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HISTORY OF CONTAMINATION OF SEDIMENTS
IN COMMENCEMENT BAY, TACOMA, WASHINGTON

Rockville, Maryland
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HISTORY OF CONTAMINATION OF SEDIMENTS IN COMMENCEMENT BAY, TACOMA, WASHINGTON

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HISTORY OF CONTAMINATION OF SEDIMENTS
IN COMMENCEMENT BAY, TACOMA, WASHINGTON

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ABSTRACT. The concentrations of metals, aromatic hydrocarbons (AH), and chlorinated butadienes (CBD) in age-dated sediment cores from Commencement Bay indicate contamination of these sediments has occurred during the past 80 years. The period of maximum metal and CBD discharge occurred during the 1960s while the AH maximum was as early as 1900. The contaminant concentrations are much lower in sediments from the open bay than in sediments from the industrial waterways adjacent to the bay. Sediment cores collected from two historic dredged-spoil dump sites do not indicate that the toxic industrial waste has specifically accumulated at these dump sites. The general contaminant concentrations are typical for an industrial harbor. From the standpoint of heavy metals contamination, the bay sediments contain smaller concentrations of metals than sediments from central Puget Sound. The concentrations of AH and CBD are approximately 10 and 100 times higher, respectively, in the bay sediments than in sediments from nonindustrial sites outside the central basin of Puget Sound.

1. INTRODUCTION AND OBJECTIVES

Commencement Bay is one of the major deep-water commercial seaports in Puget Sound (Figure 1). It is located at Tacoma, Washington, between Point Defiance and Brown's Point at the southern end of the central basin of Puget Sound, about 25 km south of Seattle. There are eight commercial waterways along the southeastern shore. Two of these waterways are natural, Hylebos Creek and the Puyallup River, and contain sources of freshwater. The bay measures approximately 7.5 km along the southwest shore to Point Defiance, by 4.3 km across the inner bay, by 4.7 km along its northerly shore. Depths of the bay proper range from 42 m to 185 m, with free connection to the deepest water in the main basin.

Commencement Bay has been a focus of recent investigation sponsored by NOAA's Marine Ecosystem Analysis (MESA) Puget Sound Project Office to provide environmental information regarding various Puget Sound embayments. Human activities have introduced contaminants into Commencement Bay from a variety of sources, including coal transshipment, activities at chemical plants, petroleum refining, copper smelting, activities of the paper industry, and sewage treatment. The Environmental Protection Agency (EPA) designated Commencement Bay a priority Superfund site, in part because of the high concentrations of toxic chemicals in ground water adjacent to the bay. Several studies have reported elevated concentrations of chemical contaminants in water, suspended matter, sediments, and marine animals collected both in Commencement Bay and adjacent waterways (Crecelius et al., 1975; Malins et al., 1980 and 1982; Riley et al., 1980 and 1981; and Enkeboll, 1981).

The objectives of this report are to discuss the results of a study sponsored by the MESA Puget Sound Project in order to (1) analyze the distribution of selected contaminants in age-dated sediment cores from Commencement Bay, (2) interpret the history of contaminants discharged to the bay in relation to the sedimentary record, and (3) gain a better understanding as to what extent the disposal of dredged material in open water has influenced the chemistry of the sediments in the bay. Such knowledge is necessary for formulating rational decisions on the future management of sediments impacted by toxic chemicals.

2. SAMPLING METHOD AND SAMPLING STATIONS

In late summer 1981, gravity cores were collected at the four stations in Commencement Bay by scientists from the Pacific Marine Environmental Laboratory, Seattle, Washington, using a 3-inch diameter Benthos® gravity corer with plastic coreliner. The sediment cores were stored frozen until sectioned in the laboratory for analysis.

Figure 2 shows locations of the four stations where sediment cores were collected, with the specific locations and water depths listed in Tables 2-7. The station locations were selected to cover a range of sediment types and water depths and included samples within the two open-water dredged material disposal sites shown on the NOAA National Ocean Survey, Puget Sound Chart #18448, 19th Edition, January 1981. Station CB-1 is located in the shallow water disposal site near the mouth of the Puyallup River; CB-2 is located off Old Tacoma where heavily contaminated sediment was reported by Malins et al. (1980); CB-3 is located in the deep-water disposal site; and CB-4 is located in the northeastern region of the bay near the heavily contaminated Hylebos Waterway. Also located on Figure 2 are the positions of four other coring stations (QM, BX-2, #57, and #381), for which published chemical and/or sedimentation rate data are available (QM, Crecelius, 1974; BX-2, Curl, 1982; #57, Furlong and Carpenter, 1982; and #381, Link, 1982).

A high-resolution, subbottom profiling survey was conducted in Commencement Bay in late summer 1982 by R. R. Bauer of the U.S. Environmental Protection Agency (EPA), Region 10, Seattle. The purpose of this survey was to locate suitable sediment sampling sites both within and outside the two disposal sites. R. E. Sylvester of NORTEC, Kirkland, Washington, with permission from R. R. Bauer, supplied reproductions of the subbottom records shown in this report (Figures 4-9). The subbottom records from three of the coring stations are included in this report to aid in determining whether dredge spoils are present at the stations.

3. ANALYTICAL METHODS

The sediments were analyzed for percent dry weight, metals, radionuclides, and selected organic compounds. Percent dry weight was determined by oven drying at 70°C to constant weight. Metal analysis for Ag, Cd, and Hg was done by atomic absorption, and the other metals were analyzed by energy dispersive x-ray fluorescence using the method of Nielson (1977). Chemical data in Table 6, the Quartermaster Harbor core, were produced by neutron activation analyses (Crecelius, 1974). A certified sediment standard (Canadian National Research Council, MESS-1 marine sediment) was also analyzed for quality assurance purposes. The mean and standard deviation for triplicate analysis for the study are reported in Table 1 along with the certified values. The activity of ^{137}Cs and ^{210}Pb were determined by gamma counting a 90-gm sediment pellet on an anticoincidence-shielded Ge(Li) diode, similar to the method of Gäggler et al. (1976). The efficiency of the gamma-counting system was determined by spiking sediment with known activities of gamma-emitting radionuclides supplied by the National Bureau of Standards.

The organic compounds that will be discussed here include aromatic hydrocarbons (AH) and chlorinated butadienes (CBD). Chlorinated biphenyls (PCB) were not detectable and will, therefore, not be discussed; however, detection limits for selected chlorinated biphenyls were less than 1 ppb. A total of 18 individual AH compounds were identified and quantified. For the purpose of this discussion, AH will refer to the combination of these 18 compounds. The CBD data refer to the concentrations of all chlorinated butadiene isomers containing 3, 4, 5, and 6 chlorine atoms.

The procedures used for the extraction and quantification of individual organic compounds are those previously reported for the analysis of organic constituents in sediments collected from waterways adjacent to Commencement Bay (Riley et al., 1981).

4. RESULTS

4.1 Sediment Grain Size and Circulation

The sediment grain size was not determined for gravity core samples; however, the approximate grain size can be estimated from the percentage of dry matter in the sediments and the sediment grain size data (Roberts, 1974) chart prepared by Roberts (1979), shown in Figures 2 and 3. Core CB-1 was sandy in the upper 20 cm and decreased in grain size below 20 cm to a muddy-sand texture. Cores CB-2, CB-3, and CB-4 were sandy-mud in texture and fairly uniform throughout the cores.

Observations of currents and water properties made in Commencement Bay by Cannon and Grigsby (1982) provide information in describing physical transport processes in the bay. Observations made during both low and high river runoff reported the following major circulation features: net outflow from the bay is near the surface along the north shore with a speed of about 0.8 km/day; net inflow is at depth or near bottom with a speed of 4 km/day. Near-bottom tidal currents might be large enough to resuspend bottom sediments. The transit time for water in the bay is on the order of several days; thus, suspended particles with settling velocities of less than 25-50 m/day could be transported out of the bay.

Studies of the suspended particulate matter (SPM) in Commencement Bay by Baker and Walker (1982) agree with the current observations of Cannon and Grigsby (1982). Transport of SPM from the Puyallup River plume was in the surface layer along the north shore and transport of SPM in the bottom water was governed by tidal current erosion/deposition cycles. The relatively strong and steady clockwise circulation of the bottom water in the bay explains why the sediments are relatively sandy and, therefore, contain relatively low concentrations of contaminants. The vertical flux of SPM that Baker and Walker (1982) measured using a near-bottom sediment trap indicated substantial recycling of bottom sediments by resuspension.

4.2 Age Determination of Sediment Cores

The history of sediment accumulation in Commencement Bay was estimated by ^{210}Pb dating techniques. The dates calculated from the ^{210}Pb activities were compared with the major features of ^{137}Cs profiles. The changes in radionuclide activity in the sediment cores are related to sediment accumulation, sediment mixing, radionuclide input rate, and possibly other factors. Several assumptions that are usually made when dating cores include: (1) the coring operation does not distort the length of the core, (2) the history of radionuclide input to the sediment is known,

(3) after burial, radionuclides do not change concentration in the sediment except by radioactive decay, (4) the sedimentation rate has been constant with time, and (5) sediment mixing by biological or physical processes can be estimated and corrected. For this core dating, we have assumed that sediment mixing is not significant compared to sedimentation. On the basis of these assumptions, dates have been estimated for two cores from Commencement Bay (CB-2 and CB-3), one from Quartermaster Harbor, and one from PS-7 station in the central basin of Puget Sound. We recommend caution in the use of these sedimentation rates and dates since several investigators have reported gravity core shortening during sampling (Hongve and Erlandsen, 1979; Lebel et al., 1982).

The ^{210}Pb dates shown in Tables 3, 4, 6, and 7 were calculated from a least-squares, best-fit line for the change in the log of the unsupported ^{210}Pb activity with core depth.

4.3 Distribution of Metals In Cores

The concentrations of metals in sediment cores are listed in Tables 2-7. In addition to the four cores from Commencement Bay, data from cores collected at station PS-7 in central Puget Sound (3 km north of West Point) and in Quartermaster Harbor (10 km northwest of Commencement Bay) are included for comparison. The coring station locations and water depths are included in the tables, and the locations are shown in Figure 2. Also included in Figure 2 are several coring stations, which will be used for comparative purposes.

The vertical metal profiles in all four of the CB cores show surface enrichment of 6 of the 17 metals. These metals (Cu, Zn, As, Ag, Hg, and Pb) are enriched in the upper sections of the CB cores due to anthropogenic activities in Commencement Bay and central Puget Sound. The enrichment factors for CB-2 and CB-3 (ratio of metal concentration in core section to metal concentration in bottom of core) are 5 to 10 for Ag, Pb, and Hg and less than 1.2 to 3 for Cu, Zn, and As. Cores CB-1 and CB-2 were too short to include "baseline" sediment, that is, sediment deposited more than 100 years ago. The bottom samples from CB-2 and CB-3 are typical baseline metal concentrations for uncontaminated coastal marine sandy-mud. Similar baseline concentrations have been reported for Puget Sound by Crecelius, 1975; Schell and Nevissi, 1977; and Curl, 1982.

