and involves a complex combination of many potential sources of survey related and analytical errors. Errors and accuracies for only the 1870s and 1920s data sets are critically examined in this study, although some preliminary error estimates for the 1950s and 1990s surveys are included. Below we discuss and attempt to quantify the relative effect of different errors on our data sets.

Potential errors or differences between survey periods include sounding measurement errors, horizontal positioning inaccuracies, tidal correction problems, vertical and horizontal datum inconsistencies, the accuracy and precision of the data collection techniques, and the effect of sea-state conditions and currents. Potential analytical errors include digitization errors and gridding techniques (Sallenger *et al.* 1975; List *et al.* 1994). Quantifying these errors is difficult, especially for the older surveys. Descriptive reports associated with each survey became a standard requirement in 1887. These reports document survey specific parameters and problems associated with the techniques, weather conditions during the survey, etc., however, for the earlier surveys they have been difficult to locate, and may not exist at all. The earliest instructions for hydrographic work (circa 1844), provided only general requirements of accuracy and datum standards, essentially that "The line of soundings to be so disposed as to render it probably that no inequalities in the bottom have been overlooked, and to extend to the low water line" and "The soundings to be reduced to the lowest water observed during the survey" (Shalowitz 1964). By 1883, the standards required that soundings be taken with sufficient accuracy, depending upon the depth of water, to enable them to be reduced according to Table 2. Most of the surveys used in this analysis were collected after 1883. Given these standards as a starting point, survey specific errors are discussed below relative to when the surveys were collected.

Table 2. Survey Accuracy Standards from the 1883 Instructions for Hydrographic Work

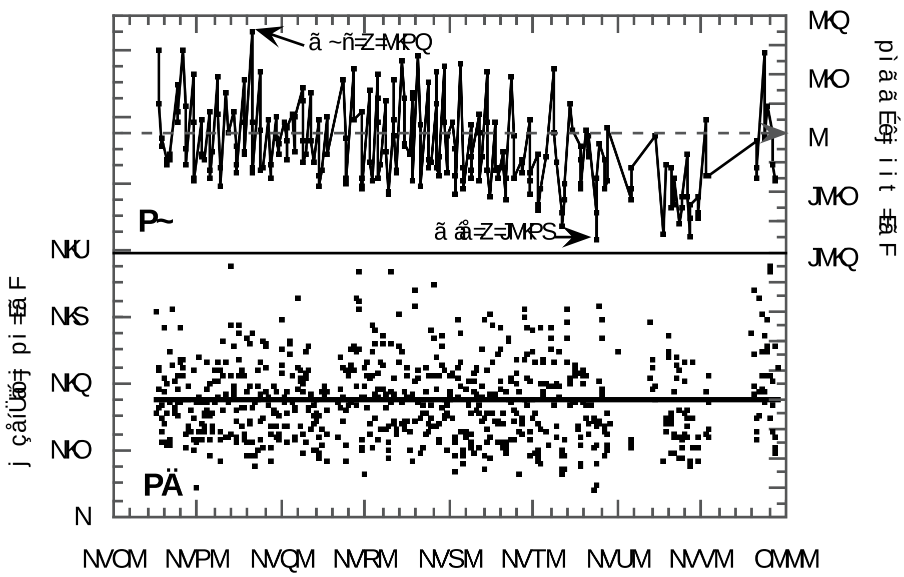
Water depth	Accuracy Standard
Deep sea soundings	Nearest fathom (~2m)
Outside 15 fathom curve (90ft, 27m)	Nearest half fathom (3ft; .91m)
Between 15 and 10 fathom curves (60-90ft; 27-8m)	Nearest foot (0.3m)
Between 10 and 4 fathom curves (60-24ft 18-7m)	Nearest half foot (0.15m)
Between 24 and 12 foot curves (7-3.6m)	Nearest quarter foot (0.08m)
Inside 12 foot curve (<3.6m)	Nearest tenth foot (0.03m)

1870s Surveys

Four surveys are included in the offshore portion of the 1870s surveys. Two surveys, H-1378 and H-1879, cover a large area extending from Willapa Bay to Tillamook Head, between approximately -5 and -100m of water, and within 25km of the shoreline. Trackline spacing is on the order of 3000-5000m. Two surveys, H-1800 and H-1019, off Grayland Plains and the mouth of the Columbia River, respectively, have much denser data coverage (100-1000m), in water depths less than -30m, and within 15km of the shoreline.

