Distribution of Radionuclides in Bottom Sediments of the Columbia River Estuary

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By D. W. HUBBELL *and* J. L. GLENN

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DISTRIBUTION OF RADIONUCLIDES IN BOTTOM SEDIMENTS OF THE COLUMBIA RIVER ESTUARY

By D. W. HUBBELL and J. L. GLENN

ABSTRACT

Radionuclides produced primarily by neutron activation of naturally occurring stable elements and chemical additives in nuclear-reactor coolant water are discharged into the Columbia River at the Hanford Reservation of the U.S. Atomic Energy Commission. In the river, the radionuclides associate with sediment and biota or remain in solution and subsequently are distributed downstream throughout the river system and the Columbia River estuary to the Pacific Ocean. To provide information on the distribution of radioactivity in the estuary, the physical and radiological character of the streambed was investigated in 1965. Gross gamma radiation was measured in situ, and surficial samples and cores were obtained with specially designed equipment at 14 cross sections between Longview, Wash., near Columbia River mile 65.8, and the estuary mouth.

To facilitate data interpretation, the estuary is divided into geomorphic classes termed "channels," "slopes," and "flats" and into longitudinal divisions called fluvial, transitional, and marine. Grouping data obtained within the same class and division improves correlations significantly, but additional classes are necessary.

In situ gross gamma radiation varies over a seventyfold range and generally correlates with the total concentration of individually measured radionuclides in surficial samples. The most abundant radionuclides measured in samples from the estuary are Cr^{51}, Zn^{65}, K^{40}, Sc^{46}, Ru^{106}, Mn^{54}, Co^{60}, and Zr^{95}-Nb^{95}. Concentrations of Cr^{51} and Zn^{65} in surficial sediment are approximately 6.2 and 2.2 times, respectively, greater than the concentration of naturally occurring K^{40}, which averages about 14 picocuries per gram of sediment; the other measured radionuclides are substantially less abundant than K^{40}. Radionuclide concentrations vary greatly from place to place, and even when samples in common geomorphic classes and longitudinal divisions are grouped, standard deviations generally are so large that positive conclusions relative to changes in individual radionuclide concentrations along the estuary cannot be made with confidence. Chromium-51, however, appears to increase relative to Zn^{65} toward the mouth of the estuary, and radionuclide concentrations are generally higher on slopes and flats than in channels.

The stratigraphic distribution of radionuclides also varies considerably. Radionuclides tend to be distributed to the greatest depths in channels and on slopes and may extend more than 60 inches below the bed surface. However, on the average, 66 percent of the total amount of measured radio-

nuclides (excluding K^{40}) is contained in the upper 8 inches of the streambed. Ordinarily, highest concentrations are at the surface or a few inches below. The total amount of measured radioactivity (excluding K^{40}) in the sediment column beneath the bed surface ranges from about 0.05 to 15 microcuries per square foot.

In the estuary as a whole, sediments in the channels are coarsest, sediments on the flats are finest and have the most positively skewed distributions, and sediments on the slopes are intermediate in size and have the least skewed textural distributions. Within each longitudinal division these same trends exist; however, channel sediments are finest in the transitional division and coarsest in the fluvial division. Sediments on slopes tend to have the same textural characteristics throughout the estuary, but sediments on flats are finest in the fluvial and marine divisions. Cores indicate that estuary sediments are stratified, that a thin fine-grained layer caps many cores that otherwise are essentially sand, and that variations in sediment texture with depth are large at some locations.

Sediment composition influences the level of radioactivity to a high degree. The total concentration of measured radionuclides (excluding K^{40}) increases as the sediment decreases in size and becomes less well sorted and as the textural distribution of the sediment becomes more skewed toward fine material. Computations based on relations between mean particle size and radioactivity in surficial sediment samples indicate that Zn^{65} concentrations associated with individual size separates decrease in a downstream direction.

An inventory of the amounts of radionuclides in the bed was computed using maps that divide the estuary into nine areas in which the level of radioactivity near the surface and the stratigraphic distribution of radionuclides are similar. In situ radioactivity and general relations among radionuclide content, geomorphic expression, and sediment composition were used in preparing the maps. The inventory shows that at the time of the survey (June 1965) the amount of measured radionuclides (excluding K^{40}) was 8,700 curies and consisted of 5,300 curies of Cr^{51}, 2,100 curies of Zn^{65}, and 1,300 curies of other activation products and fallout. The estuary appears to contain about one-quarter of all the radionuclides in the reservoir (river, estuary, and ocean) below Vancouver, Wash. Approximately 15, 48, and 37 percent of the total amount of measured radionuclides is in the marine, transitional, and fluvial divisions, respectively, and

channels, slopes, and flats contain 23, 36, and 41 percent of the total amount, respectively. The distributions of Zn^{65} and Cr^{51} are about the same as the distribution of total measured radionuclides except that, proportionately, slightly more Zn^{65} is in the transitional division.

Within the context of simplifying assumptions, the amount of Zn^{65} in the estuary and Zn^{65} transport rates at Vancouver were used in a mass-balance equation to estimate the percentage of fine sediment (finer than 62 microns) retained in the estuary. The calculations indicate that on an annual basis about 30 percent of the fine sediment that enters the estuary may be retained there. Mean particle velocities, computed from the longitudinal attenuation of Zn^{65} concentrations and Zn^{65}/Co^{60} ratios, appear to be several times too high. This suggests that factors other than decay influence the concentration of radionuclides in surficial sediment. Alternating erosion and deposition, presumed to occur at most core sampling sites, precluded computations of meaningful deposition rates from changes in radionuclide ratios with depth; however, the rate determined for one core collected in an area where fine sediment may have been depositing more or less continuously was 3.4 inches per year.

This study indicates that data on geomorphic expression and sediment composition can be combined with a knowledge of the character of actual or contemplated radioactive wastes to predict the probable spatial distributions of radioactivity in estuaries.

INTRODUCTION AND ACKNOWLEDGMENTS

The Columbia River estuary serves as a repository for radionuclides derived partly from nuclear fallout throughout the Columbia River drainage basin and partly from low-level radioactive wastes discharged into the river at the U.S. Atomic Energy Commission's Hanford Reservation near Richland, Wash. (fig. 1). The low-level wastes, which are by far the most important source, are produced primarily by neutron activation of chemical constituents in treated Columbia River water that is used to cool the nuclear reactors at the reservation. Much of the waste decays within a relatively short time (Foster, 1964); however, there are detectable amounts of longer lived radionuclides. Once radionuclides are discharged into the river they may remain in solution or become associated with sediment or biota. Regardless of their immediate fate, the radionuclides subsequently are dispersed and transported downstream. Mainly as a result of uptake and transport by sediment, radionuclides become distributed throughout the streambed to the Pacific Ocean. General levels of radionuclide content within the body of the flow have been monitored at various locations along the river by Hanford radiological health groups and by Washington and Oregon State agencies since the outset of reactor operations in 1944. However, investigations dealing with phenomenological aspects of radioactivity in the environment initially were confined mainly to reaches of the river in the vicinity of the Hanford Reservation.

In 1962, the U.S. Geological Survey, in cooperation with the U.S. Atomic Energy Commission, undertook a detailed investigation of the uptake, transport, and release of radionuclides in the reach of the Columbia River between Pasco, Wash., and Longview, Wash (fig. 1). The Richland Operations Office of the Atomic Energy Commission and one of its prime contractors, General Electric, cooperated in the investigation by arranging for and performing radiochemical analyses and by providing scientific expertise. The services originally provided by General Electric later were furnished by Battelle Memorial Institute when operation of the Hanford laboratories was transferred.

Late in 1963, the Geological Survey, also in cooperation with the Atomic Energy Commission, began a separate, but related, investigation of radioactivity in the Columbia River estuary. The purpose of the investigation was to study the disposition and movement of radionuclides in estuarine environments. In particular, information was desired on (1) the spatial and temporal distribution of radionuclides; (2) the influences that complex circulation and sedimentation patterns created by salinity intrusion, tidal action, channel geometry, and variable fresh-water flow have on the transport of radionuclides; and (3) the important processes involved during the movement of radionuclides from the fluvial environment to the ocean.

As a part of the estuary investigation, a survey was made in June 1965 of radionuclides in the streambed between the mouth and Longview. This report presents the results from the survey. At the outset it was apparent that the concentration of radionuclides was related to the composition of the sediment and that a knowledge of the distribution of one would aid in inferring the distribution of the other. For this reason, data on both radioactivity and sediment composition were obtained during the survey. In this report, data have been used to define the areal and stratigraphic distribution of radionuclides and sediment and to determine relationships among radioactivity, geomorphic expression, and physical characteristics of the sediment. This information provides the basis for a generalized qualitative description of the distribution of radionuclides in the estuary. The distributions and relations also have been utilized to inventory the amounts and species of radionuclides in the estuary bed at the time of the survey. The amounts, in turn, provide a basis for some generalizations about sediment transport.
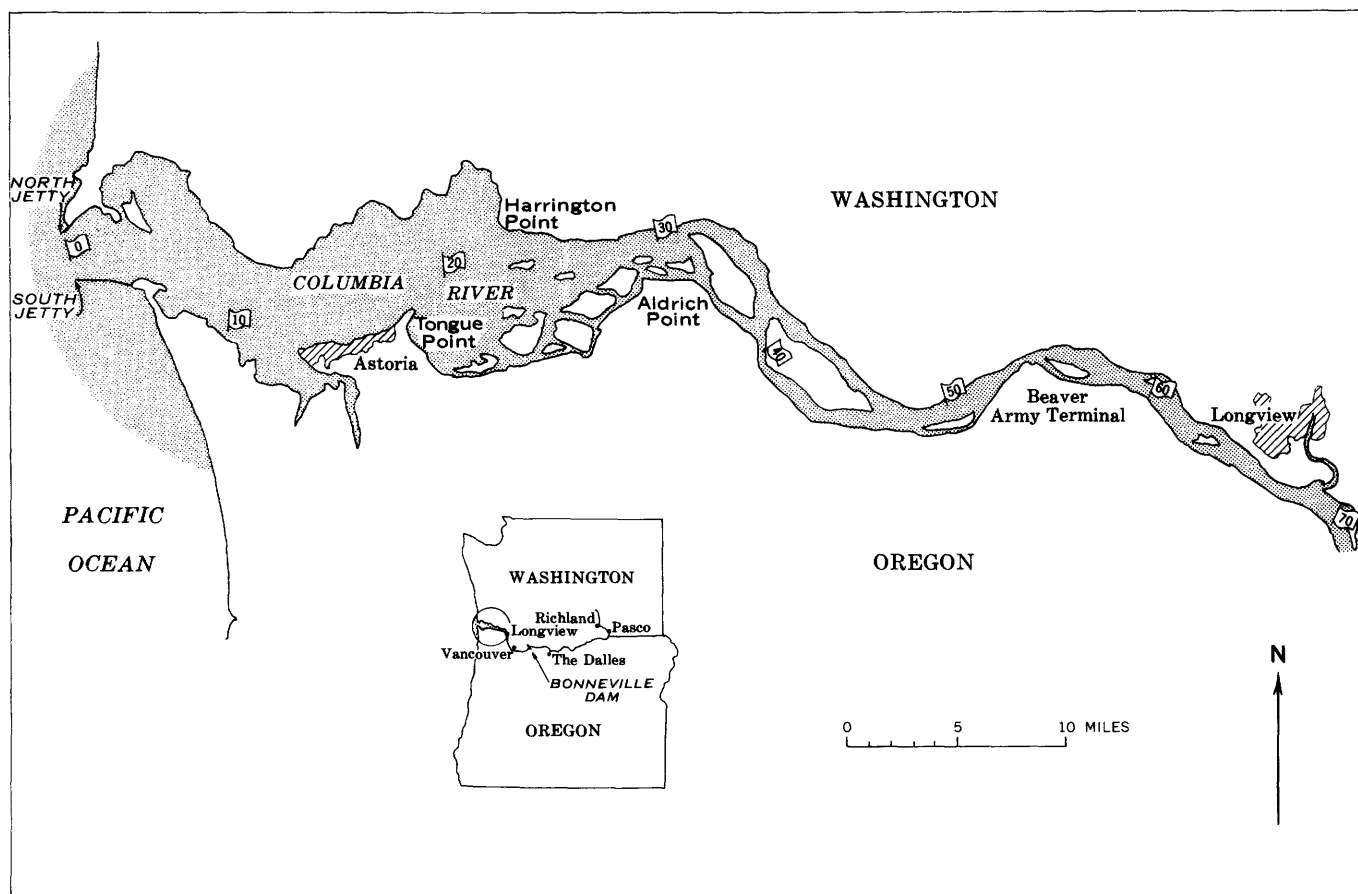
FIGURE 1. — Columbia River estuary. Flags show Columbia River mile. River mile 0 is on line with ends of north and south jetties.

All radiochemical analyses presented in this report were performed by the Battelle-Northwest Radiological Chemistry and Technical Analysis Sections under the direction of Dr. Julian M. Nielsen. Dr. Jack L. Nelson, as well as others at Battelle-Northwest, performed the difficult task of devising sample-handling and sample-analysis techniques for counting the extremely low level brackish-water samples. In addition, Drs. Nielsen and Nelson and Mr. R. W. Perkins contributed valuable advice concerning the design of an in situ counting system. The work was performed on behalf of the Division of Reactor Development and Technology, U.S. Atomic Energy Commission.

THE COLUMBIA RIVER ESTUARY

DESCRIPTION OF THE ESTUARY

The Columbia River estuary (fig. 1), for purposes of this investigation, is defined as beginning near Longview, Wash., which is about CRM (Columbia River mile) 65.8, and as extending to a line between the outer ends of the north and south jetties (CRM 0) at the mouth. The upper end of the estuary approximately coincides with the farthest upstream point of flow reversal during periods of low upland river flow.

Based on long-term records (1878–1967) for the Columbia River at The Dalles, Oreg. (fig. 1, CRM 189; U.S. Geol. Survey, 1968), the average discharge of the Columbia River at Vancouver, Wash. (CRM 107), is about 200,000 cfs (cubic feet per second). For the period 1963–67, the daily flow at Vancouver ranged from 78,900 to 675,000 cfs (U.S. Geol. Survey, 1968). Low flows occur from October through March, and high flows from April through July. During this survey (June 14–28, 1965), the discharge at Vancouver averaged about 500,000 cfs (U.S. Geol. Survey, no date).

Tides in the Columbia River are of the mixed type characteristic of the Pacific Coast (two high waters and two low waters, all of different heights, during each lunar day). At the mouth, the mean tidal range (U.S. Coast and Geodetic Survey, 1964, p. 172–173) is 5.6 feet, and the diurnal range is 7.5 feet. At Longview, the mean tidal range and the diurnal range are 3.3 and 4.0 feet, respectively. Tides affect

Columbia River stages as far upstream as Bonneville Dam (CRM 140) during periods of low upland river flow.

Cold saline water from the ocean intrudes the lower part of the estuary. The nature of the saline water–fresh water circulation in the estuary is such that Neal (1965, p. 25–26), using the system of Pritchard (1952), classified the estuary as a type B (partially mixed) estuary with a tendency to be well mixed during some flow and tidal conditions. A partially mixed estuary is one in which exchange between the relatively saline water near the bottom and the relatively fresh water near the top produces a vertical salinity gradient that varies more or less constantly with depth and a longitudinal salinity gradient that increases in the seaward direction. During low upland river flow the presence of saline water near the estuary bottom can be detected as far upstream as Harrington Point, Wash. (CRM 23); however, as the upland river flow increases, the length of the saline-water intrusion is proportionately reduced (Lockett, 1967). During the time of the survey reported herein, bottom water with significant salinity probably intruded no farther up the estuary than about Astoria, Oreg. (CRM 14).

The spatial and temporal distribution of saline water, the circulation and sedimentation patterns, and the influence of waves and tides tend to divide the estuary into areas where physical, chemical, and biological processes are significantly different. Seaward from about CRM 7–8 the environment is basically marine, and landward from about CRM 23 the environment is fluvial; the environment in the intervening area is transitional.

The Columbia River estuary may be divided into two geomorphically distinct parts. In the upper part (pl. 1), between Longview and Aldrich Point, Oreg. (CRM 31), the estuary lies between steep valley walls that are about 1.7 to 3.4 miles apart. The Columbia River occupies a main channel that ranges from about 0.4 to 1 mile in width at mean lower low water during low upland river flows. In addition, small channels, the largest of which are Cathlamet and Clifton Channels, and smaller sloughs, such as Wallace, Bradbury, and Fisher Island Sloughs, range from about 0.1 to 0.6 mile in width and carry river flow around six large permanent islands. Puget Island, the largest, is about 1.7 miles wide and 5.1 miles long and is used extensively for agricultural purposes. The remaining permanent islands are used chiefly for grazing during low-water periods, as are extensive flood plains adjacent to the river.

Below Aldrich Point (pl. 2), the estuary broadens to a maximum width of about 9.4 miles in the vicinity of Harrington Point. The minimum width in the lower part of the estuary is about 3.8 miles near Astoria. The valley walls are less steep than in the upper part, and four major embayments (pl. 2) — Youngs Bay, Baker Bay, Cathlamet Bay, and Grays Bay — extend from the estuary proper into stream valleys draining the adjacent highlands. Flow in the lower part spreads over the entire estuary at high tide but is mainly confined to a channel along the north side and to the south, or main navigation, channel (shown by dashed lines on pls. 1 and 2). Extensive areas of the estuary near the upper end of the lower part where the estuary is widest are occupied by semipermanent, diurnally inundated, vegetated islands. Equally large areas of nonvegetated islands appear throughout the lower part of the estuary during periods of low tides.

RADIONUCLIDES IN THE COLUMBIA RIVER

At Vancouver (CRM 107), approximately 96.5 percent of the total radionuclide discharge is Cr^{51} (chromium-51); 2.3 percent is Zn^{65} (zinc-65); and the remaining 1.2 percent includes a variety of other radionuclides (Foster, 1964, p. 13). Measurable amounts of P^{32} (phosphorus-32), Sc^{46} (scandium-46), Mn^{54} (manganese-54), Co^{58} (cobalt-58), Fe^{59} (iron-59), Co^{60} (cobalt-60), Sr^{90} (strontium-90), Zr^{95}-Nb^{95} (zirconium-95–niobium-95), Ru^{106} (ruthenium-106), Sb^{124} (antimony-124), I^{131} (iodine-131), Cs^{137} (sesium-137), Ba^{140} (barium-140), Ce^{141} (cerium-141), and Np^{239} (neptunium-239) have been reported at Vancouver (Foster, 1964; Haushild and others, 1966; W. L. Haushild, written commun., 1968). Radionuclide discharges depend on the operations at Hanford and on river flow. Foster (1964) reported that in calendar years 1961, 1962, and 1963, the annual mean daily discharges of Cr^{51} and Zn^{65} at Vancouver were 840, 44; 650, 29; and 860, 28 curies per day, respectively, and W. L. Haushild (written commun., 1968) computed comparable discharges for 1964 as 1,100 and 18 curies per day. Nelson, Perkins, Nielsen, and Haushild (1966) studied short-term variations and found that at Vancouver in 1964 daily discharges of Zn^{65} and of several other radionuclides were more than 10 times greater in June than they were in September. They attributed the high discharges in June to the resuspension and transport of sediment by the spring freshet. During June, the Zn^{65} transported by particulate matter (≥ 0.45 micron) was about 97 percent of the total Zn^{65} discharge; at other times of the year, the percentage was less and was as low as 48 percent in December. Other radionuclides that tend to associate with particulate matter (Sc^{46}, Mn^{54}, Fe^{59}, Co^{58}, and

Co^{60}) exhibited similar behavior, and at times the discharges of these nuclides were greater at Vancouver than they were at Pasco, which is about 223 miles upstream. In contrast, the daily discharge of Cr^{51}, which is transported mainly (92 percent) in solution, did not vary greatly during the year.