4.4 Concentrations of AH in Sediment Cores

Tables 8-11 and Figure 10 list the concentrations and summarize AH profile data of a select group of AH's and their total concentrations in sediment cores CB-1, CB-2, CB-3, and CB-4. Total selected aromatic hydrocarbon concentrations for all four cores ranged from 81 μg/kg to 5,884 μg/kg. Sections of sediment core CB-1 from the Puyallup River disposal site showed little difference in total AH concentrations to a depth of 36 cm. In core CB-2 the total AH concentration increased with depth, exceeding 5000 μg/kg in the 60- to 100-cm depth interval, then dropped to approximately 1/30 of the highest concentration observed in this core at a core depth of 130-140 cm. A similar type of AH profile was observed for core CB-3; however, the decrease in AH concentrations was observed between 50 and 60 cm. Concentrations of AHs in core CB-4 were two to four times the concentrations observed in the near-surface sediment sections of core CB-1. Highest concentrations in core CB-4 were observed at a depth of 10-20 cm.

4.5 Concentrations of CBD in Sediment Cores

Table 12 summarizes information on the concentrations of total CBD with depth in sediment cores CB-1, CB-2, CB-3, and CB-4. No polychlorinated biphenyls (PCB) were detected (at the level of detection of 1 ppb) in any of the sediment core sections analyzed. Electron-capturing peaks that might be representative of specific pesticides were also visibly absent. A cluster of electron capturing components that had GC retention times similar to those of the chlorinated butadienes was observed in the sediment core samples. The highest concentrations were observed in the near-surface sediments of cores CB-2 and CB-3. One of the components in the cluster had a gas chromatographic (GC) retention time congruent with an authentic standard of hexachlorobutadiene. Other components in the cluster had retention times similar to major components found in extracts of sediment collected from a waterway adjacent to Commencement Bay, where significant concentrations of trichlorobutadiene isomers had previously been determined by gas chromatography/mass spectrometry (Figure 11). Our earlier studies used GC-MS techniques to confirm the presence of specific chlorinated butadiene compounds (Riley et al., 1980). Thus, the compounds present in this region of narrow GC retention time have been assigned to chlorinated butadiene isomers containing from three to six chlorines. Concentrations of total CBD (Cl_3 to Cl_6) in all four cores ranged from 0.1 to 245 μg/kg. Highest concentrations of CBDs were detected at a depth of 10-20 cm in cores CB-2 and CB-3. More than 99% of the concentration of CBDs detected were located in the top 20 cm of cores CB-2, CB-3, and CB-4. Concentrations of CBDs were in the range of concentrations observed for other sediments analyzed from Puget Sound (Malins et al., 1980); but in some cases, they were considerably less than concentrations observed in sediments collected from waterways adjacent to Commencement Bay (Riley et al., 1981). The total profiles for sediment cores CB-1, CB-2, CB-3, and CB-4 are summarized in Figure 10.

5. DISCUSSION

5.1 Sediment Age Dating

The age-dating results determined by the change in ^{210}Pb activity with core depth can be compared with ^{137}Cs, As, and stable Pb profiles to evaluate the accuracy of the dating. Cesium-137 has entered the oceans during the last 30 years from the atmospheric testing of nuclear weapons. The major input occurred between 1957 and 1965. The maximum ^{137}Cs activity in ocean surface water occurred in approximately 1965. Since then the ^{137}Cs levels in ocean surface water and Puget Sound have decreased slowly as a result of mixing with the deep ocean (Livingston and Bowen, 1979). Marine sediments in contact with seawater exchange stable Cs and ^{137}Cs, thus maintaining a ^{137}Cs activity related to the ^{137}Cs level in the seawater. Once surface sediments are removed from interaction with seawater through burial, the ^{137}Cs activity can change either by radioactive decay or through movement of sediment pore water. Both irrigation of sediments by benthic animals and diffusion of soluble ^{137}Cs could transport ^{137}Cs downward in sediments. The importance of postdepositional migration of ^{137}Cs has not been well documented. Bennett (1980) did not measure significant ^{137}Cs migration relative to ^{210}Pb and $^{239+240}Pu$ in Dabob Bay sediments. Livingston and Bowen (1979) compared the ^{137}Cs and $^{239+240}Pu$ activities in sediment cores from the northeastern United States coastal waters. Both radionuclides decrease with depth in the cores; however, ^{137}Cs decreased at a slower rate which indicates possible migration of either ^{137}Cs or $^{239+240}Pu$. None of their coastal bay or continental shelf cores contained the large ^{137}Cs inventories or subsurface maximum present in Puget Sound as shown for PS-7 (Table 7). The radionuclide distributions reported by Livingston and Bowen (1979) are probably due mainly to sediment mixing of the upper 10 cm. In comparison, the ^{137}Cs profiles for the Puget Sound cores (Crecelius, unpublished data) indicate high sedimentation rates and relatively little redistribution due to sediment mixing. The presence of the subsurface ^{137}Cs maximums suggests that neither mixing nor migration have been intense; otherwise this feature would not be preserved. The subsurface ^{137}Cs maximum has been assigned a date of 1965, the year that maximum ^{137}Cs levels were present in the surface oceans. The core depth where ^{137}Cs becomes undetectable has been assigned a date of 1950.

The concentrations of As and Pb in Puget Sound sediments have been significantly elevated by anthropogenic activities. The date at which both As and Pb began to exceed baseline concentrations in cores from Puget Sound and Lake Washington was approximately 1900 (Crecelius and Piper, 1973; Crecelius et al., 1975; Crecelius, 1975). The major source of As is the Tacoma copper smelter which began operation in 1890. Several sources contribute Pb, including the smelter, leaded gasoline, and sewage.

The sediment dating results from PS-7 and Quartermaster Harbor will be discussed first because these cores are examples of high and low sedimentation sites. The sedimentation rate is relatively rapid at PS-7, resulting in 130 cm of mud deposited since 1935. The ^{137}Cs activity increased with depth in the core to a maximum at the 30- to 40-cm depth interval, then decreased to background at 80-90 cm (Table 7). The agreement between ^{137}Cs age dates and ^{210}Pb is fair. The ^{137}Cs maximum should occur in about 1965 (^{210}Pb dated 1969), and the bottom of the ^{137}Cs profile occurs in the early 1950s as ^{210}Pb predicted. This core is not long enough to include the sediments deposited before As and Pb contamination commenced. Sediment mixing processes are assumed not to be significant compared to sedimentation because the ^{137}Cs subsurface maximum is preserved and the ^{210}Pb and ^{137}Cs ages are in agreement.

The Quartermaster Harbor core data (Table 6) indicate this site has a relatively low sedimentation rate. The profiles of elements in the upper 15 cm of the core can be explained by sediment mixing. The activities of ^{210}Pb, ^{137}Cs, and concentrations of As and Sb (derived from the smelter) approach baseline levels at core depths of 11-15 cm even though these elements were added over different time periods. These profiles could be due to a sediment mixed layer of approximately 5-10 cm and a sedimentation rate of approximately 5 cm during the last century.

Age dating of the short cores from CB-1 and CB-4 was not attempted because of the lack of detailed data. The sediment layer cored at CB-1 (0-36 cm) was deposited during the last 25 years according to the ^{137}Cs and ^{210}Pb data. Because the CB-1 core is from the shallow water disposal site off the mouth of the Puyallup River, the sedimentation rate would be expected to be both rapid and variable. The sediment layer cored from northeastern Commencement Bay (CB-4) (0-32 cm) was deposited during the last 30 years, as estimated from the activity of ^{137}Cs and ^{210}Pb. The decrease in heavy metals in this core is due in part to the increase in sand content in the bottom of the core. This increase in sand is reflected in the increase in dry matter in the 20- to 30-cm section.

The approximate ages of sediment layers in core CB-2 agree with the ^{137}Cs and heavy metal profiles. The sedimentation rate at this site appears to have been rapid, with 90 cm deposited since the early 1900s. The As and Pb concentrations are elevated above baseline levels in the 90- to 100-cm section as would be expected for sediments deposited during the early 1900s.

Core CB-3 was taken from the deep-water disposal site. The subbottom profiles (Figures 7-9) from this location indicate the sediments have been disturbed by disposal of dredged spoils. The dates of layers in the core (Table 4) were calculated assuming ^{210}Pb activities and sedimentation rates were not affected by dredging. Based on ^{137}Cs and stable Pb data, the 60- to 70-cm section is dated at approximately 1900, not 1835 as calculated from ^{210}Pb.

Several investigators have dated cores collected near Commencement Bay. Furlong and Carpenter (1982) dated a box core (STA 57) that was collected northwest of Brown's Point (Figure 2). They reported a coal-rich layer between 30 and 40 cm to have been deposited during 1917-1925. Link (1982) reported a sedimentation rate of 0.669 cm/yr for a core (381) collected west of Brown's Point (Figure 2). This rate would result in approximate ages similar to those reported by Furlong and Carpenter (1982). Dated sediment cores from locations in and between industrial waterways adjacent to Commencement Bay indicate much disturbance of sediments due to dredging activities (Riley et al., 1981). At many locations, more than 30 cm of sediment had been deposited during the last 30 years.

5.2 Distribution of Metals in Surface Sediments and Cores

The published data for As, Sb, Cu, Pb, Zn, and Hg concentrations in Commencement Bay surface sediments have been summarized by Dexter et al. (1981). All of these data are from two studies: Crecelius et al., 1975 and Malins et al., 1980. A note of caution is included here for users of the Malins et al. (1980) sediment metals data. The Cd and Ag values in this report are approximately five times higher than values reported here for similar sediment types. This may be due to a matrix effect in their analytical technique. The As and Se values in the 1980 report are significantly higher than we have determined; however, the As values in the Malins et al. (1982) report are in agreement with those we are reporting here. Crustal metals (Fe, Al, Cr, and Mn) values from Malins et al. (1980) are approximately a factor of two lower than ours due to partial dissolution of the sediment in the analysis procedure. The analytical results for several intercomparison sediments were reported by Riley et al. (1980). These results document some of the discrepancy between the two analytical laboratories.

There is reasonable agreement between Cu, Pb, Zn, Hg, and As in surface sediments at stations CB-1, CB-2, and CB-4 and at Malins et al. (1980 and 1982) stations 6, 13, and 8, respectively. Also the As and Hg data of Crecelius et al. (1975) are in agreement for corresponding sediment stations.

A comparison between heavy metal concentrations in sediments from Commencement Bay with those in central Puget Sound sediments (PS-7) shows that concentrations are approximately equal, even though Commencement Bay sediments are nearer to heavy metal sources than fine-grained sediments of the central basin. Core PS-7 is representative of metal concentration for the central sound

(Table 7). Curl (1982) also reported similar values for other stations in the central basin of Puget Sound. Sediments in the waterways adjacent to both Commencement Bay and Elliott Bay are more contaminated with metals than those of Commencement Bay, presumably because of their proximity to sources of metals.

Commencement Bay sediment is relatively uncontaminated because fast tidal currents largely prevent accumulation in the sediment of the fine-grained, contaminated particles suspended in the water column (Cannon and Grigsby 1982; Baker and Walker, 1982). A second factor may be dilution of the contaminated sediments by "clean" sediment transported into the bay by the Puyallup River. The waterway sediments adjacent to the bay are contaminated because they are near the sources of the metals. These sediments are also often finer grained than the bay sediments (Malins et al., 1980). The effect of the sediment dilution is most apparent at station CB-1, near the mouth of the river, where sandy, uncontaminated sediment is rapidly accumulating.

