Historical changes in the Columbia River estuary based on sediment cores: feasibility studies

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Executive Summary

The importance of the Columbia River estuary to salmon, other fishes, migratory birds, and other species is fairly well established. Relatively little is known, however, about long-term, historic variations in biological processes and conditions within the estuary. For example, have conditions varied greatly with climatic regime shifts and how has dam construction on the Columbia River influenced biological communities over time? We conducted a feasibility study to see if sediment cores from the estuary could be aged and whether biological or contaminant indicators could be identified. Such information could be useful in understanding long-term environmental variation and in restoration studies.

From a set of cores that were originally collected for a regional sediment study, we selected three for analysis, one each from Youngs Bay, Grays Bay, and Clatskanie Flats (flood plain). ^{210}Pb was used to age strata in these cores, with the oldest sediments being deposited in about 1850 (Grays Bay, 150 cm core; Clatskanie Flats, 140 cm core). ^{137}Cs activity was used to corroborate the predicted ^{210}Pb ages, with good success. Fitted second-order polynomials ($r^2 > 97\%$) were used to extrapolate ages prior to 1900 in the two deeper cores. Sections from cores (2 cm thick, taken about every 10 cm) were examined for 30 heavy metals, diverse algal pigments, percent organic content, diatom species, stable isotopes of C and N, and grain size distributions. Polynuclear aromatic hydrocarbons (PAH) were quantified in sediment from the Grays Bay core. Smaller samples of cores were also examined for invertebrate parts and fish scales, although none were observed.

The Youngs Bay core was the shortest of the three examined (80 cm) and contained sediment that was deposited from about 1910 to 2000. During this period, there appeared to have been a major change in the physical conditions and biological community at this site. Grain size distributions changed around 1940, along with a shift from primarily benthic freshwater diatoms early in the century to planktonic freshwater species after 1940. The shift at this time was also well represented in algal pigments. For example, diatoxanthin and beta-carotene declined five- to ten-fold, while alloxanthin and chlorophyll-a increased sharply. These changes suggest that there may have been an overall 80% reduction in algal standing crop. We cannot identify specifically the mechanism(s) that led to these changes, but mainstem impoundment or local alterations in the Youngs River drainage can be suggested. The concentration of a few heavy metals such as lead showed slight increases between 1920 (14 ppm) and 2000 (21 ppm).

The core from Grays Bay spanned the period from about 1853 to 2000, and there appeared to be less change in the biological community at this site, but significant accumulation of heavy metal contaminants. Throughout this period, the diatom community was dominated by benthic freshwater species (>82% of all identified species) and algal pigments showed few trends, although the percent organic matter doubled from ~3% prior to 1970 to ~6% after 1970. As in Youngs Bay, the ratio of ^{13}C to ^{12}C (δ^{13}C) was characteristic of planktonic carbon sources. This core, however, showed the strongest evidence of increasing heavy metal contamination beginning about 1960. Mercury concentration, for example, was very consistent in sediments deposited between 1850 and 1950 (~0.03 ppm), but concentration increased steadily from about1960 to the

1990s with a final concentration of ~0.08 ppm. Lead, copper, zinc, and other heavy metals showed similar increasing accumulations during the last 40 years.

Sediments in the core selected from the Clatskanie Flats area were composed of finer, siltier material than the other two cores, and the base of this core extended back to about 1855. Diatom analyses were not conducted for this core, but shifts in algal pigments, decreased percent organic material near the surface, an increase in an ultraviolet index, and change in $\delta^{13}C$ suggest some significant changes in the biotic community after the early 1900s. A few heavy metal concentrations (e.g., lead and zinc) increased gradually over the last 150 years, while other metal concentrations remained fairly constant (e.g., mercury and copper).

In conclusion, we were able to successfully age the sediments within these cores and to document historical change in abiotic and biotic conditions. A variety of indicators suggested that major shifts in algal communities and contaminant levels have occurred either locally or regionally in the Columbia River estuary. These sorts of findings can be refined to assist with historical interpretations and hypothesis tests about mechanisms. Averages of indicators from deeper and older sediments often had small variances, suggesting they could be used in evaluating restoration actions, considering the impacts of dredging, or for detecting natural change. Overall measures of bioproductivity, such as total diatom concentration, might be used to compare the type of environment that juvenile salmon now encounter with the historical environment. Finally, a larger study may be useful in distinguishing the role of climate regime shifts and human impacts on estuarine or freshwater conditions within the Columbia River Basin.

Introduction

The importance of the Columbia River estuary to salmon, other fish species, migratory birds, and other species is fairly well established (Emmett and Durkin 1985; Bottoms and Jones 1990). Historically, 10-16 million Pacific salmon migrated up the Columbia River each year to spawn, whereas recent salmon returns are less than 1 million per year (Lichatowitch 1999). Chinook salmon were the most abundant, but all five species of salmon reproduce within the basin (Groot and Margolis 1991). Outmigrating juvenile salmon must pass through the Columbia River estuary and the estuary may be an important rearing or transition area for many stocks of salmon (McCabe et al. 1983; Bottoms and Jones 1990; Ledgerwood et al. 1991). However, relatively little is known about many of the physical and biological processes in the estuary. For example, how have primary production and higher trophic levels in the estuary responded to man's activities upstream (Simenstad et al. 1990; Sullivan et al. 2001)? Have observed changes been gradual, only associated with human impacts, or occurred rapidly during "regime" shifts on scales of 20-30 years (Hare et al. 1999; Petersen and Kitchell 2001; Austin 2002)? Little is known about how dam construction, land and water management, and increased human population might be influencing conditions in the estuary, through changes in nutrient levels, introduction of exotic species, contaminants, or other factors. A better understanding of these processes could help to interpret which changes might be cyclical, which are likely human-caused, and which might be positively influenced by active management.

Sediments in estuaries may offer a particularly good resource for quantifying the historical variation in the near-shore environment (Bianchi et al. 2002). Cores have been taken in oceans, lakes, reservoirs, and wetlands and used to examine shifts in primary producers, fish populations, and trophic structure (Smol et al. 2002). The accretion rates of organic and inorganic material can be determined from cores, and sediments can entomb physical remains from algae (e.g., diatoms, chrysophytes), invertebrates (zooplankton, zoobenthos), and fish (as scales or bones). Biochemical remnants can be detected in sediments, including plant and algal pigments, diverse cellular metabolites (e.g., fatty acids), and stable isotopes (C, N, S, H, O). Recent research has indicated that stable isotope ratios of N, C, and other elements can provide clues about changes in primary production, vegetation types (e.g., C3 vs. C4; upland vs. riparian; emergent marsh versus plankton) or nutrient sources from both marine (Finney et al. 2000) and terrestrial environments (Struck et al. 2000). Temporal sequences of diatom cell walls (frustules), invertebrate exoskeletons, and plant pigments often preserve well and can be extracted from cores using established methods. Strata in cores can be aged using radioisotopes (^{210}Pb, ^{137}Cs) so that the impacts of specific events (e.g., dam construction, contaminant spills) on ecosystem properties can be inferred. Multivariate statistics (e.g., variance partitioning) can be used to quantitatively compare core measurements with historical time series of water temperature, land use or climate change (e.g. Hall et al. 1999).

The objective of this study was to test the feasibility of using sediment cores from the Columbia River estuary to establish "historical" conditions, and to study temporal change in the river system. The age of sediments at different levels within cores was estimated. A range of indicators was examined from selected cores to look for trends or patterns. Results will be used to develop new hypotheses and propose more in-depth work.

Study site

The Columbia River is the largest river entering the northeast Pacific Ocean, draining a watershed of over 660,000 km^2 that includes portions of seven U.S. states and two Canadian provinces. The drainage basin includes portions of the Cascade Range, the western slope of the Rocky Mountains, and the large, semi-arid region between these mountains. Most runoff occurs as snowmelt during April to July, although river flows have been greatly modified by dam construction during the last 60 years. The Columbia River has been an important cultural, transportation, and food resource for Native Americans, and was the first land-based link to the Pacific Northwest coast during westward explorations by Lewis and Clark in 1805-1806.

The Columbia River estuary is a drowned river valley that was incised to 110 m depth below present sea level during the last ice age. Following the last ice age the global marine transgression (sea level rise) first began to submerge the Columbia River's ancestral valley floor near Warrenton, Oregon by 16,000 years ago (16 ka) (Baker, 2002). The onset of estuarine circulation near the present bay mouth, i.e., the first presence of marine diatoms, occurred at 11 ka.

As the valley was submerged by the transgression it filled with sediments. The sediment sources transitioned from glacial outwash out of the metamorphic eastern drainages (16-11 ka) to the Cascade volcanic arc drainage basins (9.5-2 ka). The

ancestral valley was filled to capacity by sand during the Missoula Floods resulting in intertidal peat deposition at 11.5 ka. However, continuing rapid rise of sea level increased basin accommodation space, trapping mud and sand between 11.5 and 9.5 ka. However, declining rates of sea level rise permitted the basin to fill up with sediments again by 9.5 ka, and from that time onward the basin by-passed nearly all of its suspended load (silt and clay), and most of the bedload (sand) to the marine side.

Based on Holocene isopach maps (topographic fill) some 73 cubic kilometers of sediment has accumulated in the Columbia River tidal basin (river mouth to Bonneville Dam) since 16 ka (Gates, 1994). Basin depositional rates dropped from 18 million cubic meters per year ($18x10^6$ m^3yr^{-1}) during 11-9 ka to only $4x10^6$ m^3yr^{-1} after 9 ka (Baker, 2002). This corresponds to a dramatic decline is sedimentation rates from 2 cm per year prior to 9 ka to 0.3 cm year after 9 ka. During latest-Holocene time the basin sedimentation rates were entirely controlled by available accommodation space provided by relative sea level rise of about 0.1 cm year. In latest prehistoric time the Columbia River retained minor amounts of its suspended load in flood plains, and in marginal bays such as Cathlamet Bay, Grays Bay, Youngs Bay, and Baker Bay. Sand dominates the shallow subsurface (1-5 m depth) throughout the main tidal channels, tidal flats, and channel islands (Peterson and others, 2000). For at least the last millennium lateral channel migrations have reworked sand island shoals of the upper estuary. Interbasin wind-waves have scalped intertidal sand shoals of the lower estuary during low-tides. The reworked and remobilized bedload (sand) was then effectively transported out of the riverine-tidal system by combined ebb tides and seasonal (spring) peak fluvial discharge.

The conditions discussed above represent sedimentation in the Columbia River estuary prior to potential anthropogenic impacts. Impacts to the Columbia River sedimentation could occur from drainage basin logging, jetty construction, channel dredging, and tributary impoundments beginning in the early 1900's. Other environmental baselines, such as organics, heavy metals, and bioproductivity indicators, have not previously been evaluated from prehistoric deposits in the Columbia River estuary. Historical changes and prior studies were summarized by Sherwood et al. (1990) and Simenstad et al. (1990)

Field sampling

Field methods are described in detail in Appendix 2, with a more brief description given here. Portland State University conducted sampling of sediment cores in the Columbia River estuary (Figure 1) during the two-week field period of July 9-24, 2000. A total of 44 samples were collected by vibracoring. Samples were collected with a 7.5 cm diameter aluminum pipe at 6.5 m lengths, with a Honda turbo 3000 engine, and CANUSA slim-line core-catcher. Field investigations of shoreline erosion or accretion (50 localities) were recorded on-site during reconnaissance surveys for the vibracoring. Digital photographs were taken of many core sites and shoreline conditions during the field study.

An average vibracore penetration of 5 m (lower reaches), and maximum penetration of 7 m in flood plain settings (upper reaches) were obtained during this study. The improved penetrations obtained this year are ascribed to a higher power vibracore motor, lower compaction of fluvial-tidal deposits, and reduced profile design of the new

CANUSA core-catchers. An average compaction of 1.3 m, or 20% is calculated for the recovered vibracores. Compaction was greatest in soft sandy deposits of channel and shoal margins. Core recovery was greater than 90% complete (including loss from pullout and rodding). Sediment cores were frozen at –10°C and stored in darkness.

Vibracore and cut bank sites were located by NOAA Navigation charts (numbers 18521, 18523), and two Garmin CX GPS units for positioning with 2-5 m horizontal resolution (real-time). Water depth and time were recorded at all vibracore sites for calibration of deposit surface to MTL with NOAA predicted tide tables.

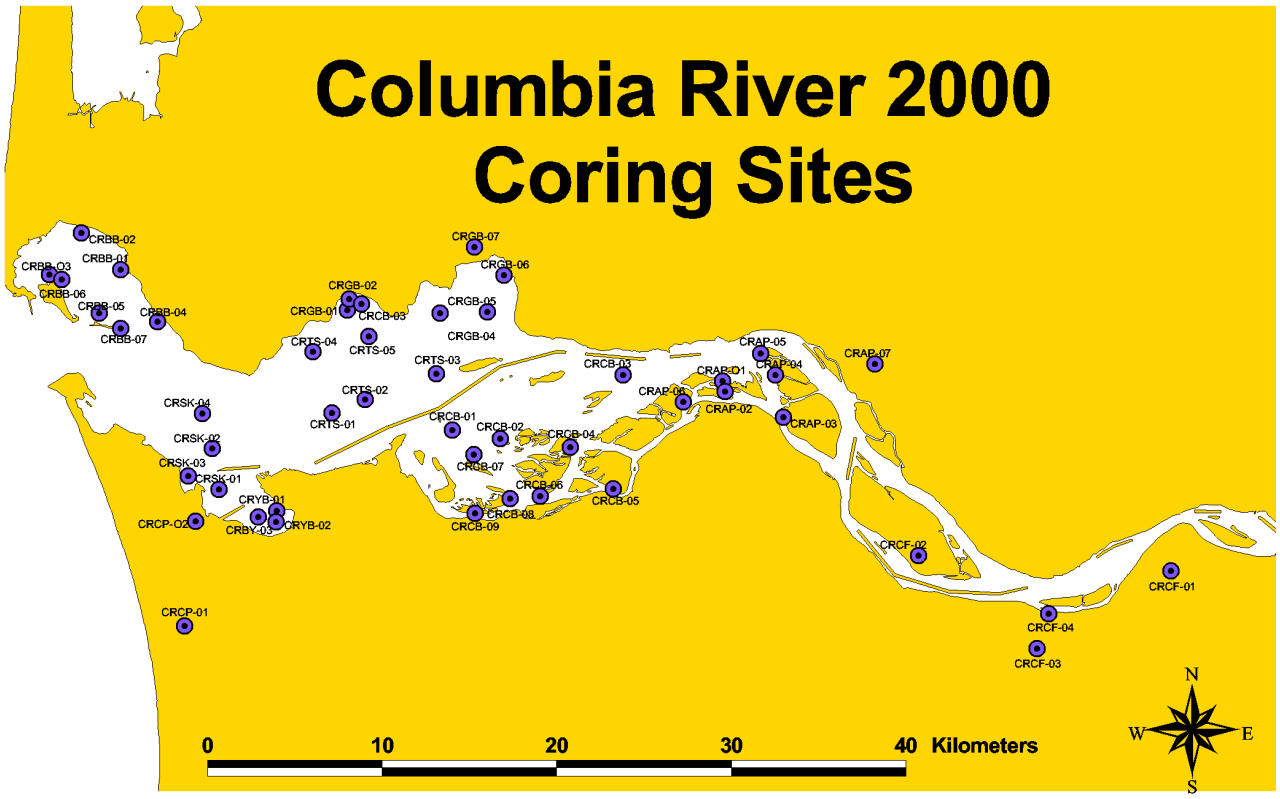


Figure 1. Location of original cores collected in the Columbia River estuary by Portland State University during 2000. Portland State University graphic.

Core selection and sub-sampling

A workshop was convened and held at Portland State University (see Appendix 1), where participants discussed techniques, measures, and options. Participants included a range of individuals with expertise in sedimentology, fisheries, reservoir function, wetland function, paleolimnology, and geology. For this pilot study, we selected a subset of all cores that were available from the 2000 survey, to limit sampling cost and because many cores contained little organic material.

Workshop participants used the following criteria to select cores for examination from among the 44 available cores: 1) locations where sedimentation was expected to be steady over time, 2) avoidance of areas which were known to be largely sand, 3) cores were distributed along a longitudinal range in the estuary (mouth to upriver sites), and 4) cores were expected to have a reasonable amount of organic material. Although five cores were originally selected (Table 1), preliminary analyses suggested that cores from Youngs Bay, Grays Bay, and Clatskanie Flats had the best preservation, therefore, the data presented are from these cores only.

Two-cm thick slices of sediment cores (called samples or strata below) were taken along the length of each core. See Figure 1 for the specific location of samples. More samples were taken near the surface to improve resolution of recent ages. Core samples were homogenized by hand within a plastic bag and subdivided for analysis at different laboratories (Table 2). Samples were placed in sealed bags and kept frozen prior to analysis. Once isolated, sediment sub-samples for pigment analysis were frozen (<-20^{o}C) in the dark under an inert atmosphere (N_2) until isolation and quantification of sedimentary pigments and isotopes.

Table 1. Five cores collected in the Columbia River estuary in summer 2000 that were selected for analysis. See Figure 1 for locations.

Code	Location	Latitude and longitude[1]
CRYB-02	Youngs Bay	Easting 434341 Northing 5112676
CRGB-06A	Grays Bay	Easting 446912 Northing 5127269
CRCF-04A	Clatskanie Flats	Easting 478716 Northing 5108806
CRAP-06A	Aldrich Point	Easting 457414 Northing 5120310
CRAP-07A	Aldrich Point	Easting 468292 Northing 5122850

[1]NAD 27

Table 2. Sediment indicators examined for Columbia River cores, with the analytical method and the laboratory where samples were processed.

Indicator	Analytical method	Laboratory / Investigator[1]
Heavy metals	Energy-Dispersive X-ray Fluorescence Spectrometry	USGS/Siems
Mercury	Spectrophotometer	USGS/Brown
C and N isotopes	Mass spectrometer	UR / Leavitt
Pigments	reversed-phase high performance liquid chromatography	UR / Leavitt
PAH	Selective ion monitoring capillary gas chromatography – mass spectrometry	OSU / Prahl
LOI (% organic)	Combustion @ 500 ^{o}C	UR / Leavitt
Organic Carbon / Total Nitrogen	Elemental Analyzer	OSU / Prahl
Grain size	Seive, SediGraph 5100	PSU / Peterson
Diatoms	Permanent slide mounts	EHH
^{210}Pb, ^{137}Cs	Gamma radiation	USGS/Budahn

[1]USGS/Siems – USGS, Denver, Colorado, David Siems
USGS/Brown – USGS, Denver, Colorado, Zoe Ann Brown
USGS/Budahn – USGS, Denver, Colorado, Jim Budahn
UR – University of Regina, Peter Leavitt
OSU – Oregon State University, Frederick Prahl
PSU – Portland State University, Curt Peterson
EHH – Eileen Hemphill-Hailey, private consultant

Sample processing methods

Grain Size

The sample sediment was sieved with a STD US Sieve Size 230 (63 microns) to separate the fine grain sediments from the sand size sediments. Both size fractions were

dried in a 300 ºC oven for approximately 2 hours. The sample splits were then dry weighed on a Metler Balance. The sand size fractions were dry sieved at splits of 600, 500, 425, 250, 150, 125, 106, and 75 μm. The individual sand splits were then weighed on a Metler Balance and the weights recorded. The fine grain fraction was mixed with 80 mL of a 20% glycol, 70% de-ionized water and 10% dispersant mixture. The suspension was then processed through a Micrometrics SediGraph 5100 to determine the hydraulic grain size. The hydraulic grain size data from the SediGraph 5100 is reported in percent by weight. The weight percents were then normalized to the initial weight of the sample to integrate with the sand fraction weights.

Aging of cores

Approximate ages of sediment samples were based on the activities of ^{210}Pb and ^{137}Cs in the samples. Sediment samples were weighed before and after drying to compute percent water. Samples were analyzed for ^{210}Pb and ^{137}Cs using semi-conductor gamma-ray detectors by the U.S. Geological Survey. Gamma-ray spectra were accumulated using a GENIE-ESP computer with an OpenVMS-based acquisition and multi-channel analyzer system. Samples were counted for periods ranging from 24 to 96 hours. This insures that adequate counts were obtained to generally limit the counting statistic errors to less than 15%. The samples were packaged in appropriate sealed vessels in order to establish radioactive equilibrium between ^{226}Ra and its relatively short-lived daughters (^{222}Rn, ^{218}Pb, ^{214}Pb, ^{214}Bi and ^{214}Po) and to maintain a constant geometry from sample to sample. All data are in disintegrations per minute (dpm). Samples were not contiguous, so we assumed that ^{210}Pb samples represented an "average" value throughout a section of core (see Results).

Sediment age was estimated using the CRS (constant rate of supply) method, summarized in Binford (1990). Excess (unsupported) ^{210}Pb in a sample was the difference between total ^{210}Pb and the average activity of ^{226}Ra, ^{214}Pb and ^{214}Bi. To use the CRS method, an estimate of bulk or dry density (ρ; g/cm^3) was computed using proportion dry weight and percent organic and inorganic material (Binford 1990; his formula 5). The proportion dry weight (D) of unit wet volume was assumed to be the proportion of dry:wet mass, values that were measured for most but not all samples (Jim Budahn, personal communication). The density of inorganic material was assumed to be 2.65 g/cm^3 (C. Peterson and D. Baker; value from their grain size report) and inorganic density was 1.6 g/cm^3 (Binford 1990). The percent organic content was based on loss on ignition at 500 ^{o}C for 1 h (P. Leavitt, personal communication), and the percent inorganic was 100 - % organic. Values of ρ were linearly interpolated from adjacent estimates when needed.

^{210}Pb ages of each sample in a core were estimated using the formulae in Binford (1990), incorporated into a spreadsheet (C. Holmes, USGS, personal communication). The ^{210}Pb ages were corroborated with plots of ^{137}Cs, which we assumed would begin to increase in about 1954 (Davis et al. 1984; Blais et al. 1995). Since we did not age the deeper strata in the cores from Clatskanie Flats and the Grays Bay, we fit second or third order polynomials of depth (depth, depth^2, depth^3) to extrapolate the age of sediments deeper than 100 cm.

Pigments

Sedimentary pigments were extracted, filtered and dried under N_2 gas following the procedures of Leavitt et al. (1989). In order to improve the reproducibility of pigment extraction, well-mixed sediment sub-samples were freeze-dried under a hard vacuum (<0.1 Pa) for 72 h. Lipid-soluble (polar) pigments were extracted from the bulk sediments by soaking powdered sediments in a mixture of degassed acetone:methanol:water (80:15:5, by volume) for 24 h in the dark and under an inert N_2 atmosphere at 0^oC. Pigment concentrations were quantified by reversed-phase high performance liquid chromatography (RP-HPLC), which separates complex mixtures according to the relative attraction of individual pigments for the non-polar stationary phase (both coating and support material) and the polar mobile solvent phase.