Other factors that affect the magnitude of daily radionuclide discharge include stable element concentrations and uptake and release reactions. Silker (1964) observed that the concentrations of Zn, Co, Mn, Fe, and Sc in solution in the Columbia River upstream from the reactors vary throughout the year and are higher in the spring than in the winter. It seems likely that as the concentrations of stable elements increase, the concentrations of activated radioisotopes of some of these elements also increase. The sorption and desorption of radionuclides by sediment and biota also influence radionuclide transport rates; however, the magnitude of such reactions is not well documented.

Seymour and Lewis (1964) estimated the amount of radionuclides from Hanford in the entire system below Vancouver (river, estuary, and ocean) during calendar years 1961, 1962, and 1963 from mean daily radionuclide discharges at Vancouver. For the estimates, they assumed that the system was essentially in equilibrium and computed the amount of radionuclides that would decay at a rate just sufficient to offset (equal) the continuous inflow of radionuclides. The average of the three yearly estimates was 40,000 curies, of which 29,000 curies was Cr^{51} and 11,000 curies was Zn^{65}.

Data on radionuclides in Columbia River bed sediments generally are more limited than data on radionuclides in water and suspended sediments. Nielsen (1963, p. 91–112) and Nelson (1965, p. 3.80–3.88; 1967, p. 88–93) reported on the concentration and distribution of radionuclides in Columbia River and reservoir sediments in the vicinity of Hanford. W. L. Haushild (written commun., 1968) surveyed radionuclides in Columbia River bed sediments between Pasco and the head of the estuary at Longview and computed an amount of about 38,000 curies in that reach.

Some data on the general radiation levels and kinds of radionuclides in Columbia River estuary bed sediments have been obtained in conjunction with studies on the distribution of the Columbia River plume in the Pacific Ocean (Barnes and Gross, 1966). Jennings (1966) used an immersible scintillation detector for in situ measurements of radioactivity at about 35 locations in the estuary and in Youngs River. He readily detected Cr^{51}, Zn^{65}, Mn^{54}, and naturally occurring K^{40} (potassium-40) at most measurement sites. Highest levels were observed along the eastern side of Tongue Point, Oreg. (CRM 18). His data also indicated that the ratio of Cr^{51} to Zn^{65} decreased substantially in December 1964 shortly after a Columbia River flood: the change was attributed to scour of the streambed.

Johnson, Cutshall, and Osterberg (1967) studied the retention of Zn^{65} by Columbia River estuary sediment. In laboratory experiments, they found that when sediment from the lower estuary was leached with sea water, only about 3 percent of the Zn^{65} was displaced. When the sediment was leached with dilute copper sulfate, however, approximately 40 percent of the Zn^{65} was displaced. They concluded that most of the Zn^{65} was held by a mechanism termed "specific sorption," whereby a sorbed metal cannot be displaced by alkali or alkaline earth ions but can be displaced by other transition metals.

EQUIPMENT, DATA COLLECTION, AND ANALYTICAL TECHNIQUES

During the early phase of this investigation, special equipment was developed to measure radioactivity and collect samples of the bed material. In order to monitor directly levels of radioactivity in the
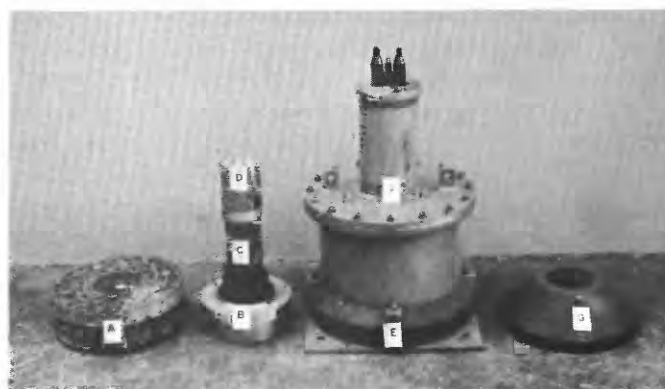
FIGURE 2. — Scintillation detector housing and components: (A) battery pack, (B) phosphor, (C) photomultiplier tube, (D) preamplifier, (E) annular shield, (F) housing and (G) conical shield. (From Prych and others, 1967.)

streambed, a single-channel radiation-detection system was adapted for in situ measurements (Prych and others, 1967). The scintillation detector (fig. 2), which consists of a 5- by 2-inch plastic phosphor coupled to a 3-inch-diameter photomultiplier tube, is encased in a waterproof aluminum housing having a $\frac{3}{8}$-inch-thick bottom. A plastic phosphor was selected because of its sensitivity and its resistance to damage from mechanical and thermal shocks, rather than its resolution, which is relatively low. Both a preamplifier and an annular-battery pack of forty-
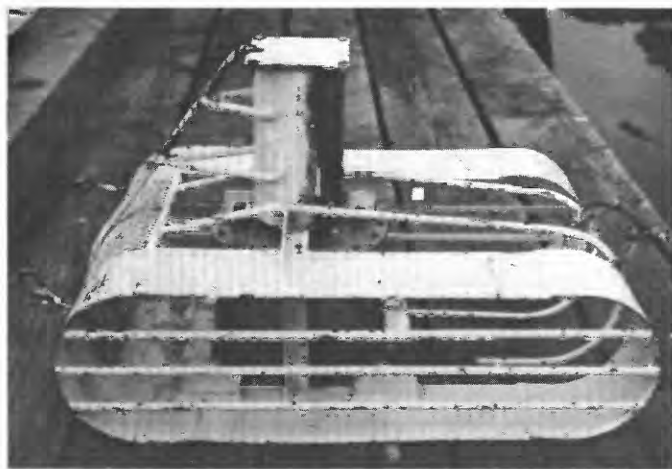
FIGURE 3. — Radiation detector and sled. (From Prych and others, 1967.)

two 30-volt batteries are housed with the detector. Radiation emanating from the sides and top of the detector is attenuated by a conical lead shield inside the housing and an annular lead ring at the base of the housing. The detector housing mounts into and forms part of the bottom of a towing sled (fig. 3). A ⁹⁄₁₆-inch-OD single-conductor armored cable serves as both the signal line and the tow line.

In early experimental work, several towing tracks were made with the sled detector unit. Although the equipment operated satisfactorily, the sled appeared to skip along the bed whenever the towing speed exceeded about 4 feet per second, with the result that the counting geometry varied sufficiently to affect the count rates. In addition, obstructions on the bottom snagged the sled on numerous occasions. Because of these difficulties, towing was discontinued, and in situ measurements were made by lowering the sled detector unit to the bed while the boat hovered or was anchored in essentially a fixed position.

The radiation-detection system was used to measure only gross gamma radiation, and no effort was made to identify, in situ, individual radionuclides in the bed. In order to maintain a standard reference energy level, the instrumentation was adjusted, on the basis of energy-voltage calibrations with a Cs^{137} source, to exclude all absorbed radiation having an energy less than 100,000 electron volts. During normal operation the battery-pack voltage decreased gradually, with the result that the reference energy level shifted between calibrations. Count rates were adjusted by applying a proportionality factor determined from the magnitude of the energy shift and the rate of change of count with energy as determined from integral spectrums of the activity in the bed at many locations throughout the estuary. On the
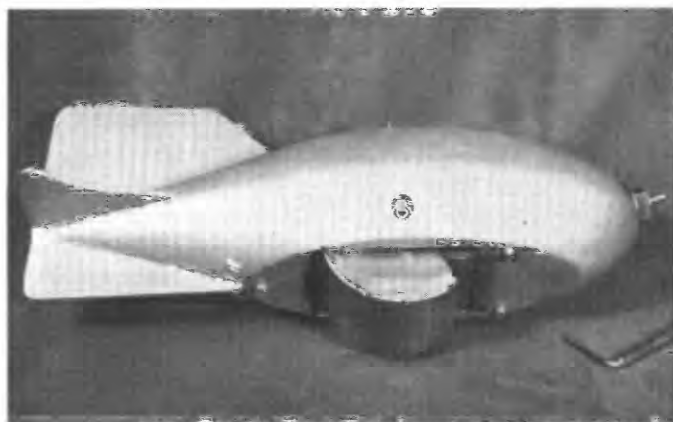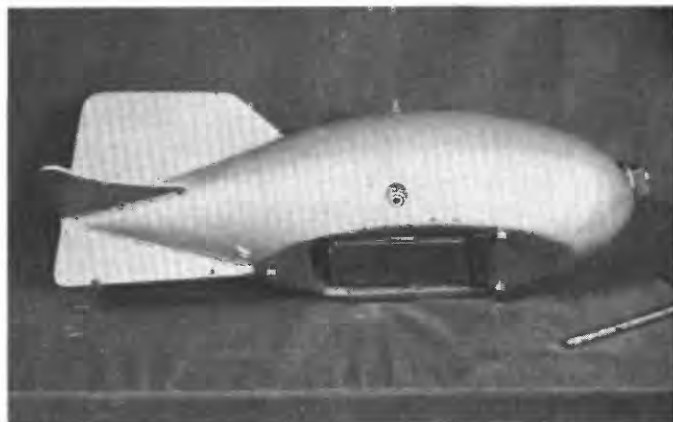
FIGURE 4. — Bed-material sampler, US BM–54. *Top*, bucket retracted; *bottom*, bucket exposed. (From U.S. Water Resources Council, 1966.)

average, adjustments increased count rates about 13 percent.

Samples of the sediment at the surface of the streambed were obtained with a standard US BM–54 bed-material sampler (U.S. Water Resources Council, 1966). This sampler (fig. 4) collects a 300- to 400-gram semicyclindrical slice from the bed and retains both fine sediment and interstitial water collected with the sample.

Cores were obtained throughout the estuary with a portable vibrocorer (Prych and Hubbell, 1966) that was designed specifically for use in the Columbia River and in the estuary, where the bed material is coarse grained and flow velocities may exceed 5 feet per second. The corer (fig. 5) penetrates about 6 feet into the bed as a result of the combined effects of an electromechanical vibrator mounted at the top of the core barrel, a piston that slides inside the core-barrel liner but remains stationary with respect to the bed, and a suspension system that converts an upward force on the main suspension cable to a downward axial force on the barrel. The cores, which

FIGURE 5. — Core sampler prepared for coring. (From Prych and Hubbell, 1966, pl. 1.)

were collected and retained in a plastic liner, were relatively undisturbed although some smearing occurred at the sediment-liner interface, some slight interior warping may have occurred, and small quantities of water may have percolated upward in cores of coarse sand.

Data for this survey were collected in 14 cross sections[1] (pls. 1 and 2) spaced approximately 5 miles apart, between Longview and the estuary mouth, and at other selected locations; data for ten surficial-sediment samples collected in the Astoria area in 1964 and for two cores (C3 and C6) collected in January 1965 also are included in this report for comparative purposes. At each cross section, in situ measurements were made of radioactivity in the streambed, and samples of the surficial bed sediment were collected. At most points, the in situ measurement and the surficial sample were collected simultaneously while the boat hovered in a nearly fixed

[1] In this report the term "cross section" designates a location where samples were collected along an irregular line that crosses the estuary approximately normal to the flow.

position. Because of the positioning of equipment on the boat and some boat movement, the in situ measurement and the sample were obtained at slightly different spots on the bed. In or near most cross sections one or more cores were obtained. The data-collection points were spaced in an attempt to define variations in levels of radioactivity and in textures of the bottom sediments. In all, 177 surficial sediment samples and 27 cores were collected, and 187 measurements of in situ radioactivity were made.

Portions of 71 surficial sediment samples and 287 selected 1- or 2-inch-thick segments from the cores were analyzed in the Battelle-Northwest Laboratory by multidimensional gamma-spectrometry counting techniques (Perkins, 1965) to provide information on the concentrations of specific radionuclides. In addition, particle-size distributions of 172 surficial sediment samples and 147 segments of cores were determined. Many, but not all, surficial samples and core segments were analyzed to determine both radionuclide content and size distribution.

In subsequent tables and graphs, individual surficial sediment samples are designated by a number preceded by a "G." The first three digits of the number indicate the sampling location (pls. 1 and 2), and the last two digits indicate the year in which the sample was collected (such as G344--65). Replicate samples or analyses are indicated by a number between the location number and the year number (G344–1–65). Special samples, which normally were a separate from the bulk sample, are designated with a letter between the location number and the year number (G254–A–65). Cores are designated by a location number (pls. 1 and 2) preceded by a "C"; replicate cores have a Roman numeral following the location number. Individual segments of each core are designated by the core location number followed by two or three additional digits; the last digit is the length of the segment, in inches, and the preceding digit(s) is the distance, in inches, from the bed surface to the top of the segment. For example, C367–23–2 represents a segment of the core collected at location 367; the segment extends from 23 to 25 inches below the bed surface.

Surficial sediment samples were split, and one part was retained in a wet condition for size analysis; the second part was sent to Battelle-Northwest for radionuclide analysis. Core samples, however, were so small that the same material had to be used for both radionuclide and size analyses. Because the sediment was dried for the radionuclide analyses, it was retained in that condition during preparation for size analyses. The distribution of particles coarser than 0.062 mm (millimeters) and finer than

2 mm was defined by the visual-accumulation-tube method (U.S. Inter-Agency Comm. on Water Resources, 1957), and the distribution of particles finer than 0.062 mm was determined by the pipette method (U.S. Inter-Agency Comm. on Water Resources, 1941). Standard sieving techniques were used to define the distribution of particles coarser than 2 mm. Samples collected in the part of the estuary that is continuously or periodically exposed to salt water were rinsed with distilled water prior to analysis to remove excess salt and reduce the possibility of flocculation. Rinsing was repeated as necessary until the supernatant liquid contained a chloride content of less than that of Columbia River water. Before pipette analysis, each sample was treated with a defloculating agent (sodium hexametaphosphate) and agitated in a laboratory mixer for 10 minutes.

Results of the size analyses are presented in appendixes 1 and 2 in terms of the size-distribution statistics of Inman (1952), which are based on the phi system[2], and in terms of the statistics of Trask (1932). The various statistics in the appendixes were determined by a computer program according to a technique that defines critical values (millimeter or phi values at 5, 10, 16, 25 percent finer, and so forth) from the size distribution in a manner exactly equivalent to linear interpolation between defined points on a graph of probability (percent-finer scale) versus logarithm of size (phi scale). In some analyses the distribution at one or both extremes was not defined adequately. For these distributions, critical values were obtained by linear extrapolation from the two closest defined points on the distribution. Whenever the extrapolations indicated that 5 percent or more of a sample was finer than 6.2×10^{-5} mm, the 5-percent-finer value was arbitrarily set at a phi value of 14.00. All analyses characterized by values determined by extrapolation may be somewhat in error; these analyses accordingly are footnoted in the appendixes.

The statistics computed with the formulas of Inman (1952) are derived from analogies to central-moment measures. In accordance with Inman (1952) and McManus (1963), the following nomenclature is used in appendixes 1 and 2 and throughout the text: "Mean," mean size, mean grain size, or mean grain diameter characterizes central tendency; "sort," or deviation measure, characterizes dispersion; "alph 1," or skewness measure, characterizes skewness based on the central 68 percent of the distribution; "alph 2" characterizes skewness based

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[2] $\phi = -\log_2 D$ (Krumbein, 1934) or $\phi = -\log_2 \frac{D}{1.0\,\text{mm}}$ (McManus, 1963), where D is the particle diameter, in millimeters.

on the central 90 percent of the distribution; and "beta" characterizes kurtosis. Values of "sort" (or deviation measure) represent the number of size classes on the Wentworth (1922) scale spanned by the central 68 percent of the distribution, and "alph 1" (or skewness measure) represents the relative number of size classes on the Wentworth scale between the median and a mean computed for the central 68 percent of the distribution. A positive value of "alph 1" indicates the distribution is skewed toward the fine sizes (the "tail" of the distribution extends toward the fine sizes), and a negative value indicates the distribution is skewed toward the coarse sizes.

The statistics of Trask (1932) are computed from actual size values expressed in millimeters rather than from millimeter values converted to phi values. Trask's "sort" and "skew" (app. 1 and 2) represent measures of dispersion and skewness, respectively, determined from the ratios of sizes at quartiles on the distribution curve.

TEXTURAL CHARACTERISTICS OF BOTTOM SEDIMENTS
SURFICIAL SEDIMENT

Textural data for 172 surficial sediment samples from the estuary are shown in appendix 1 and are summarized in figure 6. These data indicate that sand ($-1.0 < \text{phi} \geqslant 4.0$) is the dominant sediment size in the estuary. Many samples contain small but significant quantities of silt ($4.0 < \text{phi} < 8.0$), and clay-size material ($\text{phi} \geqslant 8.0$) generally is represented only sparsely. Although not shown in the triangle diagram of figure 6, about 24 percent of all samples from the estuary contained some gravel-size material ($\text{phi} \; -1.0$); the proportion of gravel in these samples ranged from 1 to 51 percent and averaged about 6 percent. The available data indicate that an "average" sediment sample from the estuary would consist of about 1 percent gravel, 84 percent sand, 13 percent silt, and 2 percent clay.