Several specific sources of error can be attributed to the 1870s data set. Horizontal datum inconsistencies must be considered because several surveys have unknown and/or unshifted horizontal datums. The offset between NAD13 and NAD27 within the CRLC is less than 40m (Steve Baumgardner, written comm.). A selection of a large grid cell size (>250m) will minimize this error. Where surveys with "unknown" datums can be manually shifted relative to "fixed" geographic features or reference points, the horizontal error is typically less than 100m, again within the resolution of the grid cell spacing. Where no fixed features or reference points exist, the surveys cannot be rectified within a reasonable distance. These surveys are located within the Columbia River and Willapa Bay and were collected between 1851 and 1852. They are useful only in a qualitative sense and are not included in our comparisons.

Vertical datum inconsistencies between surveys are more problematic. The relative datum difference between any two survey periods could have been influenced by decadal tidal variations, tide corrections based on tides measured at the shore applied to surveys far offshore, eustatic sea-level rise, and tectonic movement (Shalowitz 1964; Sallenger *et al.* 1975; List *et al.* 1994). Although all surveys in this study are referenced to MLLW, during the early surveys this elevation was based on tide records from gauges deployed specifically for the individual survey (months to years). Because of the short-term nature of the tide records, the vertical datum during the survey period may have been influenced by seasonal, annual, or wind-induced variations in the sea level. Thus, the MLLW datum to which the surveys were corrected during the 1870s may not be equivalent to the MLLW datums used for later surveys. The only information we have regarding the MLLW datum for the 1870s surveys is that the hydrographic charts state the “reference plane is the mean of the lowest low water of each 24 hours”. A MLLW datum was established in the Columbia River region circa 1925. Temporary gauges used for tide corrections were referenced to this benchmark datum (C&GS Descriptive Reports). The relative difference between these two datums is unknown. To obtain a maximum estimate for this potential error, we examined the range of monthly MLLW values recorded at the Tongue Point, Astoria tide gauge during the summer months (when the 1870 surveys were collected) between 1925 and 1999. The Astoria tide gauge, located within the Columbia River approximately 20km from the mouth, is the longest recording tide gauge in the Pacific Northwest (recording since 1925). The range of MLLW during this time interval is 0.70m, with a standard deviation of 0.15m (Fig 3a). Assuming the 1926 surveys are corrected to the long-term MLLW datum, we use half the maximum range, or 0.35m, to constrain the potential vertical datum difference of the 1870s surveys. The actual difference is likely closer to the standard deviation of 0.15m.



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Changes in local sea-level position are important when considering how differences in vertical datums influence historical bathymetric data sets. It is generally accepted that within the CRLC eustatic sea-level rise is countered by tectonic uplift and glacial rebound, so that the net sea-level rise is essentially zero (Hicks 1972; Canning 1991;

Komar 1998). This assumption is based primarily on tide-gauge data from the Astoria gauge. A linear regression on the annual mean sea level from this station shows a relative sea-level fall of 0.0028 cm/yr (Fig 3b). Records from other stations on the Washington Coast with much shorter time series (Neah Bay near the Straits of Juan de Fuca and Toke Point in Willapa Bay), show significantly different slopes, or rates of relative sea-level change (Table 3).

Table 3. Rates and Amount of Sea-Level Change Within the CRLC*

NOAA Tide Gauge	Years of record	Rate cm/yr	1868-1927 (59 years) cm	1926-1958 (32 years) cm	1958-1998 (40 years) cm	1868-1998 (130 years) cm
Astoria	**72**	**-0.0028**	**-0.16**	**-0.09**	**-0.11**	**-0.36**
Toke Pt.	31	0.21	12.3	6.7	8.4	27.3
Neah Bay	39	-0.15	-8.8	-4.8	-6.0	-19.5

* Rate refers to the least squares fit to a linear trend of annual MSL over the life of the gauge.

We use the Astoria gauge to constrain the amount of relative change in sea level between 1868 and 1998. However, even if the higher values from Toke Point or Neah Bay are used, the influence on our bathymetric change analysis is negligible relative to other errors discussed in this section (Table 3).