Carotenoid, Chlorophyll (Chl), and pigment-derivative concentrations were quantified using a Hewlett-Packard 1050 HPLC system following the reversed-phase procedure of Mantoura and Llewellyn (1983), as modified by Leavitt et al. (1989). The Hewlett-Packard (HP) 1050 system was equipped with a Rainin Model 200 Microsorb C-18 column (5-µm particle size; 10 cm length), an HP model 1050 scanning photodiode array spectrophotometer (435-nm detection wavelength), and an HP fluorescence detector (435-nm excitation wavelength, 667-nm detection wavelength). Analytical separation was achieved by isocratic delivery (i.e., no gradient) of mobile phase A (10% ion-pairing reagent in methanol) for 1.5 min at 1.5 ml min^{-1} and 21,000 kPa pressure, followed by a linear ramp to 100% solvent mixture B (27% acetone in methanol) over 7 min and isocratic hold for an additional 12.5 min. IPR was prepared as 7.7 g ammonium acetate and 0.75 g tertrabutyl ammonium acetate in 100 mL of deionize, distilled water. The column is re-equilibrated by a continued isocratic delivery for 3 min, a linear return to 100% solution A over 3 min, and a further isocratic hold for 12.5 min. An internal reference standard (3.2 mg $\cdot L^{-1}$) of Sudan II (Sigma Chemical Corp., St. Louis, MO) was injected in each sample. This dye runs at a central, unique position on the chromatogram (near myxoxanthophyll), has carotenoid-like absorption characteristics (lambda max = 485, 442.5 nm in acetone), and allows correction for dilution and injection errors. If the reference peak area was different from expectations based on prior calibration, a percent deviation was calculated and used to correct all pigment peak areas. Reference peaks were typically within 10% of expectations.

Pigments isolated from sediments were compared to those from unialgal cultures (Leavitt et al. 1989) and authentic standards obtained from US Environmental Protection Agency. Spectral characteristics, chromatographic mobility, and functional group assays were used to identify pigments from all sources (Leavitt et al. 1989). Acid and methyl derivatives of chlorophyllous pigments were created either by aqueous-alcohol extraction (chlorophyllides) or by acidification following the procedures of Leavitt et al. (1989). Pyropheophytin a and a compound tentatively identified as pyropheophorbide a were collected by HPLC isolation from sediments of several lakes. Not all fossil pigments were positively identified. We restricted our analysis to carotenoids characteristic of cryptophytes (alloxanthin, α-carotene in part), diatoms and chrysophytes (fucoxanthin), chlorophytes and cyanobacteria (lutein-zeaxanthin), all cyanobacteria (echinenone), filamentous or colonial cyanobacteria (myxoxanthophyll), and N_2-fixing cyanobacteria (aphanizophyll), as well as the major a, b, and c-phorbins. Lutein from green algae and

zeaxanthin from cyanobacteria coelute on our HPLC system. Similarly, chromatographic peaks from aphanizophyll (Aphanizomenon), oscillaxanthin (Oscillatoriaceae), and 4-keto-myxoxanthophyll (Anabaena) were not completely resolved on our system, and are presented as aphanizophyll. Organic content of varves was estimated by weight loss on ignition for 1 h at 500°C (Dean 1974). Pigment concentration was expressed as nmol pigment · (g organic matter)$^{-1}$, an index which is linearly related to algal biomass in the water column (Leavitt and Findlay 1994).

Past UVR [identify UVR better] penetration has been measured as a ratio of UVR-absorbing pigments:algal carotenoids, an index which is linearly related to the depth of UVR penetration in whole-lake experiments (Leavitt et al. 1997). Reconstructions were based on the UVR-absorbing pigment, C_a, which has a mass of 635 according to mass spectrometric determinations using negative ion-atmospheric pressure chemical ionization techniques (Leavitt and Hodgson 2001). Abundance of UVR-absorbing pigments is expressed relative to total algal biomass in order to distinguish whether photo-protectant production arises from a unique population (e.g., surface dwelling) or represents a general response of the phototrophic community to UVR. Total algal abundance was estimated as changes in the concentration (as nmoles pigment g^{-1} organic matter) the sum of individual algal group indicators including alloxanthin (cryptophytes), diatoxanthin (diatoms) and chlorophytes (lutein).

Stable isotopes

Stable isotopic compositions of the sediments were analyzed from freeze-dried samples using Thermoquest (Finnigan MAT; F-MAT) Delta^{Plus} XL stable isotope ratio mass spectrometer equipped with a continuous flow (ConFlo II) and a Thermoquest (Carlo Erba) NC-2500 elemental analyzer.

Depending on C and N content, 4 to 20 milligrams of dry sediment were packed into appropriate size tin capsules. Packed samples were introduced into the NC-2500 elemental analyser and N and C components of sediments were completely oxidized at 1000°C in a furnace in order to convert organic constituents into simple nitrogen-based gases and CO_2. This gas mixture was passed through a reduction column packed with fine Cu wire at a temperature of 780 °C in order to convert oxidized N gases such as N_2O and NO into N_2. Pure N_2 and CO_2 were isolated from the reduction outflow using an in-line gas chromotogram within the NC-2500. The pure N_2 and CO_2 gases were introduced into the mass spectrometer through a ConFlo II interface, and stable isotope ratios of C ($^{13}C/^{12}C$) and N ($^{15}N/^{14}N$) of samples were measured. Stable isotope ratios (δ values) were calculated relative to the international standards including Pee Dee Belemnite (PDB) for C isotopes ($\delta^{13}C$) and atmospheric nitrogen gas for N isotopes ($\delta^{15}N$). Stable isotopic composition was expressed as δ notation where $\delta = (R_{sample}/ R_{standard} -1) \times 1000$, R_{sample} represents $^{13}C/^{12}C$ or $^{15}N/^{14}N$ in the sample, and the $R_{standard}$ is the corresponding isotope ratio from a standard. The precision of repeated measurements of a laboratory reference (intercalibrated freshwater lake sediment) was 0.3‰ or better.

Diatoms and other biological remnants

Due to cost constraints, only ten samples were processed for diatoms; five samples were selected from the Youngs Bay core and five from the Grays Bay core (2, 10, 20, 40, and 60 cm depths). Permanent diatom slides were prepared by oxidizing 0.5-1 cc sediment samples in 30% H_2O_2 and rinsing with distilled water. When clean, the samples were transferred to 50 ml graduated centrifuge tubes, and water added to bring the dilution to 10x. The tube was shaken, and a 50 µml aliquot transferred via a mechanical pipette to a 22 x 30 mm cover slip and allowed to dry. The cover slips were fixed to glass slides with Hyrax mounting medium. Results are based on counts of 300 diatom valves per slide at 1250x magnification, with the exception of two samples (CRYB-02: 20 cm and CRGB-06: 40 cm) which, even after repeated processing and efforts to further concentrate the samples, yielded fewer diatoms.

Diatom concentration, in valves/cc of sediment, was determined by counting the number of all diatom valves along one or more vertical traverses on the slide, and dividing this number by the proportion of the entire sample actually observed:

valves/cc = valves counted/aliquot x % area observed

where:
% area observed = (field of view height x field of view width x traverses)/total area

and:
field of view height = 22 mm (the height of the 22 x 30 mm cover slip),
field of view width = 0.15 mm (width of the area observed at 1250x magnification),
total area = 660 mm^2 (total area of 22 x 30 mm cover slip).

Diatoms were placed in one of seven habitat categories, following previous work on Columbia River diatoms by McIntire (1982) and McIntire and Amspoker (1984), plus additional references on diatom autecology (Patrick and Reimer, 1966, 1975; Foged, 1981; Jensen, 1985; Krammer and Lange-Bertalot, 1986-1991; Snoeijs et al., 1993-1998) and observations on the distributions of modern flora in various estuaries in the Pacific Northwest: 1) FWB - freshwater benthic; 2) FWP - freshwater planktonic; 3) BWB - brackish water benthic; 4) SIB – salinity indifferent benthic (euryhaline); 5) SIP – salinity indifferent planktonic; 6) MP - marine planktonic; and 7) U – ecology unknown.

Portions of sediment cores were examined under a dissecting microscope for invertebrate parts (e.g., ostracods, cladocerans, chironomids) and for fish scales.

Heavy metals

Heavy metals, except for mercury, were analyzed using an Energy Dispersive X-ray Fluorescence Spectrometry (EDXRF) technique (Siems 2000). The method is used for the determination of 30 elements in geological materials. EDXRF spectrometry is a qualitative and quantitative technique for the rapid, non-destructive, elemental analysis of liquid and solid samples. Sample preparation is a simple matter of lightly pressing a

powdered geologic sample into a Mylar cup fitted with a Prolene foil. Then the sample is bombarded by X-rays of a selected energy and the characteristic X-ray photons of the analytes are detected and measured. By using selected secondary and polarizing targets a greater peak to background ratio for the various peaks are obtained than when using direct tube excitation. With this method 30 trace elements: V, Cr, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Cs, Ba, La, Ce, Nd, W, Pb, Bi, Th and U are determined routinely.

Samples were processed in a Spectro X-lab 2000 Energy Dispersive X-ray Spectrometer. A 2- to 3-g portion of a powdered sample or reference material was poured into a spectro cup fitted across the bottom with stretched 4µ Prolene film held with a concentric ring. This required no weighing. The powder was then packed into the cup at approximately 10 lbs/in^2 using a Panavise torque wrench. Full details of the EDXRF procedure, calibrations, and calculations were provided in Siems (2000).

To determine mercury, samples were digested with nitric acid and sodium dichromate in a disposable test tube. After digestion, samples were diluted with water to 12 mL. All samples were then mixed with air and a sodium chloride-hydroxylamine hydrochloride-sulfuric acid solution and Hg (II) was reduced to Hg° with stannous chloride in a continuous flow manifold. The mercury vapor was separated and measured using continuous-flow cold vapor-atomic absorption spectrometry (CV-AAS; Perkin-Elmer 3030B Spectrophotometer). The method was fully described by Brown et al. (2002), available on the internet at USGS Open file 02-0223.

Polycyclic Aromatic Hydrocarbons (PAH)

PAH fractions were isolated from Grays Bay core samples only. Wet sediments (~3-5 dry) spiked with a known quantity of perdeuterated perylene (d12-perylene) were extracted ultrasonically(3x, 20 mL each) with a 3:1 mixture of dichloromethane (DCM) and methanol (MeOH). Upon addition of deionized water (~20 mL), the combined extracts were fractionated in a separatory funnel into hexane (3x, 20 mL each). The combined hexane fractions were then washed against a 50% saturated sodium chloride solution (20 mL), dried over anhydrous sodium sulfate (24 hrs) and subsequently evaporated to just dryness using a rotary evaporator. The resultant total extractable lipid (TEL) residue was then separated into an aliphatic hydrocarbon, a PAH and several more polar lipid fractions by silica gel column chromatography (see Prahl et al. 1989 for further details)). All fractions were concentrated to near dryness on a rotary evaporator, transferred to a small (1 dram), clean borosilicate glass vials with Teflon-line caps and then evaporated to dryness under a stream of pre-purified nitrogen for storage (-10^{o}C) until needed for chemical analysis. Only results from analysis of the PAH fractions are presented in this report.

PAH fractions diluted with iso-octane containing a known concentration of d10-pyrene (an internal standard) were analyzed quantitatively by capillary gas chromatography – mass spectrometry(GC/MS) using an HP5971 mass selective detector operated in selective ion monitoring (SIM). The GC/MS was equipped with a 30 m DB-5ms capillary column (0.25 mm i.d., 0.25 µm film thickness). Compound separations were accomplished using helium as the carrier gas (1 mL/min, constant flow mode) and temperature programming (100 – 300^{o}C at 5^{o}C/min). The ions monitored for quantitative

purposes were: m/z202 (fluoranthene, pyrene), 212 (d-pyrene), 228 (benz(a)anthracene, chrysene), 234 (retene), 252 (benzo(b and k)fluoranthene, benzo(a and e)pyrene, perylene), 264 (d12-perylene), 274 (tetrahydrochrysenes), 292 (octahydrochrysenes), 324 (tetrahydropicenes). Individual compound quantification was accomplished by an internal standard method using the absolute response factor of d10-pyrene (RF) and the response factor of each analyte relative to d10-pyrene (RRF) determined through use of authentic standards for all compounds except the THChry, OHChry and THPic. The RRF for each of the latter compounds were assumed to be the same as that for Retene. All reported concentrations have been corrected for recovery of d12-perylene which were ≥ 85%.

Results

Grain size

Youngs Bay

At Youngs Bay, there appeared to be a shift in the median size of sediments deposited through the core. In samples taken from 10 - 40 cm deep (approx. 1940 to 2000) the median sediment size was about 150 μm, while deeper strata, deposited prior to ~1940, had a median sediment size of ~80 μm (Figure 2).

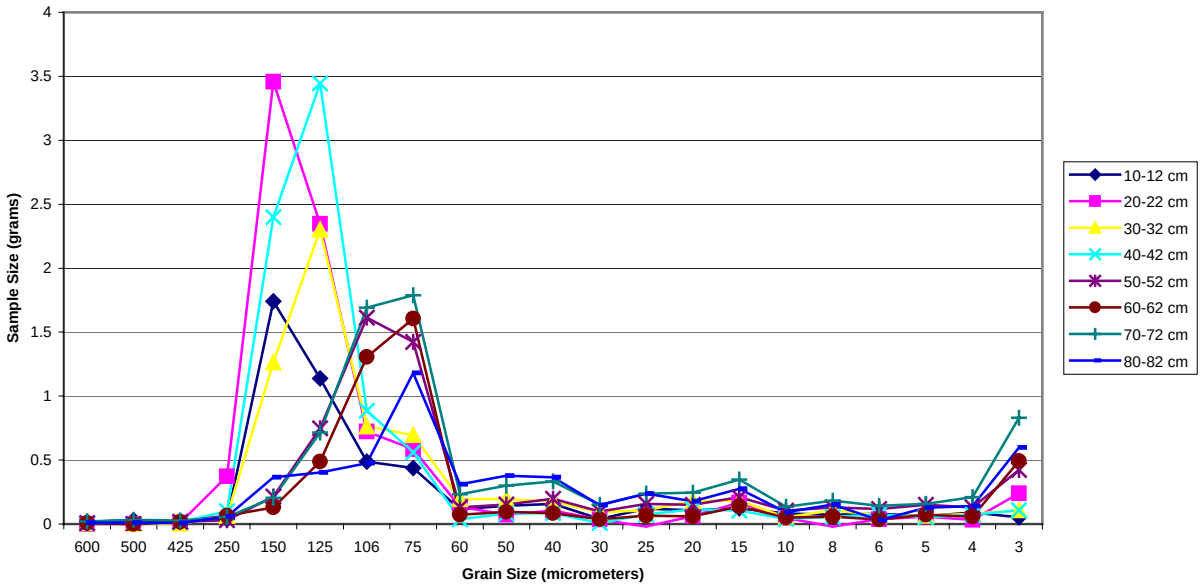
Grays Bay

Grain size distributions from the Grays Bay core did not change greatly with depth or time (Figure 2). Median grain size was 75 – 110 μm in all strata analyzed in this core.

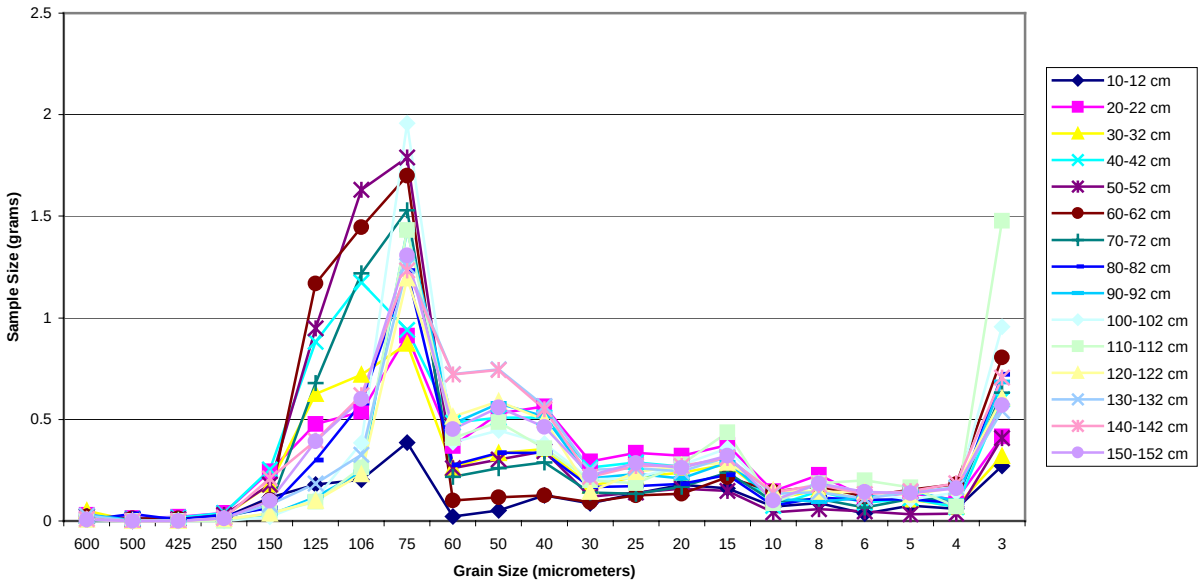
Clatskanie Flats

Grain size distributions were similar throughout the Clatskanie Flats core (with the exception of small grain sizes at 90-92 cm depth??), with peaks at about 15 and 3 μm (Figure 2), indicating a more silty sediment than was observed in the other two cores. Sediments from the Youngs Bay core were generally >50 μm while sediments from Grays Bay samples were mostly >30 μm (Figure 2).

Columbia River Young's Bay 02 Grain Size Analysis



Columbia River Gray's Bay 06A Grain Size Analysis



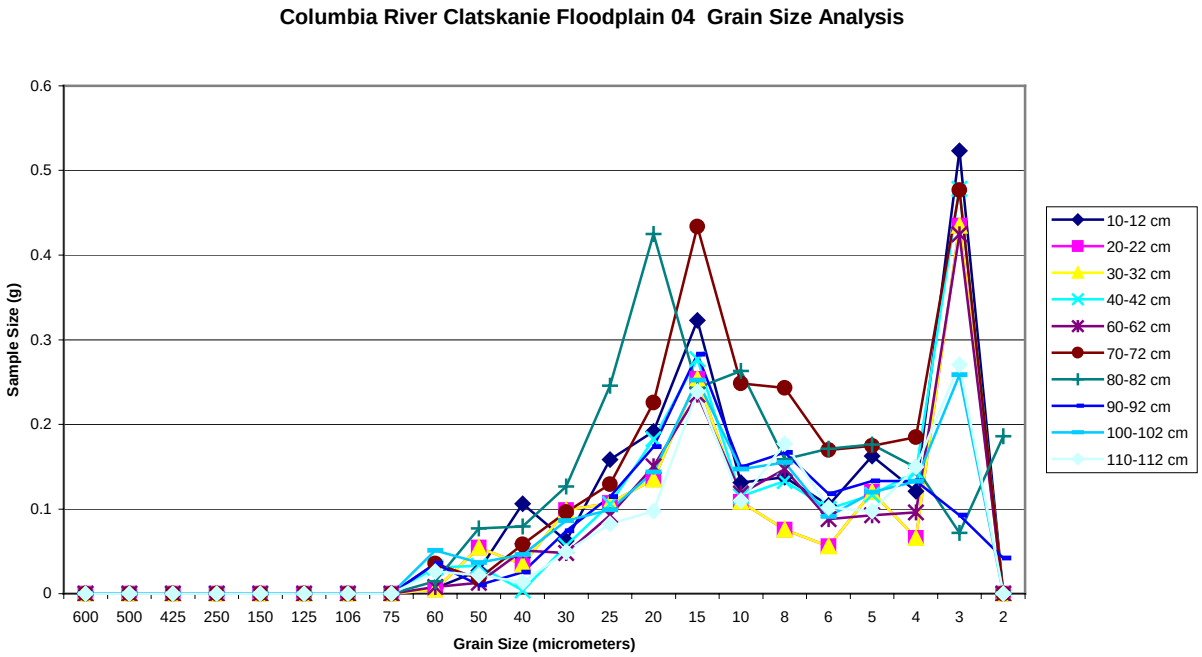


Figure 2. Distribution of grain sizes in three sediment cores in the Columbia River estuary.

Aging of cores

Counting error for ^{210}Pb was 0.15 to 0.20 dpm/g, while the total counting error for ^{226}Ra, ^{214}Pb, and ^{214}Bi was 0.2 to 0.3 dpm/g. Samples of strata from the three cores were not contiguous (Table 3), so we assumed that each sample represented an interval in the core for ^{210}Pb aging. Intervals are contiguous in the cores and have an "average" ^{210}Pb age based on one sample. The upper and lower depth bounds of intervals were adjusted to assure that the center of the aged interval was near the center of the true sample (Table 1). Samples, which came from strata that were 2 cm thick, represented intervals of sediment from 4 to 10 cm in a core (Table 3). Due to cost, we measured ^{210}Pb activity only in the upper 90 or 100 cm sections of cores, and extrapolate dates for deeper parts of the core.

Table 3. Location of strata sampled in cores and intervals represented for ^{210}Pb aging. Upper and lower bounds of intervals were adjusted so Sample and Interval midpoints were as close as possible. All data are cm from the surface.

Youngs Bay					Grays Bay					Clatskanie Flats				
True sample interval	Sample midpoint	Interval midpoint	Upper bound	Lower bound	True sample interval	Sample midpoint	Interval midpoint	Upper bound	Lower bound	True sample interval	Sample midpoint	Interval midpoint	Upper bound	Lower bound
2-6	4	3	0	6	2-4	3	3	0	6	2-6	4	3	0	6
10-12	11	9.5	6	13	6-8	7	7	6	8	10-12	11	9.5	6	13
15-17	16	16.5	13	20	10-12	11	11	8	14	20-22	21	19.5	14	25
20-22	21	21.5	20	23	15-17	16	16	14	18	30-32	31	30.5	26	35
25-27	26	25.5	23	28	20-22	21	20.5	18	23	40-42	41	40	35	45
30-32	31	31.5	28	35	25-27	26	25.5	23	28	50-52	51	50	45	55
40-42	41	40	35	45	30-32	31	31.5	28	35	60-62	61	60	55	65
50-52	51	50	45	55	40-42	41	40	35	45	70-72	71	70	65	75
60-62	61	60	55	65	50-52	51	50	45	55	80-82	81	80	75	85
70-72	71	70	65	75	60-62	61	60	55	65	90-92	91	90	85	95
80-82	81	80	75	85	70-72	71	70	65	75	100-102	101	100	95	105
					80-82	81	80	75	85					
					90-92	91	90	85	95					
					100-102	101	100	95	105					

Youngs Bay

Excess ^{210}Pb in the Youngs Bay core ranged from 2.2 dpm/g near the surface to 0.04 dpm/g at about 60 cm (Figure 3). ^{210}Pb concentration showed a general decline with depth, especially in the upper 30 cm. The samples from 20 and 40 cm may be slightly above and below, respectively, the expected concentrations from an exponential decay. The proportions of samples that were organic material was <0.05 in Youngs Bay, and bulk density (ρ) ranged from 1.2 to 1.7 g cm^{-3} (Figure 4). Sediment accumulation rate was fairly constant throughout the core (~1.7 cm/yr; Figure 5), lowest of the three cores examined.

Using the CRS model, the ^{210}Pb age at 70 cm was 1916, and the increase in ^{137}Cs showed good coherence with the predicted ^{210}Pb date (Figure 6). A second-order polynomial fit the predicted ^{210}Pb dates well over the upper 70 cm of the core (r^2 = 99%), allowing us to extrapolate that the deepest sediment in this core (80 cm) was deposited about 1910 (Figure 7).

Grays Bay

The ^{210}Pb activity in the Grays Bay core also showed an exponential decline, ranging from about 2.6 dpm/g near the surface to 0.06 dpm/g at 60-70 cm. Samples at 90 and 100 cm in this core may show a slight increase in ^{210}Pb activity compared to samples at 60-80 cm (Figure 3). The sample collected at 50 cm in this core may have been anomalous, showing a much higher ^{210}Pb activity than expected when compared to the other samples in the core (Figure 3). The proportion organic material in this core ranged

from about 0.02 to 0.1 (Figure 4). The sedimentation rate was less than 1.5 cm/yr, except for the shallowest portions of the core where the rate was ~2.3 cm/yr (Figure 5).