The textural characteristics of the samples vary widely both within any given cross section and among cross sections. As a result, individual samples cannot be compared directly to discern spatial trends in texture. These trends can be identified only by grouping the samples into various classes that can be treated statistically. The number of meaningful classes and the criteria for assigning samples to a class, of course, depend on the objectives of the comparison, on a rational basis for recognizing and delineating the classes, and on the number of samples and the amount of classification data that are available. As an example, it is of interest to determine

Texture class	Percentage of samples in class
Gravel	23.8
Sand	57.6
Silty sand	8.7
Sandy silt	8.7
Silt	0.6
Clayey silt	0.6

● 1 sample
○ 49 samples, 100 percent sand
△ 21 samples, 99 percent sand
▲ 5 samples, 98 percent sand
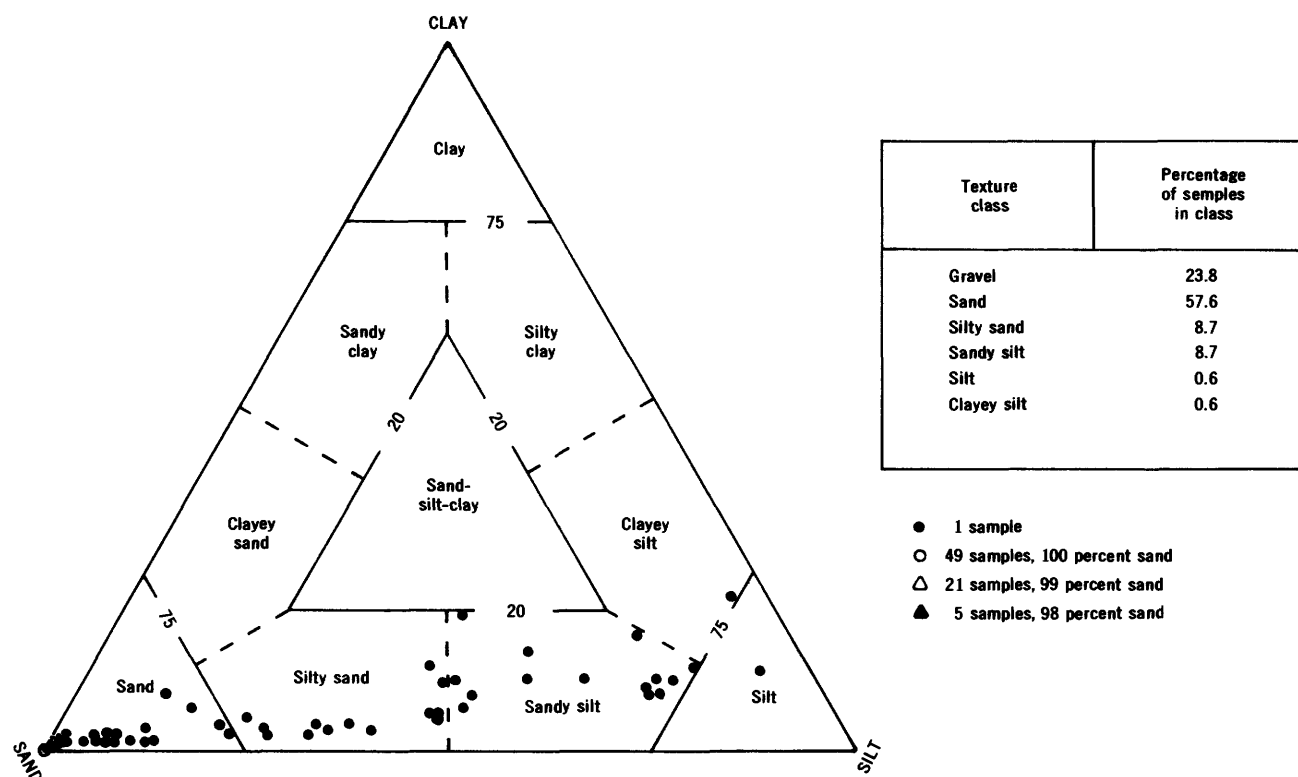
FIGURE 6. — Sand-silt-clay relations for surficial sediment samples from the estuary. Texture classes are those of Shepard (1954). All samples with any gravel-size material are excluded from the triangle diagram and are considered to be in the gravel-texture class.

whether sediment texture changes along the estuary in response to the changing hydrologic regime. This might be done by comparing among cross sections averages of selected textural statistics of all samples from a cross section. However, because the texture is variable and the sampling density is low, cross-section averages are not highly meaningful in terms of the stated objective. The assignment of samples into classes within each cross section and the grouping of cross sections seem to be a reasonable alternative.

Selected particle-size-distribution statistics for each sample are plotted in figures 7 to 13, and each sample is shown in its correct position relative to adjacent samples in the cross section. Inspection of these data indicates that part of the within-cross-section textural variance can be eliminated if cross-section samples are divided into three classes. These classes are called "channels," "slopes," and "flats." With data from subsequent studies, it is anticipated that additional classes (or divisions of the above classes) will be recognized.

As indicated by class names, geomorphic criteria are used to identify and delineate classes. Channels are areas where flow usually is conveyed continually, alternately upstream and downstream. They form a continuous interwoven network throughout the estuary and are bound laterally by slope areas. Usually channels are the deepest parts of a cross section and have flat or gently sloping transverse bed profiles. Slopes are areas that are adjacent to the channels on one side and are usually bound by either the shore or a flat on the other side. They are characterized by a relatively steep transverse bed slope. Flats are areas that are perpetually shallow or periodically inundated and are areas where flow velocities and bed slopes usually are low. Many flats are bound completely by slope areas; however, others lie between slope areas and the shore.