The concentrations of As, Ag, Hg, Pb, and Sb in the age-dated cores indicate that anthropogenic activities have contaminated the sediments of Commencement Bay and central Puget Sound during this century. The sedimentary record dates heavy metal contamination beginning in the early 1900s, reaching a maximum during the 1950s and 1960s and then decreasing slightly in the 1970s. A similar history has been reported for other studies of metals in Puget Sound and Lake Washington (Crecelius et al., 1975; Crecelius, 1975; Schell and Nevissi, 1977; Curl, 1982).

The following is a discussion of the heavy metals data for each core. The metal concentrations for the two short sandy cores (CB-1 and CB-4) from the shallower stations in Commencement Bay are slightly elevated for several metals compared to similarly textured sediments deposited more than a century ago. These cores include sediments deposited during the last 30 years and therefore should be contaminated with heavy metals.

Sediments in core CB-2 were deposited during the last 100 years. Most heavy metals began to increase in the early 1900s, reached a maximum between 1954-1970, and have decreased in the surface section, deposited during the 1970s. The concentrations of most of the heavy metals in core CB-3 began to increase in about 1900. The maximum heavy metal concentrations for most elements occurred in sediments deposited during the last 30 years. The enrichment of Pb and Hg in the 60- to 70-cm section of the core may be related to past dredged-spoils disposal at this site.

The As and Sb concentrations in the Quartermaster Harbor core (Table 6) indicate that the sedimentation rate is very low: the layer of high metal enrichment is only approximately 10 cm thick. This heavy metal distribution can better be explained by sediment mixing processes. Mixing would account for ^{137}Cs present at depths that were dated by ^{210}Pb to be deposited in the early 1900s.

The core PS-7 data indicate a high rate of sedimentation at this location in the central sound. We estimated by ^{210}Pb dating techniques that during the last 45 years, 130 cm of sediment have accumulated. The wet density of this sediment is 1.35 gm/cm^3, and the dry weight is 43% of the wet weight. Thus, the average mass of dry sediment per cm^3 of wet mud is 0.59 g/cm^3. The sediment accumulation rate at this site would be 1.68 $g/cm^2/yr$, if we assume that mixing processes are not important. However, if the increase in ^{137}Cs in the year 1952 is used as a time marker, the calculated rate of sedimentation is 1.42 $g/cm^2/yr$. This fair agreement between the sedimentation rates determined by ^{210}Pb and ^{137}Cs suggests that sedimentation is rapid and mixing is of relatively minor importance. Core PS-7 was not long enough to reach baseline heavy metal concentrations. The heavy metal data indicate that contamination began before 1935, reached a maximum during 1950-1975, and has begun to decrease slightly since then. We have additional unpublished data from box cores that support these findings.

5.3 Distribution of Aromatic Hydrocarbons (AH) and Chlorinated Butadienes (CBD) in Sediment Cores

The changes in concentrations of AH and CBD with depths in sediment cores from the bay indicate a marked difference in the historical input of these two groups of compounds in the last century. The major AH input to the bay occurred during the early 1900s and probably resulted from the transport and combustion of coal. Contamination of the bay sediment with CBD began approximately 20 years ago probably as the result of chemical wastes discharged into the bay and Hylebos Waterway.

Contamination of sediments from Commencement Bay and adjacent waterways by a variety of organic chemicals was reviewed by Dexter et al. (1981). Additional studies by Riley et al. (1981), Malins et al. (1982), and the data presented in this report are basically in agreement with those of Malins et al. (1980) except for the "Old Tacoma" station, which had extremely high concentrations of organic chemicals. Subsequent sediment sampling and analysis produced results approximately 5-10 times lower for most compounds. These later results reported by Malins et al. (1982) are in agreement with results reported here for stations CB-1, CB-2, and CB-4.

The AH and CBD concentrations in the surface sediments of Commencement Bay follow a pattern similar to that of the heavy metals. Concentrations in the sandy sediment at station CB-1, off the Puyallup River, are lowest, the finer grained sediments from deeper water at CB-2 and CB-3 contain the highest, and station CB-4 near Hylebos Waterway contains intermediate concentration levels. Comparison of these data with the data of Riley et al. (1981) and Malins et al. (1982) suggests that most of the CBD has come from industry located on Hylebos Waterway. The CBD may have been transported to Commencement Bay sediments by water currents or through the past practice of dumping dredged sediments or barge loads of chemical wastes in Commencement Bay. The concentrations of CBD in sediments of lower Hylebos Waterway are approximately 20,000 ppb (Riley et al., 1981; Malins et al., 1982).

Core CB-1 from the sandy Puyallup River disposal site showed relatively low concentrations of AH and exhibited little change in concentrations with depth. The radionuclide activities in CB-1 indicate that these sediments were deposited during the last 10-20 years.

The high concentrations of AHs reported in core CB-2 are similar to those reported for surface sediments from Puget Sound industrial waterways (Riley et al., 1981; Malins et al., 1982). What is unusual about the AH distribution in this core is the subsurface AH maximum at depth in the core. This subsurface peak has at least two plausible explanations. The first is that the sedimentation rate has been constant and rapid over the length of the core and that the age range for the AH maximum (60-100 cm) is approximately 1910 to 1940, the years when coal was an important source of energy for both shipping and industry. The sediment in the bay may have been contaminated with coal particles or coal combustion products released from ships or from shore sources. Supporting evidence for the coal-related materials in Commencement Bay sediments is the presence of coal particles and coal combustion slag or clinkers at depths of 1-1.5 m in cores collected between Seattle and Tacoma (Crecelius, unpublished data) and coal particles from 30-47 cm, dated 1917-1925, in a core collected northwest of CB-2 (Furlong and Carpenter, 1982). If coal was present in our sediment samples, the distribution patterns of AH compounds could be similar to those reported here based on other AH data for the analysis of solvent extracts of coal (White and Lee, 1980 and Tripp et al., 1981).

The second explanation that we have considered is that the sedimentation rate has not been constant and may have been affected by dredge waste disposal, thus resulting in a petroleum-rich layer of sediment with an apparent age of 40-60 years. Although station CB-2 has not been recorded as a disposal site, it is possible that sediments dredged from the industrial waterways were deposited at this site several decades ago. Another event that could have disturbed the sediment is ship anchoring. The ^{137}Cs profile indicates that during the past 25 years, sedimentation in the bay has been similar to other locations in Puget Sound. Based on data from other age-dated cores taken in Puget Sound and Lake Washington (Crecelius et al., 1975; Crecelius, 1975; Curl, 1982), the trace metal distribution indicates anthropogenic contamination beginning at the 100-cm depth, which corresponds to the years 1900-1920.

The AH profile in core CB-3 is similar to that observed in core CB-2 (Figure 10). Core CB-3 exhibits a subsurface maximum in the 40-50 cm interval, which corresponds to sediments deposited between 1910 and 1940. The AH maximum is shallower for CB-3 than for CB-2. This is in agreement with the sedimentation rate data, which are lower at CB-3 than at CB-2. Two other cores from stations 2-3 km away that have been age dated have similar sedimentation rates. In their station-57 box core, Furlong and Carpenter (1982) determined the 45-47 cm to be the year 1917. Link (1982) reported a sedimentation rate of 0.669 cm/year at core 381 which converts to 1925 at 30-cm depth in that core.

Core CB-3 was collected from the deep-water disposal area. Compared to profiles from nondisposal areas, subbottom profiles passing near the core station show evidence of disturbed sediments. There are some irregularities in the ^{210}Pb, Pb, and Hg profiles at depth intervals 30-40 cm and 40-50 cm, which could be due to sediment disposal. Frequent sampling in this and the other three cores indicates that disposal activities have not obviously altered the chemistry of the sediments of Commencement Bay.

The AH profile from core CB-4 shows a relatively high subsurface maximum in sediments containing ^{137}Cs. Also, the concentrations of ^{210}Pb and Pb suggest that these sediments have been deposited during the last 30 years. This indicates the AHs were derived from a source other than coal, presumably petroleum products. The sediments deposited during the last two decades in the waterways near CB-4 are heavily contaminated by petroleum compounds and thus could be a source of AHs to CB-4 (Riley et al., 1981). Another explanation for the AH distribution in CB-4 is that sediment mixing processes in combination with relatively slow sedimentation have mixed the ^{137}Cs and other elements to a depth of greater than 20 cm during the last 25 years. Coal particles spilled in the bay may have been mixed and buried to a depth of greater than 20 cm during the last 60 years. The obvious way to determine the amount of AH in the sediments derived from coal is to physically separate the coal particles and analyze them for AHs.

The interpretation of the CBD distribution in Commencement Bay sediments is relatively straightforward. The subsurface CBD concentration maximum occurs in sediments deposited approximately 20 years ago, which is consistent with the history of CBD accumulation in Hylebos Waterway (Riley et al., 1981). The sampling interval in core CB-4 was not adequately detailed to determine whether a CBD subsurface maximum was present. All the data available for CBD in the Commencement Bay area indicate the source of these compounds is marine discharge of chemical waste into Hylebos Waterway. Chemical waste may also have been barged to central Commencement Bay and discharged. The relatively low concentrations of CBD in core CB-4 may be due to deep-water disposal. Since CB-4 is the station closest to Hylebos Waterway, higher CBD concentrations would be expected at this station than at other stations with sediment of similar grain size and metal concentrations.

6. ACKNOWLEDGEMENTS

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Name brands found throughout this report are used to assure understanding of the methods and materials employed during the study. Their use does not imply endorsement by Battelle Memorial Institute.