Potential sounding errors for the 1870s surveys include errors associated with the data collection technique, the application of tidal corrections, horizontal positioning error, and the influence of currents, swell, and sea state conditions. These errors likely increase with the distance away from the tidal stations, distance offshore, and with increasing water depth. Errors associated with collection techniques are difficult to quantify without access to the survey reports. Use of a leadline was the preferred method during this time period. Potential errors might include the stretch on the line between the start and end of a survey, curvature of the line due to currents or ship movement (both of which would give anomalously deep depths). These errors have the potential to significantly bias the sounding records. Trackline crossing differences likely provide a good estimate of these types of errors. Errors associated with the estimation of the mean sea level on the leadline as the swell passed by, as well as difficulties maintaining a consistent course and heading because of sea-state and current conditions, are more spatially averaged and random over the survey area.

Tidal corrections are more systematically applied and could effectively bias an entire trackline or group of tracklines. At the mouth of the Columbia River, the mean tidal range is 2.0m with a maximum of approximately 3.0m. Given the possibility that a tidal correction applied to any one point was exactly 180° out of phase, a maximum error of 3m could be due to incorrect corrections. This seems unlikely. NOAA established preliminary tidal correction zones for Pacific Northwest offshore region in 1998 (NOAA-OSPD Data written comm.). These zones extend approximately 35km offshore within the study region and show tidal time offsets of -72 and -54 minutes from the Astoria and Toke Point tide gauges, respectively. Assuming a 3m tide range, and 5.5 hours between high and low tide, a linear trend between high and low shows a difference of only +/-0.54m in one hour. We use this to constrain the maximum potential error due to tidal corrections applied to the data.

Errors related to incorrect horizontal positioning can be quite large and are proportional to the slope of the seafloor (the steeper the slope the greater the vertical error), thus, errors would be greatest in deeper water, where the shelf begins to steepen. The steepest slope in the study area is offshore of the Columbia River, where the head of the Astoria Canyon intersects the shelf at ~-100m. A 250m positioning error in 60-80m of water at this location could account for as much as 6m of vertical error. To the north and south, the slopes are much lower and a 250m horizontal offset in 60-80 m of water would result in an error of less than 2m.

The identification and quantification of the cumulative effect of the potential errors discussed above is limited by the few trackline crossings in the 1870s surveys from which to make comparisons. Crossing errors that were evaluated (in only two surveys close to shore) were typically within the error envelope allowed by the 1883 accuracy standards (< +/- 0.3m). Given the large data spacing of the offshore 1870s surveys, any sounding error, or series of errors, as a result of incorrect horizontal positioning, trackline bias, or tidal correction inaccuracies would severely skew the accurate representation of the sea-floor depth in the offshore regions. Surveys closer to shore, with higher density data spacing (e.g. off Grayland and the Columbia River), have less error associated with horizontal positioning and trackline bias. These likely represent the sea-floor morphology relatively accurately.

1920s Surveys

Eleven surveys collected between 1926-27 provide a comprehensive coverage of the study area. The surveys were collected at three scales: 1) nearshore surveys at 1:20,000, extending from the shoreline to approximately -25m water depth; 2) inner-shelf surveys at 1:40,000, between -25 and -90m water depth; and 3) mid-shelf surveys at 1:80,000, in water depths greater than -90m.

Errors associated with the 1920s survey series are generally equivalent to the 1870s because similar techniques and accuracy standards were employed. Evaluation of available C&GS Descriptive Reports indicates both along trackline and trackline crossing differences ranging "…from 2 to 6 feet in depths of 30-60 ft of water". Beyond this depth "considerable differences in soundings occur. These differences occurred on hand soundings in considerable depth of water, and the heavy sea running, strong currents encountered, adverse weather conditions existing the period of the survey, all probably contribute to the discrepancies". This description seems to be characteristic of most of the sheets along this coast. Evaluated trackline crossing errors vary with respect to water depth and the scale of the survey. Crossing differences in water depths less than 5m are typically within +/-0.3m. Differences range from +/-0.2 to 1.2 m in the 1:20,000 surveys, and +/- 1 fathom in the 1:40,000 surveys (which is the precision of the soundings). Crossing differences where 1:20,000 and 1:40,000 surveys overlap range from +/-0.3 to 2.4 m, with an average of +/-1.3 m. The average trackline crossing difference for all the 1920s data is +/-1.3m. The physical conditions of the sea and currents seem to have dominated the accuracy of the 1920s, and presumably the 1870s, offshore data sets. Overall, the 1920s surveys have much smaller trackline spacing and increased data density, which should result in more spatial averaging of the potential errors, yielding a smoother, more accurate representation of the seafloor surface.