Average values of M_ϕ (mean grain diameter, in phi notation), σ_ϕ (deviation measure, in phi units), and $\alpha_{1\phi}$ (skewness measure, in phi notation) for samples from the classes (channels, slopes, and flats) in each cross section and throughout the estuary are shown in table 1 and plotted in figure 14. These data serve not only to indicate the textural characteristics of the geomorphic classes but also to suggest changes that occur longitudinally in the estuary. The data show that channel samples, as a group, are coarse, are moderately well sorted (relatively low values of σ_ϕ), and tend to have negatively skewed distributions (skewed
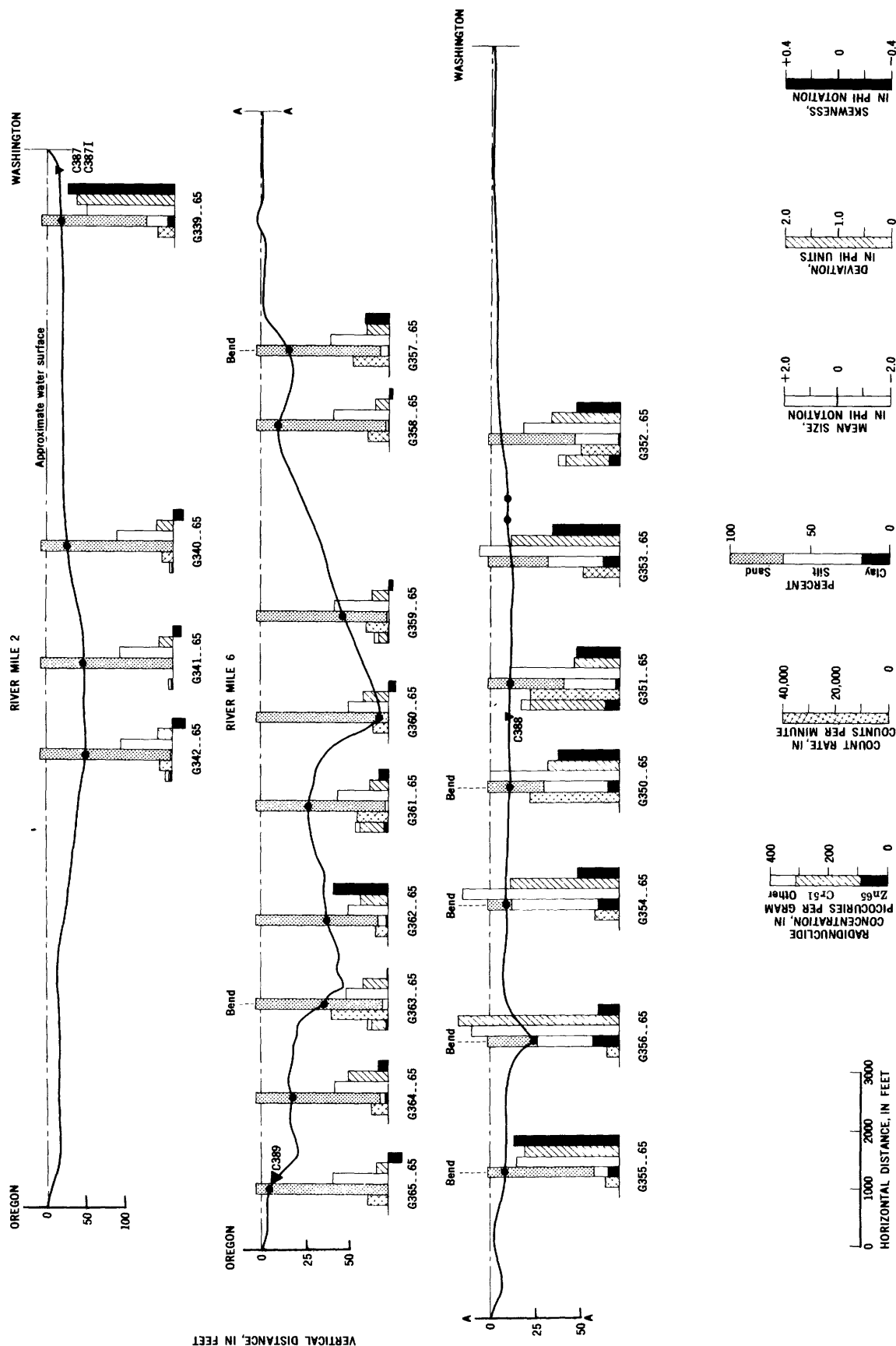
FIGURE 7.— Radioactivity and texture at surficial sediment sample locations in cross sections at river miles 2 and 6. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross sections corresponds with that shown on plate 2, and significant bends are indicated accordingly.
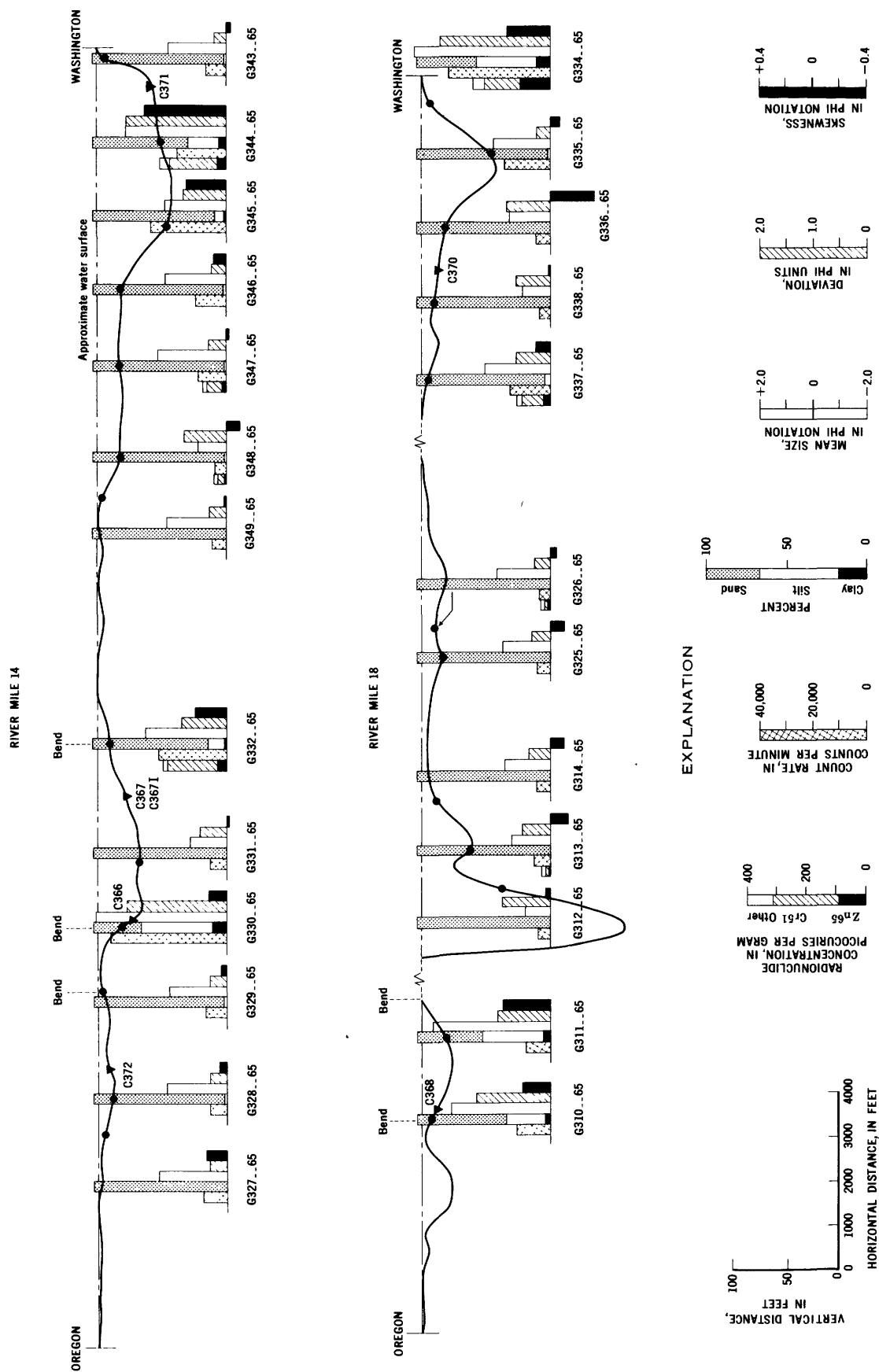
FIGURE 8. — Radioactivity and texture at surficial sediment sample locations in cross sections at river miles 14 and 18. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross sections corresponds with that shown on plate 2, and significant bends are indicated accordingly.
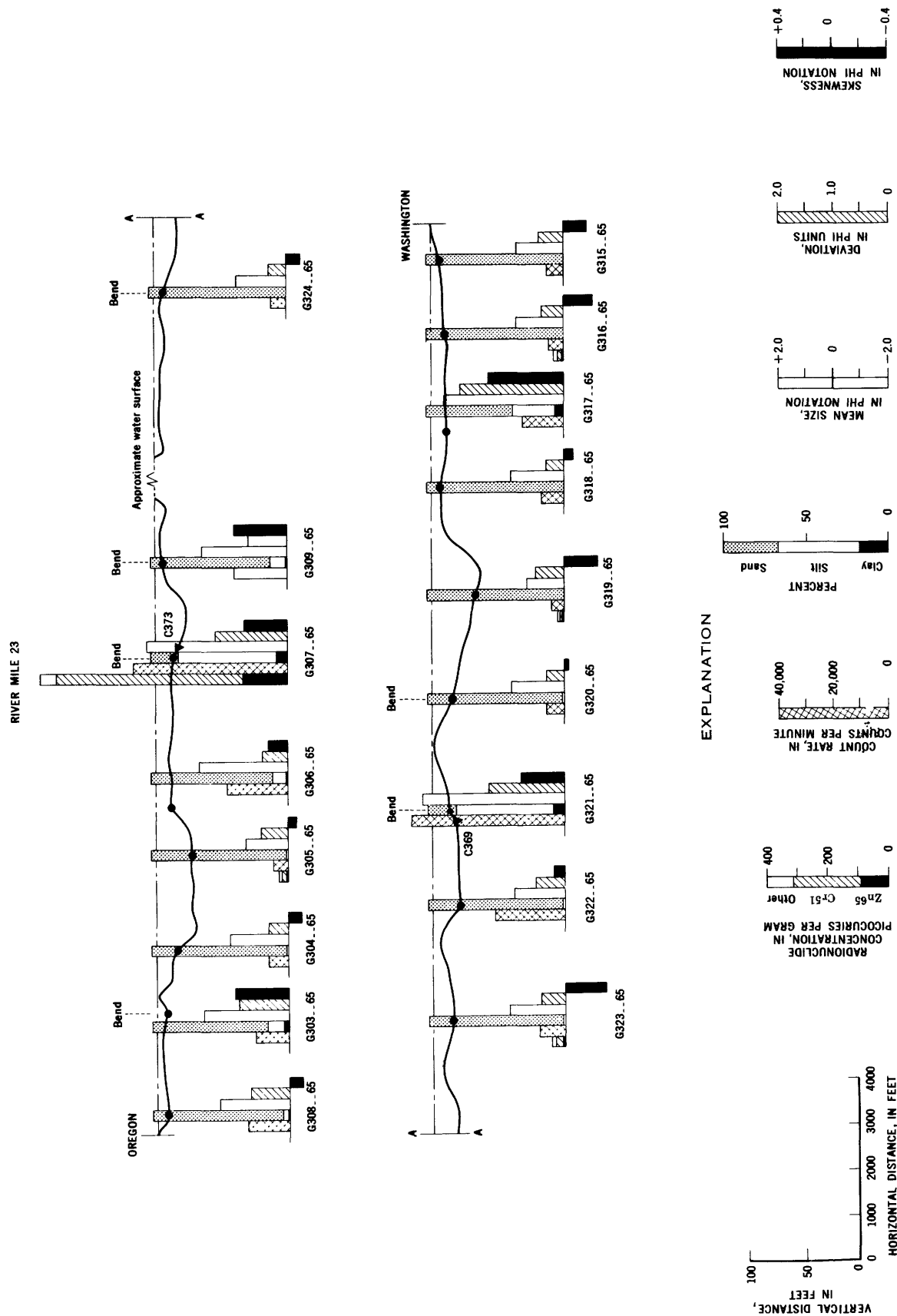
FIGURE 9. — Radioactivity and texture at surficial sediment sample locations in cross section at river mile 23. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross section corresponds with that shown on plate 2, and significant bends are indicated accordingly.
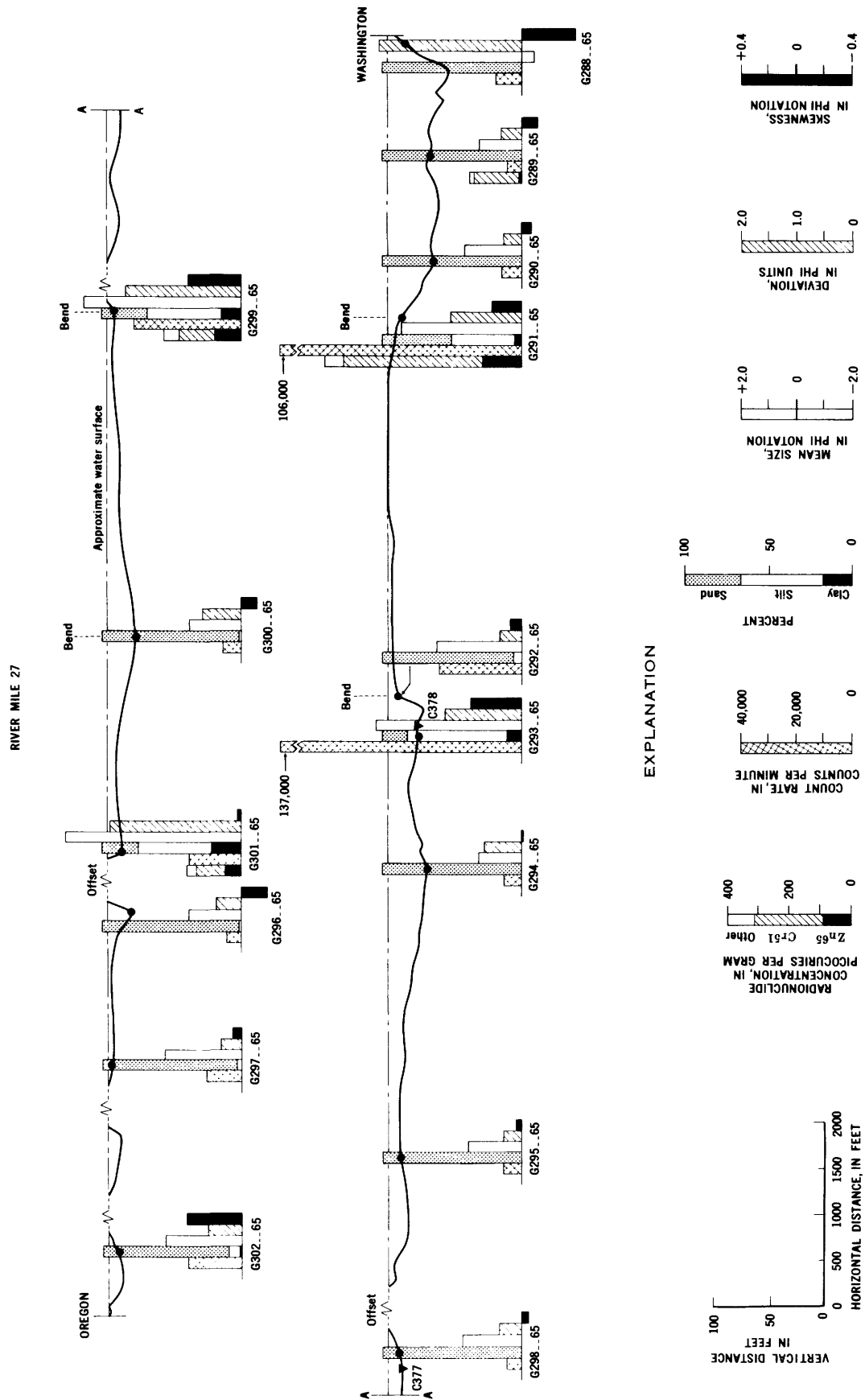
FIGURE 10. — Radioactivity and texture at surficial sediment sample locations in cross section at river mile 27. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross section corresponds with that shown on plate 2, and significant bends and offsets are indicated accordingly.
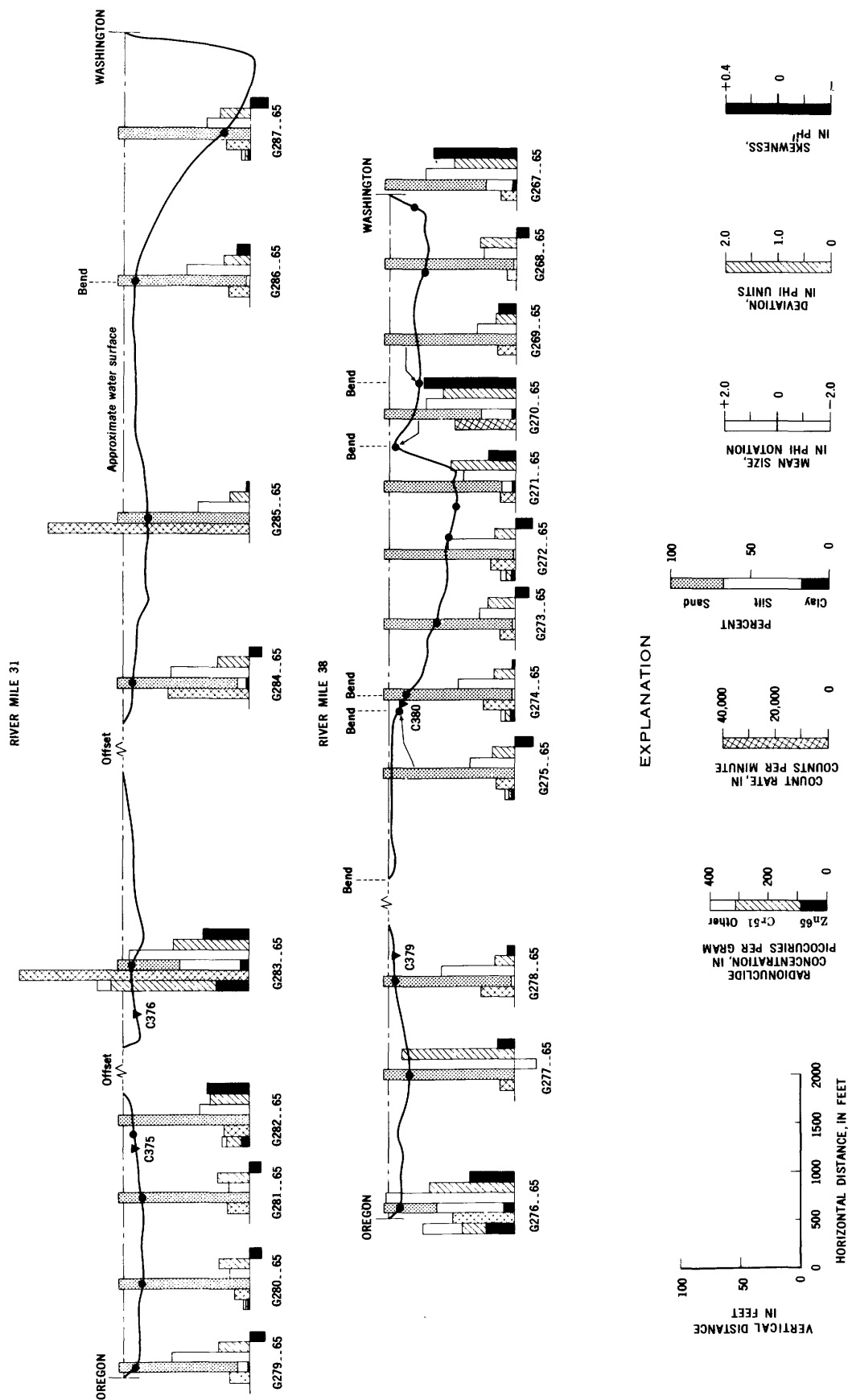
FIGURE 11. — Radioactivity and texture at surficial sediment sample locations in cross sections at river miles 31 and 38. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross sections corresponds with that shown an plates 1 and 2, and significant bends and offsets are indicated accordingly.
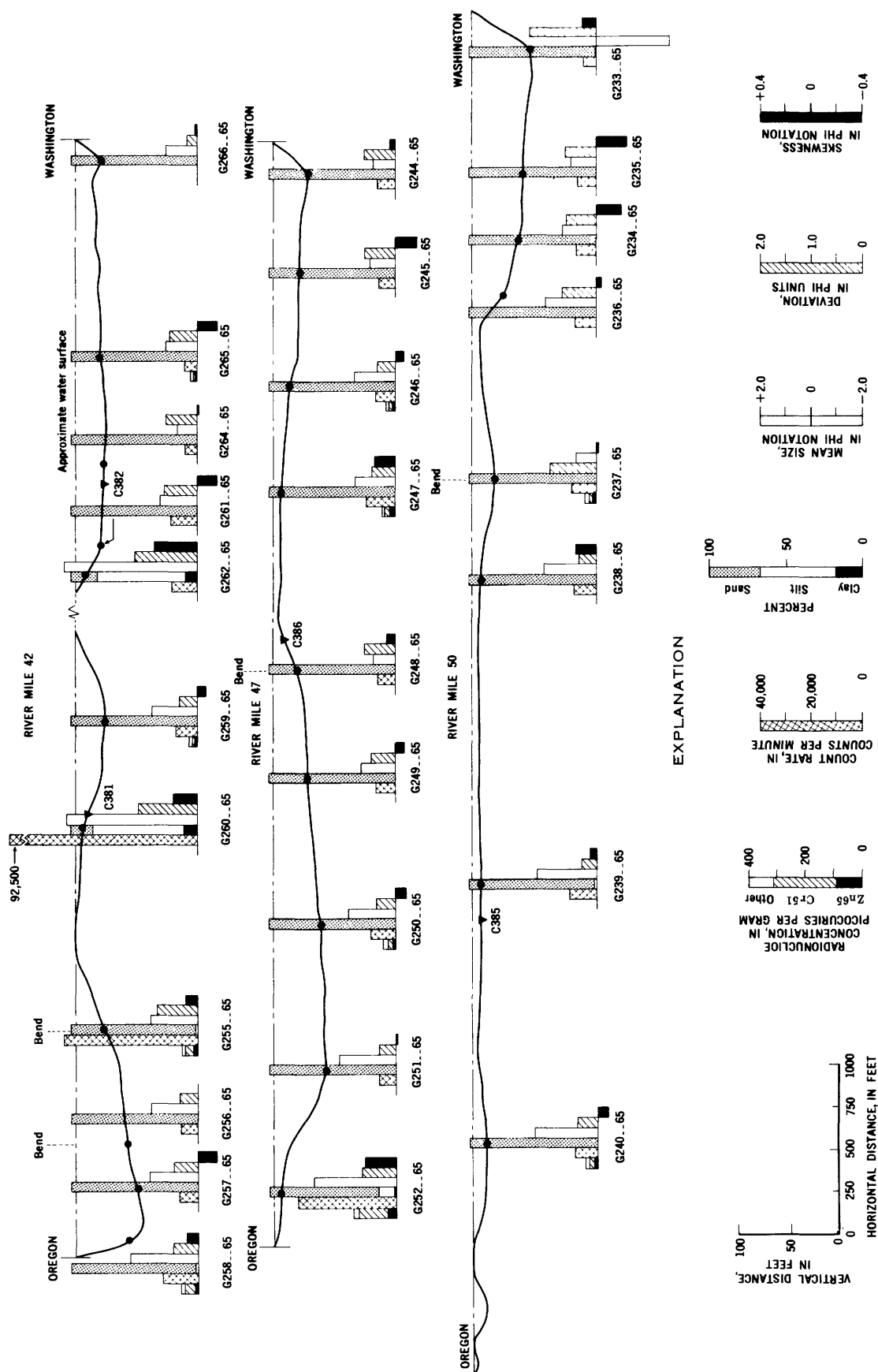
FIGURE 12. — Radioactivity and texture at surficial sediment sample locations in cross sections at river miles 42, 47, and 50. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross sections corresponds with that shown on plate 1, and significant bends are indicated accordingly.
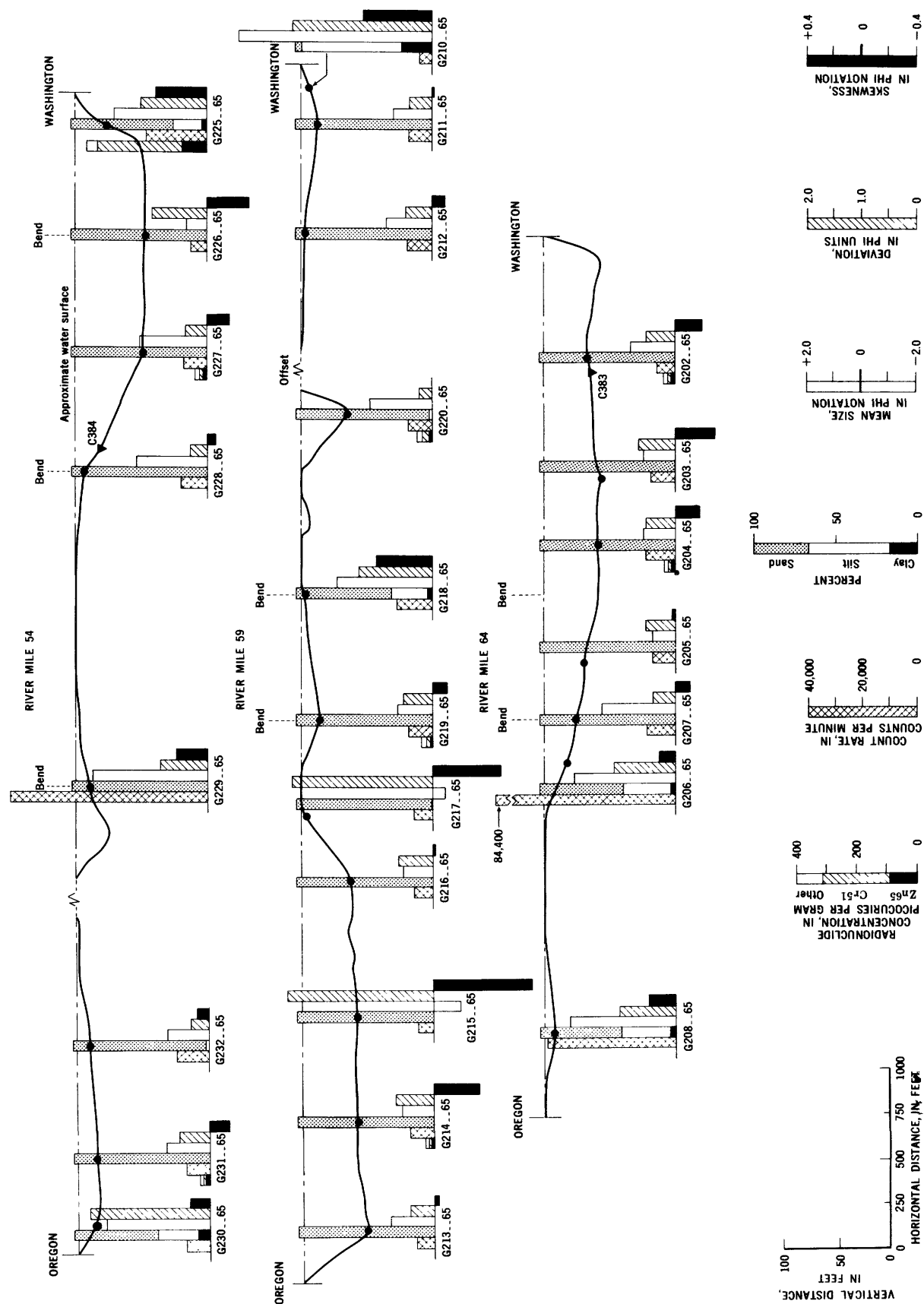
FIGURE 13. — Radioactivity and texture at surficial sediment sample locations in cross sections at river miles 54, 59, and 64. Dots and triangles on the bed profile locate positions of surficial sediment and core samples, respectively. Baseline for bar graphs is zero. Alinement of cross sections corresponds with that shown on plate 1, and significant bends and offset are indicated accordingly.
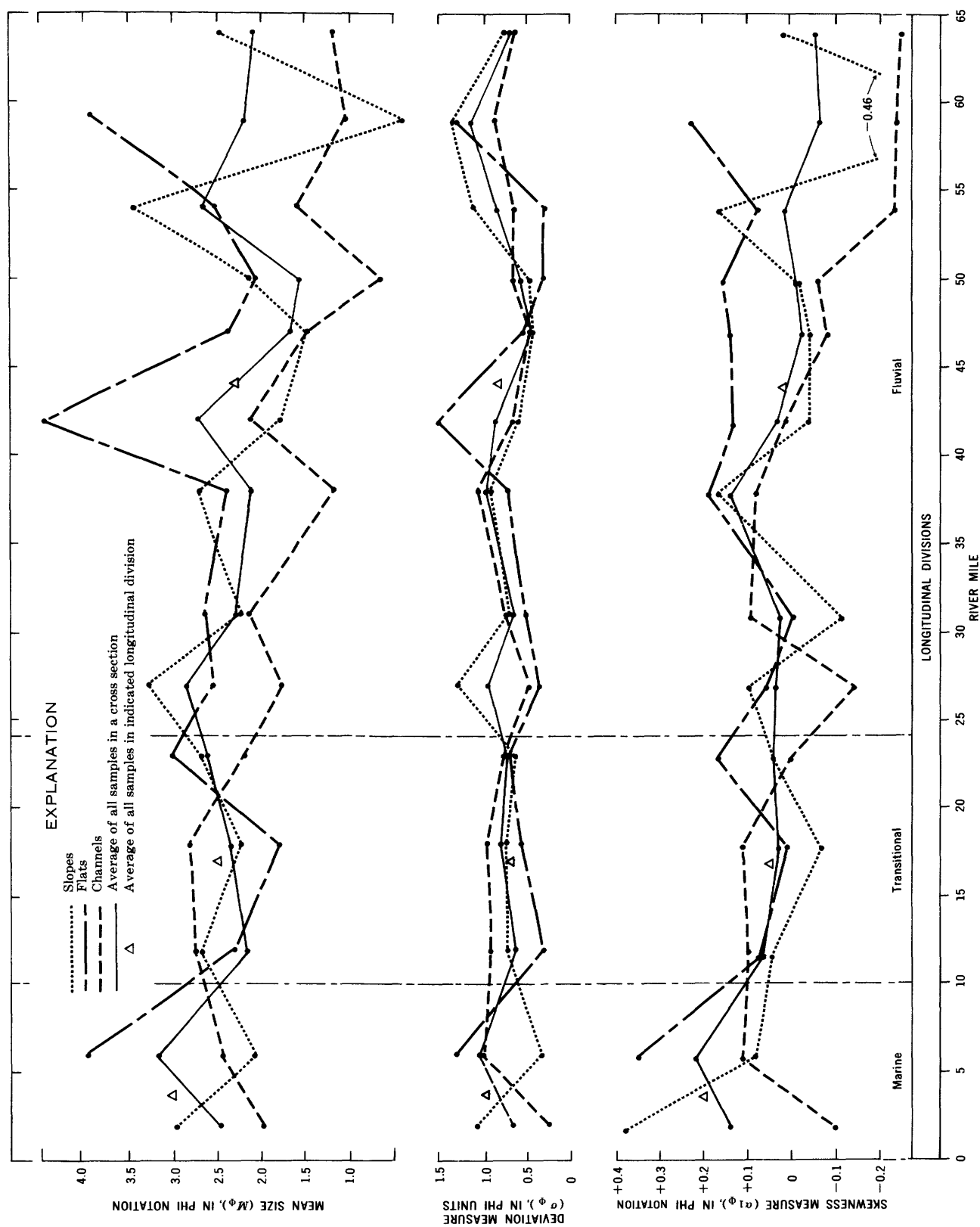
FIGURE 14.—Variation in average textural characteristics of surficial samples in geomorphic classes at cross sections along the estuary.

TABLE 1. — *Average values of M_ϕ, σ_ϕ, and $\alpha_{1\phi}$ (in phi notation) for various geomorphic classes at cross sections in the estuary*

Cross section river mile	Channels				Slopes				Flats				All			
	Number of samples	M_ϕ	σ_ϕ	$\alpha_{1\phi}$	Number of samples	M_ϕ	σ_ϕ	$\alpha_{1\phi}$	Number of samples	M_ϕ	σ_ϕ	$\alpha_{1\phi}$	Number of samples	M_ϕ	σ_ϕ	$\alpha_{1\phi}$
2	2	2.00	0.26	−0.10	2	2.99	1.08	0.37	0	....	....	....	4	2.46	0.67	0.14
6	5	2.47	.98	.12	3	2.09	.34	.08	8	3.99	1.31	0.34	16	3.16	1.03	.22
14	4	2.76	.94	.10	6	2.68	.72	.05	3	2.31	.32	.06	13	2.62	.70	.07
18	5	2.81	.96	.11	4	2.25	.74	−.06	3	1.78	.56	.01	12	2.36	.79	.03
23	5	2.23	.77	.00	8	2.70	.62	.04	4	3.03	.68	.17	17	2.64	.68	.06
27	3	1.77	.49	−.14	9	3.29	1.29	.10	3	2.55	.37	.06	15	2.84	.95	.04
31	5	2.16	.74	.10	2	2.24	.68	−.11	2	2.66	.52	−.01	9	2.29	.68	.03
38	4	1.18	1.04	.08	5	2.72	.91	.17	3	2.41	.73	.19	12	2.13	.91	.14
42	6	2.14	.61	.02	4	1.79	.62	−.03	4	4.47	1.52	.14	14	2.71	.87	.04
47	4	1.48	.45	−.08	4	1.48	.43	−.04	2	2.38	.56	.14	10	1.66	.46	−.02
50	4	.68	.62	−.06	5	2.14	.50	−.01	1	2.07	.33	.16	10	1.55	.53	−.01
54	3	1.59	.65	−.22	4	3.47	1.14	.17	1	2.50	.31	.08	8	2.64	.85	.02
59	6	1.05	.87	−.22	2	.36	1.38	−.46	6	3.92	1.34	.23	14	2.18	1.15	−.06
64	2	1.20	.62	−.25	5	2.45	.74	.02	0	....	....	....	7	2.09	.70	−.05
Average	[1]58	1.87	.75	−.02	[1]63	2.49	.81	.04	[1]40	3.18	.90	.17	....	....	....	....