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APPENDIX A

FIGURES

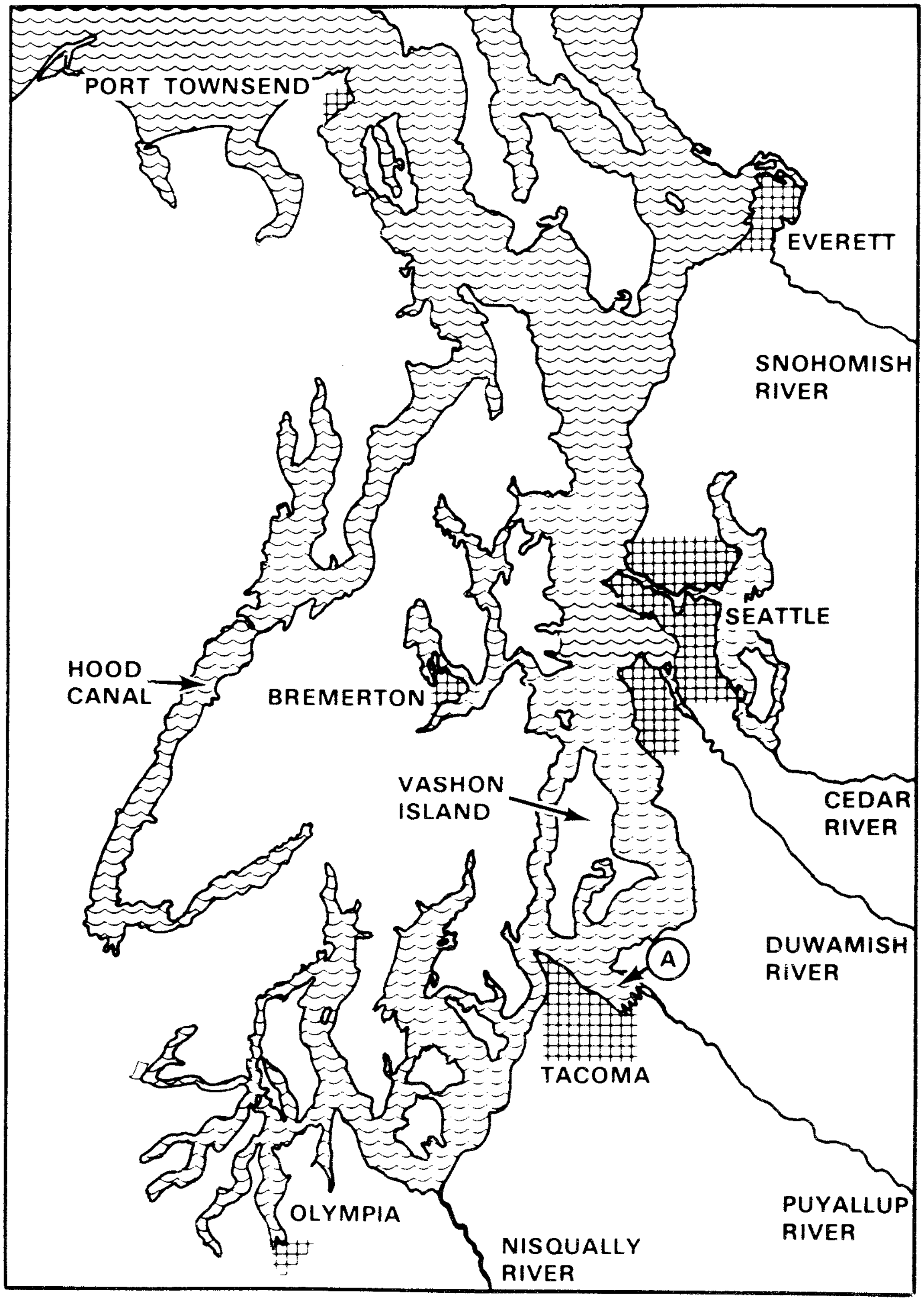


Fig. 1. General Map Showing the Location of Commencement Bay (A)

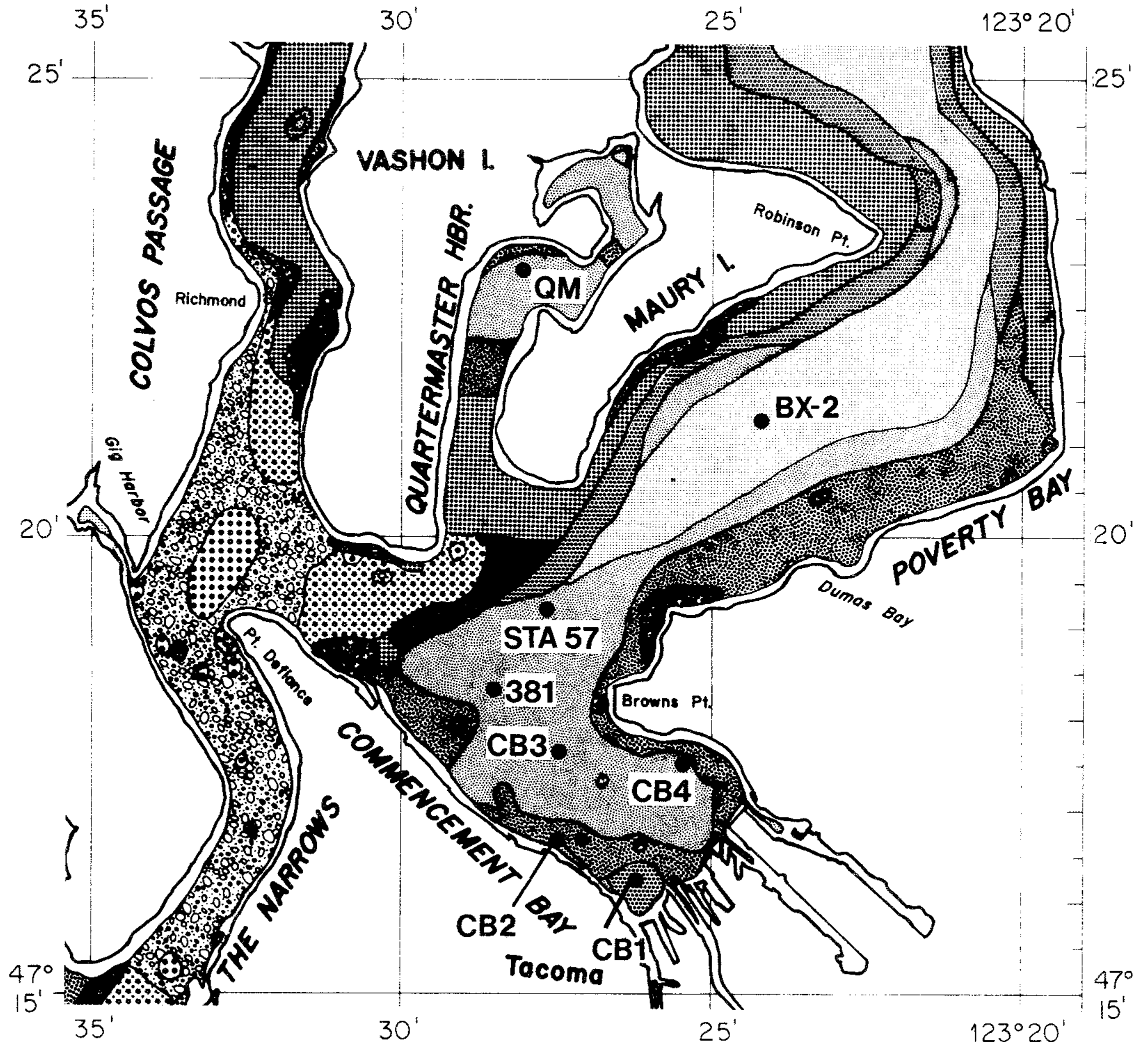
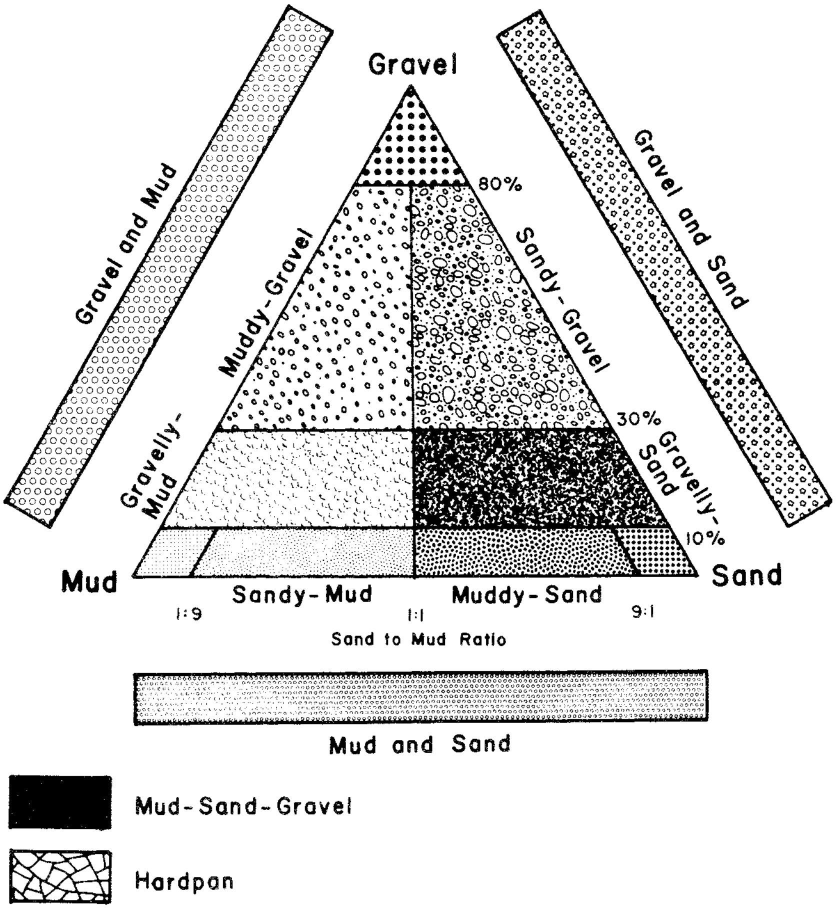


Figure 2. Location of sediment cores and grain size of surface sediments. Grain size key shown in Figure 3. Grain size data from Roberts, 1979.

BX-2 (Curl, 1982)
QM Quartermaster Harbor (Crecelius, 1974)
STA 57 (Furlong and Carpenter, 1982)
381 (Link, 1982)
CB collection locations for this report



Class Name	Particle Diameter
Gravel	Larger than 2.00 mm., 0.0787 in.
Sand	0.63-2.00 mm., 0.0025-0.0787 in.
Mud	Smaller than 0.63 mm., 0.0025 in.

Figure 3. Key to grain size chart in Figure 2, from Roberts (1979).