The core from Grays Bay had ages that were slightly less variable than the Youngs Bay core, with the 100 cm sample at Grays Bay having an average ^{210}Pb age of 1916. In the Grays Bay core, the ^{210}Pb age for 1954 occurred at ~52 cm while the ^{137}Cs concentrations started to increase at ~35 cm. The polynomial for extrapolating age in deeper parts of this core fit well (r^2 =98%) and the bottom of this core (150 cm) had an approximate date of 1853.

Clatskanie Flats

The Clatskanie Flats core showed the highest overall ^{210}Pb activity of the three cores analyzed, and activities had a consistent decline with depth (Figure 3). Organic content was also highest in this core (>10%) among the three studied (Figure 4), while the rate of sediment accumulation appeared to increase somewhat through time (Figure 5).

The Clatskanie Flats core had the lowest variability around individual age estimates, with the 90-cm sample having an average ^{210}Pb age of 1927 (Figure 6). The Clatskanie Flats core showed the poorest correspondence with the ^{210}Pb age for 1954 being near 70 cm but the ^{137}Cs increase did not occur until about 30-40 cm (Figure 6). A polynomial fit for the Clatskanie Flats core (r^2 = 99%) was used to extrapolate an age of 1855 for the deepest sample in the Clatskanie Flats core (140 cm; Figure 7).

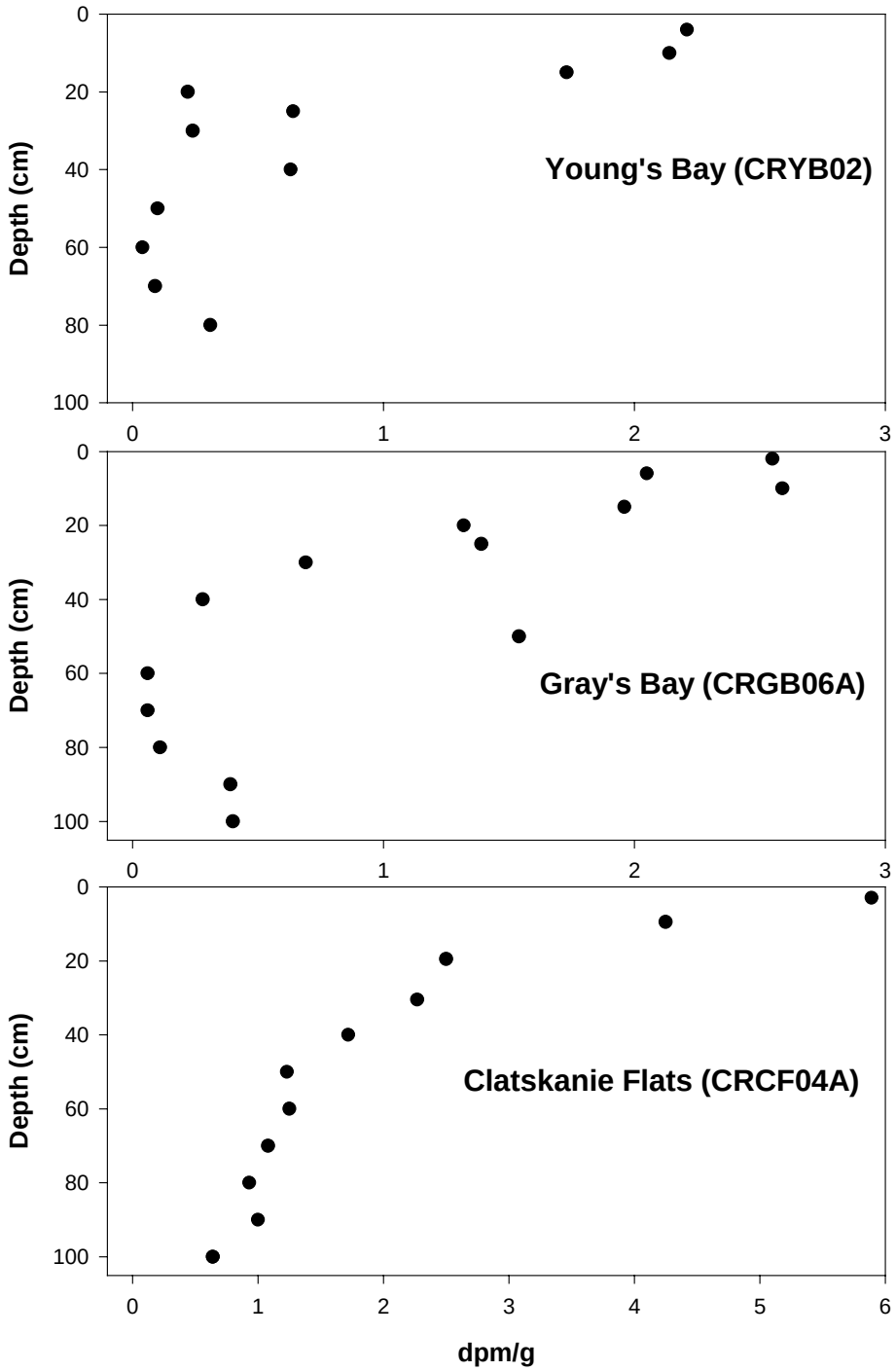


Figure 3. Excess ^{210}Pb in three cores from the Columbia River estuary. Note different scale for Clatskanie Flats core (lower panel). dpm = disintegrations per minute.

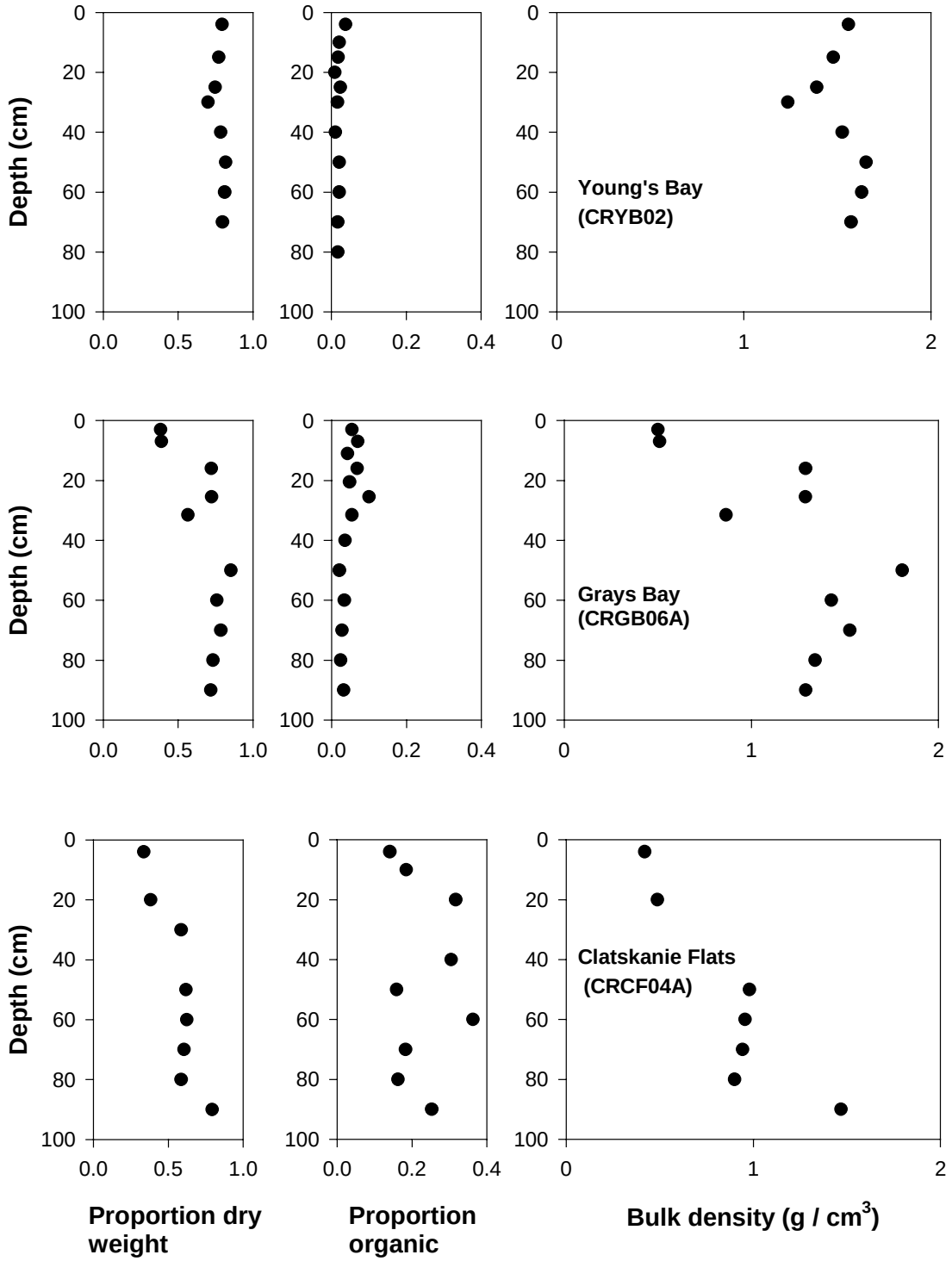


Figure 4. Proportion dry weight per unit volume, proportion organic, and bulk density (g · cm^{-3}; also called dry density) for three cores from the Columbia River estuary. Bulk density was estimated by the method of Binford (1990), and is ρ in the Binford terminology.

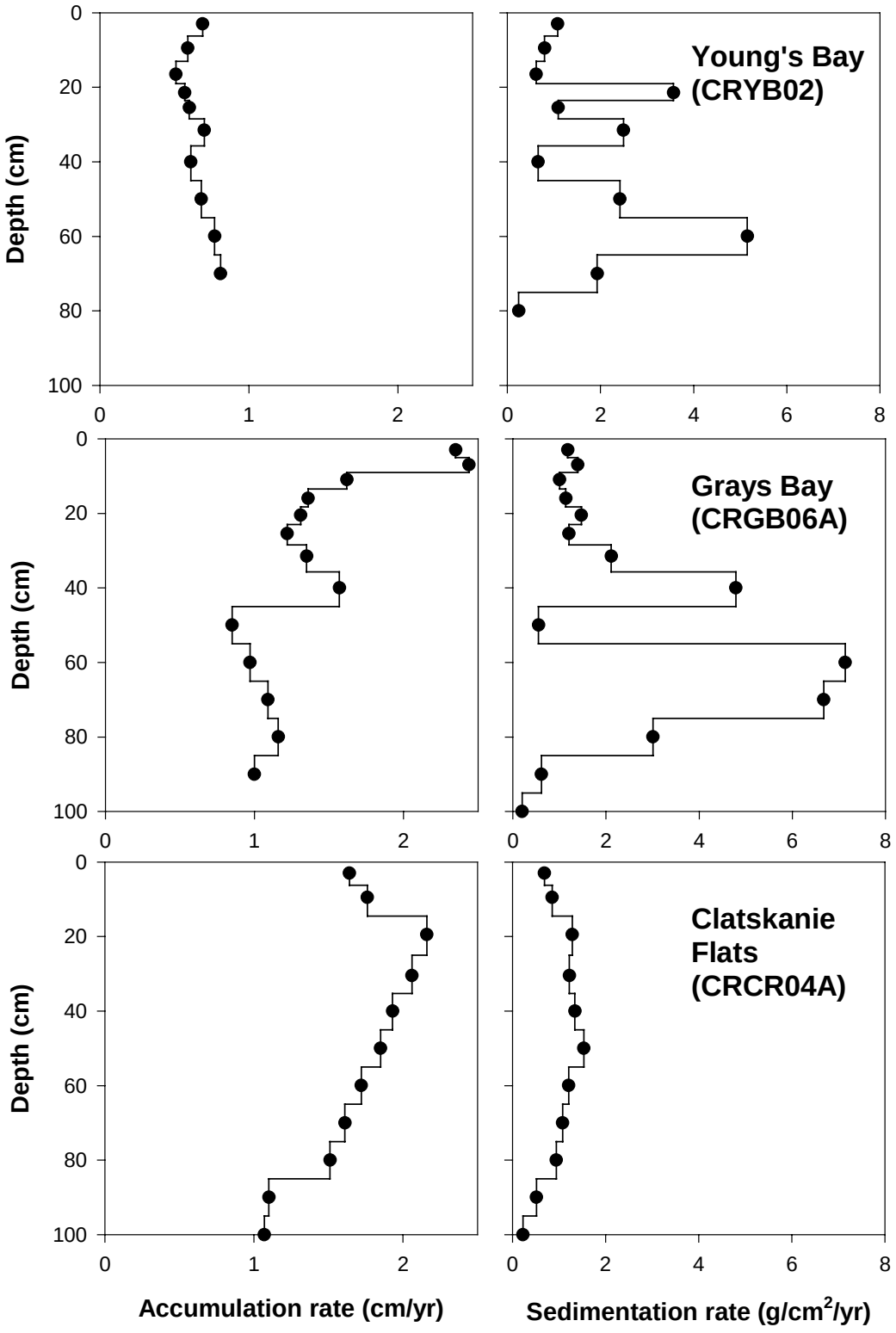


Figure 5. Sedimentation rates (cm/yr and g/cm^2/yr) in three cores from the Columbia River estuary.

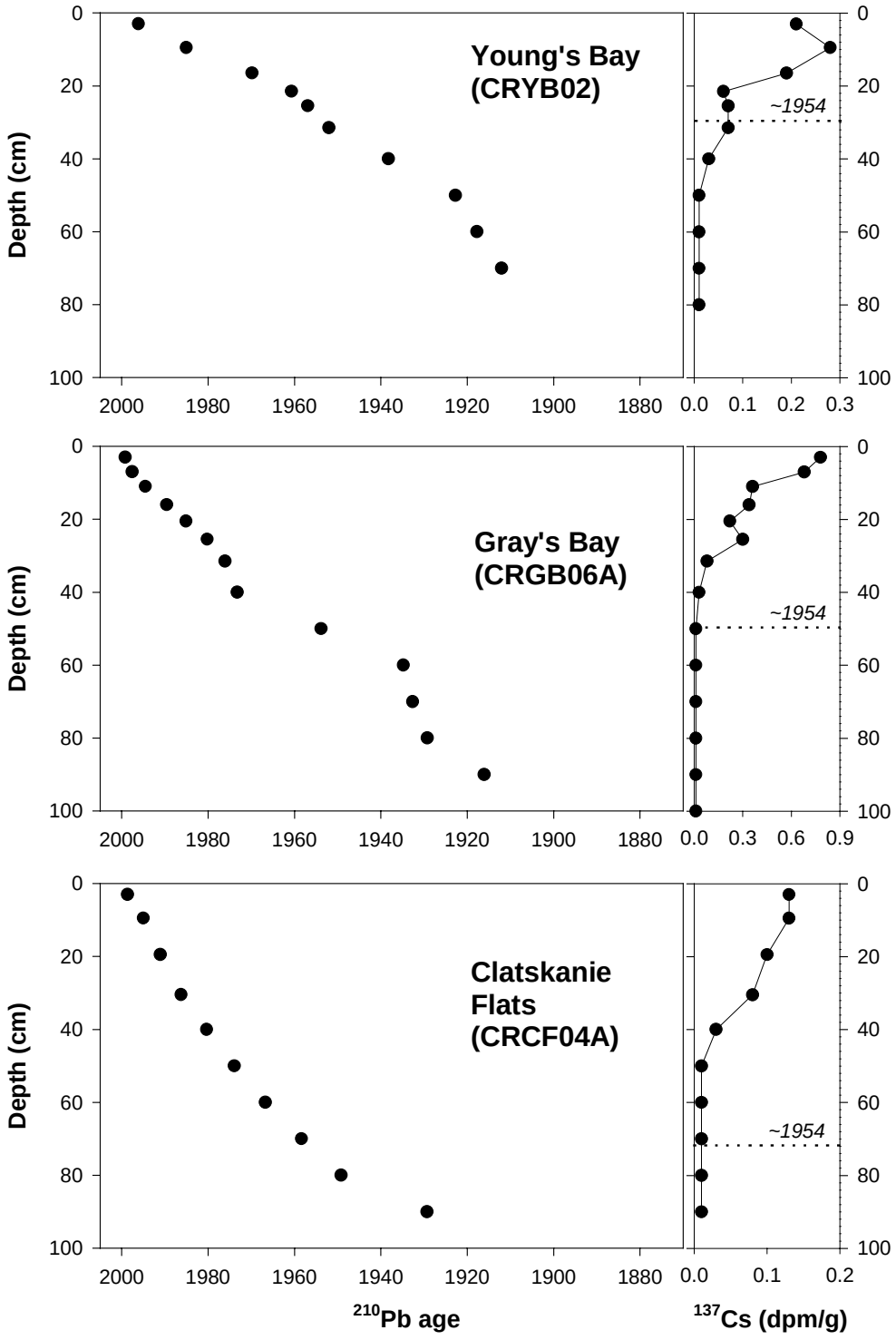


Figure 6. ^{210}Pb average age for intervals from three sediment cores from the Columbia River estuary, and corresponding ^{137}Cs concentrations (right panels). The dotted lines on the ^{137}Cs panels indicate the approximate position for 1954 based on ^{210}Pb age.

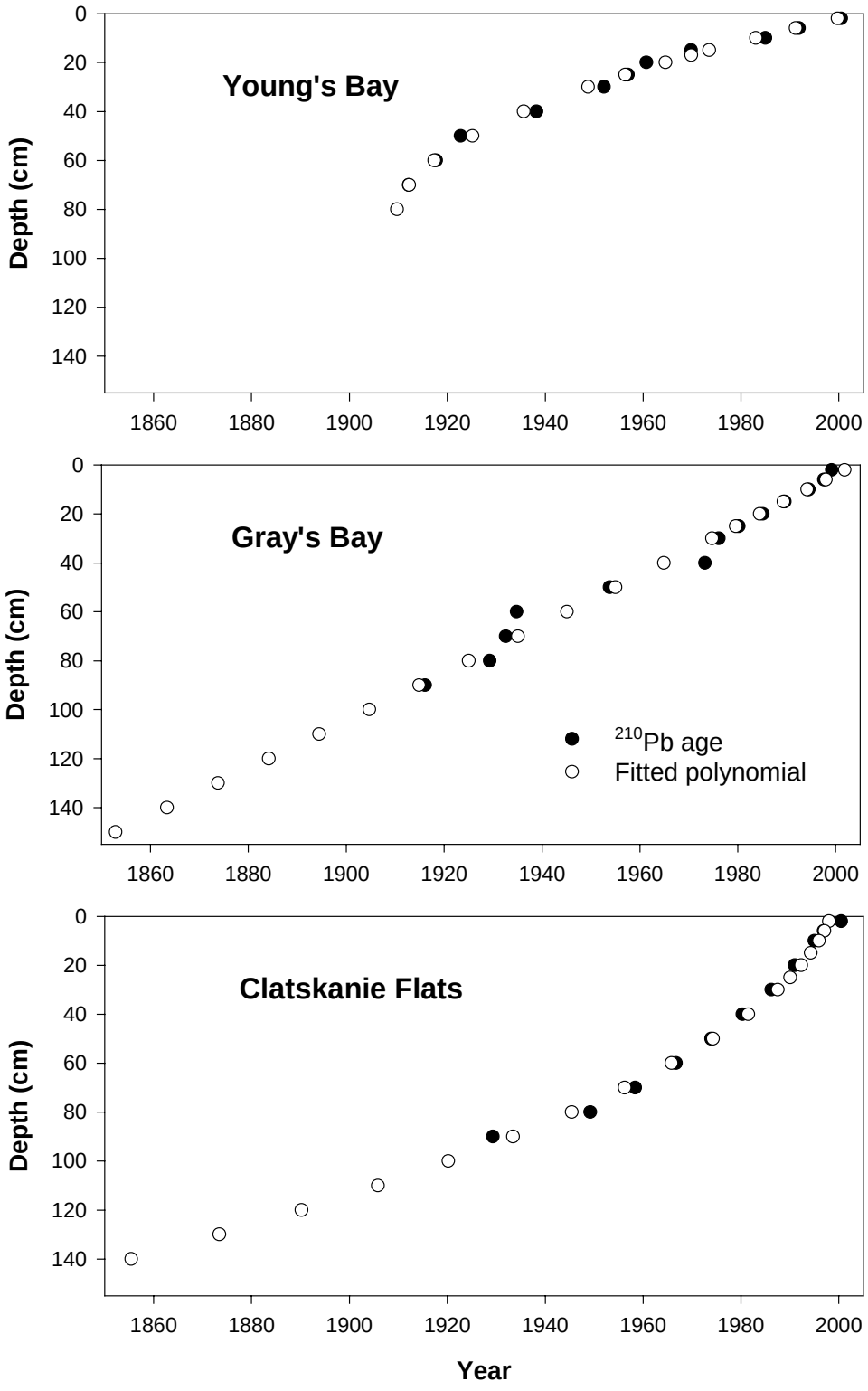


Figure 7. Predicted ^{210}Pb ages in three cores from the Columbia River estuary. Age in deeper parts of the cores was extrapolated using fitted, second-order polynomials (r^2 > 97% in each case).

Pigments

Youngs Bay

Analysis of fossil carotenoids, chlorophylls (Chl) and their derivatives by HPLC revealed that algal community composition changed dramatically during the period of analysis. Prior to 1936 (40 cm depth; Figure 8; Figure 9), algal communities were composed mainly of diatoms (as diatoxanthin) and, secondarily chlorophytes or cyanobacteria (lutein-zeaxanthin). In particular, diatoxanthin concentrations (as nmoles pigment g^{-1}organic matter) were similar to those recorded in many lake ecosystems, and were generally greater than values seen in other estuaries (e.g., Bianchi et al. 2002). However, following ca. (1936; 40 cm), diatoxanthin concentrations declined five-to-10 fold to stable values in the most recent sediments (Figure 9). In contrast, chemically-stable pigments from planktonic cryptophytes (alloxanthin) increased ~200-300% after 1973 (15 cm), as did the more labile pigment, Chl *a*. Reductions in stable and ubiquitous β-carotene after 1936 suggest that the transition from diatoms to flagellates was accompanied by an overall 400% reduction in algal standing crop, concomitant with increases in exposure of algae to UV radiation (UVR). Changes in inferred algal abundance did not appear to result from dilution of pigments with uncolored organic matter, as there were few directional changes in sedimentary organic matter content. Instead, sediment organic matter content appeared similar to that recorded at other nearshore marine locations.

Grays Bay

Sedimentary analysis of Grays Bay fossil pigments revealed few historical trends in inferred algal production during the past 150 years (based on core age; Figure 9). Overall, concentrations of all major pigments (except beta-carotene??) were similar to those recorded at the Youngs Bay site, and were greater than those at Clatskanie Flats (see below). Once again concentrations of diatoxanthin were greater than those of carotenoids derived from cryptophytes (alloxanthin), green algae or cyanobacteria (lutein-zeaxanthin) or of ubiquitous pigments (β-carotene, Chl *a*), a pattern consistent with the importance of diatoms in the algal community. Particularly noteworthy was the observation that concentrations of β-carotene were near the analytical limits of detection, a pattern most commonly associated with poor pigment preservation, despite the fact that sedimentary profiles showed little evidence of post-depositional degradation (e.g., exponential declines in concentration with burial depth; Figure 8). Instead, the absence of stratigraphic pattern is consistent with either a stable environment through time, or a high degree of pigment decomposition within the water column. Unlike both Youngs Bay and Clatskanie Flat, sedimentary organic matter content increased in Grays Bay sediment following 1985 (20 cm depth), while inferred UVR flux declined (Figure 9).