Digitizing and Gridding Errors

Few erroneous points were identified when examining the data sets, except for a fathom to meter conversion error (H8417) that was identifiable and corrected. Various gridding techniques yielded somewhat different results. This is probably a function of the widely spaced tracklines of the 1870s surveys and how the search algorithms weight a singular point relative to the overall surface. Different grid-cell sizes produced similar overall results, although the resolution of the relative changes observed decreased as the cell size increased. A 750m grid-cell size was chosen as most representative for the 1870s-1920s comparison because, although trackline spacing was large in the 1870s surveys, data spacing along individual tracklines was typically less than 500m. This irregularity in data spacing likely imparted some inaccuracy to the generated surface. Experimentation with different grid cell sizes and gridding algorithms, especially utilizing non-isotropic search patterns, may help mitigate some of this survey pattern bias.

Table 4. Estimates of Potential Errors by Survey Period (in meters)

Potential Error	1870s	1920s	1950s	1998
Vertical datum differences	+/- 0.35	--	--	--
Tide correction	+/-0.5m	+/-0.5m	+/-0.5m	--
Horizontal positioning	+/-0.3 - 6m	+/-0.3 - 6m	--	--
Trackline crossing differences	+/-0.3 - 2m (nearshore surveys only)	+/-0.3 - 3.0m (ave +/-1.3m)	Not evaluated	< 0.3m

Cumulative Error

Quantifying the cumulative error associated with a particular survey (precision and accuracy of the collection techniques, sounding and positioning errors, tidal corrections, and sea-state conditions) is difficult. Trackline crossing differences provide the best estimate of the cumulative effect of these potential errors. Unfortunately, few crossings exist in the 1870s data set. Multiple trackline crossings and detailed accounts of surveying errors are described in the C&GS Descriptive reports from the 1920s surveys. Because similar techniques were employed, and similar oceanographic and meteorological conditions encountered, these values are likely representative of the 1870s data as well. Other errors such as vertical datum differences and relative sea-level changes are better constrained, although based on numerous assumptions. By summing the average of the trackline crossing differences (+/- 1.3m), the potential vertical datum difference (+/-0.35m), and the (negligible) effect of relative sea-level rise (-0.00003*59 years = -0.0017m), a confidence error interval of +/-1.7m is established for the 1870s and 1920s bathymetric survey comparisons. The true error is likely to vary widely with respect to the individual surveys compared, the distance from shore, and water depth. Figure 4 shows the results of the 1868 to 1927 bathymetric change comparison, using a +/-1.5 error as a no significant change value on the left and +/- 2.0m on the right. The +/- error should only viewed as only a rough guideline to the uncertainty, with the true error likely to be more or less, and possibly more, for the different areas considered.

REGIONAL BATHYMETRIC CHANGE: 1868-1927

Large areas of both erosion and deposition, on the order of several meters, throughout the entire study area, characterize the changes observed in the initial comparison between the 1870s and 1920s bathymetric surveys (Fig. 4). Following the discussion on errors presented above, the question arises as to whether or not these patterns represent real changes in the sea-floor morphology, or if they instead are a function of trackline spacing and data accuracy. Preliminary results of the regional bathymetric change analysis are presented below, with discussion of the uncertainties associated with individual surveys. The study area is divided into four regions for discussion: the Grayland Plains, Long Beach Peninsula, Mouth of the Columbia River (MCR), and Clatsop Plains (Figs. 1 and 4).