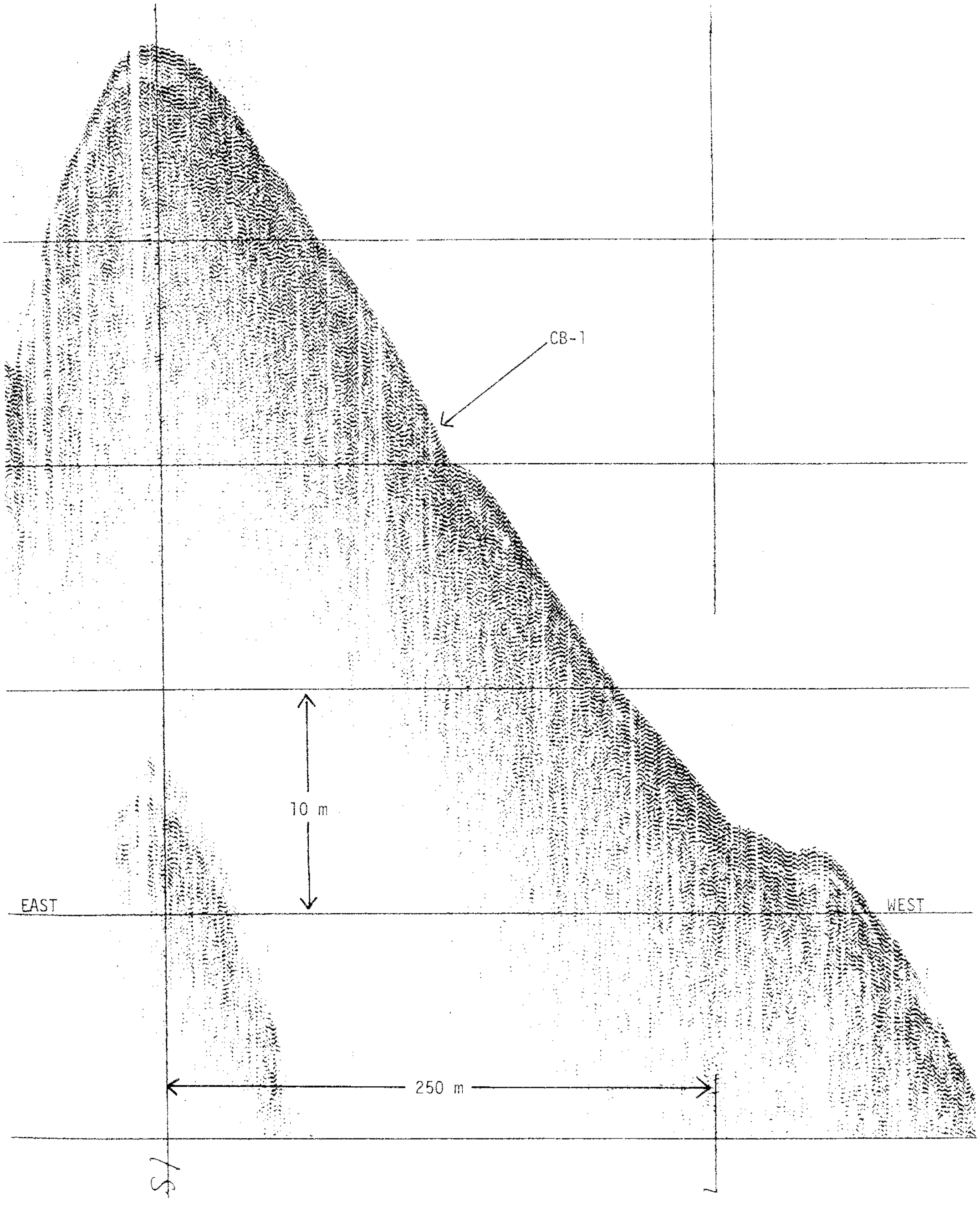


Figure 4. Subbottom profile of shallow water disposal site, east-west transect.

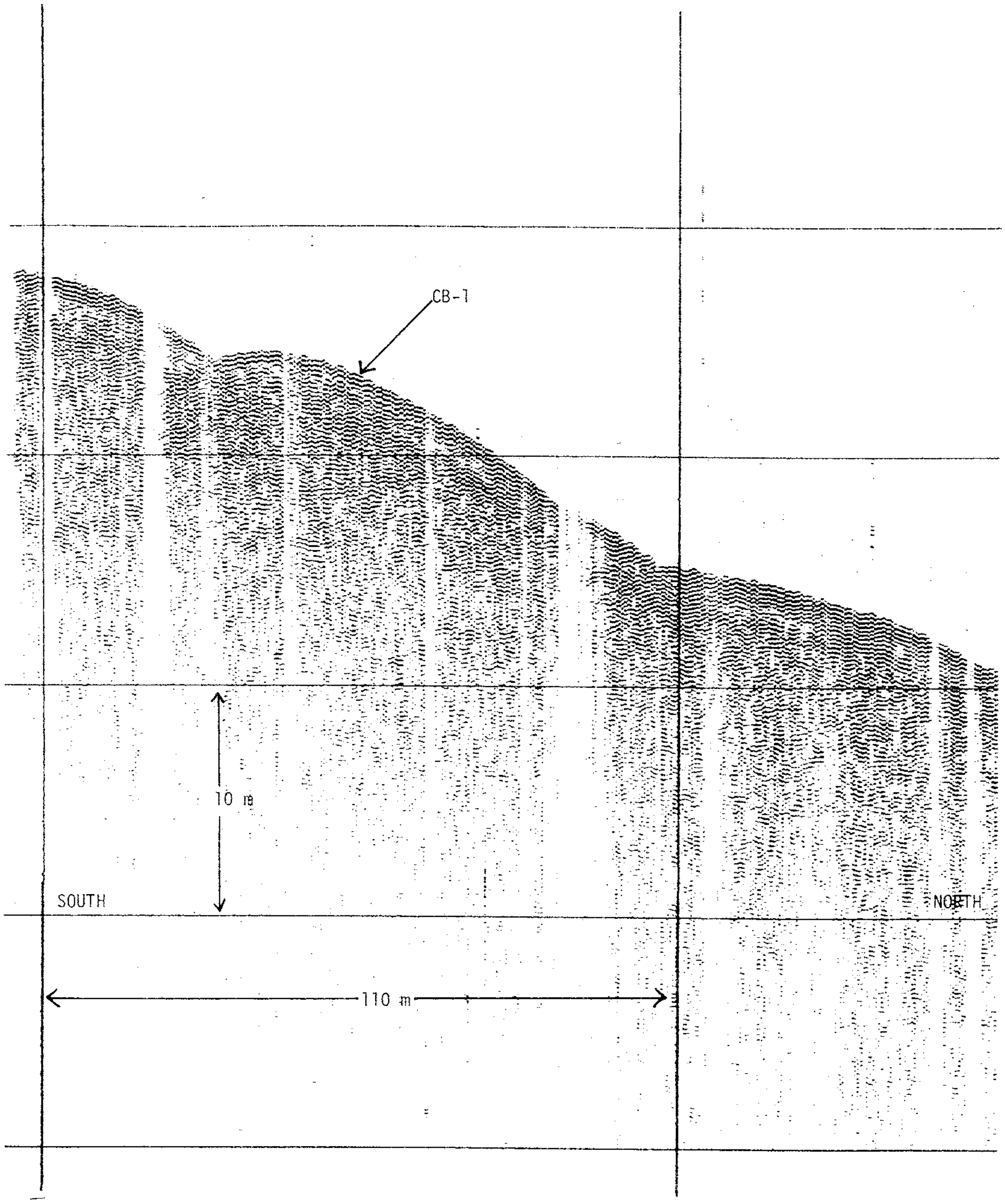


Figure 5. Subbottom profile of shallow water disposal site, north-south transect.

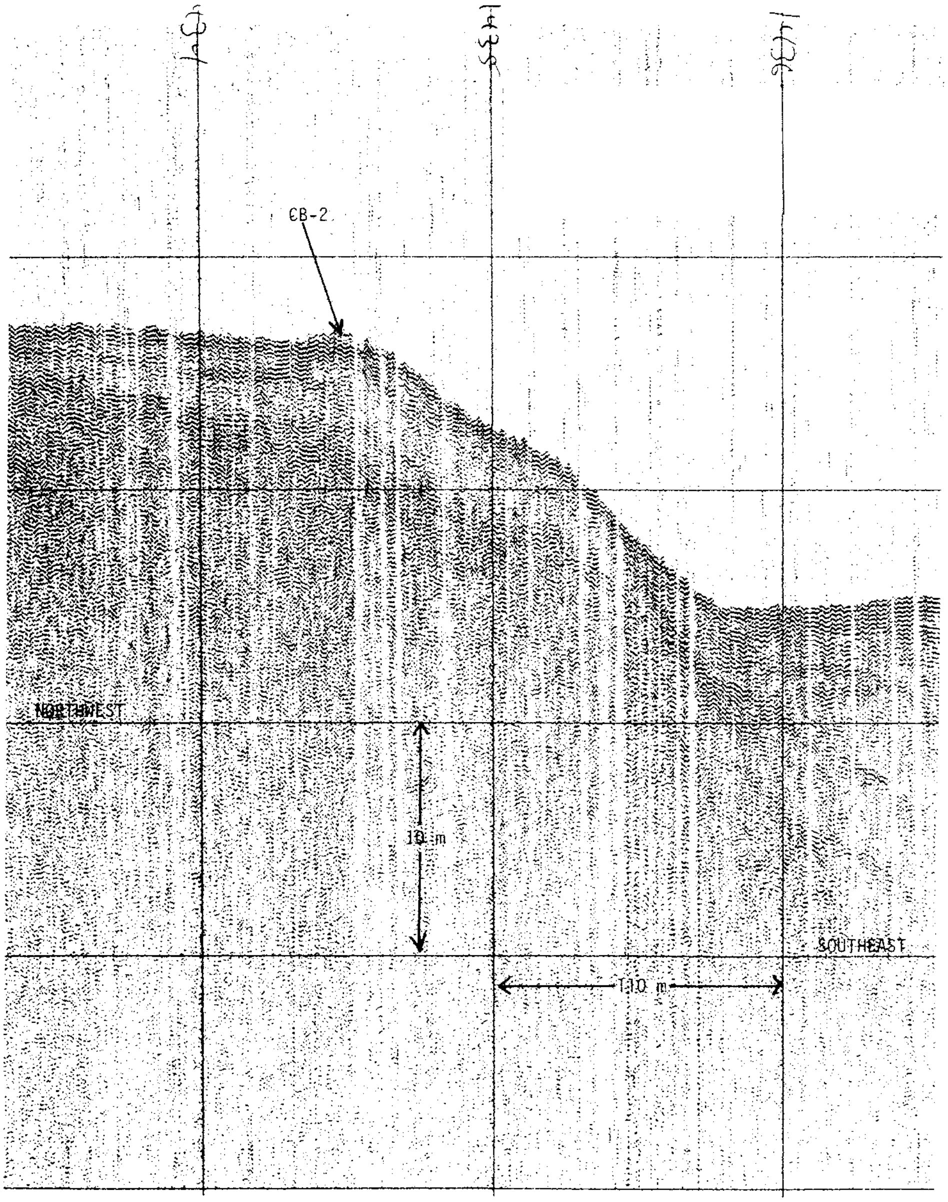


Figure 6. Subbottom profile near Station CB-2, northwest-southeast transect.

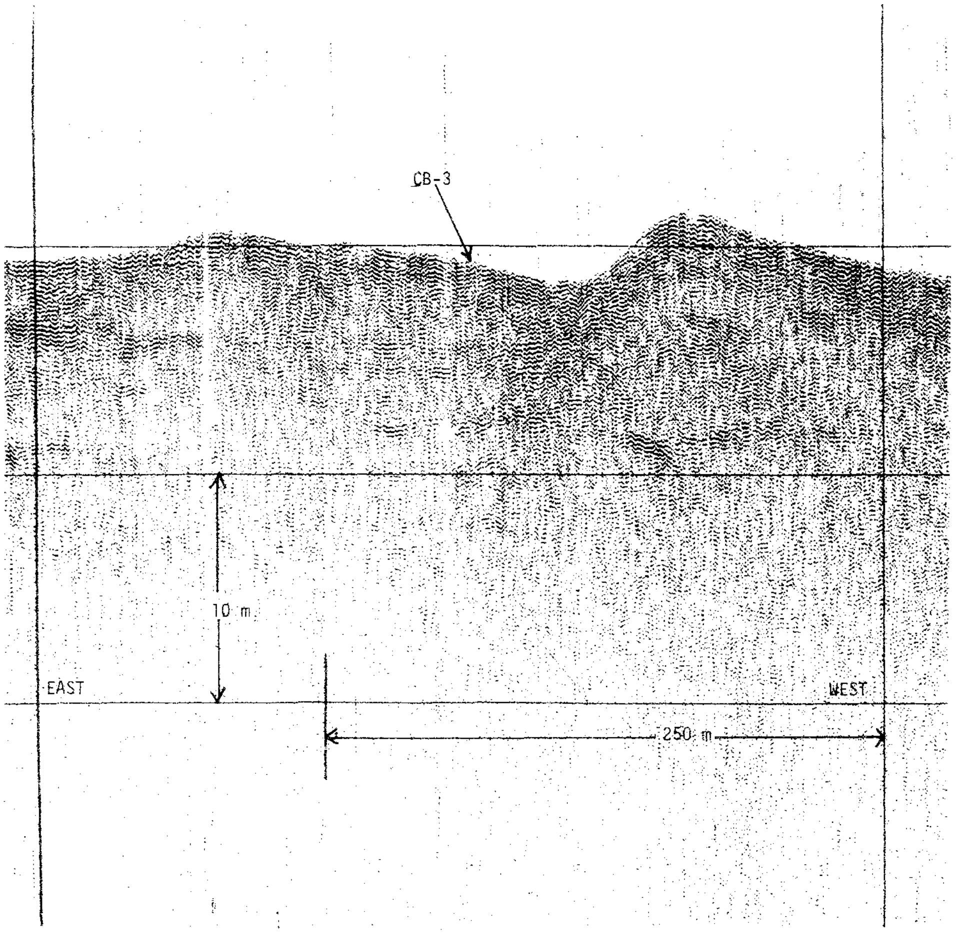


Figure 7. Subbottom profile of deep water disposal site, east-west transect.