Clatskanie Flats

Comparison among fossil pigment profiles suggests that algal production declined over five-fold during the past 150 years (age at base of core). Patterns were similar

regardless of the chemical stability of individual compounds, with elevated pigment concentrations prior to 1920 (100 cm), slowly declining concentrations in sediments deposited between 1920 and 1982 (100 cm and 40 cm), and stable, but trace, levels following 1988 (30 cm; Figure 9). In general, pigment declines occurred concomitant with increased exposure to UVR, as measured using sedimentary concentrations of sunscreen pigments produced by benthic algae. However, unlike other sites, pigment concentrations were extremely low (<1 nmole pigment g^{-1} organic matter) in all sedimentary intervals, suggesting poor preservation of biochemical markers despite extremely high organic matter content compared to Youngs and Grays Bays. Similar patterns of low fossil abundance combined with elevated organic matter content have been recorded also in freshwater wetlands and peat deposits (P.R. Leavitt, unpublished data)

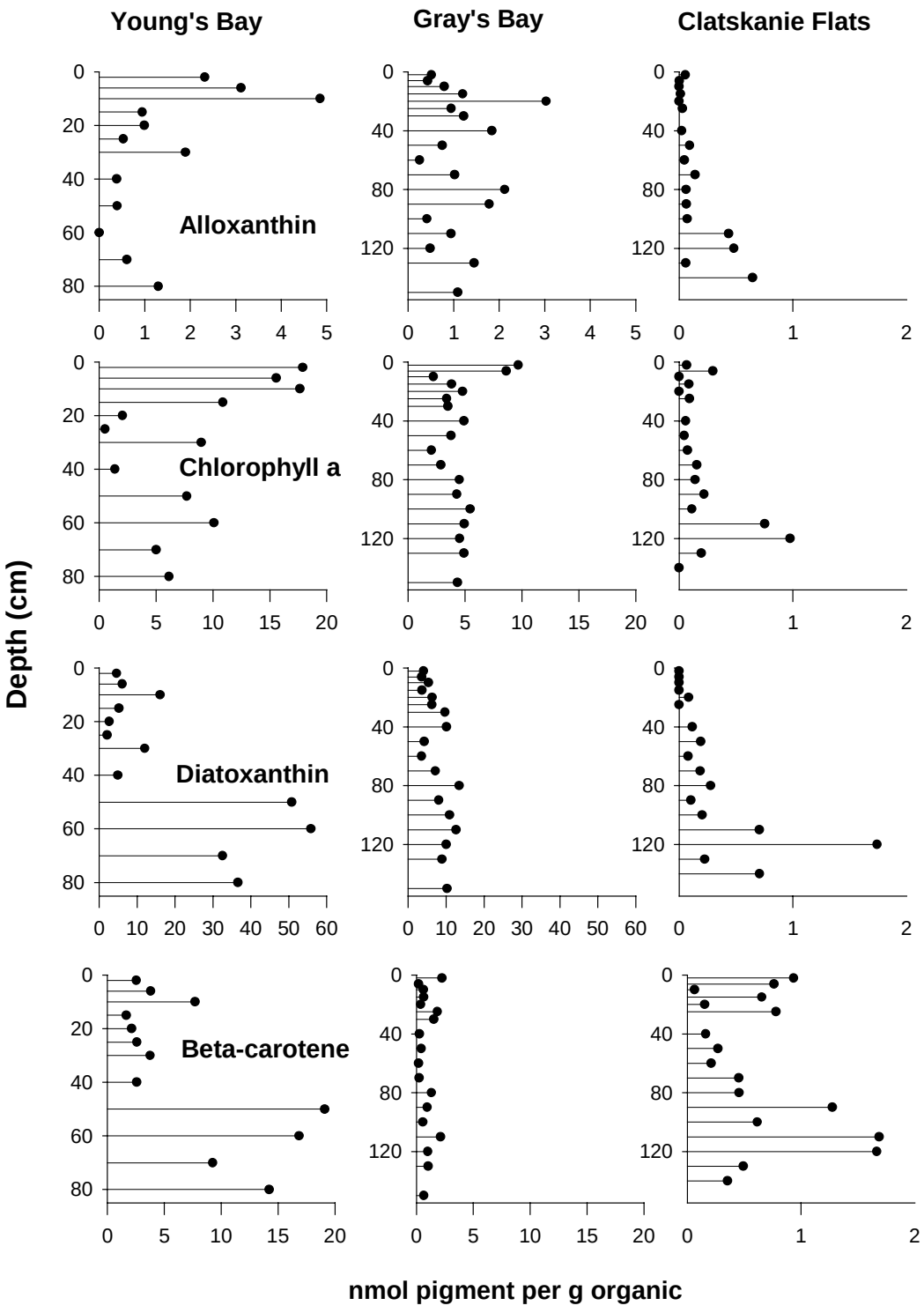


Figure 8. Five algal pigments, UVR index (following page), and percent organic material (following page) by depth in three cores from the Columbia River estuary. Units for algal pigments are nmol of pigment per g of organic matter. Note the different scales for the Clatskanie Flats core.

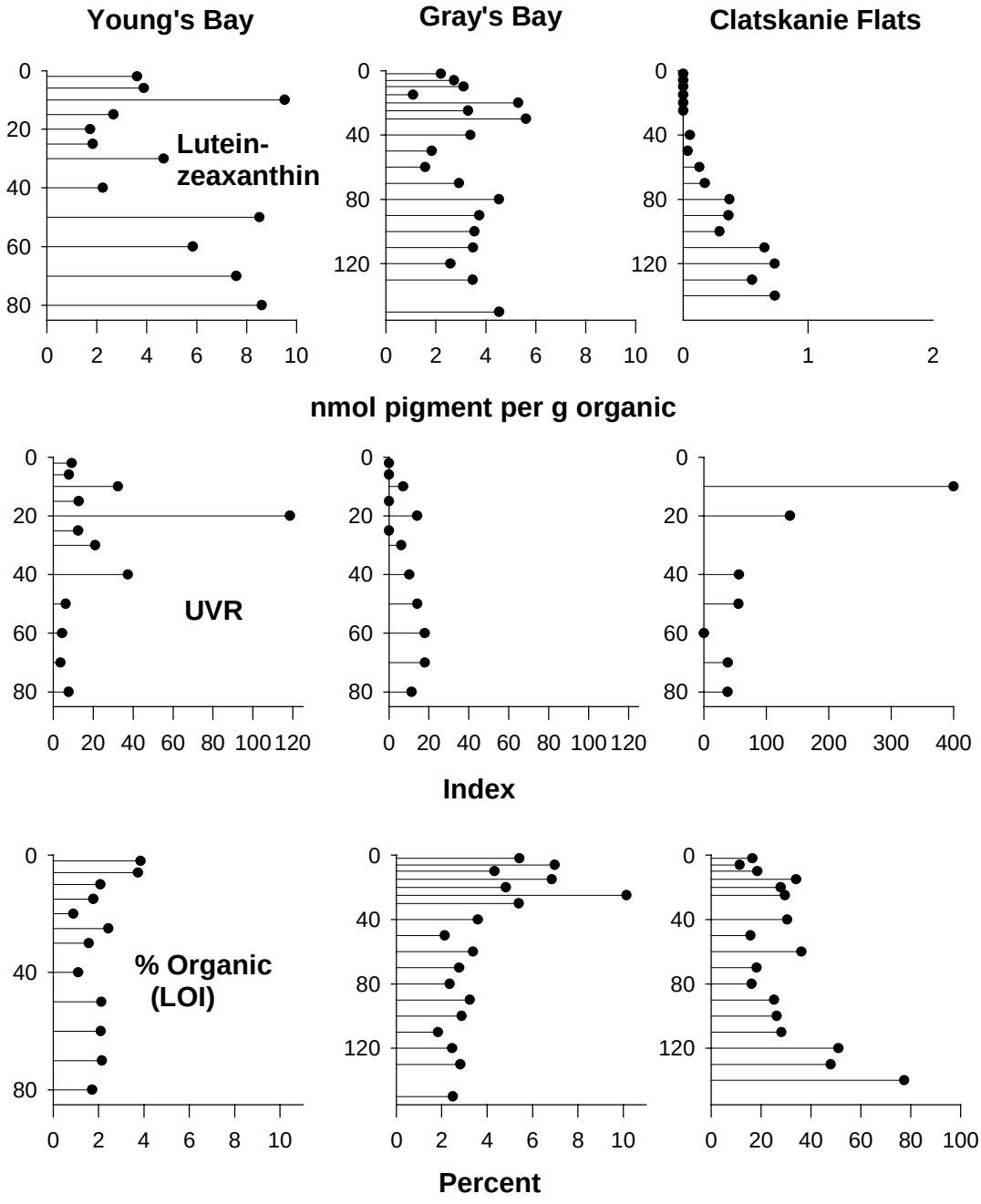


Figure 8 (continued)

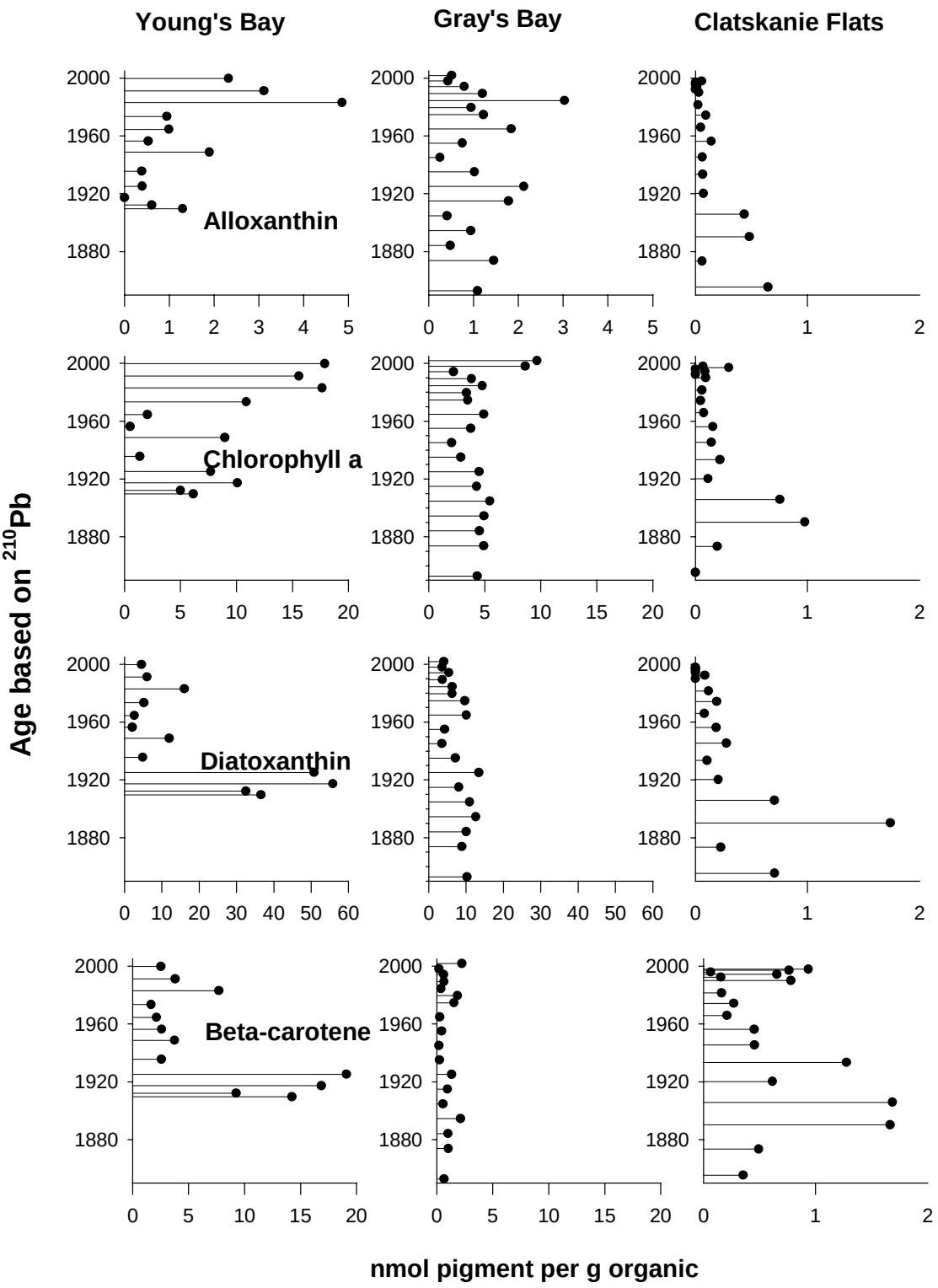


Figure 9. Predicted age of deposition for five algal pigments, UVR index (following page), and percent organic material (following page) in three cores from the Columbia River estuary. Units for algal pigments are nmole (nmol) of pigment per g of organic matter. Note the different scales for the Clatskanie Flats core.

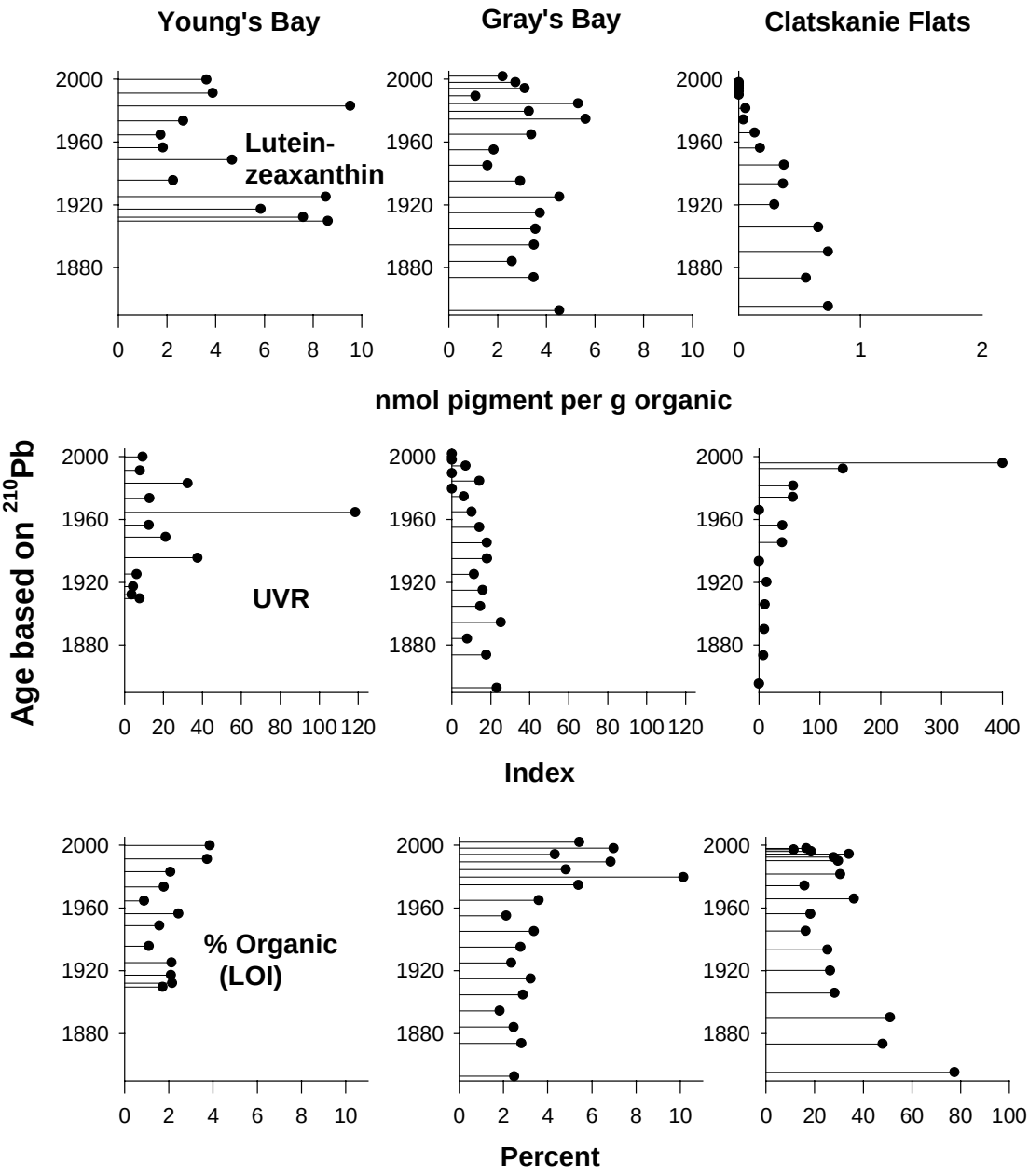


Figure 9 (cont.).

Stable Isotopes

Youngs Bay

Low N contents in estuary sediments at this site prevented quantitative analysis of stable isotopes of N in deeper strata, as well as accurate determination of N content (%). Overall, carbon contents were low (~0.4% C g^{-1} dry mass), with few sustained stratigraphic patterns. Similarly, $\delta^{13}C$ values ranged only from –25 $^{o}/_{oo}$ to –26$^{o}/_{oo}$ (Figure 10), values consistent with an algal or plant source of organic carbon (Figure 10).

Grays Bay

Low N content prevented quantification of $\delta^{15}N$ and %N analyses at all depths in the Grays Bay core. Overall, carbon content (% dry mass) was twice those recorded at the Youngs Bay site, but were 35% lower than those recorded at Clatskanie Flats. While there was a tendency for C content to increase about 50% between 1853 (age at bottom of core) to present day, this trend was obscured by apparently high inter-sample variability. C isotopic content varied between –25 and –27$^{o}/_{oo}$ (Figure 10), with generally depleted values between recorded between 1980 (25 cm) and 1935 (70 cm; Figure 10). As in Youngs Bay, $\delta^{13}C$ values were characteristic of planktonic carbon sources.

Clatskanie Flats

Stratigraphic patterns of both C and N isotopes were well developed at Clatskanie Flats (Figure 10). Overall, C and N contents were greatest in sediments older than 1890 (120 cm), but declined to stable values by 1935 (70 cm). Mean %C and %N values were similar to those recorded at freshwater sites, and were an order of magnitude greater than other Columbia River estuary stations. Fossil profiles of $\delta^{13}C$ increased rapidly from –28.5$^{o}/_{oo}$ at the base of the core (1855), to –27.0$^{o}/_{oo}$ by 1920 (100 cm), decline until ~50cm depth, then rose to maximum values of –26.5$^{o}/_{oo}$ in the most recently deposited sediments (Figure 11). In all cases, $\delta^{13}C$ values were characteristics of algal or plant production by C3 photosynthesis. In contrast, $\delta^{15}N$ levels ranged from 0.5 to 2.2$^{o}/_{oo}$, with little obvious historical trend (Figure 11). Overall, these values are close to that observed for N_2-fixing organisms (-2 to +2 $^{o}/_{oo}$), suggesting that sediments were highly reduced, and that active N_2-fixation may have occurred continuously since ~1850.

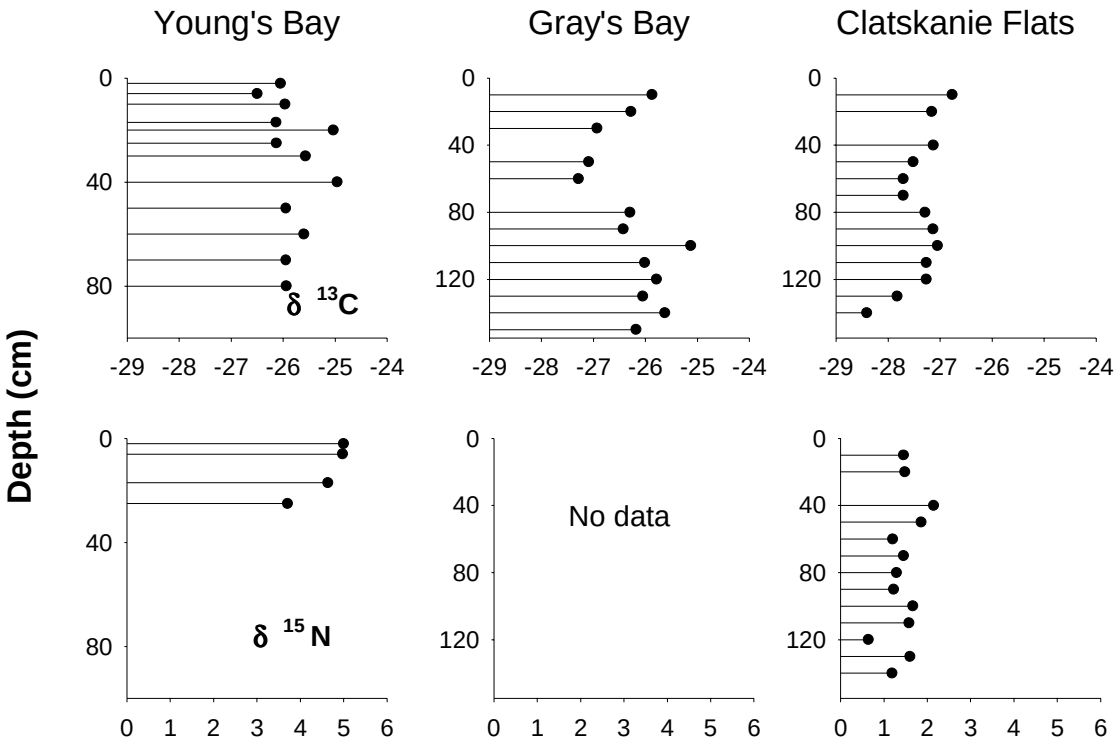


Figure 10. Depth distribution of stable isotope ratios of C and N for three sediment cores in the Columbia River estuary.

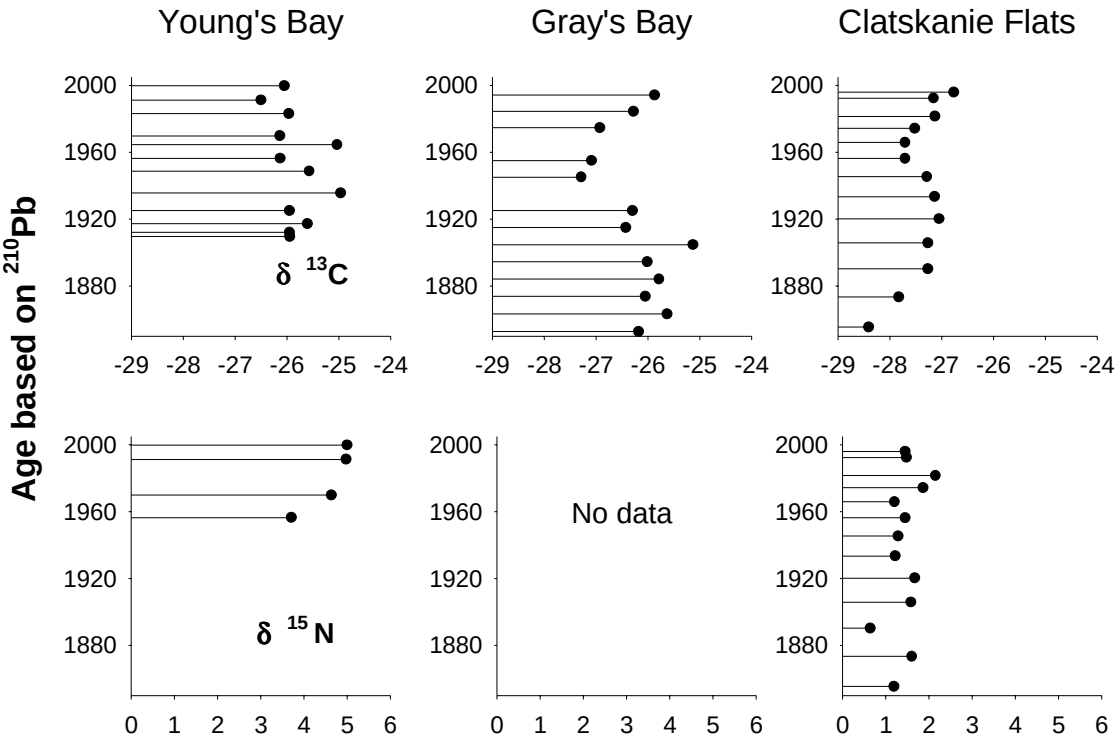


Figure 11. Age distribution of stable isotope ratios of C and N in three sediment cores from the Columbia River estuary.