Grayland Plains

The Grayland Plains region extends approximately 15km south from Grays Harbor to Willapa Bay and 9km offshore (Fig. 1). Bathymetric changes between 1887 and 1927 are characterized by alternating shore parallel bands of accretion and erosion, defined by sharp boundaries, between the shore and -37m water depth. Closest to shore, a thin band (< 0.5km) of deposition (2-4m) between 0 and -3m water depth changes to a 1km wide band of little to no significant change between -3 and -9m water depth. Between -9 and -22m meters is a 3km band of accretion (2-4m). In water depths greater than -22m, a band of mixed but predominantly accretionary change persists to -37m of water, the boundary of the 1887 survey (Fig. 4).

This region has some of the most regular data coverage within the 1870s survey period, which should decrease the biases associated with horizontal positioning errors. However, closer examination of the data suggests the results, at least in part, may be an artifact of trackline coverage and survey inconsistencies. The band of accretion between the shoreline and -3m is a function of the shoreline interpolation process and reflects the change in shoreline position (progradation) between the 1870s and 1926 (i.e. no 1926 survey data was acquired in this area). It is reasonable to assume, however, that accretion of the inner shoreface would accompany shoreline progradation, with the absolute magnitude of change varying relative to the elevation chosen for the shorelines. The band of little to no change between -3 and -9m correlates closely to surveying patterns of both the 1887 and 1926 surveys. Small crossing differences (< 0.5m) were identified in this region in both the two surveys. The transition from erosion to accretion along the -22m contour also coincides very closely with the boundary between the nearshore and inner-shelf surveys of the 1920s. As discussed above, the boundary between the two is defined by a change in survey precision (1/4 fathom vs. 1 fathom). Crossing line differences in this region range from 0.2 - 2.4 m, but average 1.3 m.

Because of the various contributions to errors in this region, it is difficult to isolate the influence of the surveys on the results observed. Certainly the pattern of alternating deposition and erosion is not as well defined when a large error envelope (+/- 2m) is applied uniformly to the region. Trackline crossing differences suggest this value may be too high an estimate.

Long Beach Peninsula

The region off Long Beach Peninsula extends 45km from Willapa Bay to the Columbia River, from the shoreline to -70m (Fig. 1). In general, this region shows the least amount of change relative to the rest of the study area, especially in water depths