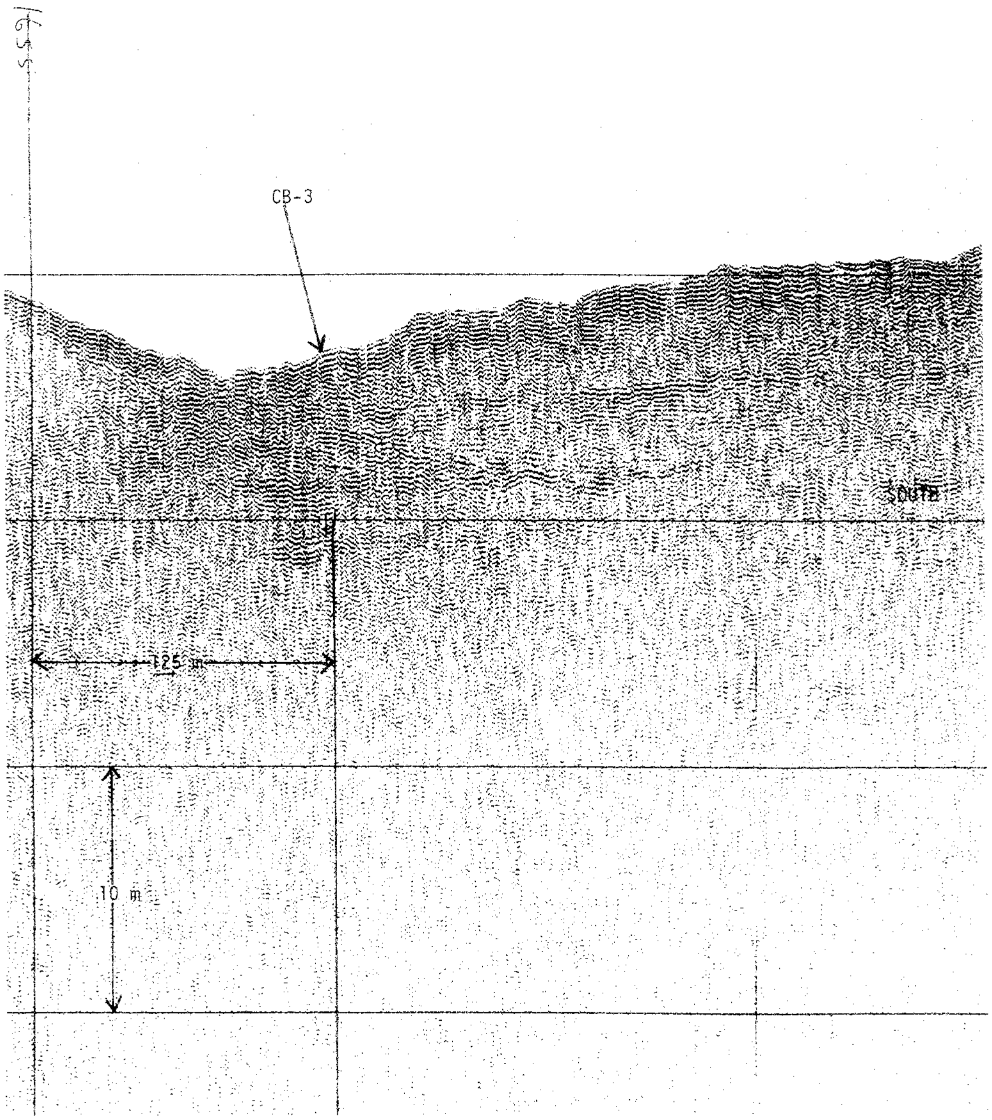


Figure 8. Subbottom profile of deep water disposal site, north-south transect.

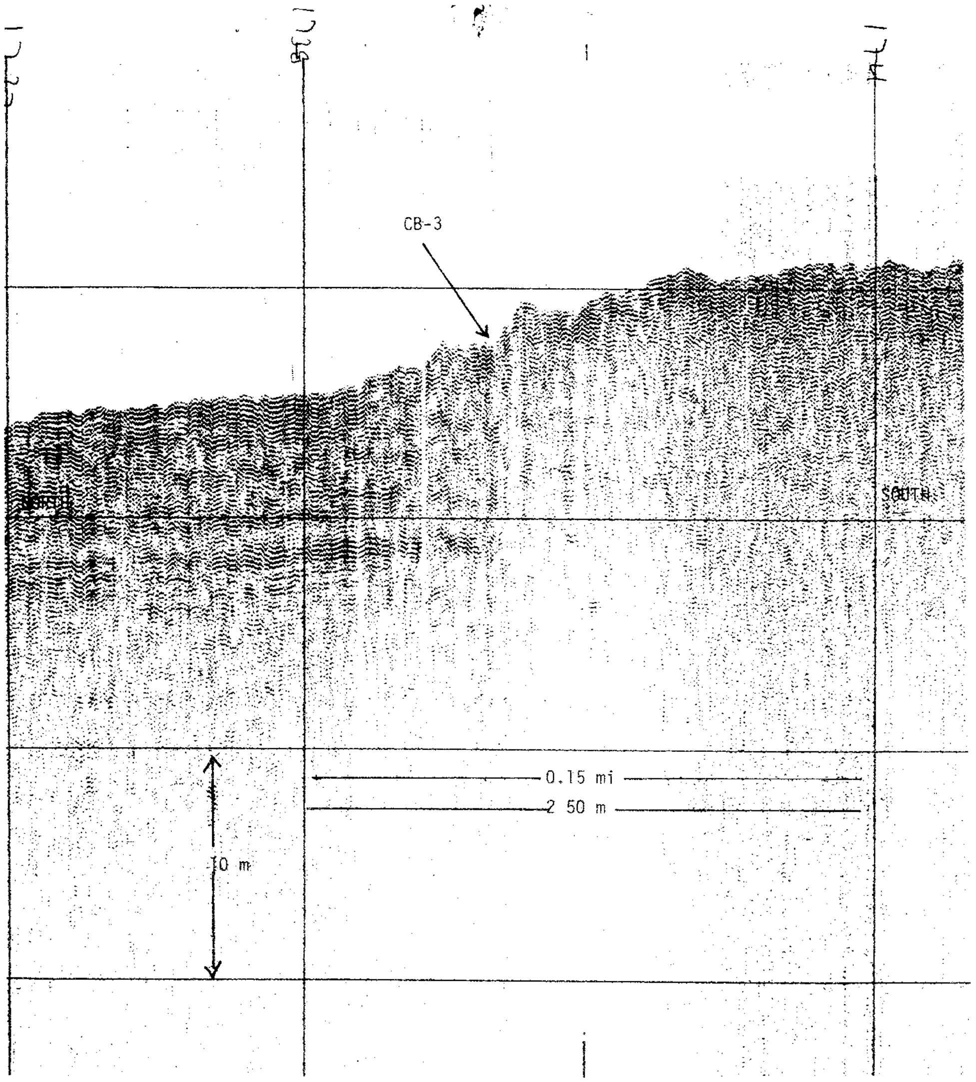


Figure 9. Subbottom profile of deep water disposal site, north-south transect.

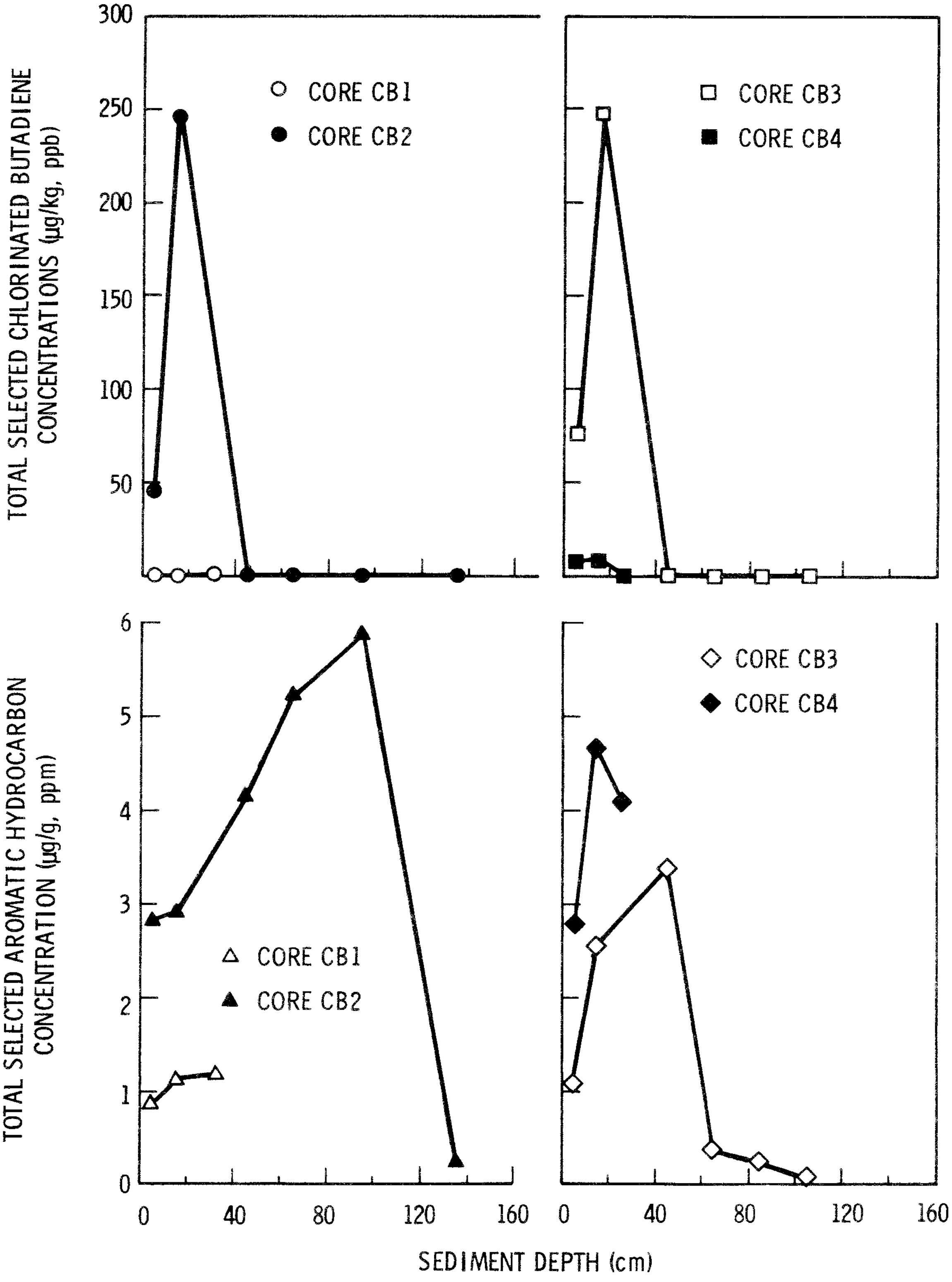


Figure 10. Concentrations of selected organic compound types in Commencement Bay sediment cores.