Diatoms and other biological remnants

A total of 94 diatom taxa (Appendix 4) were observed in the ten samples from Youngs Bay and Grays Bay. A low salinity regime (with salinities < 2 ppt) dominated throughout the record at both core localities. The dominance of freshwater taxa is prominent in both cores. Dominant taxa are consistent between the two cores, consisting primarily of benthic freshwater species, particularly *Fragillaria brevistriata*, *F. pinnata*, *Martyana martyi*, and *Navicula submuralis* (Appendix 4). Planktonic diatoms are found in all samples, but mostly represent < 5% of assemblages (Table 4). Excluding the 20 cm at Youngs Bay and the 40 cm sample at Grays Bay, in which diatoms were rare in the coarse-grained samples, planktonic diatoms are only prominent at 2 cm in Youngs Bay, in which they comprise 43% of the assemblage (Figure 12). Three freshwater planktonic taxa, *Aulacoseira italica, A. granulata* and *Stephanodiscus rotula*, account for 38% of the assemblage. Diatom concentration was relatively high in both cores (Figure 12), reflecting high diatom productivity in the upper half of the intertidal zone. Pertinent epiphytic species include *Epithemia turgida*, *E. sorex*, *Cocconeis placentula* var. *euglypta*, and *Rhoicosphenia abbreviata*; many of these were observed as intact frustules.

We found no remains of crustaceans, other invertebrates, or fish scales in the sediment samples examined.

Youngs Bay

Taxa from Youngs Bay consisted of 40 freshwater benthic, 11 brackish water benthic, 12 salinity indifferent benthic, 6 freshwater planktonic, 2 salinity indifferent planktonic, 4 marine planktonic, and 3 species with unknown ecology (Table 4). In Youngs Bay, freshwater taxa range from 81% to 90% with an average of 86.8% (Appendix 4). A lesser influence from brackish water is recorded by occurrences of salinity indifferent species and the combined categories of brackish+marine species, which in Youngs Bay account for an average of 7.8% and 4.3%, respectively. A change in conditions favoring planktonic diatoms is evident in the upper section of the Youngs Bay core (Table 4, Figure 12). Presence of epiphytic diatoms in some samples at Youngs Bay 2-cm probably record deposition in the upper half of the intertidal zone.

Grays Bay

Taxa from Grays Bay consisted of 31 freshwater benthic, 11 brackish water benthic, 9 salinity indifferent benthic, 4 freshwater planktonic, 2 salinity indifferent planktonic, 5 marine planktonic, and 3 species with unknown ecology (Table 4). In Grays Bay freshwater taxa range from 74% to 91% with an average of 86.7% (Appendix 4). respectively. In Grays Bay salinity indifferent species were 6.0% of the total and brackish+marine species were 4.2%. In the Grays Bay core, epiphytic diatoms comprise 12% at 6 cm and 15% of the samples at 10 cm and 20 cm, respectively (Figure 12). Diatoms were overall well-preserved in the sample, indicating a depositional environment with less abrasion and reworking than active lower-intertidal flats and subtidal channels.

In Youngs Bay, the percentage of all diatoms that was benthic declined from 96% in 1917 (60 cm) to about 55% in 2000 (2 cm). There was a concomitant rise in the percentage of planktonic diatom species (Figure 12). In the Grays Bay core, we observed no consistent pattern in benthic versus planktonic diatoms, with planktonic diatoms being generally <10% of the total assemblage (Figure 12).

Table 4. Salinity preferences and habitat (%) for diatoms from two cores in the Columbia River estuary.

Depth	Fresh-water benthic	Fresh-water planktonic	Brackish water benthic	Marine planktonic	Salinity-indifferent benthic	Salinity-indifferent planktonic	Ecology uncertain
				Youngs Bay			
2 cm	45.7	41.3	3.3	1.0	8.0	0.7	-
10 cm	75.5	9.9	3.4	0.7	7.5	1.0	2.0
20 cm	50.5	30.3	7.1	2.0	7.1	-	3.0
40 cm	83.3	1.7	5.1	-	7.8	-	2.0
60 cm	89.0	1.0	2.3	-	6.7	-	1.0
				Grays Bay			
2 cm	90.3	0.7	2.0	-	4.7	-	2.3
10 cm	85.6	4.0	1.8	-	4.3	1.4	2.9
20 cm	82.3	3.5	5.6	0.7	5.9	0.3	1.7
40 cm	61.8	11.8	11.8	2.2	8.1	1.5	2.9
60 cm	84.0	0.7	2.7	0.2	6.4	-	6.1

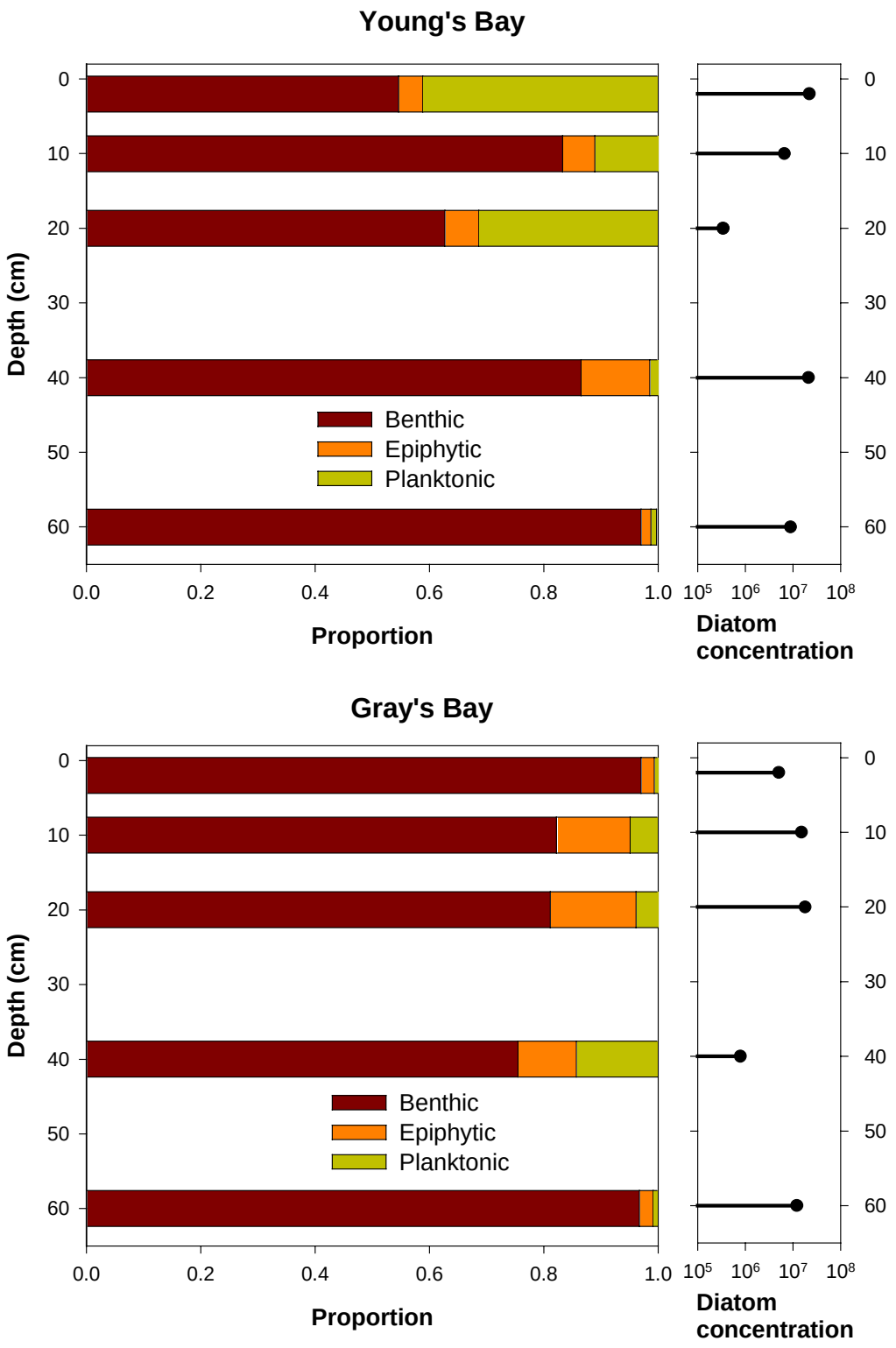


Figure 12. Diatom habitats and concentrations for two sediment cores in the Columbia River estuary. Concentration is number of diatoms per cc of sediment.

Heavy metals

In this section, we discuss general depth and time trends for four common metal contaminants: Mercury (Hg), lead (Pb), copper (Cu), and zinc (Zn). Summary results for all heavy metals are provided in Appendix 3 (except Ge, which was measured at 1.0 ppm in all samples).

Youngs Bay

Mercury concentration appeared to increase slightly near the core surface in the Youngs Bay core, with the three samples deposited after about 1983 (2, 6, and 10 cm) having the highest concentrations (Figure 13 and Figure 14). Overall, concentrations of mercury at Youngs Bay were low compared to the other two locations. The 30-cm sample in the Youngs Bay core showed an unusually high concentration of lead (33 ppm), zinc, and copper, especially when compared to adjacent samples (Figure 13). For the preliminary analyses and discussion below, we chose to disregard the 30-cm sample from Youngs Bay. Lead concentrations increased slightly after 1949 (30 cm), compared to older samples in the Youngs Bay core. Copper concentration was low (<20 ppm; Figure 13) in all samples deposited after 1983 (10 cm), with a slight increase in the near-surface samples (~24 ppm; samples at 2, 6, and 10 cm). The highest concentrations of zinc at Youngs Bay were in sediments dated ~1980 to 2000 (<12 cm deep; Figure 14), disregarding the 30-cm sample discussed above. Aside from the four metals discussed above, Br, Sr, and Zr showed increasing concentrations in recent sediments, while V, Cr, and La showed decreasing concentration patterns (Appendix 3).

Grays Bay

At Grays Bay, the concentration of mercury increased steadily in samples above 50 cm (1955), rising from <0.03 ppm to about 0.08 ppm in samples < 15 cm deep (Figure 13). At Grays Bay, there was a steady increase in lead, also starting at 1975 (30 cm), rising to ~18 ppm in recent sediments near the surface. At Grays Bay, copper was lowest prior to 1915 (below 90 cm), intermediate between 1915 to 1965 (90 and 40 cm), and highest in the samples deposited after 1965 (above 40 cm). There was a slight decline in copper concentrations in the 2- and 6-cm samples compared to the 10-cm depth, which was the highest in the Grays Bay core. At Grays Bay, zinc concentration was very similar to the pattern of copper in the core: lowest below 90 cm, intermediate between 40 and 90 cm, and increasing in samples above 30 cm. At Grays Bay, many of the metals showed very distinct patterns with depth. V, Cr, Ni, Ga, Y, Zr, and Nb had higher concentrations in surface sediments, whereas Rb, Sr and Ba appeared to have lower concentrations in shallow surface sediments (Appendix 3).

Clatskanie Flats

There was no obvious pattern with depth for mercury at the Clatskanie Flats site, although concentrations throughout this core were higher than older sediments in either of the two other cores (Figure 13 and Figure 14). The average concentration of mercury in the deeper parts of the core at Clatskanie Flats was about twice as high as mercury

concentrations in lower part of the cores from Youngs Bay and Grays Bay (0.06 ppm versus 0.03 ppm; Figure 13). The pattern for lead in the Clatskanie Flats core was less distinct. Concentrations of lead were <10 ppm in the deepest samples (1906; >110 cm), rising to ~13 ppm throughout much of the core (Figure 13). The sample from about 1998 (2 cm) from Clatskanie Flats had a relatively high lead concentration (18 ppm). The concentration of copper at Clatskanie Flats showed relatively little pattern with depth, although the overall concentrations were quite high compared to the other two sites. Zinc concentrations showed no distinct pattern in the Clatskanie Flats core. At Clatskanie Flats, surface sediments for a few metals appeared elevated (V, Cr, Ga, Sr and Th), although the pattern was not as marked as for the Grays Bay core (Appendix 3).

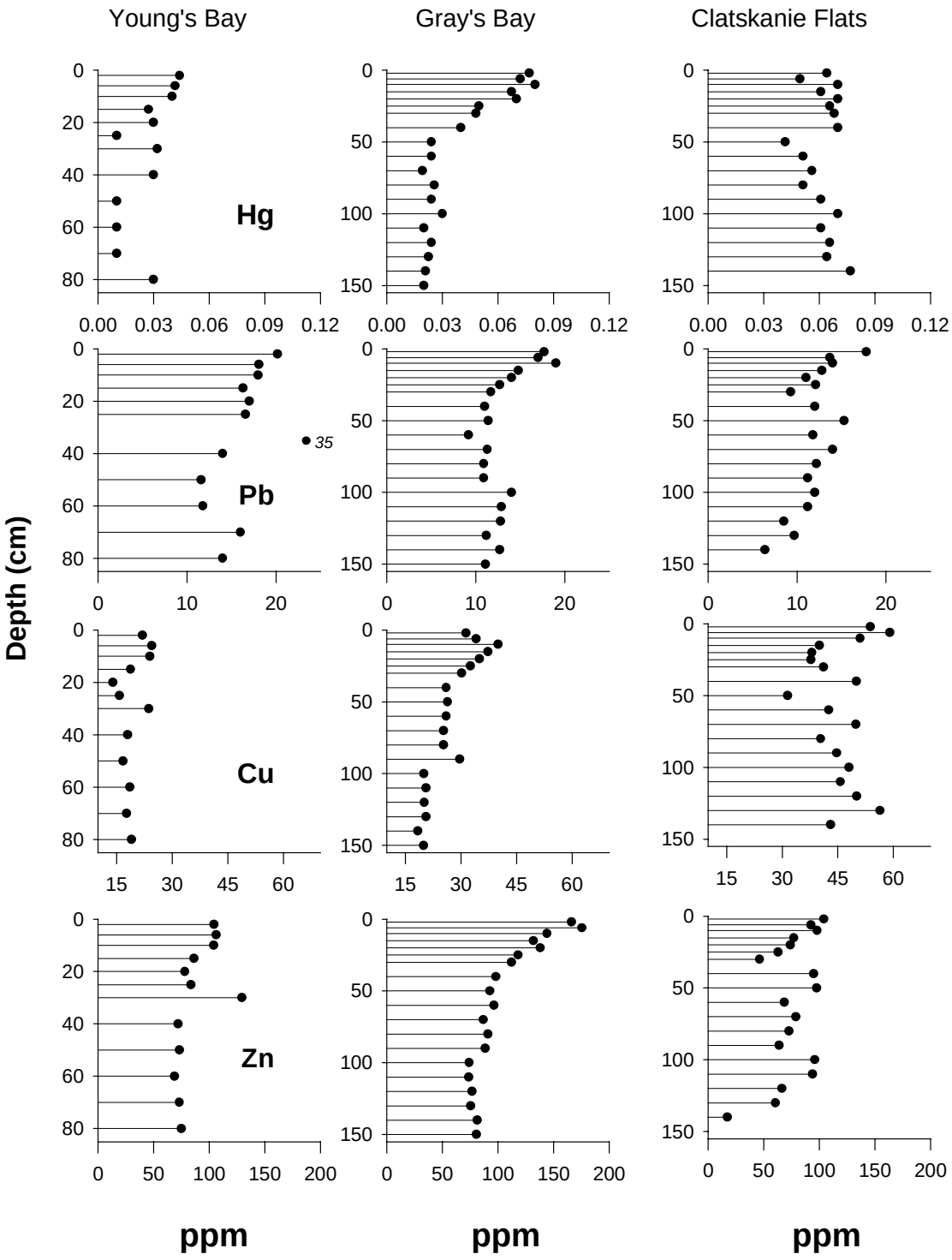


Figure 13. Depth and concentrations of mercury (Hg; top row), lead (Pb), copper (Cu), and zinc (Zn; bottom row) in three cores from the Columbia River estuary. Note different total depths for cores. For comparison, the scale for each metal is the same among cores.

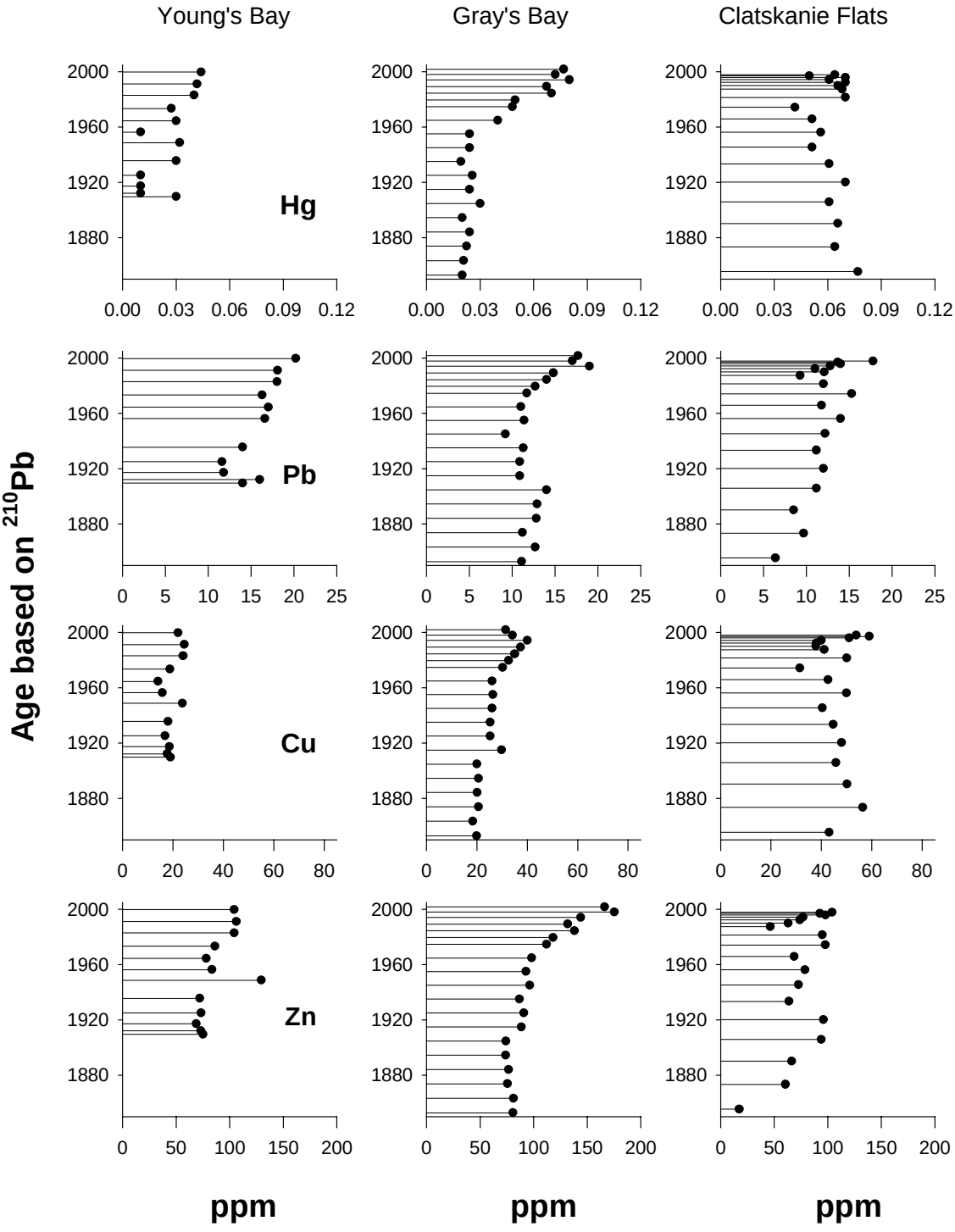


Figure 14. Sediment age and concentrations of mercury (Hg; top row), lead (Pb), copper (Cu), and zinc (Zn; bottom row) in three cores from the Columbia River estuary. For comparison, the scale for each metal is the same among cores. Ages older than about 1920 (deeper strata) in the Grays Bay and Clatskanie Flats cores were estimated using second-order polynomial regressions (see text).

Polycyclic Aromatic Hydrocarbons (PAH)

Analysis of sediments from the Grays Bay core showed PAH are measurable over the entire depth range examined, i.e. 0 to 135 cm (Figure 15). By far the most abundant PAH is a five-ring, polycondensed compound called perylene, which has a natural, but as yet unidentified origin (Wakeham et al., 1980b). The downcore profile for perylene varied randomly from 250 to 500 ng/g, averaging 368 (±92) ng/g.

The next most abundant class of PAH is a series of compounds that are ultimately derived from resins found in conifers (i.e. retene) and the triterpenoids found in deciduous trees such as alder (i.e. octa- and tetrahydrochrysenes and tetrahydropicenes) (Wakeham et al., 1980b). Like perylene, the downcore concentrations for these compounds also displayed considerable variability, but a trend of decreasing concentration with depth is arguably evident.

A suite of unsubstituted, condensed ring compounds of high temperature combustion origin (Wakeham et al., 1980a) is the final contributor to the PAH composition measured in this core. The parameter entitled 'Combined' in Figure 15 represents the composite concentration of eight combustion-derived compounds: fluoranthrene, pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benz(a)pyrene and benz(e)pyrene. Such combustion PAH can be produced by the inefficient burning of any fuel.

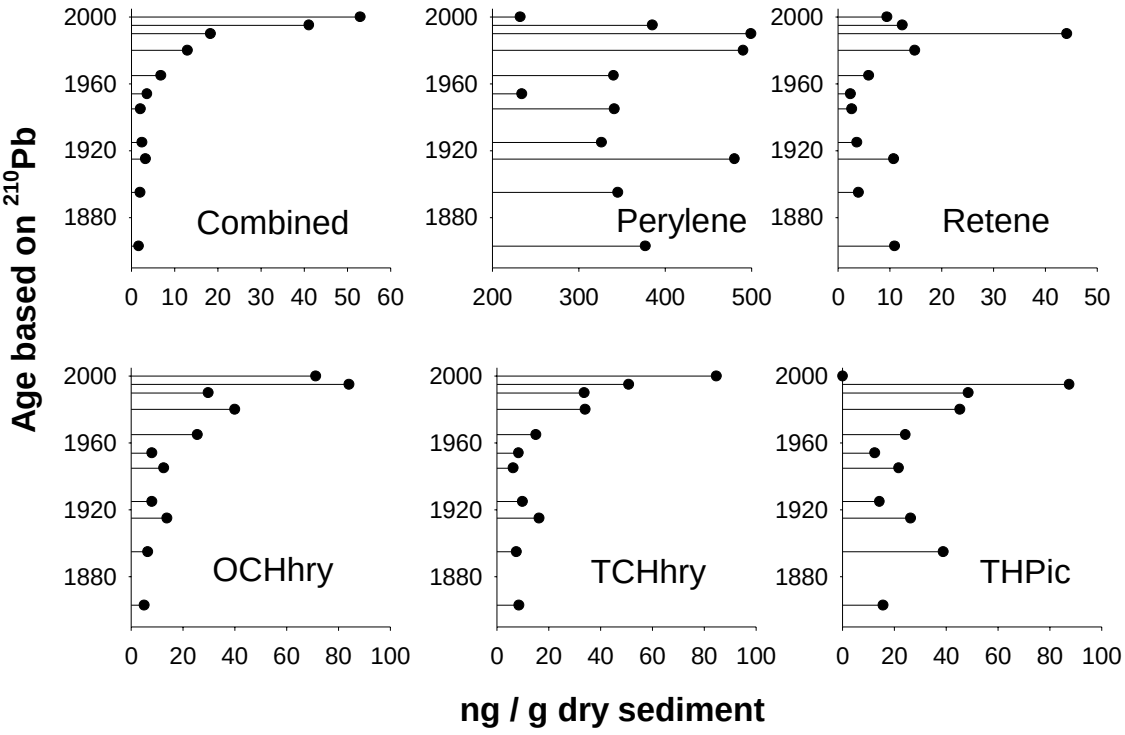


Figure 15. Age and concentration of total combustion PAH (Combined: Hites et al. 1977) and five specific 'diagenetic' PAH compounds (Perylene, Retene, OCHhry = octahydrochrysenes, THChry = tetrahydropicenes; Wakeham et al. 1980).