[1]Total.

toward coarse particles). Samples from the flats represent the other extreme; that is, they are fine, are more poorly sorted (higher values of σ_ϕ), and have positively skewed distributions (skewed toward fine particles). Samples from the slopes are intermediate in all respects.

The plot of the variation of particle-size statistics with sample location (fig. 14) suggests several trends, some of which may be more apparent than real. For samples from the channels, M_ϕ increases (samples become finer), σ_ϕ remains relatively unchanged, and $\alpha_{1\phi}$ becomes positive or less negative (distributions become less skewed toward coarse particles) from the head to the mouth of the estuary. The textural characteristics of samples from the slopes and flats show no readily apparent significant trends along the estuary.

Some rather large among-cross-section variations in textural statistics of samples from the same geomorphic class are evident from the plots in figure 14. Because of the limited number of samples available from each cross section, it was not possible to develop a more elaborate and meaningful environmental classification. As a result, at one cross section, using data from the channels class as an example, most samples may have been obtained in a large, main channel; whereas, at another cross section, most samples may have come from one of the smaller channels. With more data, it seems likely that additional significant and mappable geomorphic classes can be delineated.

Because it was evident that too few samples (table 1) from some cross sections were analyzed, data from adjacent cross sections were combined to obtain

TABLE 2. — *Summary of textural statistics of surficial sediment samples grouped according to geomorphic class and longitudinal division*

Longitudinal division	Geomorphic class	Number of samples	Mean grain diameter (M_ϕ)			Deviation measure (σ_ϕ)			Skewness measure ($\alpha_{1\phi}$)		
			Range	Average	Standard deviation	Range	Average	Standard deviation	Range	Average	Standard deviation
All samples											
Fluvial	Channels	37	−2.97 to 5.30	1.51	1.34	0.22 to 2.72	0.69	0.53	−0.77 to 0.35	−0.07	0.21
	Slopes	40	−.47 to 6.35	2.46	1.52	.30 to 2.56	.88	.62	−.52 to .63	.03	.23
	Flats	22	1.36 to 7.08	3.22	1.56	.31 to 2.67	.92	.74	−.14 to .70	.14	.21
	All	99	−2.97 to 7.08	2.27	1.59	.22 to 2.72	.82	.62	−.77 to .70	.02	.23
Transitional	Channels	14	.97 to 5.03	2.58	1.45	.25 to 2.13	.89	.66	−.30 to .55	.07	.24
	Slopes	18	1.04 to 5.17	2.59	1.12	.22 to 1.87	.68	.46	−.33 to .40	.02	.19
	Flats	10	1.07 to 5.23	2.44	1.11	.30 to 1.41	.54	.34	−.10 to .39	.09	.16
	All	42	.97 to 5.23	2.55	1.31	.22 to 2.13	.72	.52	−.33 to .55	.05	.20
Marine	Channels	7	1.55 to 5.60	2.33	1.46	.26 to 3.06	.77	1.02	−.13 to .42	.06	.18
	Slopes	5	1.90 to 3.81	2.42	.78	.26 to 1.85	.64	.68	−.07 to .81	.19	.36
	Flats	8	2.03 to 5.95	3.99	1.41	.21 to 2.10	1.31	.68	−.10 to .80	.34	.27
	All	20	1.55 to 5.95	3.02	1.48	.21 to 3.06	.96	.83	−.13 to .81	.20	.28
Samples with no extreme values[1]											
Fluvial	Channels	33	−0.83 to 2.49	1.51	0.66	0.32 to 1.48	0.62	0.32	−0.32 to 0.32	−0.06	0.14
	Slopes	36	.84 to 5.27	2.42	1.18	.33 to 2.36	.88	.58	−.40 to .38	.03	.18
	Flats	20	....	......	......	.31 to 1.67	.75	.52	....	......	......
Transitional	Channels	11	....	......	......	.25 to 2.11	.70	.50	....	......	......
	Slopes	16	1.04 to 3.74	2.29	.72	.22 to 1.31	.57	.30	....	......	......
	Flats	8	1.07 to 2.54	2.01	.46	.30 to .65	.41	.15	....	......	......
Marine	Channels	5	1.55 to 2.02	1.74	.24	.26 to .49	.36	.11	....	......	......
	Slopes	4	1.90 to 2.23	2.08	.14	.26 to .43	.34	.07	−.07 to .18	.04	.11
	Flats	....	....	......	......	....	......	......	....	......	......

[1]Dash leaders in columns indicate that no samples with outlying values were detected.

more statistically significant results. The results from one type of combination are shown in table 2. For this combination, the three cross-section classes previously discussed (channels, slopes, flats) were retained, and three longitudinal divisions were established. The longitudinal divisions are termed "marine," "transitional," and "fluvial" after the presumed dominant processes in each division. Although the locations of the boundaries between the divisions are somewhat subjective and vary during the year as upland flow and tides vary, for purposes of this report samples from cross sections near CRM 2 and 6 are considered as coming from the marine division; samples from cross sections near CRM 14, 18, and 23 are from the transitional division; and samples from the remaining cross sections are from the fluvial division. Whereas the actual boundaries between longitudinal divisions during the time of the survey may have been located differently, the boundaries selected above are probably more realistic in terms of the processes dominating through the year.

Several observations about textural characteristics of channels, slopes, and flats in marine, transitional, and fluvial divisions can be made from the data in table 2. Within each division: (1) Channels generally contain the coarsest sediment (lowest M_ϕ); (2) flats have sediment that generally is the finest (highest M_ϕ) and has the most positively skewed (highest $\alpha_{1\phi}$) size distribution; (3) slopes generally have sediments with particle sizes that are intermediate with respect to M_ϕ and have the least skewed ($\alpha_{1\phi}$ nearest 0) size distribution; and (4) sediments in all three classes are moderately well sorted. Among divisions: (1) Channel sediments in the marine division are finer and have size distributions that are more positively skewed than channel sediments in the fluvial division; (2) channel sediments in the transitional division tend to be finer than channel sediments in either the marine or the fluvial divisions; (3) slope sediments tend to have the same textural characteristics throughout the estuary, but they may become slightly better sorted (more uniform) toward the estuary mouth; and (4) on flats, sediments are finer in the fluvial and marine divisions than in the transitional division, where extensive sand flats occur. When data for all samples in each of the three major divisions are averaged (table 2), it appears that in going from the fluvial into the marine division, estuary sediments become finer and probably more poorly sorted, and their size distributions become more positively skewed.

Inspection of the ranges and standard deviations for the textural statistics given in table 2 shows that textures are quite variable within each geomorphic class and indicates the need for additional environmental classes.

The effect on averages and standard deviations of eliminating extreme values is shown in the lower part of table 2. For the channels and slopes classes in the fluvial division, the two highest and the two lowest values of each size statistic were arbitrarily eliminated, and new averages and standard deviations were computed. For the flats class in the fluvial division and for all geomorphic classes in the other divisions, a statistical test (Li, 1964, p. 548–552) was employed to detect outlying values. If outliers were present, they were eliminated, and the averages and standard deviations were recomputed from data for the remaining samples.

The statistical test, although applied to both high and low extreme values (inapplicable to both simultaneously), usually indicated that low values of each size statistic were not outliers; thus, the overall effect of eliminating outlying values was to decrease, although generally only slightly, average values (table 2). However, the effect on standard deviations of eliminating extreme values was quite pronounced, and in some instances, standard deviations were reduced more than 50 percent (table 2). Although fairly large ranges and deviations still remain and suggest that additional environmental classes could be delineated, the above data would seem to indicate that geomorphic expression can be useful in mapping environments which have sediments that differ in texture.

The removal of outlying values generally had little effect on relative textural trends previously described among classes and among divisions. In some instances, the trends of the sediments on the flats and slopes were interchanged as a result of removing extreme values; in no case, however, were complete reversals of trends noted.

CORES

Textural characterization of sediments in cores is both qualitative and quantitative. Immediately after the cores were collected, qualitative appraisals of gross physical characteristics were made. After the field appraisals, the cores (still in plastic liners) were frozen in a styrofoam-lined box that contained dry ice. The cores were then transported to the laboratory, where they were kept frozen until they could be processed. As soon after collection as possible, each core was removed from cold storage, and the core and liner were cut into 1- or 2-inch segments. After thawing, each segment was extruded from the liner, trimmed around the margins to remove sediment that possibly was stratigraphically

TABLE 3. — *Qualitative aspects of estuary cores*

Core number	Approximate water depth (feet)	Total core length (inches)	Geomorphic position	Sediments	Remarks
C3	....	65	On slope near entrance of Youngs River into Columbia River. Possibly in area of active deposition of Youngs River sediment.	Well-stratified fine sand that becomes finer with depth. Lower one-third of core consists of layers of gray-black, often carbonaceous silt with fine-sand interbeds.	Organic material is abundant in well-defined layers.
C6	....	62	Exact position unknown. Possibly on slope or flat in embayment below Grays Point.	Well-stratified brown to gray-black fine sands and sandy silts that grade downward to sandy and clayey silts.	Abundant brown and black fibrous organic material in distinct layers as well as isolated fragments.
C366	35	11	On gentle slope or flat marginal to main Columbia River channel. In general slack-water area near confluence of Columbia and Youngs Rivers.	Well-stratified blue-black silts and sandy silts.	Abundant thin layers of brown to black organic material scattered throughout the core. Sediments are very moist and are "soupy" in behavior.
C367 and C367I	15	41 41	On irregular slope marginal to main Columbia River channel. Possibly in area of dredge-spoil accumulation.	Irregularly stratified brown to gray sands and silts. Strata not evident in upper part, with the exception of a fine-grained top layer.	Layers of brown organic matter, often associated with gravel-size pumice, occur in lower part of core. Some evidence of burrowing-organism activity in lower part.
C368	18	59	On or near boundary between small channel and steep slope. In general slack-water area near confluence of South Channel with Prairie and North Channels in Cathlamet Bay.	Well-stratified green to gray sands and silts. Fine-grained gray-green top layer.	Layers of organic matter are common.
C369	17	47	On steep slope leading from small channel to adjacent flat near Harrington Point.	Well-stratified gray to gray-black sandy silts and silty sands near the surface and at depth, separated by middle zone of sand with small amounts of silt.	Organic matter common in bedding planes. Broken and whole clam shell fragments scattered throughout the core. Sandy part of core shows evidence of activity of burrowing organisms.
C370	17	40	On irregular gentle slope leading from a flat to a deep channel near Grays Point. Possibly in small channel running parallel to the slope.	Thin brown fine-grained top layer over stratified brown sands.	Organic fragments are scattered throughout core. Layers of pumice fragments are found.
C371	40	50	On slope leading from shallow to deep portion of the North Channel just above Astoria Bridge.	Fine-grained gray-black top layer overlies 2-foot-thick zone of gray-green sands that overlie well-stratified silts and sands.	Organic-matter layers and scattered flakes are abundant.
C372	7	54	On flat in Youngs Bay adjacent to Youngs River channel.	Fine-grained brown top layer over reddish-brown stratified sands that become mottled and gray below about the 12-inch depth.	Black and brown layers and particles of organic matter are common. Evidence of burrowing organisms and reworked sediments in basal part of core. One clam shell observed near top of core.
C373	14	47	In small channel with sandbar across the head end and with essentially impounded flow.	Well-stratified gray-green sands and silty sands.	Most strata related to layered accumulation of organic matter.
C375	[1]7	52	On margin of Clifton Channel. Possibly in area of small dunes near Aldrich Point.	Brown medium sand with silty top layer.	Strata in sand are not distinct except where caused by rare organic layers.
C376	8	55	In small slough along north side of Tenasillahe Island. Possibly in small dune area.	Gray-green fine sand with silty sand top layer. Strata are present but not sharply defined.	Organic matter occurs as scattered fragments.
C377	[1]10	63	On gentle point-bar slope. Possibly in an area of small dunes.	Gray-green to gray-black fine to very fine sands with interlayered silt beds. Strata well defined.	Organic-matter layers common.
C378	31	63	In small channel with sandbar across lower end. Essentially a "dead" channel.	Well-stratified gray-black sandy silts overlying uniform fine sands that coarsen with depth.	Organic-matter layers common in upper part of core. Scattered organic particles occur in lower part.
C379	[1]4	58	On gentle slope or flat near margin of Clifton Channel.	Well-stratified gray-black silts and brown sands.	Organic-matter layers widespread.
C380	18	47	Exact position unknown. Probably in area of recent deposition downstream from new groin.	Fine brown sands with scattered silt layers and a silty cap layer.	Organic matter rare.
C381	[1]6	64	On flat adjacent to small slough in which flow has been restricted by relatively new river-control structures.	Well-stratified brown sands and gray-black silts.	Many layers of brown organic fragments throughout core. Some indication of sediment disruption by burrowing organisms.
C382	23	23	On crest of 7-foot dune in Cathlamet Channel.	Clean brown medium sand. Strata not evident.	Organic matter absent.

See footnote at end of table.

TABLE 3. — *Qualitative aspects of estuary cores*—Continued

Core number	Approximate water depth (feet)	Total core length (inches)	Geomorphic position	Sediments	Remarks
C383	41	11	Probably in poorly consolidated sedimentary bedrock in main channel near Longview.	Compacted gray clayey silts with some thin sand layers.	Black fragments of organic matter and small branches present.
C384	....	48	Exact position unknown. Probably near boundary between slope and flat.	Clean fine brown sand below a thin silty cap layer. Grades downward into medium sands with some interbeds of silt.	Organic material is rare and occurs as thin layers.
C385	[1]10	42	In small channel in an area of 2-foot dunes. Possibly in area of recent accretion due to main-channel control structures.	Clean brown fine sand that coarsens slightly with depth and has a silty top layer. Faint textural stratification.	Only a few scattered fragments of brown organic material.
C386	....	58	Exact position unknown. Probably on slope near boundary with adjacent flat. May be in recent dredge-spoil area.	Clean greenish-brown to gray medium sands that coarsen with depth. Strata, due to thin layers of pumice fragments, common in lower part of core.	Organic material as brown scattered fragments.
C387 and C387I	25 25	46 30	On gentle slope, almost a flat, in sheltered area between the north jetty and Cape Disappointment.	Dominantly clean green fine sand with gray-black silty top layer and a few silty layers at depth. Strata faint but present.	Organic-matter layers and scattered fragments are present but not abundant.
C388	16	66	In small channel with smooth bottom.	Well-stratified sandy and clayey black silts.	Organic-matter layers are common. Shell fragments and some evidence of activity of burrowing organisms.
C389	8	52	On tidal flat.	Stratified clean gray-green fine sands with a top silty layer and with occasional silty layers at depth.	Small scattered brown organic-matter fragments occur in the lower part of the core. A living clam was found in the upper part of the core.

[1]Estimated.

displaced, and visually inspected to note composition and other physical characteristics.

General qualitative field and laboratory observations for each core are summarized in table 3. Data on geomorphic position and water depth at the time of coring indicate that core sites (figs. 7–13; pls. 1 and 2) may have been overly concentrated in areas peripheral to channels and flats; thus, data for this set of cores may present a somewhat biased picture of the stratigraphic distribution of sediments and radionuclides. The following conclusions can be drawn from table 3: (1) Sediments almost invariably show easily visible evidences of stratification that is generally in the laminated to very thin bedded categories (Ingram, 1954); (2) sediment color varies with texture, with geographic location, and predictably, with depth, from brown to green to gray and black; (3) sediments are chiefly sands with varying but moderate amounts of interbedded silts; (4) a fine-grained generally thin top layer caps many cores, even those that contain little fine sediment at depth; and (5) organic matter, either as layers or as isolated fragments, occurs in most cores.

General aspects of the stratigraphy in Columbia River estuary cores are illustrated in figure 15. Although the cores shown (fig. 15) were collected at an earlier date than those described herein, their geomorphic positions and stratigraphic sequences are nearly identical with those for cores C368 and C369 (pl. 2). Alternating layers of sand (light color) and silt, mostly horizontal but in part inclined and resembling crossbedding, are obvious, as is disruption of strata due to burrowing organisms. Some warping caused by the corer is also apparent and is particularly noticeable where sediments are fine grained.

Quantitative textural data for selected segments from each core were obtained after the segments had been analyzed for radionuclides. Because segments were dried prior to radionuclide analyses, the textural data may not be exactly comparable with data from surficial sediments, which were analyzed without prior drying. Also, for those segments analyzed by the pipette method, only two sizes (16 micron and 4 micron) were determined. In general, textural data for core segments are less reliable than similar data for surficial sediments.

The selection of segments to be analyzed for size was based on two considerations; results from radionuclide analyses, and visual observation of the overall stratigraphic characteristics of the core. To characterize the stratigraphy of the core, segments that had been used in delineating the distribution of radionuclides in the core were usually selected for size analyses. However, for some cores, particularly those in which only two or three segments were analyzed for either radionuclides or size, the results may not be indicative of the core as a whole.

Particle-size-distribution statistics for 147 segments from cores are shown in appendix 2, and selected statistics are summarized in figure 16. In this figure, if percentages of silt and clay had not

A

B

C
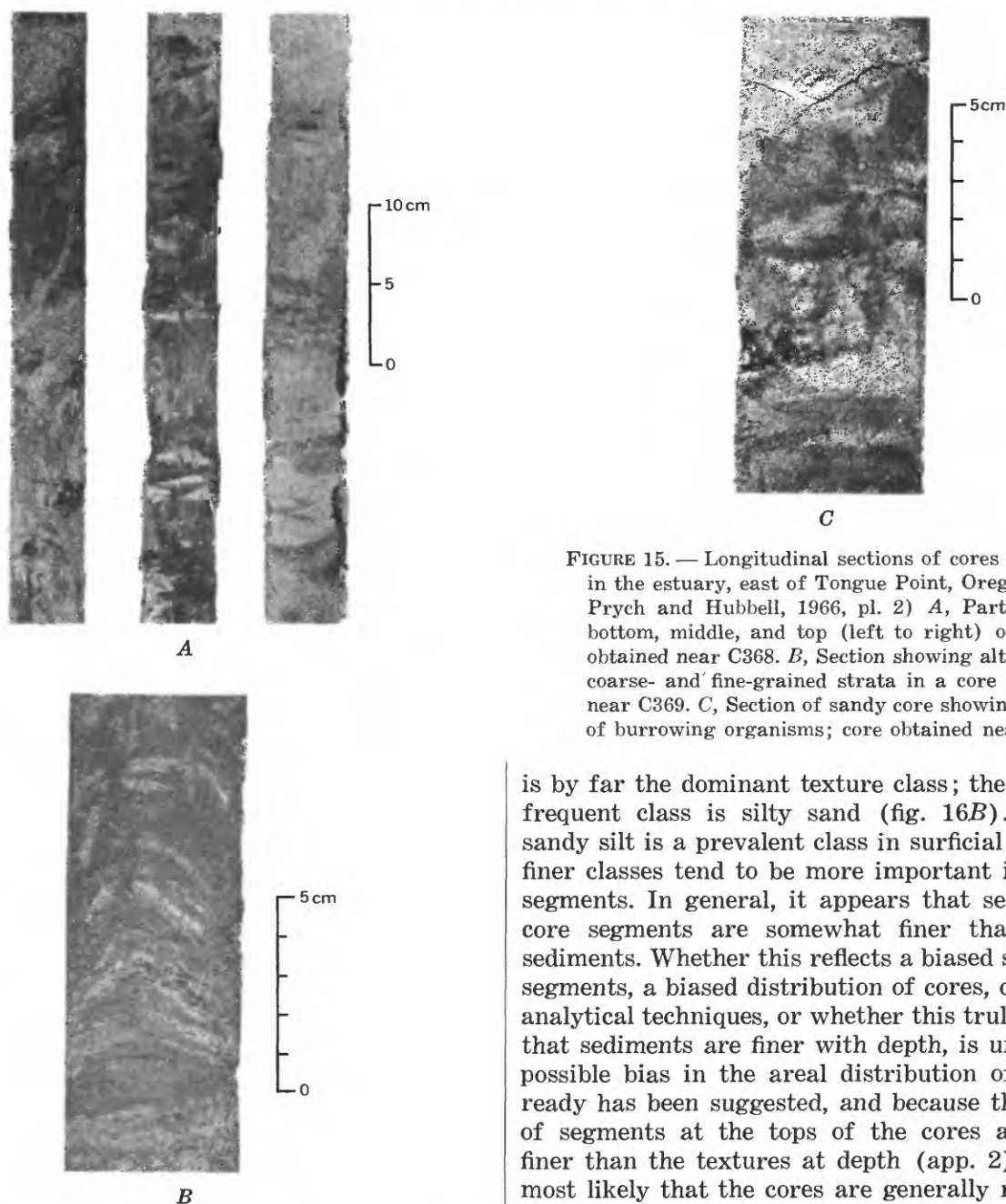
FIGURE 15. — Longitudinal sections of cores collected in the estuary, east of Tongue Point, Oreg. (From Prych and Hubbell, 1966, pl. 2) *A*, Parts of the bottom, middle, and top (left to right) of a core obtained near C368. *B*, Section showing alternating coarse- and fine-grained strata in a core obtained near C369. *C*, Section of sandy core showing effects of burrowing organisms; core obtained near C369.

actually been determined (app. 2), they were estimated from the average ratio of silt to clay determined for other segments in the core, or if no other segments in a core had been analyzed, they were estimated from the average ratio of silt to clay in surficial sediments (p. L8). The results from either technique generally were only slightly different.