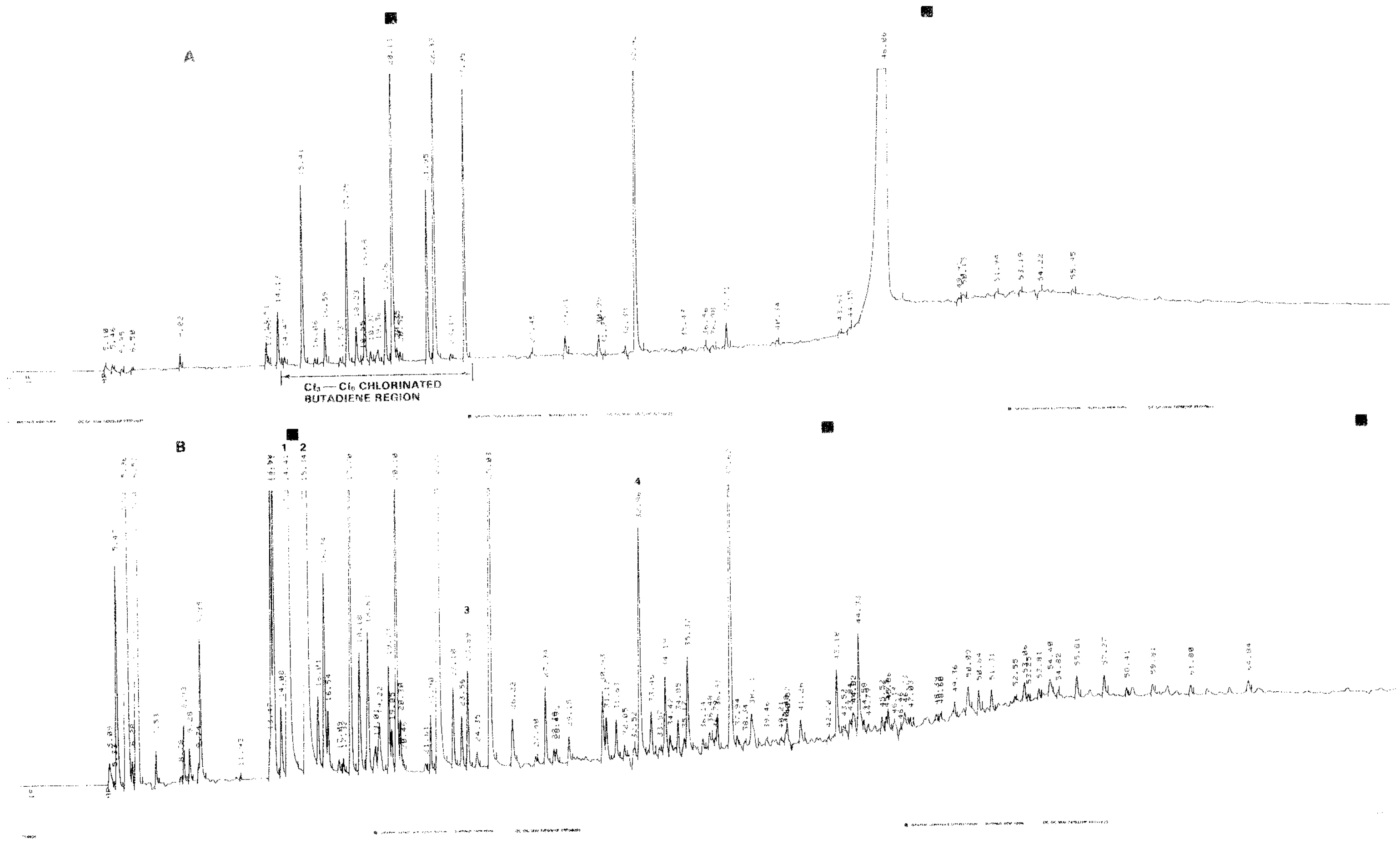


Figure 11. GC chromatograms depicting electron-capturing components in extracts of sediments from (A) Commencement Bay Core CB3, and (B) sediment core 6 from waterway adjacent to Commencement Bay (Riley et al., 1981). Note: Component 1 and 2 correspond to trichlorobutadiene isomers. Component 3 corresponds to hexachlorobutadiene and component 4 is bromonaphthalene internal standard.

APPENDIX B

TABLES

Table 1. Elemental concentrations in marine sediment reference material supplied by National Research Council of Canada, Ottawa.

SAMPLE ID	Major Constituents, Percent Dry Weight K	Ca	Ti	Mn	Fe
MESS-1 "A"	1.81	0.49	0.473	0.044	2.98
MESS-1 "B"	1.94	0.52	0.510	0.047	3.22
MESS-1 "C"	1.74	0.46	0.447	0.040	2.91
This study, mean and	1.83	0.49	0.477	0.044	3.04
± standard deviation	0.10	0.03	0.032	0.004	0.16
Certified values reported by NRC	1.86	0.481	0.543	0.051	3.05

SAMPLE ID	Trace Components, Parts Per Million (Dry Weight) V	Cr	Ni	Cu	Zn	As	Se	Ag	Cd	Sb	Hg	Pb
MESS-1 "A"	67	100	29.2	23.5	163	13.5	<0.9	0.122	0.56	0.96	0.189	30.5
MESS-1 "B"	<69	82	30.1	26.7	171	12.4	<0.9	0.111	0.59	0.80	0.187	32.4
MESS-1 "C"	102	74	27.5	21.4	165	13.7	<0.9	0.115	0.56	0.93	0.174	28.0
This study, mean	--	85	28.9	23.9	166	13.2	--	0.116	0.57	0.90	0.183	30.3
and ± standard deviation	--	13	1.3	2.7	4	0.7	--	0.006	0.02	0.09	0.008	2.2
Certified values	72.4	71	29.5	25.1	191	10.6	(0.4)[a/]	--	0.59	0.73	0.171	34.0

[a/] Not a certified value.

Table 2. Elemental concentration in Commencement Bay, core #CB-1

47° 16.4'N 122° 26.2'W Depth 73 m

	Major Constituents, Percent Dry Weight							Radionuclides dpm/g	
Depth (cm)	Dry Matter	Al	K	Ca	Ti	Mn	Fe	^{137}Cs	^{210}Pb[a/]
0-10	71.4	6.5	1.33	2.76	0.45	0.053	4.20	0.226	0.92
10-20	72.7	6.8	1.35	2.67	0.45	0.050	3.96	0.204	0.51
20-36	66.6	5.1	1.28	3.25	0.46	0.051	4.05	0.470	0.73

Trace Components, Parts Per Million Dry Weight

Depth (cm)	V	Cr	Ni	Cu	Zn	As	Se	Ag	Cd	Hg	Pb
0-10	89	72	37	57	94	17	<0.8	0.07	0.20	0.035	35
10-20	87	60	30	53	87	16	<0.8	0.03	0.05	0.024	32
20-36	74	71	33	49	73	8	<0.8	0.13	0.18	0.064	15

[a/] Unsupported ^{210}Pb.

Table 3. Elemental concentration in Commencement Bay, core #CB-2.

47° 16.7'N 122° 27.5'W Depth 91 m

Depth (cm)	Dry Matter	Major Constituents, Percent Dry Weight						Age[a/]	Radionuclides dpm/g	
		Al	K	Ca	Ti	Mn	Fe		^{137}Cs	^{210}Pb[b/]
0-10	53.5	6.6	1.33	2.81	0.42	0.057	4.09	1977	0.530	3.47
10-20	53.5	5.3	1.16	2.61	0.41	0.050	3.77	1970	0.513	3.42
20-30	54.3	5.3	1.29	2.76	0.43	0.049	3.88	1962	0.351	3.21
30-40	58.1	6.4	1.31	2.94	0.45	0.048	3.89	1954	0.047	--
40-50	59.6	7.5	1.31	2.98	0.46	0.050	4.03	1947	0.021	1.00
50-60	57.6	5.9	1.18	2.57	0.42	0.045	3.35	1940	0.022	1.45
60-70	61.5	5.6	1.08	2.51	0.35	0.042	3.12	1922	<0.01	0.42
90-100	53.6	5.0	1.26	2.62	0.41	0.048	3.80	1910	<0.01	1.27
110-120	60.4	6.2	1.31	3.16	0.44	0.052	3.80	1895	<0.01	1.04
130-140	54.6	4.3	1.26	2.59	0.39	0.048	3.77	1870	<0.01	0.50

[a/] Approximate ages based on ^{210}Pb dating.
[b/] Unsupported ^{210}Pb.

Table 3. Continued.

Depth (cm)	Trace Components, Parts Per Million Dry Weight										
	V	Cr	Ni	Cu	Zn	As	Se	Ag	Cd	Hg	Pb
0-10	122	62	31	65	87	19	<0.8	0.34	0.17	0.152	29
10-20	84	78	34	67	97	21	<0.8	0.40	0.10	0.254	40
20-30	97	73	34	66	101	24	<0.8	0.44	0.27	0.283	36
30-40	93	66	33	66	90	19	<0.8	0.27	0.22	0.266	30
40-50	169	73	32	53	80	12	<0.8	0.15	0.17	0.142	23
50-60	129	64	27	59	79	13	1.1	0.19	0.54	0.246	37
60-70	140	46	28	45	65	11	<0.9	0.12	0.21	0.160	21
90-100	111	94	31	45	72	12	1.4	0.10	0.32	0.124	19
110-120	128	74	36	37	72	7	<0.8	0.03	0.16	0.060	8
130-140	<57	104	36	38	70	8	1.2	0.04	0.07	0.041	8

Table 4. Elemental concentration in Commencement Bay, core #CB-3.

47°F 17.7' N 122° 27.5'W Depth 157 m										
	Major Constituents, Percent Dry Weight								Radionuclides dpm/g	
Depth (cm)	Dry Matter	Al	K	Ca	Ti	Mn	Fe	Approx. age[a]	^{137}Cs	^{210}Pb[b]
0-10	58.0	5.1	1.25	2.74	0.40	0.053	3.76	1970	0.318	4.77
10-20	55.6	5.7	1.25	2.59	0.43	0.050	3.94	1948	0.103	1.45
20-30	55.4	5.9	1.26	2.52	0.42	0.047	3.74	1924	0.043	0.75
30-40	57.3	6.0	1.23	2.73	0.40	0.051	3.69	1902	<0.01	0.19
40-50	57.9	4.4	1.21	2.45	0.39	0.053	3.68	1880	<0.01	0.20
60-70	53.7	6.2	1.24	2.78	0.42	0.050	3.73	1835	<0.01	0.45
80-90	56.4	4.5	1.20	2.47	0.37	0.048	3.46		<0.01	<1.0
100-110	58.4	5.9	1.32	2.65	0.40	0.053	3.91		<0.01	<1.0

[a] Approximate ages based on ^{210}Pb dating. Dates biased by disposal activities, see text.