Discussion

This study was designed to examine the feasibility of aging sediment cores in the Columbia River estuary, and to see whether specific biological or contaminant indicators could be measured in sediments. These indicators might be used to study changes that have occurred in this estuary through time. We were able to age several cores with radionuclides of ^{210}Pb and ^{137}Cs, and could assign approximate dates of sediment deposition. Algal pigments, diatoms, stable isotopes, heavy metals, and polycyclic aromatic hydrocarbons (PAH) were measurable, and many of these indicators showed temporal change suggesting shifts in the physical and biological environment.

Youngs Bay

The Youngs Bay core was the shortest of the three examined (80 cm) and contained sediment dated from about 1910 to 2000. During this period, there appeared to have been a major change in the physical conditions and biological community at this site. Grain size distributions changed around 1940, along with a shift from primarily benthic freshwater diatoms early in the century to planktonic freshwater species after 1940. The shift at this time was also well represented in algal pigments. For example, diatoxanthin and beta-carotene decline five- to ten-fold while alloxanthin and chlorophyll-a increased sharply. These changes suggest that there may have been an overall 80% reduction in algal standing crop, and that much of this reduction occurred in benthic algal species. In general, alloxanthin from flagellates is a 'planktonic' marker, hence a shift from diatoms (potentially benthic) to cryptophytes (probably planktonic) is certainly consistent with a change in the habitat of algal production and is consistent with the diatom record.

We cannot identify specifically the mechanism(s) that led to the changes observed at Youngs Bay, but mainstem impoundment or local alterations in the Youngs River drainage can be suggested. Sullivan et al. (2001) argued that dams on the Columbia River have caused a decrease in suspended particulate material, clearing of the water column, and thus improved conditions for planktonic diatom growth. Some of our results appear to corroborate these findings, particularly the diatom community and algal pigments in Youngs Bay. The concentration of a few heavy metals such as lead showed slight increases between 1920 (14 ppm) and 2000 (21 ppm).

McIntire (1982) reported modern diatom assemblages from Youngs Bay were dominated by euryhaline benthic taxa, in contrast to older samples from Youngs Bay that show a stronger freshwater, rather than brackish, influence in the diatom record. This may show a change in brackish-water incursion in Youngs Bay from prehistoric to modern times. However, McIntire's sampling site was located on the west side of Youngs Bay, whereas our Youngs Bay sample is located in proximity to the mouths of the Youngs and Lewis and Clark rivers. Therefore, it is possible that river outflow is controlling the record of low salinity in this core. According to McIntire (1982), high concentrations of planktonic diatoms in the benthos of the Columbia River estuary often occur where fresh and marine water meet in a mixing zone.

Grays Bay

The core from Grays Bay spanned the period from about 1853 to 2000, and showed less change in the biological community at this site, but significant accumulation of heavy metal contaminants. Throughout this period, the diatom community was dominated by benthic freshwater species (>82% of all identified species) and algal pigments showed few trends, although the percent organic matter doubled from ~3% prior to 1970 to ~6% after 1970. As in Youngs Bay, the ratio of ^{13}C to ^{12}C ($\delta^{13}C$) was characteristic of planktonic carbon sources. This core, however, showed the strongest evidence of increasing heavy metal contamination beginning about 1960. Mercury concentration, for example, was very consistent in sediments deposited between 1850 and 1950 (~0.03 ppm), but concentration increased steadily from about 1960 to the 1990s with a final concentration of ~0.08 ppm. Lead, copper, zinc, and other heavy metals showed similar increasing accumulation during the last 40 years. Patterns that are more complex than simple increases or decreases with depth were present for many of the metals. Copper and several metals from Grays Bay, for example, appeared to have low concentrations prior to ~1910 (below 90 cm), higher and constant metal concentrations between 1910 and 1960 (90 to 40 cm), and gradually increasing concentrations after 1960 (above 40 cm; Appendix 3). These more complex patterns, and tests of hypotheses, could be further explored with the data.

Clatskanie Flats

The core selected from the Clatskanie Flats area was composed of sediments with more silt than in the other two cores, and the base of this core extended back to about 1855. Diatom analyses were not conducted for this core, but shifts in algal pigments, decreased percent organic material near the surface, an increase in an ultraviolet index in recent times, and change in $\delta^{13}C$ suggest changes in the biotic community after the early 1900s. A few heavy metal concentrations (e.g., lead and zinc) increased gradually over the last 150 years, while other metal concentrations remained fairly constant (e.g., mercury and copper).

Recommendations

Not all cores could be aged, and careful selection of coring sites is probably a necessary prerequisite to successful aging. We examined 2-cm sections of cores that were spaced from two to ten cm apart in the cores. In future studies, analysis of sediment throughout a core for ^{210}Pb and ^{137}Cs activities should provide better age estimates with tighter confidence bounds. We also recommend collection of surface sediments in future studies, with a box corer for example; our shallowest sample was from 2-4 cm deep in the core. The pros and cons of using alpha particle activity versus gamma counts of ^{210}Pb might also be considered (C. Holmes, USGS, personal communication). If possible, deeper cores should be collected since they would allow a longer extension of the paleoecological record. Radiocarbon sampling could be considered in some cores.

Diatom concentration can be a useful proxy for paleoproductivity in samples of consistent grain size. However, the data are equivocal when grain size is variable since diatoms are silt-sized particles and will automatically be more abundant in muddy samples than in sandy samples. In the Youngs Bay and Grays Bay samples, the results

for diatom concentration aren't entirely comparable because of differences in grain size. For example, the 20 cm sample at Youngs Bay and the 40 cm sample at Grays Bay are sandy samples (as determined by qualitative observation during sample processing) and contain the fewest diatoms (Figure 12). In order to make more use of the diatom-concentration data, they should be compared with grain-size analyses. Concentrations might also be standardized using the grain size distribution in a stratum (E. Hemphill-Hailey, personal communication).

Although we observed no microinvertebrate fossil remains or fish scales in these sediment samples, such remnants may be present in other sediment cores. Cladocerans from lake sediments have been used to evaluate trout stocking in lakes (Miskimmin and Schindler 1994) and a variety of fossil remains have been found in lake and marine sediments (e.g., Hall et al. 1999; Guilizzoni et al. 2000; Hofman and Winn 2000; Smol et al. 1999). Morphometric change in *Bosmina* (cladocerans) fossils have been correlated with food web change in large aquatic systems such as Lake Michigan (Kitchell and Carpenter 1987). The presence of fish scales in cores might be particularly instructive if they could be used to reconstruct trends or variation in populations or stocks (Finney et al. 2000). Future studies should continue to examine cores for fossil remains.

We used simple descriptions of the patterns in these cores, but various other analyses are possible. Cluster analysis could be applied to the diatom data to better describe compositional changes through time or among sites. The patterns of heavy metals in the cores suggest hypothesis tests concerning the time when metal concentrations began increasing or decreasing at specific sites. Through the National Water-Quality Assessment program (NAWQA) of USGS, metal concentrations have been measured in sediments from the Willamette River Basin, the upper Snake River Basin, and the central Columbia Plateau (Rice 1999). These watersheds drain into the Columbia River and metal concentrations from the NAWQA dataset might be used to describe source concentrations of metals for the Columbia River estuary. Finally, additional work could be done to see if changes in pigments, diatoms, and grain size distributions correlate among sites.

Assuming that ^{137}Cs concentrations would begin to show an increase in about 1954 (Blais et al. 1995), the three cores showed various degrees of correspondence between the three radionuclides, but overall the match was reasonably good. The concentration of ^{137}Cs does not show a peak around 1963, as is often seen in lake sediments, since ^{137}Cs is continually supplied from the watershed in river sediments (C. Holmes, USGS, personal communication).

Sources of the combined PAH in the Columbia River Basin include, among other things, exhaust emissions from automobiles, wood burning (both natural and anthropogenic), and wastewater discharge from aluminum smelting. The profile for combustion PAH in the Grays Bay core shows a pronounced concentration maximum at the surface and rapid decline with depth. This shape is to be expected as anthropogenic production of combustion PAH overshadows natural production throughout the world (Hites et al. 1977). The timing for the sharp increase in combustion PAH noted at ~40 cm core depth conceivably corresponds to the early 1950s, the period when major water reclamation projects commenced throughout the Columbia River Basin and human development increased throughout the Pacific Northwest (Sullivan et al. 2001 and references therein). Notably, this time stamp inferred from the profile data for

combustion PAH concentration is reasonably consistent with the age assigned based on the depth profile for excess ^{210}Pb activity in the same core (see Figure 15), thus lending credibility to the ^{210}Pb age estimates.

Conclusions

There appears to be considerable potential for further work on sediment cores from the Columbia River to assist in interpretation of long-term trends and changes. These cores can provide a temporal baseline for evaluating ongoing restorations or changes, and for interpreting the impacts of human activities. For many indicators, measurements were fairly constant in the older sediments and the variance of means was small, making tests of change powerful and sensitive to small increments. The costs of collecting these data are reasonable, and other studies are showing the usefulness of paleoecological datasets in understanding problems related to salmon and aquatic ecosystems in general (e.g., Finney et al. 2000). A longitudinal collection of cores along the length of the estuary might be used to evaluate how flows have changed through time, influencing the extent of various environments (salt, brackish, freshwater). Cores might also be collected in specific wetland sites and used to assist in the evaluation of restoration activities.

Acknowledgements

Frank Shipley, Director of the USGS Western Fisheries Research Center, provided funding for most analyses, while cores were collected through funds from the USGS Coastal Marine and Geology Program. Lyman Thorsteinson and Jim Seelye provided encouragement and ideas. Dave Siems, Jim Budahn, Zoe Ann Brown, and their staffs, analyzed samples for ^{210}Pb, ^{137}Cs, and heavy metal, and assisted with interpretations. Eileen Hemphill-Hailey identified diatoms and helped with interpretations of those results. Katy Huskey helped greatly with data organization. Chuck Holmes (USGS) provided comments on age analysis and the spreadsheet for estimating ^{210}Pb ages.

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Appendicies

Appendix 1. Workshop participants and agenda.

Agenda for workshop / meeting

Columbia Estuary Sediment Cores

Meeting at:
Portland State University
Smith Memorial Center, Room 290

July 30, Monday

1. 12 noon - Introductions. What are your specific interests in this project? Where did the funds come from and why? Petersen & all
2. 1 p.m. - Physical processes in the Columbia River Estuary. Where are we most likely find well-laminated cores, which can be aged? What will be the limitations? Gelfenbaum, Peterson, and Simenstad.
3. 2 p.m. - Discuss potential indicators in sediments. Fossil pigments, stable isotopes, invertebrate structures, etc. Leavitt
4. 3 p.m. - Review of USGS/PSU available cores (spreadsheet summary and photos). Make preliminary selection of some representative cores for tomorrow.
5. 4 p.m. - Geology Dept., PSU, begin search for selected cores for tomorrow's examination.
6. 5 p.m. - Happy hour.
7. Evening. Discussion of potential for ongoing work/proposals. What are some outstanding questions? What would be the sources(s) of funds? Timing? Other ideas? Other collaborators?

July 31, Tuesday

1. 8 a.m. - Examine specific cores in the PSU Geology Dept.: lamination, sediment types, etc.
2. 10 a.m.- Make Decisions: Can the existing cores be used? If so, what samples are needed, how many, aging needed, etc. If these cores cannot be used, can we collect ones that with a different technique? Field procedures needed? Logistics – who will do sampling, transfer of funds, etc.
3. 11 a.m.- Wrapup. Final comments.
4. 12 noon - Disperse to far corners of the NW.

5.

Items to cover or discuss

- Ageing techniques – what can be used? Pb, Cs, introduced species (Corbicula, plant pollen), tephra, cut wood (first occurrence), tsunami sand, anthropogenic tracers (metals, organic byproducts, radioisotopes)
- Peter's suggestion of doing pigments and isotopes on surface samples from all cores. Might give evidence of N15 impacts and where things are preserved. Compare with Baltic estuary work? 40 cores x $25 per sample = $1000
- Get diatom estimates. Eileen Hemphill-Bailey,
- General framework ideas – how to approach? Other regional research models that have worked? Baltic estuary study?
-

Workshop participants and overall responsibilities on project:

Jim Petersen, USGS, Cook	Overview, coordination, climate change
Reg Reisenbichler, USGS, Seattle	Salmon biology, marine-derived nutrients
Guy Gelfenbaum, USGS/GD	Sedimentology, estuarine processes
Curt Peterson, PSU	Sedimentology, history of Columbia River estuary
Diana Baker, PSU	History of Columbia River estuary
Dave Percy, PSU	Database management
Si Simenstad, Univ. Wash., Seattle	Estuarine ecology
Peter Leavitt, Univ. Regina, Canada	Paleoecology

Appendix 2. Field methods and summary

COLUMBIA RIVER VIBRACORING STUDY

PRELIMINARY FIELD REPORT, JULY 2000

By:

Curt Peterson, Portland State Univ., Portland, Oregon
Sandy Vanderburgh, Univ. College of the Fraser Valley, British Columbia, Canada
Diana Baker, Portland State Univ., Portland, Oregon
Dave Qualman, Portland State Univ., Portland, Oregon
Jeff Heeren, Portland State Univ., Portland, Oregon
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Submitted to:

SWW Beaches Study Participants and Collaborators
US Geological Survey, Coastal and Marine Program, Menlo Park, CA

INTRODUCTION

A vibracoring study of protected bay environments, tidal flats, and shallow shoals of the Columbia River estuary was proposed to the USGS SWW Beaches Project in January of 2000. This work was funded (USGS Coop. Agreement #1434-HQ-96-AG-01612) to compliment existing vibracore data from (1) the shipping-channel (USACE Portland District), and (2) paleoliquefaction studies in the lower Columbia River islands (Atwater and Peterson, unpublished data, 1995-96). These three data sets are to be compiled to produce a shallow stratigraphic record of historic and late-prehistoric sediment dispersal and accumulation in the lower tidal basin. The specific study objectives for the summer 2000 vibracoring work are listed below:

(A) Ground-truth the historic bathy-change maps (CREDDP) in shallow tidal flats and broad bays, e.g., Baker Bay, Youngs Bay, Grays Bay, and Cathlamet Bay by shallow vibracoring.
(B) Establish sediment composition, i.e., relative abundance of sand and mud, in the latest-prehistoric, early-historic, and late-historic deposits.
(C) Establish latest-prehistoric sedimentation rates (stratigraphic time lines from 1700 AD subsidence at 300 cal. ybp, and earlier events.
(D) Obtain core sections that record historic time intervals, potentially datable by anthropogenic tracers.

SCOPE OF WORK

A total of 20 shallow vibracore sites were initially proposed for the Columbia River estuary. The sites are located away from channels and dredging/disposal sites. The channels represent localized sedimentation or erosion, rather than the broader dynamics of sediment supply and retention in the estuary. Furthermore, historic bathymetric changes along the shipping channel(s) are well documented by the USACE. The vibracoring strategy for this study focused on shallow flats and broad bays of the Columbia River estuary between Baker Bay and Marsh Island. Based on the CREDDP maps the selected sites should generally show 1-5 m of net historic accumulation.

The target vibracore sites include representative depth sections from the upper, middle, and lower reaches of the estuary. These cores might contain several different prehistoric time-marker horizons including Cascadia earthquake subsidence horizons, tephra layers, and/or gross-lithologic changes that can be dated by radiocarbon. Early historic time lines that might be apparent in the cores include Corbicula bivalves (early 1900's), sawn lumber or artifacts (early 1900's), and oxidized core tops (recent bioturbation). Early historic time lines might also be established from introduced pollens, diatoms, and anthropogenic geochemical tracers in the muddy sections.

In addition to establishing recent basin sedimentation rates the prehistoric-historic transitions should be of interest to environmental studies. For example, the cores could be used to establish background contaminant levels, pre-impoundment bio-productivity (macro- and micro-fossils), and local substrate conditions of oxidation/reduction, permeability, etc. For these reasons, the cores are to be archived in freezers for at least three years after the collection date to be used by interested parties.

RESULTS

The preliminary fieldwork results are listed below.

CORE SITES: A total of 44 vibracore sites were occupied, and 3 cut bank sections were measured during the two-week field period July 9-24.

VIBRACORING: Vibracoring was performed with 7.5 cm aluminum pipe at 6.5 m lengths, with a Honda turbo 3000 engine, and CANUSA slim-line core-catcher. Field investigations of shoreline erosion or accretion (50 localities) were recorded on-site during reconnaissance surveys for the vibracoring. Digital photographs were taken of many core sites and shoreline conditions during the field study.

CORE SITE LOCATION: Vibracore and cut bank sites were located by NOAA Navigation charts (numbers 18521, 18523), and two Garmin CX GPS units for positioning with 2-5 m horizontal resolution (real-time). Water depth and time were recorded at all vibracore sites for calibration of deposit surface to MTL with NOAA predicted tide tables.

CORE PENETRATION: An average vibracore penetration of 5 m (lower reaches), and maximum penetration of 7 m in flood plain settings (upper reaches) were obtained during this study. The improved penetrations obtained this year are ascribed to a higher power vibracore motor, lower compaction of fluvial-tidal deposits, and reduced profile design of the new CANUSA core-catchers.

CORE LOGGING: About 200 meters of core were logged at the 1 cm resolution level during the field period at the Camp Rilea facility in Warrenton, Oregon, by Vanderburgh, with assistance from Baker and Peterson. Cores were logged for lithology, sedimentary structures, sand grain-size, woody fragments, shell fragments, and paleo-liquefaction. The core sections were labeled and photographed digitally (150 photos) during the core logging procedure. Core log records were entered into an Excel spread sheet for daily updating of the subsurface findings. The core logs, digital photographs, and sub sample spread sheets, are linked by core site reference code (XXXX locality name, 00 site number, a-d section number down hole, i.e., XXXX00.a-d).

DISTURBANCE: An average compaction of 1.3 m, or 20% is calculated for the recovered vibracores. Compaction was greatest in soft sandy deposits of channel and shoal margins. Core recovery was greater than 90% complete (including loss from pullout and rodding). An Excel spreadsheet of core length, penetration, and core loss was prepared during the logging to track core recovery. The compaction values will be compared to core lithology and depositional setting to constrain re-expansion models.

SUBSAMPLING: A total of 60 radiocarbon samples were sub-sampled from the vibracores during the field logging procedure. Shell fragments were rare, and included bivalves. Corbicula Fluminea (non-native clam—early historic) was found in several cores. Up to 10 tephra layers were observed in the flood bank settings (maximum of three in a single core site). About 5 tephra samples were sub-sampled during the field logging. The radiocarbon samples are described as wood or shell, bulk or AMS, and are recorded in the Core Log spreadsheet under each core site. The C14 samples, as well as all of the vibracores are currently archived in deep-chest freezers in the Geology Department at Portland State University.

COMPLETED OBJECTIVES

(1) Ground Truth Historic Bathy-Change (Baker Bay, Youngs Bay, Grays Bay, Taylor Sands, Cathlamet Bay, Woody Islands). Desdemona sands were not cored to sufficient depth to test the bathy-change maps.

(2) Establish Sediment Composition: We estimate that at least 30 cores reached prehistoric deposits. All of the cores recovered modern deposits. The vibracores record sediment composition in the lower Columbia River valley from late prehistoric to modern times.

(3) Sedimentation Rates: At least 30 cores contain abundant woody material, peat and/or shells for radiocarbon dating to establish prehistoric sedimentation rates. Subsidence events dating prehistoric earthquakes were observed in 10-15 of the core sites.

(4) Anthropogenic Tracers: At least 20 cores contained muddy top sections that can be used to search for anthropogenic tracers, e.g., Cs137 and other radioisotopes, organic byproducts, and trace metals, serving as historic time lines.

PRELIMINARY FIELD OBSERVATIONS

The Columbia River basin is filled nearly to its brim, i.e., shallow tide flats, shoals, central islands, and lateral flood plains dominate the system. Wind wave re-suspension in the lower basin erodes exposed shoal tops to just below MLLW, giving the appearance of more accommodation space than does actually exist in the lower tidal basin. Deep channels (10-15 m) are incised into shoals of the central bay area, or are pinned against valley-wall hard-points. Some secondary channels that are located adjacent to past disposal sites (Cathlamet Bay and the Woody Island Reach) have shallowed dramatically (2-7 m) since the last update to the bathymetric charts. However, the distal channels (shoreward of the islands) show relative stability or slight erosion, and little or no shallowing relative to the latest bathymetric updates. In contradiction to the geologic 'late-stage' filling of the lower tidal basin, the modern shorelines show little or no progradation. Wind-wave erosion has produced modern scarps (>0.5 m) around most of the exposed shorelines (observed scarp measurements will be put in a GIS data base). The overall look is one of channelized sediment throughput, rather than shoreline ravinement on the one hand or tidal flat progradation on the other. USACE channel maintenance reports (deepening, disposal and re-survey records) from critical areas could provide minimum, historic bedload-flux rates to the lower tidal basin from the fluvial side. Based on the summer reconnaissance surveys we would suggest the following areas, (a) head of Puget Island, (b) Jim Crow to Rice Islands, and (c) Astoria channel/ anchorage to constrain flux rates of the lower tidal-basin sediment supply.

The general lithologies of the shoals, open bays, and island platform deposits in the lower Columbia River tidal basin are dominated by sand (see core site map and corresponding core logs). The modern surface deposits are relatively similar to early historic and late-prehistoric deposits in most of the central bay settings. Muddy tops of prehistoric islands, and flood plains downriver of the Clatskanie Reach are shallow (1-4 m), being underlain by tidal flat or channel sand. The thickest mud units (> 1 m) in the basin's tidal-flat settings are restricted to (1) back-bay delta heads (Youngs Bay, Grays Bay), (2) wind protected shorelines (Baker Bay), (3) abandoned channels protected by windward shoals (Cathlamet Bay). Mud caps on flood plains at Clatskanie and Woody Island Reaches dramatically thin to the north, indicating northward migration of the main channel in latest prehistoric time. Latest-prehistoric channel migration is evident from sharp-edged features associated with translational bar forms, oxbows, and drainage channels. Additional air-photo interpretation of the flood plain vibracore sites is needed to establish the lateral context of the subsurface sections. The valley-side flood plain vibracores will be compared with the channel margin and island flood plain records of Atwater and Peterson to produce across-valley traverses. Radiocarbon dating is needed to constrain the ages of late-prehistoric channel migrations, the tephra layers, and the catastrophic flood-sand layers in the Clatskanie and Puget Island sites (see core logs). Future

vibracoring in upriver flood plains is warranted to establish event correlation towards source tributaries, volcanic centers, etc.