Comparison of sand-silt-clay ratios (fig. 16*A*) for core segments with similar ratios for surficial sediments (fig. 6) generally reveals a similarity in their distributions. As with surficial sediments, core segments are chiefly sand with some silt and clay. Sand

is by far the dominant texture class; the next most frequent class is silty sand (fig. 16*B*). Although sandy silt is a prevalent class in surficial sediments, finer classes tend to be more important in the core segments. In general, it appears that sediments in core segments are somewhat finer than surficial sediments. Whether this reflects a biased selection of segments, a biased distribution of cores, or different analytical techniques, or whether this truly indicates that sediments are finer with depth, is unknown. A possible bias in the areal distribution of cores already has been suggested, and because the textures of segments at the tops of the cores are usually finer than the textures at depth (app. 2), it seems most likely that the cores are generally representative of environments having sediments that are finer grained than sediments in the environments represented by the surficial samples.

Average size statistics for sediments of each core are shown in table 4 and figure 16*C*. The relatively large standard deviations reveal the wide range of texture that exists within a core, and comparison of average size statistics reveals large differences among cores. The average of the mean grain size among cores varied from a phi value of 7.00 (about 0.008 mm) to one of 1.24 (about 0.423 mm), and in one core (C378) the average for segments from the upper 10 inches is more than twice the average from

A. Sand-silt-clay relations for individual segments of cores. Forty-nine segments contain 100 percent sand.

C. Average sand-silt-clay relations for all segments from a core. Numbers are last digits of core numbers

Number of segments in texture class

Texture class	C366	C367	C367I	C368	C369	C370	C371	C372	C373	C375	C376	C377	C378	C379	C380	C381	C382	C383	C384	C385	C386	C387	C367I	C388	C389
Sand	7	--	1	5	4	1[a]	5	6	4	5[a]	7	6	5	8	7	4	1[a]	--	4	4	5	4	2	2	--
Silty sand	1	--	1	3	3	--	2	1	1	--	--	1	1	1	1	3	--	--	4	--	1	--	--	1	--
Sandy silt	1	--	--	--	1	--	--	--	--	--	--	1	2	--	--	2	--	--	--	--	1	1	--	--	3
Silt	4	--	--	--	--	--	--	--	--	--	--	--	2	--	--	--	--	--	--	--	--	--	1	--	--
Clayey silt	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3	3	--	5	--	--	1	--	3

*Excludes segments containing gravel (app. 2).

B. Classification of segments from cores into texture classes (Shepard, 1954)

FIGURE 16. — Textural characteristics of estuary cores.

TABLE 4. — *Summary of average textural characteristics of cores from the estuary*

Core number	Number of segments analyzed	Particle-size statistic, in phi notation						Textural distribution, in percent							
		Mean grain diameter (M_ϕ)		Deviation measure (σ_ϕ)		Skewness measure ($\alpha_{1\phi}$)		Gravel		Sand		Silt		Clay	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
C366	[1]4	4.85	0.46	1.30	0.36	0.09	0.02	....	....	27	15.7	67	15.4	6	17.1
C367	7	2.02	.33	.55	.17	.01	.25	....	....	94	6.0	4	3.9	2	1.9
C367I	3	2.60	1.30	1.00	.30	.06	.51	....	....	88	20.2	9	15.6	3	14.6
C368	8	3.58	.52	.79	.41	.23	.23	....	....	79	16.6	18	14.1	3	2.5
C369	8	3.56	1.05	1.00	.56	.16	.14	....	....	74	25.5	22	21.6	4	3.9
C370	5	1.31	.45	.83	.30	—.24	.27	5	6.2	95	6.2	....	....	....	....
C371	7	3.12	1.38	1.44	1.41	.29	.42	....	....	83	15.9	13	12.6	4	3.5
C372	6	2.69	.22	.42	.17	.15	.19	....	....	96	6.0	3	12.6	1	2.1
C373	5	3.54	.43	.57	.34	.21	.19	....	....	84	15.7	15	14.1	1	1.7
C375	7	1.84	.38	.74	.19	.11	.14	1	1	99	1.6	....	....	....	....
C376	7	2.68	.10	.38	.07	.12	.12	....	....	99	.9	1	.9	....	....
C377	7	3.50	.83	.82	.55	.24	.16	....	....	81	20.8	16	17.1	3	3.8
C378	[2]6	4.78	1.06	1.29	.41	.22	.16	....	....	38	31.4	54	28.0	8	3.5
C378	[3]4	2.29	.64	.51	.19	.02	.08	....	....	100	0	....	....	....	....
C379	9	3.24	.57	.73	.41	.24	.25	....	....	88	11.4	10	9.4	2	2.0
C380	7	2.54	.25	.44	.12	.09	.11	....	....	97	4.5	2	3.8	1	.8
C381	9	3.96	.72	.89	.43	.22	.21	....	....	64	27.9	32	24.6	4	3.3
C382	5	1.24	.11	.58	.07	—.06	.01	1	.8	98	2.0	1	1.8	....	....
C383	[1]2	7.00	.20	2.03	.17	.04	.07	....	....	6	4.2	64	3.6	30	1.0
C384	4	1.82	.39	.49	.11	—.06	.07	....	....	100	0	....	....	....	....
C385	4	2.30	.19	.31	.06	.02	.12	....	....	98	4.0	2	4.0	....	....
C386	5	1.76	.17	.45	.09	—.05	.08	....	....	100	0	....	....	....	....
C387	5	2.82	.95	.71	.78	.70	.15	....	....	87	25.4	11	21.5	2	3.9
C387I	3	3.10	1.53	.80	.91	.02	.09	....	....	78	37.5	18	31.8	4	5.8
C388	[1]3	6.39	.87	2.57	.53	.13	.28	....	....	13	7.5	61	11.7	26	9.8
C389	[1]2	2.13	0	.22	0	—.06	0	....	....	100	0	....	....	....	....

[1]Excludes segments with poorly defined or missing size statistics (app. 2).
[2]Segments from 0–10 inches below surface.
[3]Segments from 11–58 inches below surface.

segments lower in the core. Even larger within-core textural differences exist in sand cores that had a single fine-grained top layer—a not infrequent occurrence. Overall, sediments from core segments have an average mean grain size in the fine-sand range (Wentworth, 1922), are moderately well sorted, and have size distributions that tend to be slightly positively skewed. In only five cores are the sediments sufficiently fine grained throughout to fall in texture classes other than sand (fig. 16C).

Stratigraphic variations in mean grain size and deviation measure are shown in figure 17. Although it is difficult to generalize at this point about the variations, when quantitative data are combined with qualitative data pertaining to locations of cores and physical characteristics of all core segments, some general patterns emerge relative to sedimentation characteristics and environments. In terms of channels, flats, and slopes, which are the three geomorphic classes utilized to summarize surficial sediment data, core data indicate stratigraphic homogeneity (at least in the upper few feet) in channels and stratigraphic complexities on slopes and flats. It is anticipated that additional core data will allow classification of stratigraphic environments that quite possibly can be recognized by geomorphic criteria in most fluvial-estuarine systems.

RADIOACTIVITY IN BOTTOM SEDIMENTS

Radioactivity data include gross gamma count rates from in situ measurements of the streambed, gross gamma count rates from laboratory measurements of surficial sediment samples, and concentrations of five to eight individual gamma-emitting radionuclides from spectrometry measurements of sediment samples by the Battelle-Northwest Radiochemical Laboratory. A total of 187 in situ gross gamma measurements were made, and 59 samples, which were collected in conjunction with the in situ measurements, were counted later in the project laboratory. The concentrations of individual radionuclides were determined from 71 selected surficial samples and from selected segments of 27 cores. These concentrations, together with concentration totals, radionuclide ratios, and in situ count rates at the sampling locations are presented for the surficial sediment samples in appendix 3 and for the core segments in appendix 4. An explanation of the content of these appendixes is given on pages L29 and L33. On the average, in every 10 square miles of the estuary, in situ gross gamma measurements were made at about nine locations, radionuclide concentrations were determined at three locations from surficial sediment samples, and radionuclide concentrations were measured in segments from one core.

GROSS GAMMA RADIOACTIVITY

In order to utilize effectively the relatively large number of in situ gross gamma measurements and to optimize the usefulness of all radioactivity data, relations between gross gamma count rates and radionuclide concentrations were developed. To sup-
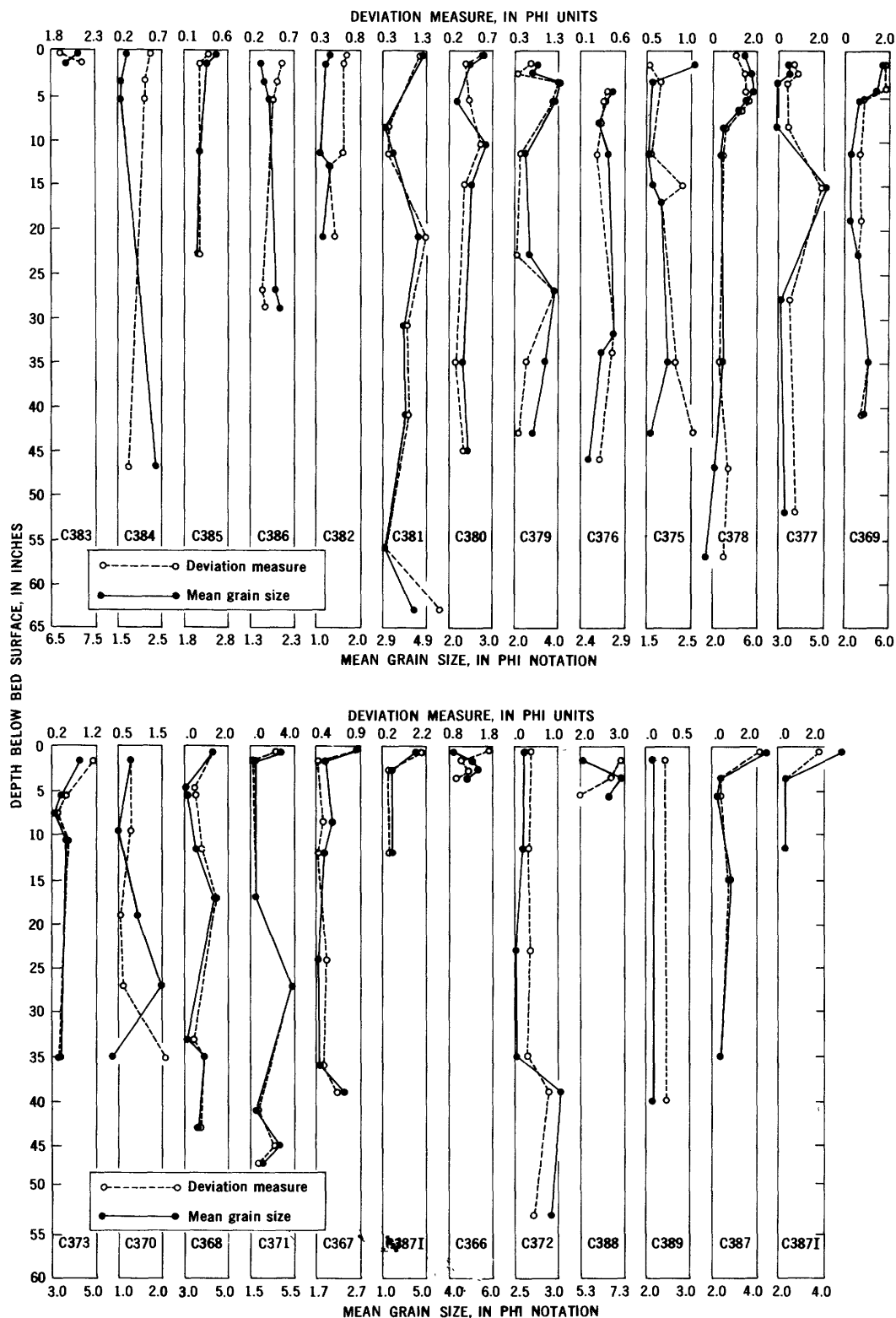
FIGURE 17. — Vertical distribution of mean particle size and deviation measure in cores from the estuary.

plement this effort, gross gamma radioactivity in some surficial sediment samples was determined in the project laboratory prior to sending the samples to the Battelle-Northwest Radiochemical Laboratory for detailed radionuclide analyses. In the project laboratory, it was possible to calibrate and to main-
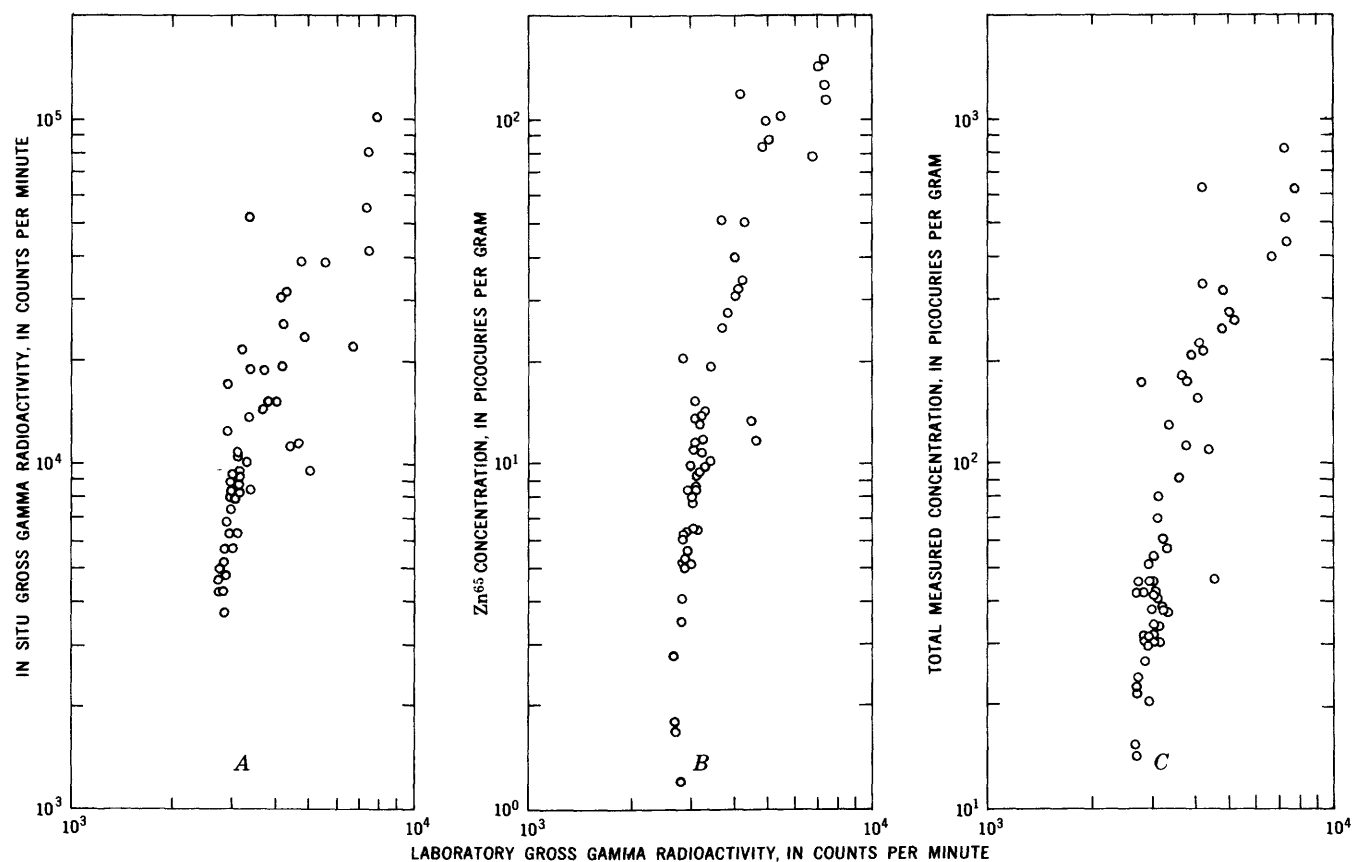
FIGURE 18. — Comparison of laboratory gross gamma count rates with in situ count rates and radionuclide concentrations.

tain the detection system under more uniform conditions of electronic stability and of sample geometry than were experienced in field operations.

Comparisons among field (in situ) count rates, laboratory count rates, and radionuclide concentrations in surficial samples are shown in figure 18. As expected, the plot of field versus laboratory count rates (fig. 18A) shows considerable scatter although a definite relation is evident. Only about 5–10 percent of the data points are so far removed from the trend of the points as to indicate possible errors. Plots of laboratory count rates versus both Zn^{65} concentrations (fig. 18B) and the total of measured radionuclide concentrations, including K^{40} (fig. 18C), generally indicate better relations than the relation between field and laboratory count rates. However, even in these graphs, 2–5 percent of the data points are removed somewhat from lines that could be drawn to depict general relations.

The variation of in situ count rates with the total of measured radionuclide concentrations (including K^{40}) in surficial samples is shown in figure 19, and the relation is fairly well defined. Scatter in this data and that shown in figure 18A resulted in part from counting differences that occurred because of

(1) variations in counting geometry due to different vertical distributions of radionuclides in the bed and to positioning of the sled, and (2) differential adsorption of radiation due to variations in the composition of the radioactivity at various locations. However, the large deviations may be the result of collecting the sample in sediment of one activity level and counting, in situ, on sediment of a different activity level; experience has shown that in some locations large differences in radioactivity occur within short distances. Overall, however, it is apparent that in situ measurements can be used to estimate the concentration of an individual radionuclide, such as Zn^{65}, as well as the total concentration of radionuclides in surficial sediments.