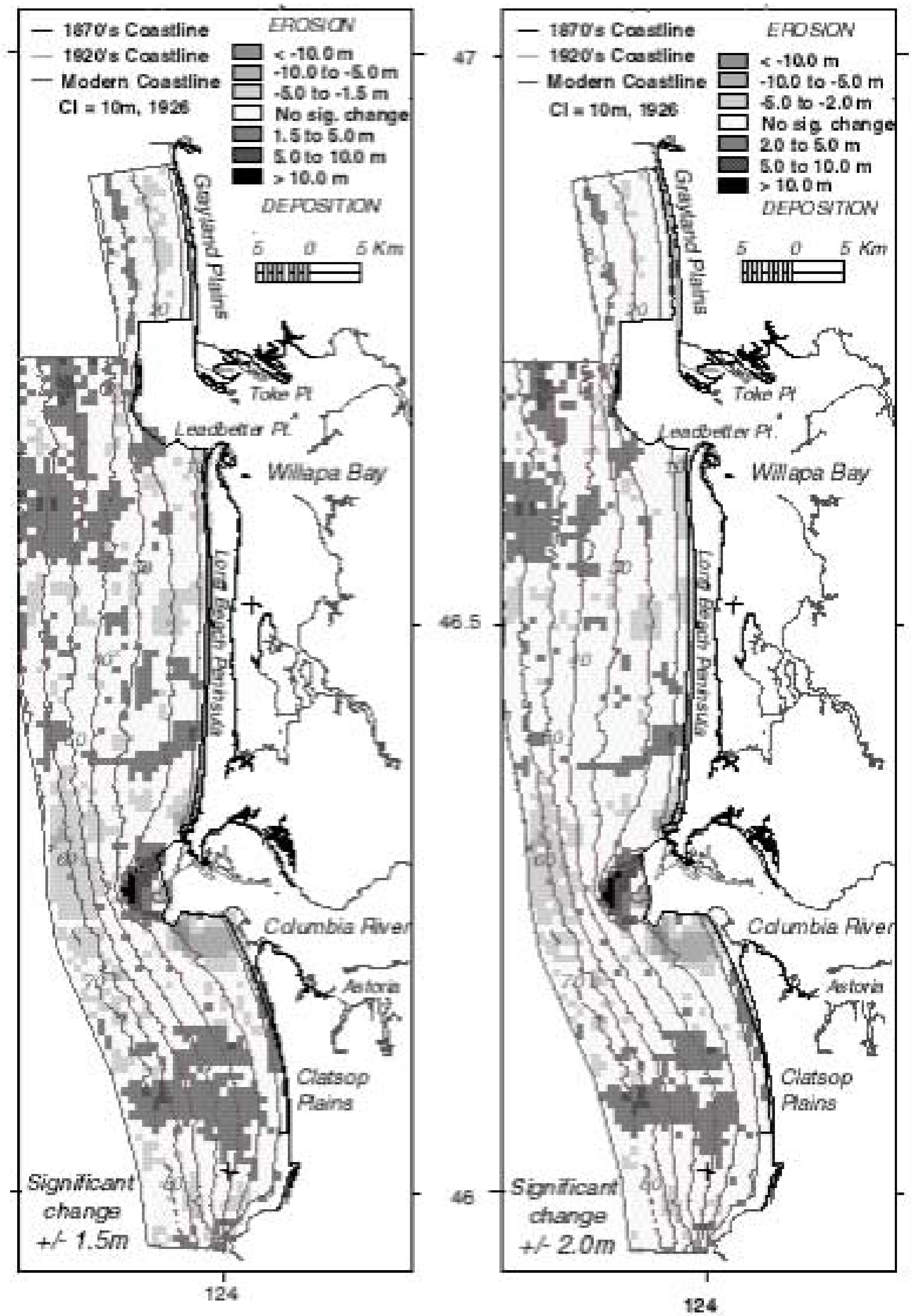

Figure 4. Bathymetric change within the CRLC between 1868 and 1927. Light colors are erosion, dark colors accretion. The plot on the left show significant change greater than +/- 1.5m, the plot on the right shows signifcant change of +/- 2m. The patterns of change are discussed in the text.

greater than -30m. Alternating zones of erosion and accretion, about 10km in length, are present between the shoreline and ~-20m along the central portion of the Long Beach Peninsula (Fig. 4). Between -20 and -30m, an apparent break in the depositional/erosional pattern marks the transition between the nearshore and inner-shelf region. Beyond this break, a relatively contiguous pattern (11km x 9km) of minor deposition, and localized areas of higher values, is found in water depths ranging from -30 to at least -70m approximately 8km off Leadbetter Point. South of this region, a discontinuous, 5km wide band of deposition extends from east to west across the shelf. Little significant change is observed between this area and the Columbia River.

The alternating erosional and depositional patterns within the nearshore region of this region are controlled somewhat by both the 1870s and 1920s tracklines and surveys, which lends some question to their validity. Anecdotal evidence suggests these may be related to large migrating sand bodies, nearshore rips, or zones of localized downwelling associated with coastal eddies. The pattern change between -20 and -30m may be due to survey precision differences associated with overlapping nearshore and inner-shelf surveys. Trackline crossing differences between the two, however, are less than +/-1m. Alternatively, this may represent the physical boundary between the nearshore and shelf systems. The only change pattern within the Long Beach region that is defined by multiple 1870s tracklines, with no obvious bias relative to the 1920s survey, is the region of deposition off Leadbetter Point. Although the origin of this feature is unknown at this time, recent AVHRR photography suggests that sediment plumes exiting the Columbia River during the winter may be responsible for its accumulation. This area also corresponds closely with the mid-shelf silt deposit identified by Nittrouer (1978) and discussed by Sternberg (1986).

Columbia River Mouth

Bathymetric changes observed at the Columbia River Mouth generally agree with results of previous studies (Sherwood *et al.* 1990). Between 1868 and 1926, the ebb-tidal delta (ebb shoal) migrated offshore and to the north approximately 2km, narrowing in dimensions from a broad, gently sloping feature to a narrow, crescentic lobe approximately 7km by 3km, about half the size of the 1868 shoal (Fig. 4). The large areas of erosion both east and south of the depositional center represent the previous location of the 1868 ebb shoal. Peacock Spit, represented by the large subtidal band of accretion extending from the delta to Cape Disappointment formed during this time as well. The changes observed are well constrained by the data and likely represent real changes in sea-floor morphology between 1968 and 1926. The limit of the observed offshore migration of the ebb shoal is constrained by the coverage of the 1868 survey (H1019) and the boundary between two 1920s surveys, H4634 and H4618, and thus, may represent a minimum distance of ebb shoal migration.