Modern tidal flats from the exposed areas of Grays Bay, Taylor Sands, and Cathlamet Bay are dominated by active wind-wave re-suspension superimposed on tidal currents. No seasonal mud drapes were preserved on any of the exposed shoals from the previous winter's discharge. Burrow openings are uncommon in most of the central bay tidal flats. Wave compacted sand was experienced during vibracoring of the shoal tops (+0.5 m MLLW = <1 m penetration) but not in deeper shoal margins (-0.5 m MLLW = 2-3 m penetration) in the Taylor Sands and Desdemona Sands. Channel margin vibracores in the central bay areas showed no muddy accretionary banks, and only rare mud laminae hosted in FU-MU sand. More specifically, mud laminae are common, but thin, in sand fining-upward units of Woody Island Reach, Cathlamet Bay, and Grays Bay. Mud laminae (drapes) are rare but present in the deeper (3-4 m subsurface) sand sections of Taylor Sands and Desdemona Sands. Quantitative sediment size analysis from core tops, middles and bottoms would suffice to characterize most vibracore sites throughout the study area. Dredge spoils from the channel axes of the tidal inlet show coarser sand (CL-CU) in the channel axes than was found in the central bay shoals or on the adjacent beaches or shelf. Deeper vibracore records (USACE shipping channel) might help resolve the relative age and origin of the coarser sand fractions in the lower bay channel axes.

Organics in the basin tidal-flat deposits change in color from black (downriver of Tongue Point) to gray (upriver of Cathlamet Bay). GCMS analyses might explain the differences in spectra adsorption, sources of the organics, and paleo-circulation history in the estuary. Mica is an abundant trace mineral (3-5%) downriver to Cathlament Bay, but is rare (<1%) in the Taylor Sands and Desdemona Sands. Shell fragments in all of the vibracore sections of the shoals and bays are rare throughout the entire lower Columbia River tidal basin. Although woody material is abundant in muddy sections from the flood plains, it is rare in tidal flat or channel deposits. Beach and inlet bivalve fragments (razors, cockles, sand dollars, etc.) are absent from the Desdemona deposits recovered by vibracore. By contrast razor clam shell fragments were observed in dredge spoils from the Baker Bay Sand Island. Together with the mud laminae distributions (discussed above), these characteristics define three facies in the open-bay shoals of the lower tidal basin, i.e., (1) fluvial-tidal facies upriver of Tongue Point, (2) tidal-fluvial facies between Tongue Point and Chinook Point, and (3) tidal inlet facies west of Chinook Point.

Oxidation zones in the upper sections of vibracores occur in several sites in Baker Bay, Youngs Bay, and Grays Bay . These zones might represent historic sedimentation intervals. At least one such transition occurred just below an in-situ Corbicula bivalve. Diatoms and/or radiocarbon dating will be required to test this hypothesis, and to establish historic sedimentation rates in the more uniform sand deposits in the Taylor Sands and Cathlamet Bay deposits. Coseismic subsidence features are apparent but uncommon in the Columbia River cores. The coseismic subsidence sequences are restricted to the back-bay settings of Grays Bay, Cathlamet Bay, the Woody Island Reach, and the Clatskanie Flood plains. At least 3-4 coseismic subsidence events are

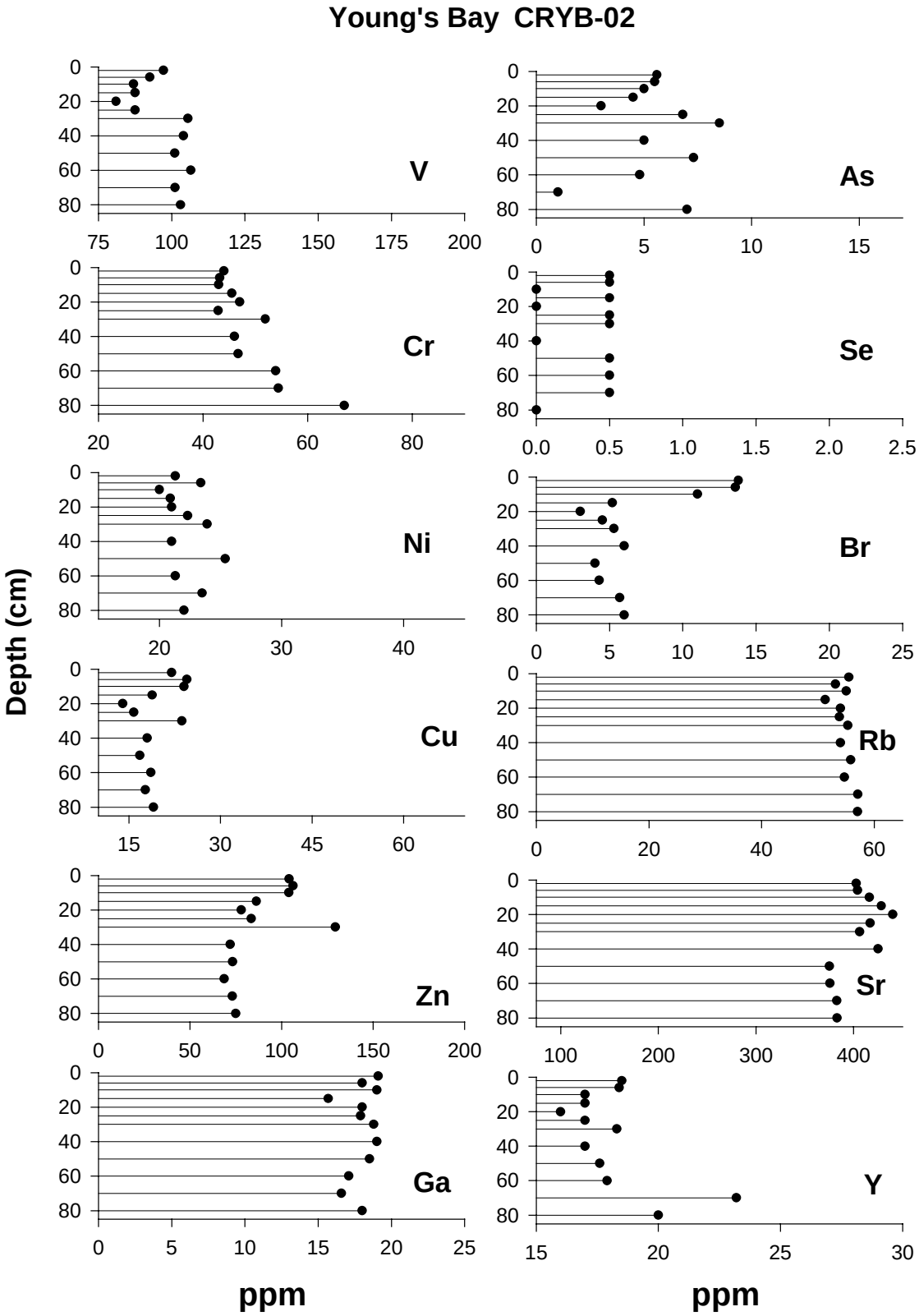
recorded in the Clatskanie Flood plains, confirming Atwater's assertion of subsidence east of Skamokowa (see core logs). Cut bank exposures of buried peat horizons were measured in Grays Bay, and the Woody Island Reach. The westward-most record of buried peat horizons is from the Clatsop vibracore site and cut bank site east of the Skipanon channel (see core site map). The cutback section at the Skipanon entrance contains a 3 cm thick tsunami sand above the latest buried peat (1700 AD? event) and a patchy tsunami sand laminae above the second buried peat (1,100 yrbp event?).

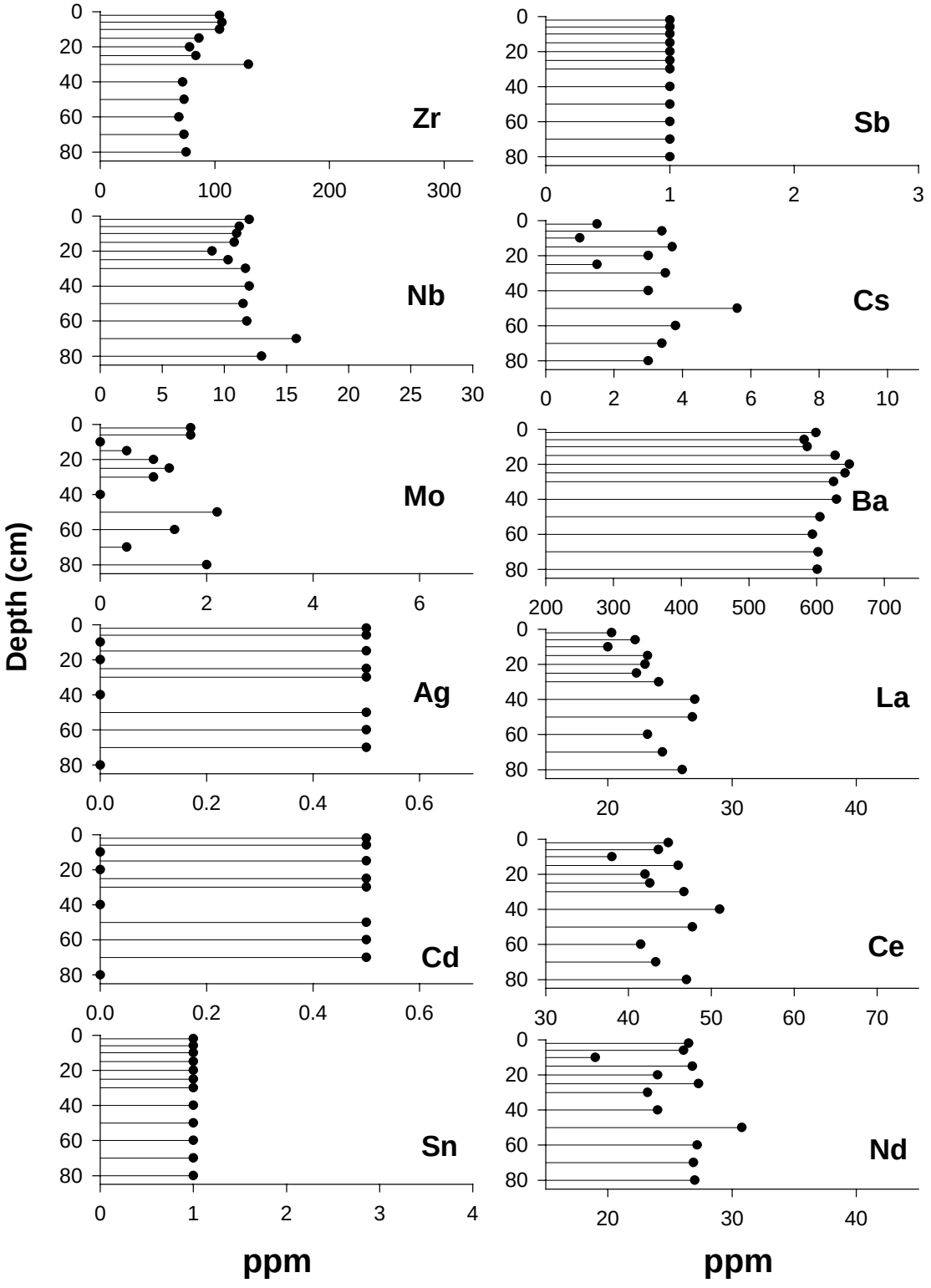
The muddy core sections above the latest buried peat at some of the Woody Island Reach sites contain two anomalous woody layers. The upper layer contains sawn wood, so it represents historic time. Additional work is needed to establish the age and origin of the lower woody-silt layer above the 1700 AD event contact. Anthropogenic tracers (metals or organic byproducts) and/or introduced plant pollens should be useful in establishing an early-historic time line in many of the muddy vibracore sections from the lower Columbia River tidal basin and lateral flood plains. Correlation of the tephras and catastrophic flood sand will provide prehistoric time lines in the flood plain settings.

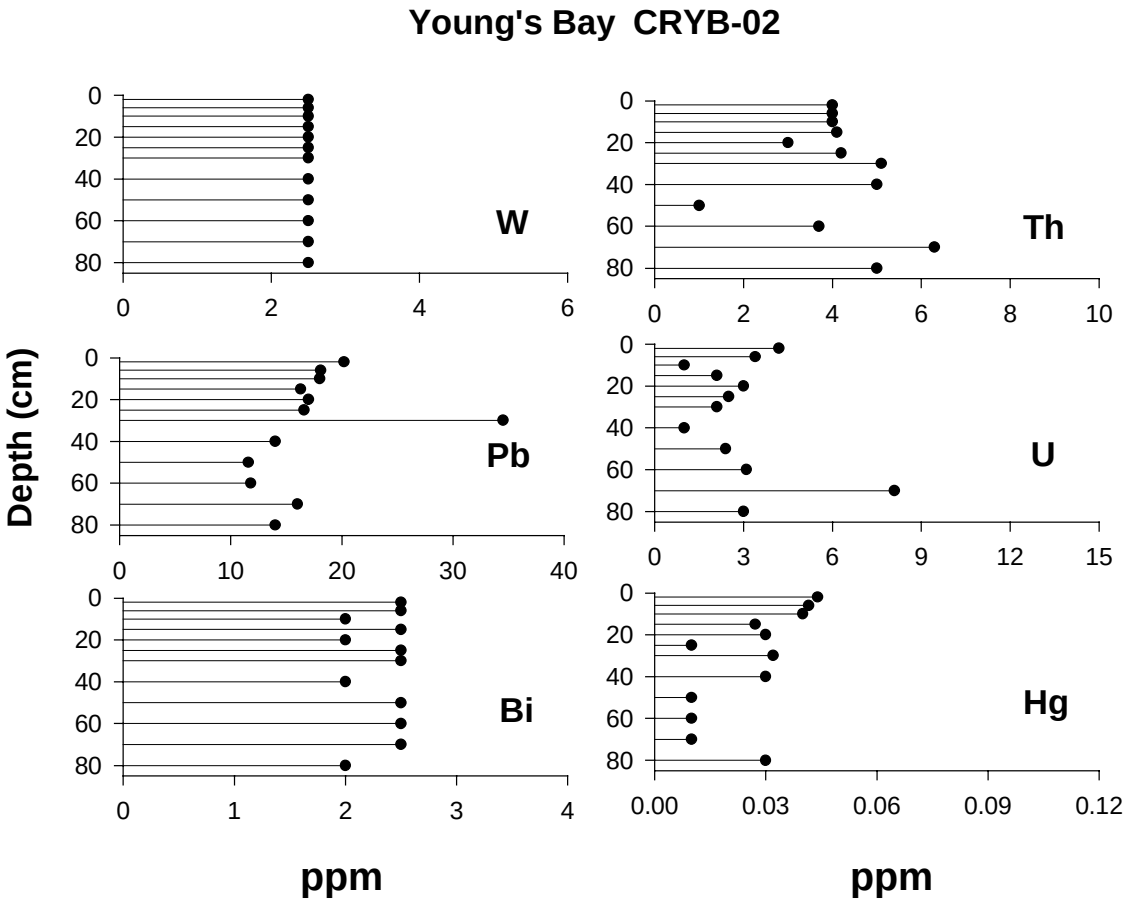
PRELIMINARY FIELD CONCLUSIONS

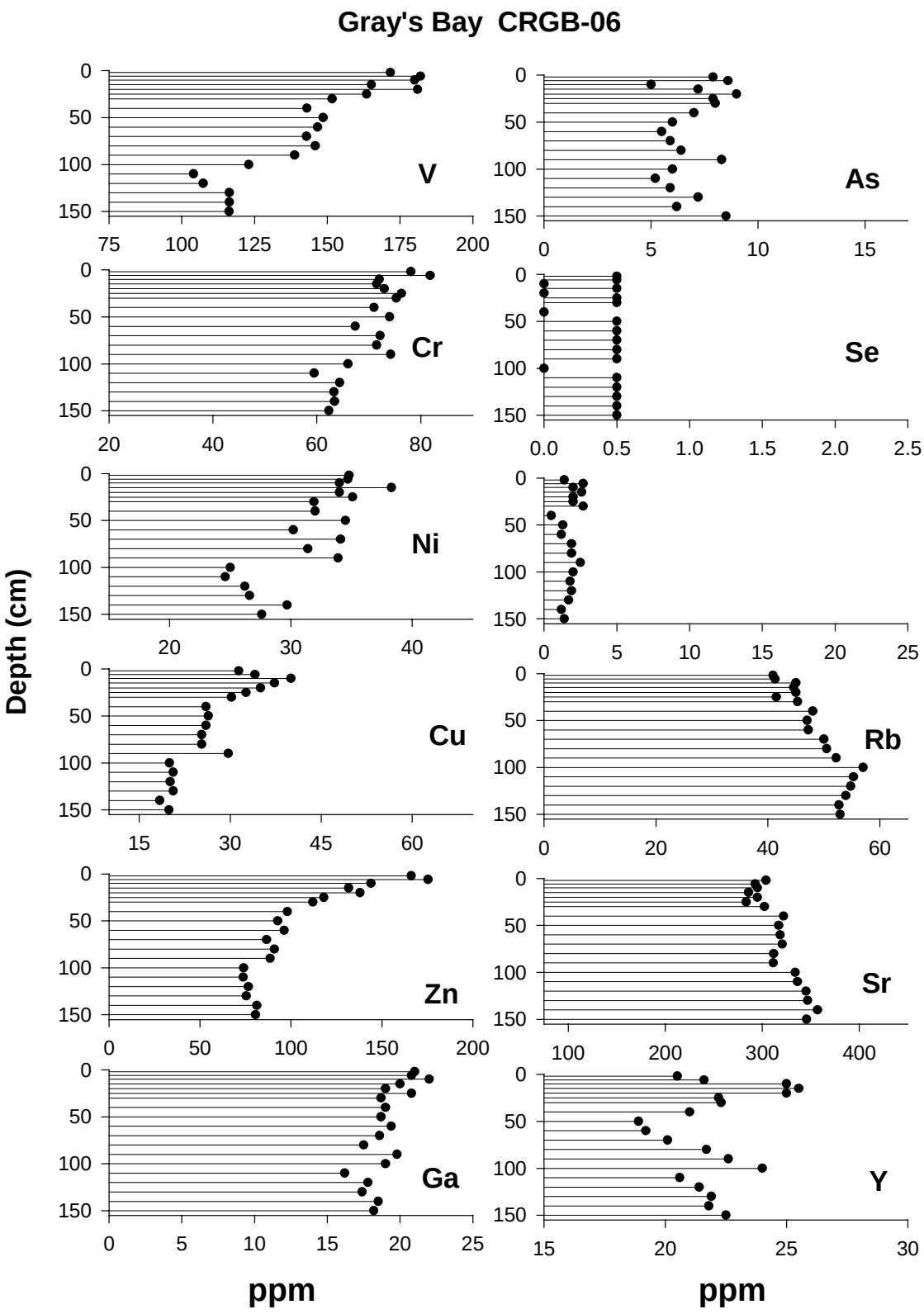
A bay head delta has prograded downriver from the Clatskanie Flood plains to the Woody Island Reach in late Holocene time. Lateral channel migration dominates the latest-prehistoric time period in the bay head delta islands of the Woody Channel Reach, demonstrating a lack of accommodation space there. The delta front or central bay depo-center has been located in the lower Cathlamet Bay, Grays Bay, and Taylor Sands shoal areas for the last part of the latest-Holocene. The inter-tidal sand shoals and deeply incised tidal channels demonstrate active sand flux, but little accommodation space in the central bay area at the present time. Fine fractions are apparently winnowed-out of the central bay shoals by wind wave re-suspension, superimposed on ebb surface flow. The lowermost tidal basin is constricted by narrow valley walls, (Astoria Bridge area), and it is transitional with the tidal inlet to the west. Thin sand veneers over the Skipanon-Youngs Bay flats, over the Chinook Point flats, and over the Baker Bay entrances argue for relatively little accommodation space in the marginal bays prior to any early-historic sand influx. The potential thick nesses of the lower central-bay sand shoals (Desdemona and Taylor Sands) are not addressed in this shallow vibracore study.