In situ count rates are influenced most by radiation emanating from close to the detector; thus, although they indicate the concentration of radionuclides near the surface, they cannot be used directly to obtain the amount of radionuclides in the whole sediment column beneath the bed surface. This must be done by using average relationships.

In order to relate in situ count rates to an actual amount of radionuclides, count rates at core sites have been correlated with the amounts of radionu-
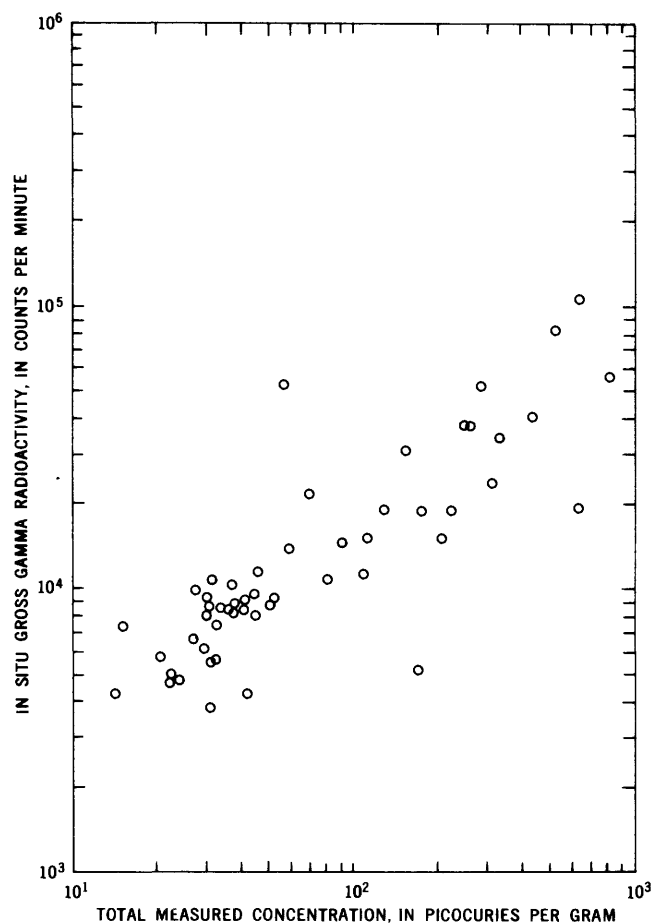
FIGURE 19. — Variation of in situ gross gamma count rate with the total concentration of measured radionuclides in surficial sediment.

clides per unit area[3] in the upper 8 inches of the bed (figs. 20 and 21). This particular correlation was used because calibrations in sand with several radionuclides (Sayre and Hubbell, 1965) indicated that with a uniformly distributed source of infinite depth, well over half of the counts result from radiation emanating from within about 8 inches of the surface. Also, in most cores the radionuclides extended at least 8 inches in depth, and the radionuclide content often was defined by 1-inch increments down to about the 8-inch level.

Most scatter of the data in figures 20 and 21 appears to have resulted from measuring the in situ count rate at a location slightly offset from the core site—the booms for handling the corer and the sled detector unit were located at different positions on the boat so that identical positioning rarely was accomplished. This type of problem could have been particularly serious for the data from two cores that are farthest removed from the general trend of

[3]The computation procedure used to determine the amount of radionuclides per unit area is described in appendix 5.

the points. For one other core (C386, fig. 21), which deviates substantially from other points with similar count rates, radionuclide concentrations (app. 4) for one segment (C386-3-1) appear to be in error by an order of magnitude. The dashed curves in these figures were defined from average values for selected ranges of in situ count rates (data that deviated greatly from the majority of points were excluded from the averages).

A histogram that depicts the distribution of all in situ count rates obtained during the survey is shown in figure 22. The distribution is markedly asymmetrical, with a predominance of count rates at two or three times the general background level, which is estimated to be 2,500 cpm (counts per minute), and with a scattering of count rates up to almost 60 times greater than the background level. Assuming that the distribution of data points in the estuary is reasonably representative, in situ count rates indicate that about 60 percent of the estuary bed had gross gamma levels less than 10,000 cpm, about 19 percent had levels ranging from 10,000 to 20,000 cpm, and the remaining 21 percent had levels between 20,000 and 142,000 cpm.

Measurement locations and measured levels of gross gamma radioactivity in each of the 14 cross sections are shown in figures 7 to 13. Inspection of these data indicates that the level of activity varies markedly within cross sections. The general impression obtained from studying these figures is that low levels are associated with the channels, whereas the activity level varies over a fairly wide range on the slopes and flats.

A summary of cross-sectional and longitudinal variations in gross gamma radioactivity is shown in table 5. The within-cross-section groups for this summary are the channels, slopes, and flats used to

TABLE 5. — *Average in situ gross gamma radioactivity at sample sites within each geomorphic class in each cross section*

[Number of samples in average is shown in parentheses]

Longitudinal division	Cross section river mile	In situ gross gamma radioactivity (cpm)			
		Channels	Slopes	Flats	All classes
Fluvial	64	9,600 (2)	31,000 (5)	.... (0)	25,000 (7)
	59	7,200 (6)	6,400 (2)	22,000 (6)	14,000 (14)
	54	7,600 (3)	28,000 (4)	12,000 (1)	18,000 (8)
	50	6,500 (4)	12,000 (5)	8,600 (1)	9,200 (10)
	47	7,200 (4)	7,200 (4)	20,000 (2)	10,000 (10)
	42	7,300 (5)	20,000 (4)	85,000 (3)	31,000 (12)
	38	7,000 (4)	10,000 (5)	14,000 (3)	10,000 (12)
	31	22,000 (5)	11,000 (2)	19,000 (2)	19,000 (9)
	27	5,800 (3)	39,000 (9)	16,000 (3)	28,000 (15)
	27–64	9,100 (36)	22,000 (40)	26,000 (21)	18,000 (97)
Transitional	23	10,000 (5)	17,000 (8)	23,000 (4)	16,000 (17)
	18	15,000 (5)	7,000 (4)	8,400 (3)	11,000 (12)
	14	15,000 (4)	17,000 (6)	7,600 (3)	14,000 (13)
	14–23	13,000 (14)	15,000 (18)	14,000 (10)	14,000 (42)
Marine	6	9,300 (5)	11,000 (3)	16,000 (8)	13,000 (16)
	2	5,000 (1)	5,500 (2)	.... (0)	5,300 (3)
	2–6	7,800 (6)	8,900 (5)	16,000 (8)	12,000 (19)
All	2–64	9,800 (56)	19,000 (63)	21,000 (39)	16,000 (158)
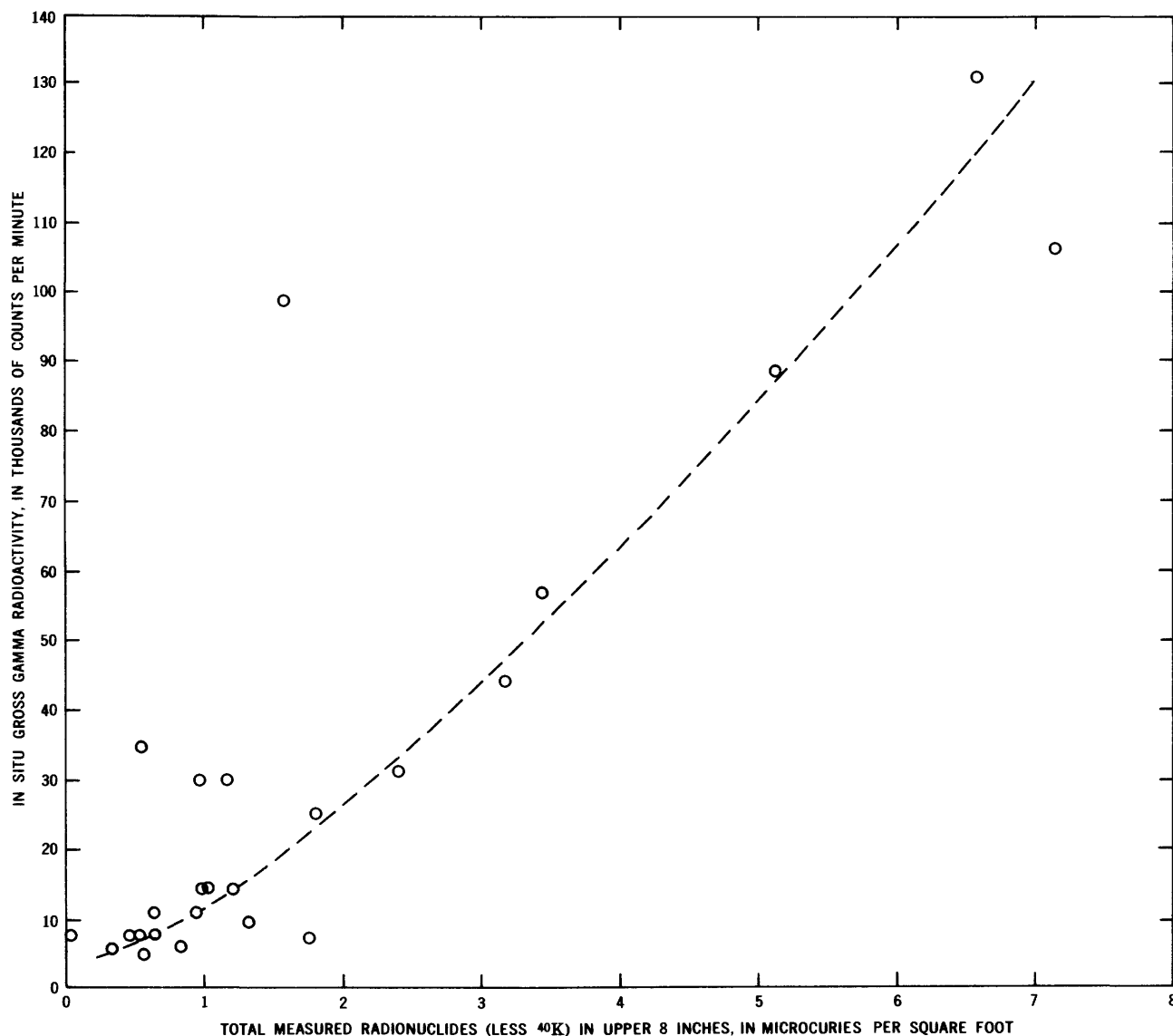
FIGURE 20. — Relation between in situ gross gamma count rate and the total amount of measured radionuclides (less K^{40}) in the upper 8 inches of the streambed.

group surficial sediment textural data (table 2) ; cross sections and fluvial-transitional-marine divisions are the longitudinal groups. The summary (table 5) tends to substantiate the impressions mentioned above as well as to indicate possible longitudinal trends. In eight out of 12 cross sections where a comparison can be made, average gross gamma levels in channels are lower than or equal to levels on slopes and flats; in the latter two classes, the data suggest that flats tend to have higher levels than do slopes. In analyzing the data for longitudinal trends, comparisons among individual cross sections are probably not highly informative, chiefly because of insufficient data. However, when cross sections are combined into fluvial, marine, and transitional

divisions, it appears that gross gamma radioactivity levels generally decrease toward the estuary mouth, although not uniformly for all geomorphic classes.

RADIONUCLIDES IN SURFICIAL SEDIMENT

Information on individual gamma-emitting radionuclides associated with surficial sediments was obtained by analyzing selected samples from each cross section. In general, the selection of samples was based on the variation in "uncorrected" in situ count rates in a cross section and on rough qualitative appraisals of the physical characteristics of all cross-section samples. The attempt was to provide samples that would define the range in radioactivity and that as a composite would be representative of the sedi-
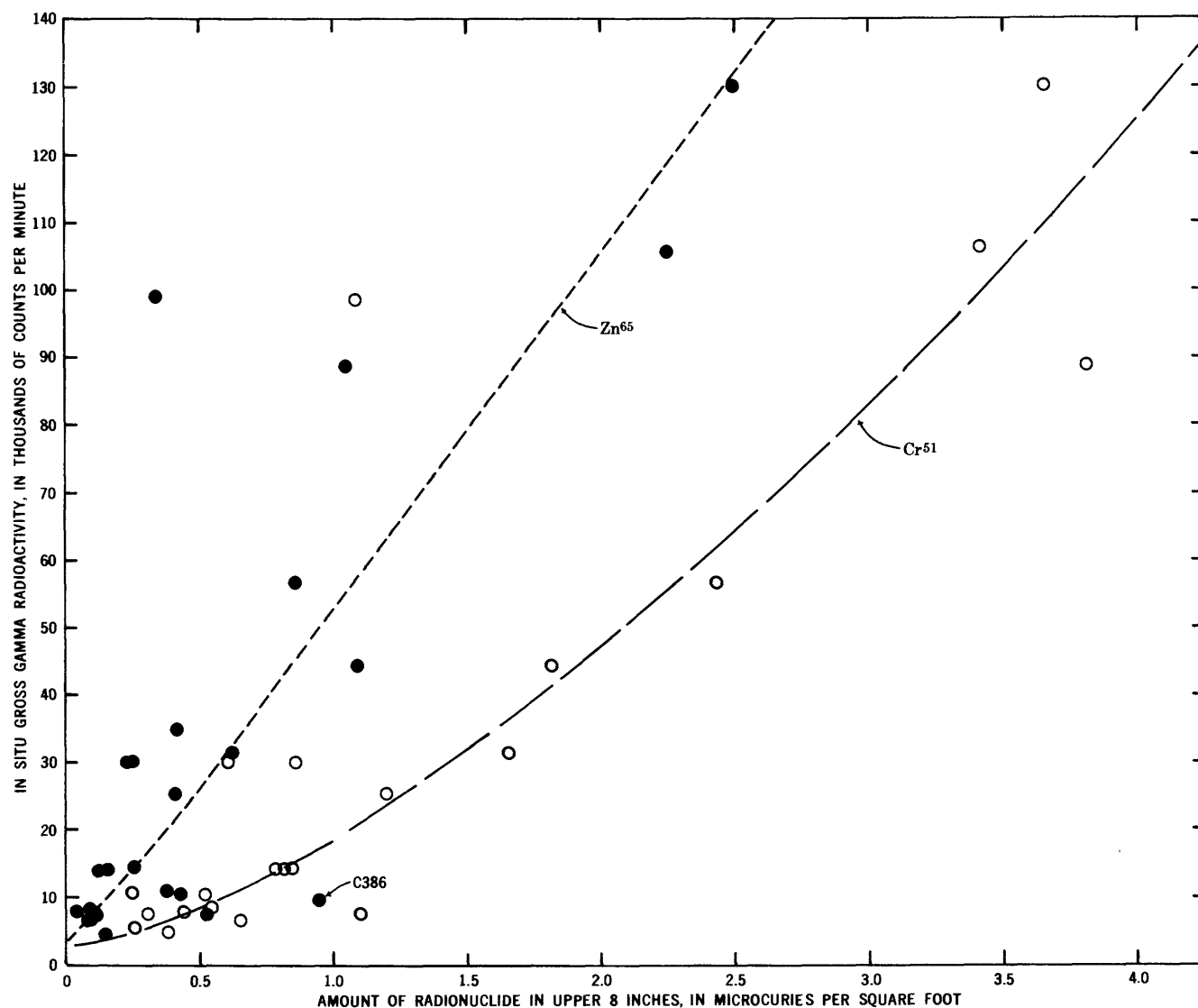
FIGURE 21. — Relations between in situ gross gamma count rates and the amounts of Zn^{65} and Cr^{51} in the upper 8 inches of the streambed.

ment and radioactivity of all the samples in the cross section. That such early and empirical assessments were only moderately successful is indicated by comparing the averages of selected size statistics and of in situ count rates for all samples in the cross section with the averages for the samples selected for radionuclide analysis (table 6). Overall, the samples selected for radionuclide analysis (table 6) were finer grained and had higher in situ count rates than the whole group of samples from the cross section. As a result, radionuclide data suffer not only because the overall sampling density was low, but also because the average of individual concentrations may not be directly representative of the concentration in the entire cross section.

In the radionuclide analyses, which were per-

formed by the Battelle-Northwest Radiochemical Laboratory, the concentrations of eight gamma-emitting nuclides were determined. The radionuclides include the five major activation products from the Hanford facilities, Sc^{46}, Cr^{51}, Mn^{54}, Co^{60}, and Zn^{65}; two abundant fallout radionuclides, Zr^{95}-Nb^{95} and Ru^{106}; and the naturally occurring radionuclide, K^{40}. These radionuclides make up the bulk of the radioactivity in the estuary; however, inasmuch as minor amounts of other radionuclides are present, henceforth in this report the term "measured radionuclides" is used to designate the eight gamma-emitting radionuclides quantified by the analyses.