Jetties emplaced on the Columbia River between 1885 and 1917 to control shoaling and channel migration were designed to move the ebb shoal offshore, which they did very successfully. The erosion of the southern portion of the region was likely due to a combination of the emplacement of the jetty and the subaerial accretion (exposure) of Clatsop shoal, which effectively cut off sand delivery to this portion of the delta.

Ten kilometers west of the Columbia River mouth, an extensive area, nearly 21km from north to south, at least 6km wide, and in water depths greater than -30 to -50m, represents the greatest erosion within the study area. Separating this band of apparent erosion from the migrating ebb-tidal delta complex is a 1-4 km wide buffer of little to no change. The pattern is defined by several, although widely spaced, tracklines from the 1870s surveys. As discussed above, the potential error of the surveys increases with water depth, slope angle, and distance from the tidal station. The shelf in this area has the steepest slopes within the study area, with the head of the Astoria Submarine Canyon just offshore at approximately -100m water depth. The bias of the trackline spacing and accumulated survey errors, suggests that the amount of change observed may be severely exaggerated. This erosion also seems unlikely given the tremendous volumes of sediment supplied annually by the Columbia River (Sternberg, 1986). Considering the magnitude of change to the tidal delta associated with jetty emplacement, however, significant changes in the offshore region might also be expected. Massive slope failures or preferential transport of fine material out of the region, perhaps associated with unusual meteorological conditions, such as the 1926 El Niño event, might also effect erosional change in this typically depositional environment.

Clatsop Plains

The Clatsop region extends 26km south from the Columbia River to Tillamook Head and 24km offshore to the -80m contour (Fig. 1). A narrow band of deposition characterizes the bathymetric change pattern between 0 and -10m, south along the coast from position of the 1870s ebb-tidal delta (Fig. 4). This pattern persists, although irregularly, south to Tillamook Head. A band of no significant change parallels this band of deposition to a water depth of -18m. In deeper water, the pattern becomes more complex. An extensive area of accumulation dominates the inner and mid-shelf region except for a discontinuous area of erosion between -60 and -80m water depth and a more continuous area of erosion to the south.

Although patterns observed within this subcell show no apparent bias relative to the 1920s tracklines, the influence of the 1870s series is more problematic. The depositional area within the central region is defined by five tracklines, while the erosional pattern to the south by only three. The slope of the shelf is relatively steeper in the south, possibly increasing the sounding errors as the water depth and distance from shore increased. Some deposition south of the Columbia River occurs due to dominant transport of river derived material in the spring and summer (Sternberg, 1986), however, the magnitude of absolute change is may be less than is represented here.

SUMMARY AND CONCLUSIONS

The analysis of historical bathymetric change on a regional scale within the Columbia River Littoral Cell is problematic due to the age of the surveys (1870s and 1920s), the original intent of the surveys (to identify the depth of the seafloor as an aid to navigation), the techniques involved (potential sounding and horizontal positioning errors), and the high-energy conditions (seas, swell, and currents) along this stretch of coast. A cumulative error of +/-1.7m for the 1868-1927 bathymetric change comparison was determined through a detailed analysis of survey related and analytical errors. The true error likely varies as a function of the accuracy of the particular surveys compared, the distance offshore, and the water depth.

The 1870s data set provides detailed coverage in only two locations (off the Grayland Plains and the Columbia River Mouth), where a reasonable representation of sea-floor morphology can be interpreted. In these areas, calculation of volumetric changes is likely accurate within the bounds of our confidence interval. In other locations, the quantitative value of the data set is more questionable due to the large range of uncertainties. Large signals that exceed our potential error estimates suggest that real changes in the offshore sea-floor morphology are occurring. However, without additional insight into the magnitude and distribution of these errors, primarily related to the application of tidal corrections and sounding errors associated with horizontal offset, only a first order, qualitative application of the volumetric change data should be expected.

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