[b] Unsupported ^{210}Pb.

Table 4. Continued.

	Trace Components, Parts Per Million Dry Weight										
Depth (cm)	V	Cr	Ni	Cu	Zn	As	Se	Ag	Cd	Hg	Pb
0-10	84	49	31	46	94	20	<0.8	0.21	0.15	0.131	30
10-20	88	68	34	53	88	16	<0.8	0.20	0.15	0.241	34
20-30	82	57	28	50	83	15	<0.8	0.10	0.13	0.211	31
30-40	113	55	29	55	63	10	1.0	0.11	0.09	0.152	15
40-50	123	67	36	33	67	7	<0.8	0.04	0.20	0.045	9
60-70	138	53	31	40	64	8	1.1	0.05	0.11	0.081	14
80-90	<56	66	32	33	65	7	<0.8	0.03	0.12	0.037	9
100-110 cm	125	78	38	37	71	7	1.5	0.02	0.18	0.029	6

Table 5. Elemental concentration in Commencement Bay, core #CB-4.

47° 17.6'N 122° 25.5'W Depth 55 m

	Major Constituents, Percent Dry Weight							Radionuclides dpm/g	
Depth (cm)	Dry Matter	Al	K	Ca	Ti	Mn	Fe	^{137}Cs	^{210}Pb[a/]
0-10	52.9	5.3	1.26	2.96	0.40	0.047	3.75	0.523	2.2
10-20	59.6	6.2	1.28	3.00	0.43	0.045	3.74	0.136	0.83
20-32	64.8	6.4	1.29	2.97	0.42	0.044	3.59	0.041	0.80

	Trace Components, Parts Per Million Dry Weight										
Depth (cm)	V	Cr	Ni	Cu	Zn	As	Se	Ag	Cd	Hg	Pb
0-10	111	72	31	58	90	15	<0.8	0.31	0.38	0.149	25
10-20	100	70	27	51	74	<5	<0.8	0.12	0.24	0.146	22
20-32	101	59	24	44	63	6	1.0	0.07	0.20	0.091	15

[a/] Unsupported ^{210}Pb.

Table 6. Concentrations of radionuclides and elements in sediment core from Quartermaster Harbor.

Lat. 47° 22.9'N. Long. 122° 28.1"W. Depth 14 m

Depth (cm)	Al[a] (%)	Fe[a] (%)	Approx. Age[b]	^{137}Cs (dpm/g)	^{210}Pb[c] (dpm/g)	As (ppm)	Sb (ppm)
0-1	6.8	3.6	1970		1.32	54	3.6
1-2	6.4	3.2	1957	0.38		39	3.2
2-3	6.9	3.3	1948	0.38		46	3.2
2-3	6.9	3.4				46	3.3
3-4				0.33			
4-5	6.9	3.4	1933	0.21	0.92	42	2.9
5-6				0.17			
6-7				0.19			
7-8				0.12			
8-9				0.05			
9-10	8.2	3.4	1890	0.06	0.47	26	1.6
11-12				0.03			
14-15	6.0	3.4	1850		<0.05	12	0.7
19-20	6.4	2.7	1808		<0.05	7.2	0.4
29-30	6.5	2.8			<0.05	6.9	0.4
49-50	7.1	3.5			<0.05	8.7	0.7

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[a] Element concentrations from Crecelius, 1974.

[b] Approximate ages based on ^{210}Pb dating. Dates biased by sediment mixing (see text).

[c] Unsupported ^{210}Pb.

Table 7. Elemental concentrations in core #PS-7, Central Puget Sound.

47° 42.0' 122° 27.5' Depth 210 m

	Major Constituents, Percent				Radionuclides dpm/g	
Depth (cm)	Dry Matter	Mn	Fe	Approx age[a/]	^{137}Cs	^{210}Pb[b/]
0-10	40.5	0.056	3.88	1979	0.498	9.41
10-20	42.5	0.052	4.24	1975	0.530	8.65
20-30	43.0	0.053	4.16	1972	0.578	8.55
30-40	43.1	0.049	4.14	1969	0.596	5.54
40-50	42.9	0.053	4.27	1965	0.408	5.09
50-60	43.8	0.047	4.16	1961	0.119	5.45
60-70	44.8	0.051	4.32	1957	0.341	4.23
70-80	45.0	--	--	1952	0.237	3.95
80-90	43.8	0.050	4.17	1949	<0.01	3.62
90-100	44.0	0.053	4.13	1945	<0.01	3.54
100-110	44.2	0.049	3.91	1942	<0.01	2.74
110-120	44.4	0.052	4.33	1938	--	--
120-130	44.5	0.047	4.04	1935	<0.01	2.85

[a/] Approximate age of sediment section based on ^{210}Pb dating.
[b/] Unsupported ^{210}Pb.

Table 7. Continued.

SAMPLE ID	Trace Components, Parts Per Million Cr	Ni	Cu	Zn	As	Ag	Hg	Pb
0-10 cm	99	53	48	111	13	0.474	0.178	32
10-20 cm	99	48	51	124	15	0.521	0.227	35
20-30 cm	123	53	49	127	14	0.456	0.194	35
30-40 cm	96	55	49	115	14	0.428	0.207	33
40-50 cm	96	52	51	125	14	0.405	0.225	32
50-60 cm	94	58	47	115	15	0.340	0.204	33
60-70 cm	104	56	47	115	15	0.312	0.210	28
70-80 cm	--	--	--	--	--	0.288	0.200	--
80-90 cm	78	55	45	114	14	0.233	0.206	29
90-100 cm	100	53	44	111	12	0.233	0.197	30
100-110 cm	97	47	41	100	11	0.205	0.202	29
110-120 cm	96	56	47	111	12	0.177	0.164	23
120-130 cm	94	50	42	97	10	0.140	0.135	18

Table 8. Concentrations (μg/kg dry wt.) with depth of selected aromatic hydrocarbons in sediment core CB-1.

	Core depth (cm)		
Compound	0-10	10-20	26-36
naphthalene	82	77	63
2-methylnaphthalene	57	45	60
1-methylnaphthalene	54	39	47
biphenyl	24	35	39
2,6-dimethylnaphthalene	62	47	38
2,3,5-trimethylnaphthalene	68	33	52
fluorene	<2	14	<3
dibenzothiophene	50	21	31
phenanthrene	110	106	127
anthracene	<2	10	<2
1-methylphenanthrene	77	52	64
fluoranthene	140	99	138
pyrene	53	60	84
benzanthracene	90	450	287
chrysene	45	62	141
benz(e)pyrene	<3	<2	<2
benz(a)pyrene	<3	<3	<4
perylene	<3	<3	<4
Total selected aromatics	912	1,150	1,171

Table 9. Concentrations (μg/kg, dry wt) with depth of selected aromatic hydrocarbons in sediment core #CB-2.

	Core depth (cm)					
Compound	0-10	10-20	40-50	60-70	90-100	130-140
naphthalene	186	154	165	173	232	11
2-methylnaphthalene	84	79	186	203	171	11
1-methylnaphthalene	69	61	166	162	68	11
biphenyl	54	51	77	74	98	22
2,6-dimethylnaphthalene	100	96	264	260	244	23
2,3,5-trimethylnaphthalene	67	77	310	316	370	13
fluorene	46	73	168	195	247	<3
dibenzothiophene	79	104	412	430	539	<5
phenanthrene	247	260	417	504	530	85
anthracene	<2	<2	<2	<2	<2	<2
1-methylphenanthrene	266	313	437	672	666	14
fluoranthene	395	350	378	571	1,517	<3
pyrene	458	447	578	836	625	12
benzanthracene	178	204	189	237	148	<3
chrysene	150	168	214	229	236	<3
benz(e)pyrene	<2	36	<2	28	<2	<2
bena(a)pyrene	48	69	56	124	25	<4
perylene	350	325	94	193	168	<4
Total selected aromatics	2,777	2,867	4,111	5,207	5,884	202

Table 10. Concentrations (μg/kg, dry wt) with depth of selected aromatic hydrocarbons in sediment core #CB-3.

Compound	Core depth (cm)					
	0-10	10-20	40-50	60-70	90-100	130-140
naphthalene	116	171	75	16	32	<3
2-methylnaphthalene	65	109	130	18	20	<3
1-methylnaphthalene	70	97	122	19	19	<3
biphenyl	32	55	55	19	24	16
2,6-dimethylnaphthalene	74	131	198	29	4	<3
2,3,5-trimethylnaphthalene	56	116	225	17	<3	<3
fluorene	47	70	90	7	7	<3
dibenzothiophene	36	151	279	<4	<5	<5
phenanthrene	193	256	298	75	79	55
anthracene	<2	<2	<3	<2	<3	<2
1-methylphenanthrene	91	189	424	31	31	<3
fluoranthene	333	265	922	<3	15	<3
pyrene	<3	480	199	15	24	<3
benzanthracene	<3	133	88	44	18	18
chrysene	<3	143	121	<3	<3	<3
benz(e)pyrene	<2	35	<3	<2	<2	<2
bena(a)pyrene	<4	81	<4	<4	<4	<4
perylene	<4	88	213	88	<4	<4
Total selected aromatics	1,113	2,570	3,339	378	273	81

Table 11. Concentrations (µg/kg dry wt) with depth of selected aromatic hydrocarbons in sediment core #CB-4.

	Core depth (cm)		
Compound	0-10	10-20	26-32
naphthalene	166	341	75
2-methylnaphthalene	62	257	198
1-methylnaphthalene	51	208	166
biphenyl	71	88	83
2,6-dimethylnaphthalene	78	317	300
2,3,5-trimethylnaphthalene	49	347	318
fluorene	<4	167	175
dibenzothiophene	27	412	461
phenanthrene	217	406	427
anthracene	<3	<2	<2
1-methylphenanthrene	172	553	581
fluoranthene	818	568	268
pyrene	347	495	335
benzanthracene	174	176	153
chrysene	174	202	180
benz(e)pyrene	<3	<2	<2
benz(a)pyrene	<5	52	22
perylene	380	122	328
Total selected aromatics	2,786	4,711	4,070

Table 12. Concentration (μg/kg, dry wt) with depth of total CBD[a] in sediment cores[b].

	Core depth (cm)									
Sediment Core	0-10	10-20	26-36	20-32	40-50	60-70	80-90	90-100	100-110	130-140
CB-1	0.3	0.3	1.7							
CB-2	41.3	239.1			<0.001	<0.001		0.1		<0.001
CB-3	78.8	244.9			0.3	<0.001	<0.001		<0.001	
CB-4	15.5	17.7		0.2						

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[a] Cl_3 to Cl_6.

[b] Concentrations of individual PCBs were less than 1 ppb for Cl_1-biphenyls, <0.03 ppb for Cl_2-biphenyls, and <0.006 ppb for Cl_3-Cl_6-biphenyls.