Appendix 3. Heavy metals data summary

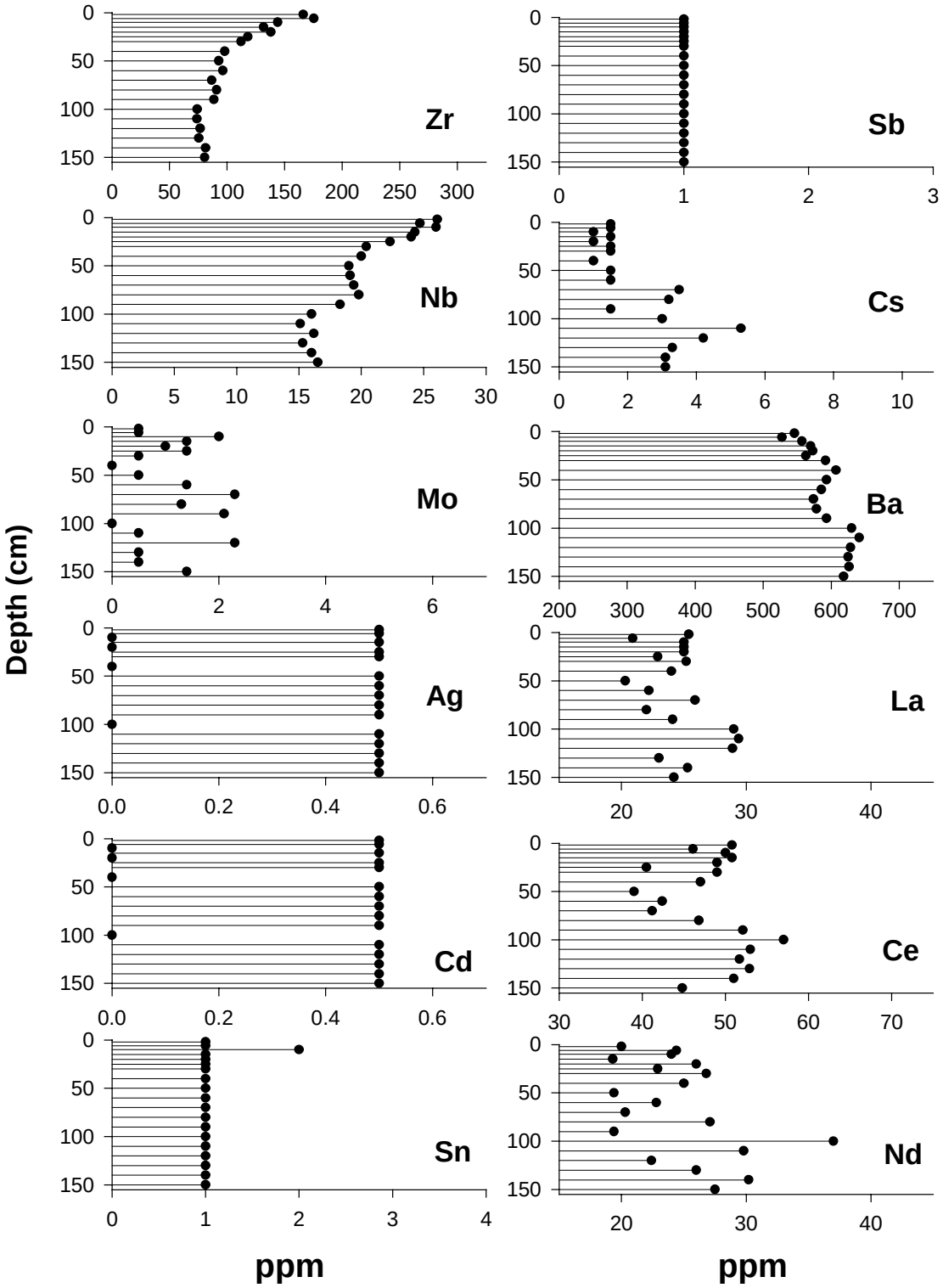


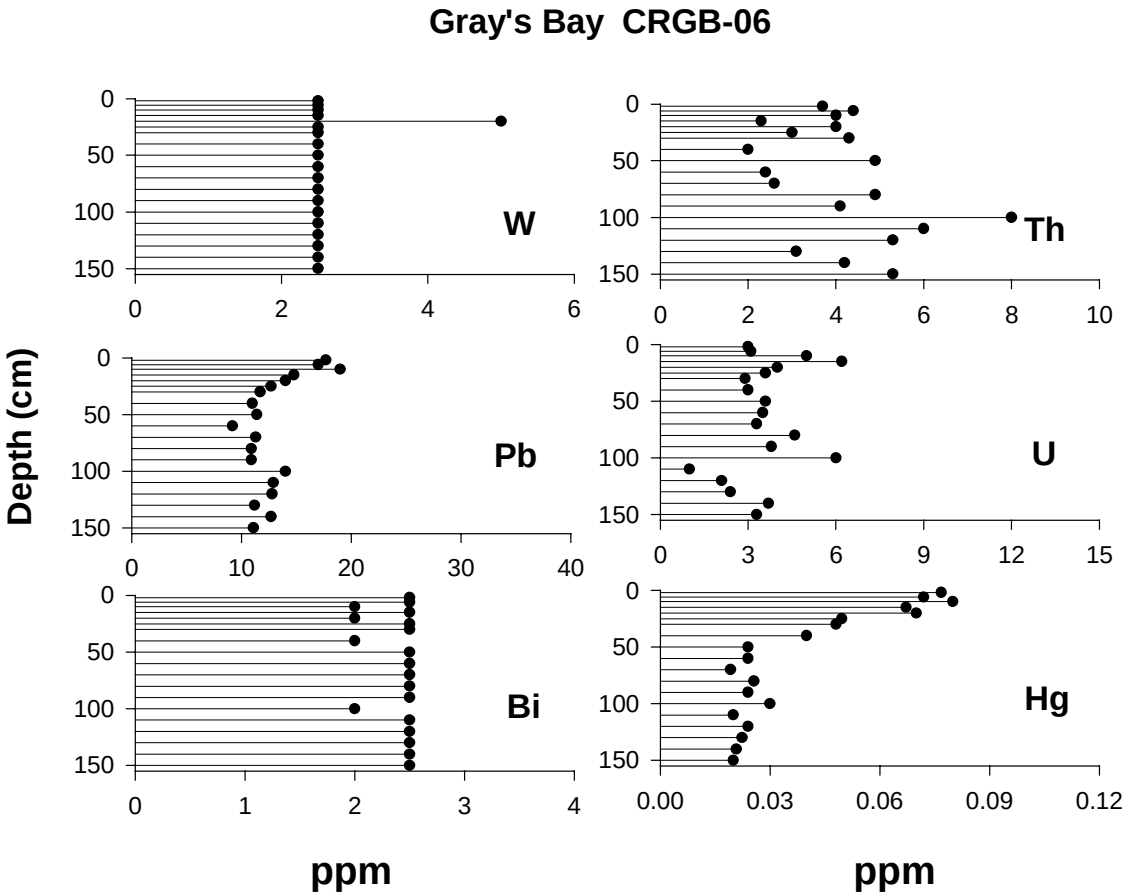

Young's Bay CRYB-02
Depth (cm)
Zr
Sb
Nb
Cs
Mo
Ba
Ag
La
Cd
Ce
Sn
Nd
ppm
ppm

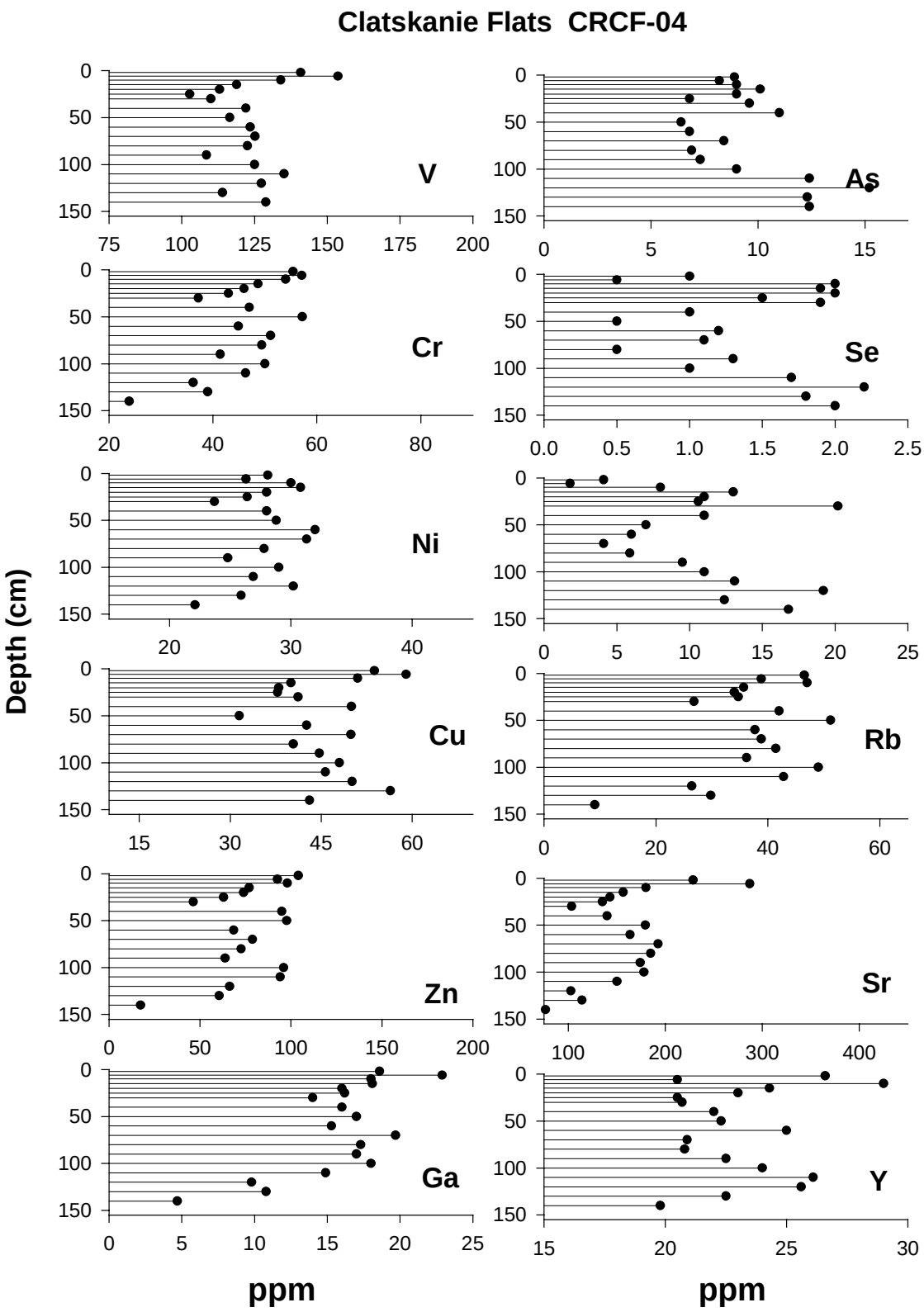

Young's Bay CRYB-02
Depth (cm)
W
Th
Pb
U
Bi
Hg
ppm
ppm

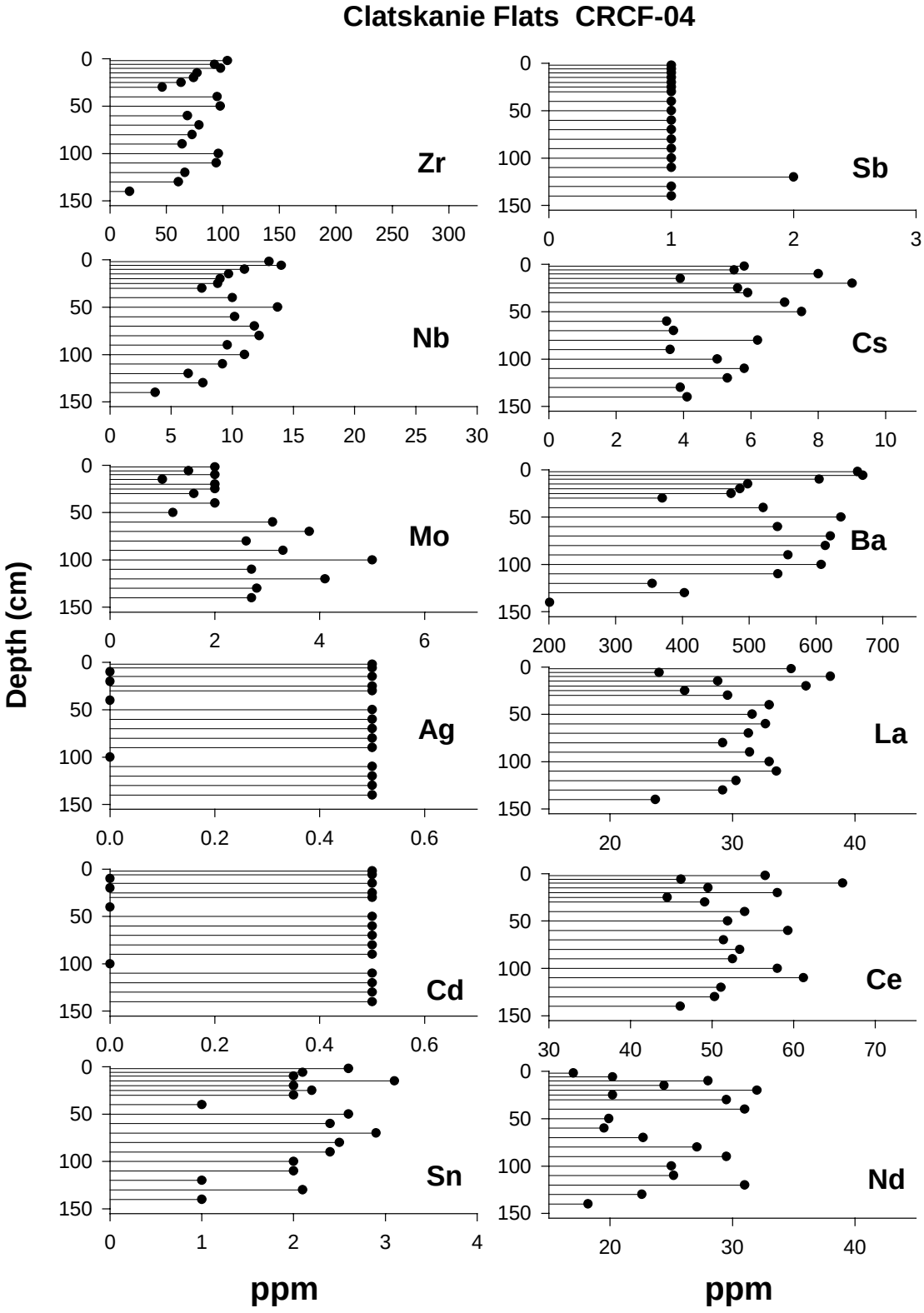

Gray's Bay CRGB-06
Depth (cm)
V
As
Cr
Se
Ni
Cu
Rb
Zn
Sr
Ga
Y
ppm
ppm

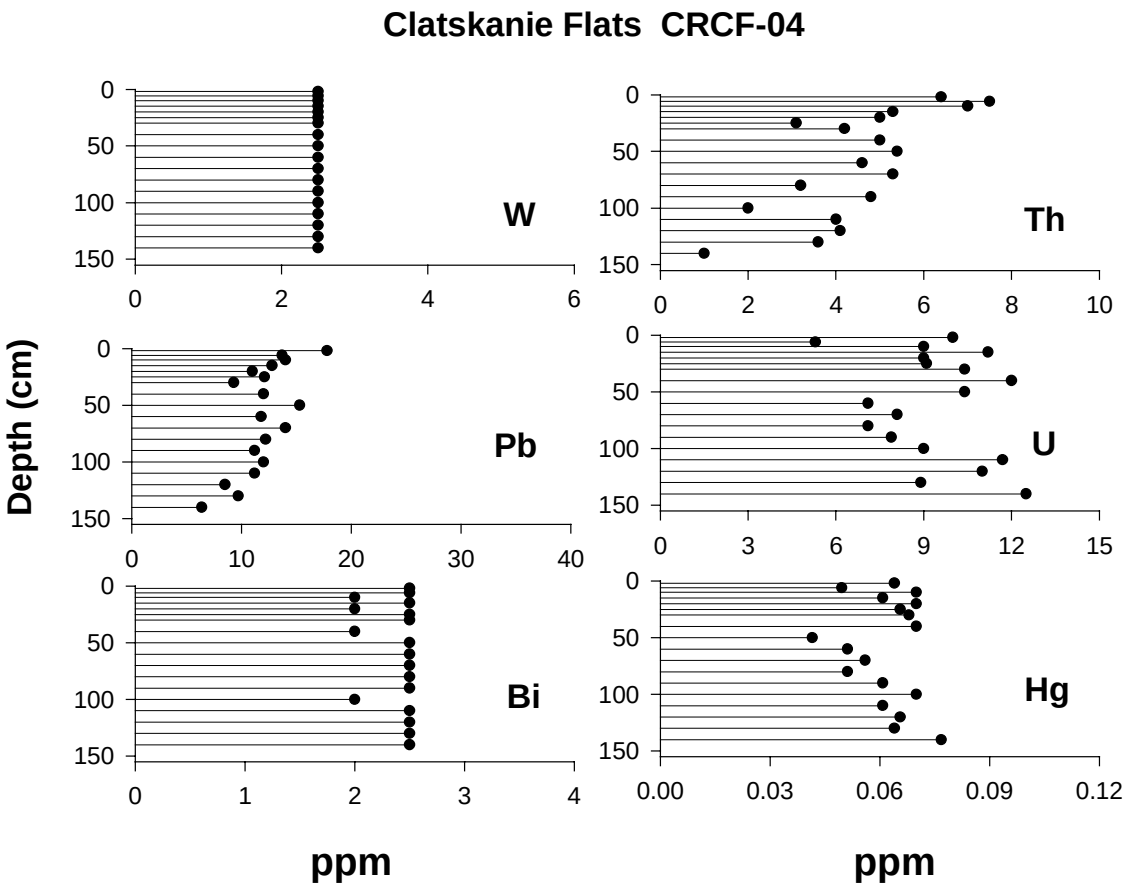
Gray's Bay CRGB-06




Gray's Bay CRGB-06
Depth (cm)
W
Th
Pb
U
Bi
Hg
ppm
ppm


Clatskanie Flats CRCF-04
Depth (cm)
V
As
Cr
Se
Ni
Cu
Rb
Zn
Sr
Ga
Y
ppm
ppm


Clatskanie Flats CRCF-04
Depth (cm)
Zr
Sb
Nb
Cs
Mo
Ba
Ag
La
Cd
Ce
Sn
Nd
ppm
ppm


Clatskanie Flats CRCF-04
Depth (cm)
W
Th
Pb
U
Bi
Hg
ppm
ppm

Appendix 4. Diatoms data summary

Diatom species and general ecology identified in 2 cores from the Columbia River (Youngs Bay and Grays Bay).

Key:
FWB = freshwater benthic
FP = freshwater planktonic
BWB = brackish water benthic
SIB = salinity indifferent benthic
SIP = salinity indifferent planktonic
MP = marine planktonic
U = ecology unknown

Diatom species	**Ecology**
Achnanthes clevei	FWB
Achnanthes haukiana	SIB
Achnanthes haukiana var. *rostrata*	SIB
Achnanthes lanceolata	FWB
Achnanthes lemmermanni	SIB
Achnanthes minutissima	FWB
Actinocyclus normanii	FP
Amphora aequalis	FWB
Amphora libyca	FWB
Amphora ovalis	FWB
Amphora pediculus	FWB
Aulacoseira granulata	FP
Aulacoseira italica	FP
Bacillaria paradoxa	BWB
Caloneis silicula	SIB
Chaetoceros spp. Spores	MP
Cocconeis diminuta	FWB
Cocconeis placentula var. *euglypta*	FWB
Cocconeis sp.1	U
Cyclotella meneghiniana	SIP
Cymbella cistula	FWB
Cymbella sinuata	FWB
Cymbella tumida	FWB
Delphineis karstenii	BWB
Diatoma tenue var. *elongatum*	FWB
Diploneis ovalis	SIB
Diploneis smithii var. *dilatata*	BWB
Diploneis subovalis	FWB
Epithemia sorex	FWB
Epithemia turgida	FWB
Fragilaria brevistriata	FWB
Fragilaria construens	FWB

Fragilaria construens var. *venter*	FWB
Fragilaria pinnata	FWB
Fragilaria schulzii	BWB
Fragilaria ulna	FWB
Gomphonema grovei	FWB
Gomphonema parvulum	FWB
Gyrosigma spencerii	BWB
Hantzschia amphioxys	FWB
Luticola mutica	FWB
Lyrella pygmaea	SIB
Martyana martyi	FWB
Melosira moniliformis	BWB
Navicula aff. cocconeiformis	U
Navicula capitata	FWB
Navicula capitata var. *hungarica*	FWB
Navicula cincta	BWB
Navicula costulata	BWB
Navicula cryptocephala	SIB
Navicula eidrigiana	BWB
Navicula elginensis	FWB
Navicula gastrum	FWB
Navicula gregaria	SIB
Navicula protracta	FWB
Navicula pupula	FWB
Navicula radiosa	FWB
Navicula rhyncocephala	SIB
Navicula scutelloides	FWB
Navicula spp.	U
Navicula submuralis	FWB
Navicula veneta	FWB
Navicula viridula var. *rostellata*	FWB
Nitzschia angustatula	FWB
Nitzschia communis	FWB
Nitzschia frustulum	SIB
Nitzschia palea	SIB
Opephora olsenii	BWB
Pinnularia borealis	FWB
Pinnularia lagerstedtii	FWB
Pinnularia obscurus	FWB
Pinnularia viridis	FWB
Plagiogramma pulchella	BWB
Rhaphoneis amphiceros	BWB
Rhaphoneis psammicola	BWB
Rhoicosphenia abbreviata	SIB
Rhopalodia gibba	FWB
Stauroneis obtusa	FWB
Stephanodiscus hantzschii	FP
Stephanodiscus rotula	FP
Surirella brebissonii var. *kuetzingii*	FWB
Surirella linearis	FWB

Surirella ovalis	BWB
Tabellaria fenestrata	FP
Thalassionema nitzschioides	MP
Thalassiosira eccentrica	MP
Thalassiosira oestrupii	MP
Thalassiosira pacifica	MP
Thalassiosira visurgis	SIP
Tryblionella compressa	BWB
Tryblionella constricta	BWB
Tryblionella victorae	FWB

Diatom counts by core and depth. Species are categorized into habitat types (see text).

	Youngs Bay					Grays Bay				
Depth (cm)	2	10	20	40	60	2	10	20	40	60
Total_diatoms_counted	300	300	103	300	300	300	300	300	140	300.5
Freshwater benthic										
Achnanthes clevei							4	3	0	
Achnanthes lanceolata		2	1	4	14	6	11	5	1	
Achnanthes minutissima		2	4	4	0					
Amphora aequalis	1					2			0	
Amphora libyca	4				2	4	0			
Amphora ovalis									1	
Amphora pediculus	2	1	3	16	18	7	15	3	3	16
Cocconeis diminuta	7	5	4	3	6	6	3	4	63	
Cymbella cistula	1	1	2	2	1					
Cymbella sinuata										1
Cymbella tumida	1		1						0	
Diatoma tenue v. elongatum		2	1	0						
Diploneis subovalis	6				1				1	
Epithemia sorex							3	6	1	
Epithemia turgida							3	10	3	
Fragilaria brevistriata	55	72	16	75	40	72	103	100	25	29
Fragilaria construens	2	3	1	3	1	1	4	8	7	9
Fragilaria construens v. venter						12	15	1	4	2
Fragilaria pinnata	12	37	8	25	59	42	22	4	4	
Fragilaria ulna	4	5	3	5	3	2	2			
Gomphonema grovei				2			2		5	
Gomphonema parvulum	2	4	1	1	3					
Hantzschia amphioxys		1	1	0						
Luticola mutica	3	3	10	1	2	1	0	9		

Martyana martyi	22	38	6	24	15	33	39	33	8	18
Navicula capitata				1					0	
Navicula capitata v. hungarica		23	1	6	0					
Navicula elginensis		2		2	1	1	0			
Navicula gastrum		1		6	3	5	3	2		
Navicula protracta							2		0	
Navicula pupula				3		3		1	0	
Navicula radiosa	2			1					0	
Navicula scutelloides					2	2	2	0		
Navicula submuralis	2	6	2	56	91	75	24	22	8	96
Navicula viridula v. rostellata				1	2	1	0			
Navicula veneta	1								0	
Nitzschia angustatula		1							0	
Nitzschia communis	1								0	
Pinnularia borealis	2							5	1	
Pinnularia lagerstedtii	1	2	0							
Pinnularia obscurus	1	2	0							
Pinnularia viridis			1						0	
Rhopalodia gibba				1				3	1	
Stauroneis obtusa	1	9	0							
Surirella brebissonii v kuetzingii	2								0	
Surirella linearis							1	2	1	
Tryblionella victorae	2			1	1	1				
Freshwater planktonic										
Actinocyclus normanii	1		3		2				0	
Aulacoseira italica	53	21	12	5	3	3	2			
Aulacoseira granulata	18	4	8	1	2	6	10	2		
Stephanodiscus hantzschii	7		4						2	
Stephanodiscus rotula astraea	44	4	3	2	6	1	2			
Tabellaria fenestrata	1								0	
Brackish water benthic										
Bacillaria paradoxa	1								0	
Delphineis karstenii				1				1	0	
Diploneis smithii v. dilatata	1	1	1	1	0					
Fragilaria schulzii	5	5	1	0						
Gyrosigma spencerii								1	0	
Melosira moniliformis				11	1	3	6	0		
Navicula cincta		1			2		1		2	
Navicula costulata	1		3		2			1	2	1
Navicula eidrigiana								1	2	
Opephora olsenii pacifica		2	3	2	1	5	1	6	8	3
Plagiogramma pulchela										3

Rhaphoneis amphiceros									1	
Rhaphoneis psammicola		1							1	1
Surirella ovalis						1			0	
Tryblionella compressa	1								0	
Tryblionella constricta	1								0	
Marine planktonic										
Chaetoceros spp Spores								1	0	
Thalassionema nitzschoides	2	1	1	0	0.5					
Thalassiosira eccentrica			1						1	
Thalassiosira oestrupii		1							1	
Thalassiosira pacifica	1							1	1	
Salinity indifferent benthic										
Achnanthes haukiana	6	14	6	3	4	7	3	3	5	13
Achnanthes haukiana v. rostrata		1		1	5	1	2	1	0	5
Achnanthes lemmermanni					1		2		0	
Caloneis silicula				1		1			1	
Cocconeis placentula v. euglypta	3	6	4	7	1	2	23	12	4	3
Diploneis ovalis					1			1	1	
Lyrella pygmaea	4								4	1
Navicula cryptocephala	2				2			1	0	
Navicula gregaria					1		2		0	
Navicula rhyncocephala				1	1	0				
Nitzschia frustulum	3								0	
Nitzschia palea		1			1				0	
Rhoicosphenia abbreviata	6	6	1	17	4	5	3	11	0	
Salinity indifferent planktonic										
Cyclotella meneghiniana	2	1	1							
Thalassiosira visurgis		2					4	1	1	
Unknown ecology										
Cocconeis sp 1 tiny		6	2	4	1	7	6	4	4	14
Navicula aff coccon				2			2	1	0	4
Navicula spp Unidentified			1		2				0	