The concentrations of individual radionuclides and selected computed totals and ratios for surficial sediment samples are shown in appendix 3. The concen-

TABLE 6. — *Comparison of average values of several size statistics and in situ gross gamma count rates for different sample groups at each cross section*

[Sample group: A, all samples from cross section; B, samples from cross section analyzed for radionuclides]

Longitudinal division	Cross section river mile	Sample group	Number of samples in group	M_ϕ	σ_ϕ	$\alpha_{1\phi}$	In situ gross gamma radioactivity (cpm)
Fluvial	64	A	7	2.09	0.70	−0.05	25,000
		B	2	1.38	.55	−.19	8,300
	59	A	14	2.18	1.15	−.06	14,000
		B	4	2.33	.78	−.05	17,000
	54	A	8	2.64	.85	.02	18,000
		B	3	2.46	.71	.01	13,000
	50	A	10	1.55	.53	−.01	9,200
		B	2	2.13	.39	−.06	8,800
	47	A	10	1.66	.46	−.02	10,000
		B	4	2.05	.45	.03	14,000
	42	A	14	2.71	.87	.04	31,000
		B	5	2.39	.97	−.01	20,000
	38	A	12	2.13	.91	.14	10,000
		B	4	2.69	.70	.02	13,000
	31	A	9	2.29	.68	.03	19,000
		B	4	2.12	.84	.01	28,000
	27	A	15	2.84	.95	.04	28,000
		B	4	4.45	1.53	.13	42,000
	27–64	A	99	2.27	.82	.02	18,000
		B	32	2.53	.81	.00	20,000
Transitional	23	A	17	2.64	.68	.06	16,000
		B	5	2.36	.64	−.10	16,000
	18	A	12	2.36	.79	.03	11,000
		B	4	2.74	.90	.07	16,000
	14	A	13	2.62	.70	.07	14,000
		B	4	2.92	1.02	.04	15,000
	14–23	A	42	2.55	.72	·.05	14,000
		B	13	2.65	.84	−.01	16,000
Marine	6	A	16	3.16	1.03	.22	13,000
		B	5	2.67	.66	.14	18,000
	2	A	4	2.46	.67	.14	5,300
		B	3	2.01	.28	−.09	4,600
	2–6	A	20	3.02	.96	.20	12,000
		B	8	2.42	.52	.06	14,000
All	2–64	A	161	2.44	.81	.05	16,000
		B	53	2.54	.78	.01	18,000
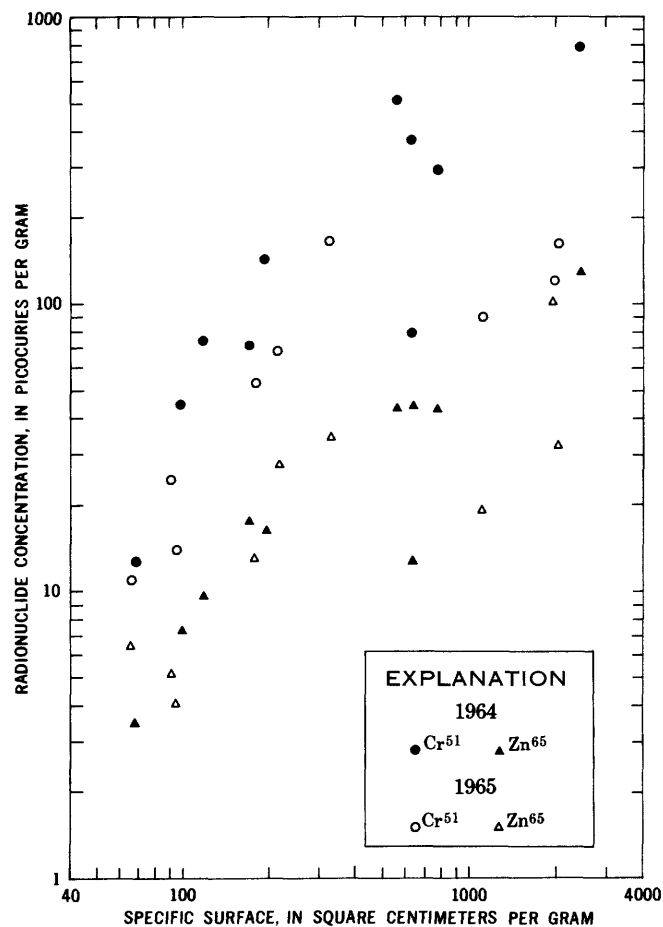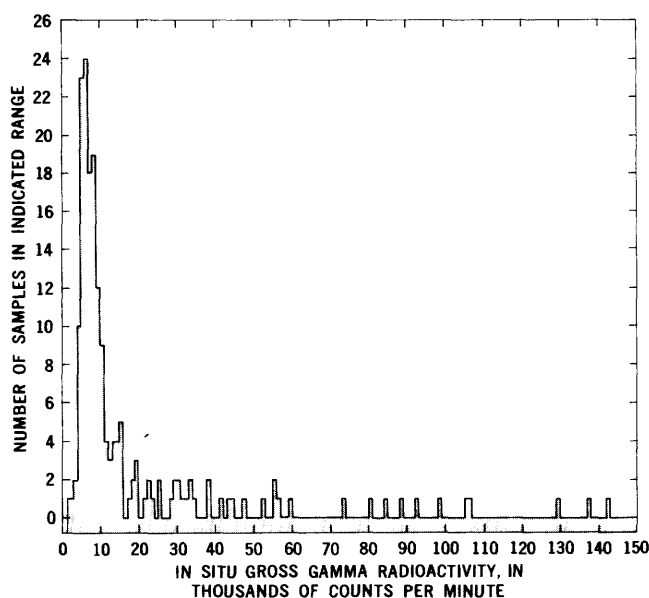
FIGURE 23. — Relations between Cr^{51} and Zn^{65} concentrations and specific surface of surficial sediment samples obtained between Columbia River miles 14 and 18 in October 1964 and June 1965.

trations of the individual radionuclides are conversions to picocuries[4] per gram (pc/g) of data originally presented in disintegrations per minute per gram (d/m/g). The original data were reported to, and are believed to be accurate to, 0.1 d/m/g for all concentrations greater than 0.5 d/m/g, except for Cr^{51} concentrations, which were reported to the nearest whole disintegration per minute per gram for concentrations greater than 5 d/m/g. The computed picocurie values reflect the number of significant figures in the original disintegrations-per-minute-per-gram data except for Cr^{51}, which usually has one additional significant figure. Certain values have been denoted as "questionable" (app. 3). In general, the assignment of these values to a

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[4] One picocurie is equivalent to 10^{-12} curie.

FIGURE 22. — Histogram of frequency distribution of in situ gross gamma count rates at estuary cross sections.

questionable category was done by the analyst if anomalous concentration(s) of a radionuclide(s) appeared to be present. As a general and arbitrary rule, less-than values were added into computed totals as if they were real values, under the general assumption that their small magnitude would not affect seriously the results. Totals and ratios were not computed if questionable or missing values were involved, nor were ratios computed from questionable or less-than values.

Data on radionuclides in 10 surficial sediment samples that were collected on preliminary cruises during October 1964 are also shown in appendix 3. Results from these samples (as well as from some early cores) have not been utilized in this report except in figure 23. (See equation 1, p. L35, for definition of specific surface.) Data in this figure suggest that different correlations exist between variables from the 1964 data and similar variables from the 1965 survey. Information obtained since 1965 has indicated that the amount of radionuclides associated with surficial sediment varies seasonally, apparently in response to the changing hydrologic regime, and that it is diminishing with the reduction in the number of reactors in operation at Hanford. Very likely the generally lower levels of Zn^{65} and Cr^{51} in 1965 (fig. 23) reflect both the decrease in reactor operations between 1964 and 1965 and the tendency (ill-defined) for levels in June to be somewhat lower than levels at other times throughout the year. As a result of these influences, the levels of radioactivity and the amounts of radionuclides vary somewhat, and the values reported herein probably are higher than have existed since 1965.

Total concentrations of measured radionuclides and the proportions of the totals that are Zn^{65} and Cr^{51} are shown in figures 7 to 13 along with in situ count rates and particle-size statistics. As would be anticipated from the discussion on the distribution of gross-gamma radioactivity, individual radionuclide concentrations appear to attain highest levels in samples from sites on slopes and flats adjacent to channels.

Individual radionuclide data are summarized by cross section, geomorphic class, and longitudinal division in tables 7 and 8. Inspection of these data indicates the following:

1. Average amounts of Cr^{51}, Zn^{65}, Sc^{46}, Ru^{106}, Mn^{54}, Co^{60}, and Zr^{95}-Nb^{95} are about 6.2, 2.2, 0.2, 0.1, 0.07, 0.06, and 0.05 times as abundant, respectively, in Columbia River estuary surficial sediments as K^{40}, which is fairly constant and averages about 14 pc/g in inorganic estuary sediments.

2. Mean radionuclide ratios appear to indicate significant changes in relative amounts of some radionuclides along the estuary; for example, Cr^{51} appears to increase relative to Zn^{65} toward the estuary mouth.

3. Large differences, reflecting the selection of samples for analysis as well as probable extreme natural differences, exist between the average radionuclide concentrations of the various cross sections.

4. Even when samples from cross sections are combined and only fluvial, transitional, and

TABLE 7. — *Summary of measured radionuclides in surficial sediment samples from cross sections*

[Statistic: $\bar{x}$ and s are mean and standard deviation of samples, respectively; ratio values computed by using only individual ratios listed in appendix 3]

Longitudinal division	Cross section river mile	Number of samples	Statistic	Radionuclide concentration (pc/g)								Ratios		
				Co^{60}	Zn^{65}	Mn^{54}	Sc^{46}	Cr^{51}	Ru^{106}	$ZrNb^{95}$	K^{40}	$\frac{Zn^{65}}{Co^{60}}$	$\frac{Sc^{46}}{Zn^{65}}$	$\frac{Cr^{51}}{Zn^{65}}$
Fluvial	64	4	$\bar{x}$	0.7	28.0	0.7	2.1	[1]59.2	1.7	0.5	12.2	50	0.05	1.338
	59	5	$\bar{x}$	1.5	36.0	.8	3.1	61.0	.9	.7	12.8	30	.073	1.77
	54	3	$\bar{x}$	.6	32.3	1.0	[1].2	101.0	1.2	1.0	12.8	50	.03	1.97
	50	3	$\bar{x}$	.3	11.2	.3	.2	11.4	.3	.2	13.3	40	[2].02	1.58
	47	5	$\bar{x}$	.3	15.0	.5	.8	[1]33.9	.4	.3	12.0	40	.05	2.11
	42	5	$\bar{x}$	.8	30.9	1.2	3.4	110.5	1.4	.7	12.3	40	.06	2.7
	38	4	$\bar{x}$	1.1	32.5	.9	1.9	56.9	1.2	.8	14.9	[2]26	.05	1.79
	31	4	$\bar{x}$	.9	37.8	1.3	3.8	106.9	1.7	.7	12.9	50	.07	1.84
	27	4	$\bar{x}$	2.1	66.0	2.2	8.5	170.7	4.2	1.6	18.6	34	.11	2.37
	27–64	37	$\{\bar{x}$	.9	32.3	1.0	[1]2.8	[1]81.9	1.4	.7	13.5	40	.06	2.01
			$\{s$	1.4	41.1	1.3	5.6	125.5	1.9	.9	4.4	14	.04	.9
Transitional	23	5	$\bar{x}$	.8	33.9	1.3	4.0	133.9	1.6	.8	13.4	30	[2].129	2.98
	18	4	$\bar{x}$	1.0	35.0	1.3	2.9	53.4	1.3	.8	13.2	30	.07	2.2
	14	5	$\bar{x}$	.9	20.7	.8	[1]2.2	97.0	1.4	.5	14.8	27	.12	4.62
	14–23	14	$\{\bar{x}$	.9	29.5	1.1	[1]3.1	97.7	1.4	.7	13.9	30	.10	3.3
			$\{s$	.9	42.7	1.6	5.3	156.5	1.6	.9	4.1	14	.05	1.3
Marine	6	5	$\bar{x}$	.8	22.9	.6	2.3	111.2	2.0	.5	14.2	30	.12	5.61
	2	3	$\bar{x}$	.2	1.6	.2	.2	3.8	.2	.2	12.1	....	....	[2]3.8
	2–6	8	$\{\bar{x}$	.6	14.9	.5	1.5	71.0	1.3	.4	13.4	30	.12	5.3
			$\{s$	.6	19.1	.4	1.7	88.5	1.6	.3	2.4	6	.03	1.4
All	2–64	59	$\{\bar{x}$	.8	29.3	1.0	[1]2.7	[1]84.3	1.4	.7	13.6	34	.076	2.78
			$\{s$	1.2	39.2	1.3	5.1	127.7	1.8	.9	4.0	15.4	.044	1.59

[1]Includes less-than values but excludes questionable values.
[2]One sample only.

TABLE 8. — *Variation of measured radionuclides in surficial sediment samples with geomorphic class and longitudinal division*

[Statistic: $\bar{x}$ and s are mean and standard deviation of samples, respectively]

Longitudinal division	Geomorphic class	Number of samples	Statistic	Radionuclide concentration (pc/g)							
				Co60	Zn65	Mn54	Sc46	Cr51	Ru106	ZrNb95	K40
Fluvial	Channels	17	$\bar{x}$	0.4	15.2	0.5	1.1	32.9	0.7	0.3	12.1
			s	.6	25.4	.9	3.2	84.5	1.3	.5	2.7
	Slopes	13	$\bar{x}$	1.2	40.6	1.3	3.5	106.4	1.9	1.0	14.7
			s	1.4	41.2	1.4	6.8	133.6	2.1	1.1	5.8
	Flats	7	$\bar{x}$	1.8	58.6	1.7	5.9	168.5	2.3	1.1	14.4
			s	2.2	56.9	1.7	6.7	165.6	2.7	1.1	4.5
Transitional	Channels	7	$\bar{x}$	1.0	25.4	.9	2.7	61.5	1.6	.7	13.3
			s	1.0	35.7	1.3	3.7	61.9	1.2	.9	4.1
	Slopes	6	$\bar{x}$	.8	34.8	1.4	4.1	144.8	1.4	.7	14.6
			s	.9	56.1	2.2	7.5	233.3	2.2	1.1	4.9
	Flats	1	$\bar{x}$	.6	27.1	1.0	1.4	68.5	.6	.2	13.6
			s	....	....	....	....	....	....	....	....
Marine	Channels	4	$\bar{x}$	.2	3.8	.4	.5	21.8	.3	.2	12.7
			s	.1	2.4	.1	.4	21.3	.2	0	.6
	Slopes	2	$\bar{x}$	.4	7.4	.8	1.0	41.3	.8	.2	11.1
			s	.3	8.7	.8	1.1	55.1	.8	0	.8
	Flats	2	$\bar{x}$	1.4	44.8	.4	4.1	199.0	3.8	.9	17.0
			s	.3	7.4	.1	.7	79.2	.4	.1	.3

marine divisions are recognized, the standard deviations of radionuclide concentrations typically are greater than the means and generally are so large as to preclude positive conclusions relative to changes in individual radionuclide concentrations along the estuary. The apparent decrease in average concentrations of some radionuclides along the estuary, although such a decrease would not be unexpected, may be entirely fortuitous.

5. When samples from the fluvial, transitional, and marine divisions are divided and assigned to previously described geomorphic classes (table 8), standard deviations of radionuclide concentrations appear to be reduced somewhat, although differences among classes within a division and among classes between divisions are still not highly significant.

Data in appendix 3 indicate that some sample localities exhibit extreme local variations in radionuclide content whereas other localities are fairly homogeneous. Samples at location G344 (pl. 2) illustrate the one extreme; that is, over a twofold difference in radionuclide concentrations between duplicate samples. Samples from location G214 (pl. 1) show the other extreme. Unpublished data from five to 20 replicate samples (collected after the 1965 data reported herein) from four locations in the Astoria area have indicated that with some radionuclides standard deviations are as large as 50 percent of mean concentrations. These data indicate that rather large deviations in radionuclide concentrations may be the rule rather than the exception.

Several possible reasons exist for the rather large observed variances in radionuclide concentrations in duplicate samples, and three possible reasons can be illustrated with the available data. Probably the major influence, which is discussed in more detail in a subsequent section, is the physical composition of the sample. If particle size is used as an indicator of composition, size data (app. 1) for the duplicate samples from location G344 indicate a pronounced difference in composition between the two samples, with the coarser sample containing generally less radionuclides. In addition, at the G344 sample site, as well as at other sample sites in the marine and transitional divisions of the estuary, variable amounts of pebble-to-cobble-size blue-black rounded clay balls occur. Radionuclide analysis (G344–B–65) of the clay balls from the G344 sample site shows that they contain less radionuclides than their fine texture suggests should be present. Although the exact origin of the clay balls can only be inferred at the present time, their characteristics and known distribution suggest that they represent erosion products from an ephemeral clay cap found principally in areas influenced by intrusion of saline waters.

Organic-matter content is another factor that may influence radionuclide concentrations. Sample G254–A–65 (app. 3) consisted exclusively of wood fibers and chips from a sample site near where these materials are loaded on barges for transport to markets. Radionuclide concentrations for this sample are several times greater than for other samples from the cross section (app. 3) that consisted mostly of coarse inorganic detritus. However, because the concentrations in G254–A–65 were less than those in sample G254–65, which consisted of both fine inorganic detritus and organic materials, it is apparent

that fine inorganic materials are a more important radionuclide-bearing component than organic material. Low concentrations (app. 3) of naturally occurring K^{40} generally are an indication that large amounts of organic material are present.

RADIONUCLIDES IN CORES

Limitations on the number of core segments that could be analyzed for individual radionuclides necessitated the selection of segments for analysis. The selection procedure began with an empirical judgment on the possible depth to which significant radioactivity might extend in each core. Then, segments that illustrated the stratigraphy and stratigraphic changes within each core were designated for possible radionuclide analysis. The final selection of segments, however, was necessarily in the hands of the analyst, who attempted to portray as completely as possible the stratigraphic distribution of radionuclides in each core. For most cores, this procedure resulted in an analysis of an initial set of core segments followed by an analysis of a second set when preliminary results from the initial set indicated stratigraphic gaps in radionuclide data. Concentrations of Cr^{51} often were not determined in the segments from the second set because of its decay (half life equals 27.8 days).

Results from radionuclide analyses of 258 segments from the 25 cores collected during the survey and of 29 segments from two cores (C3 and C6) collected earlier in the year are shown in appendix 4. As with data for the surficial sediment samples, less-than values have been added into the totals but have not been used in ratio computations, and no totals were computed for segments with missing or questionable data. Additional data pertaining to the geomorphic position, texture, and stratigraphy at each core site are included in table 3 and figure 17.

Stratigraphic distributions of Zn^{65} and Cr^{51} concentrations and of the total concentration of measured radionuclides (excluding K^{40}) are shown in figure 24 for five cores, and summary data for all cores are contained in table 9. (See p. L26 and app. 5 for details on computation of amounts of radionuclides in the streambed.) Inspection of the data in figure 24 and tables 3 and 9 indicates the following:

1. The amount of radionuclides in the streambed as well as the stratigraphic distribution of radionuclides vary considerably among core sites.
2. Estimated total amounts of measured radionuclides (excluding K^{40}) at the core sites range from about 0.05 $\mu c/ft^2$ (microcuries per square foot) to about 15 $\mu c/ft^2$ and average about 3.6 $\mu c/ft^2$ ($s = \pm 3.9$ $\mu c/ft^2$).
3. On the average, nearly 66 percent of the estimated total amount of measured radionuclides at core sites occurs in the upper 8 inches of the streambed. However, at some sites radionuclides extend well below 60 inches in depth.
4. Radionuclides usually are distributed so that highest concentrations are at the streambed surface or a few inches below the surface. Below the depth of highest concentrations, the levels of radionuclides decrease either fairly uniformly or very irregularly.

TABLE 9. — *Summary of the stratigraphic distribution of measured radionuclides (excluding K^{40}) in cores from the estuary*

[Types of radionuclide distributions: 1, decreasing; 2, increasing then decreasing; 3, inadequately defined; A, regularly; B, irregularly]

Core number	Core length (in.)	In situ gross gamma radioactivity (cpm)	Number of segments analyzed	Estimated depth to which radionuclides extend (in.)	Type of stratigraphic distribution of radionuclides	Computed total amount of measured radionuclides at core site ($\mu c/ft^2$)	Percent of total measured radionuclides in upper 8 in.	Percent of total measured radionuclides Zn^{65}	Cr^{51}
C366	11	44,200	10	37	3	7.40	42.8	28.5	58.1
C367	41	29,900	15	39	1B	2.68	44.0	21.3	70.8
C367I	41	29,900	8	39	1B	2.48	39.6	21.0	66.3
C368	59	31,200	8	24	1A	2.97	81.1	23.6	69.7
C369	47	56,700	10	24	2A	3.78	91.0	23.5	70.1
C370	40	4,900	8	26	1A	1.10	51.8	33.6	52.7
C371	50	14,400	10	76	1B	12.97	9.2	31.9	61.7
C372	54	7,600	10	6	2A	.46	98.9	21.3	68.1
C373	47	88,600	11	46	1B	7.82	65.7	17.4	64.9
C375	52	7,400	12	41	1B	3.48	50.3	36.5	47.7
C376	55	25,400	13	11	1A	1.95	92.8	21.5	64.6
C377	63	98,900	16	10	1B	1.61	98.8	21.1	67.7
C378	63	130,000	15	23	2A	6.84	96.6	38.9	53.4
C379	58	34,900	13	14	1B	.80	69.2	62.5	....
C380	47	10,500	9	52	1B	4.51	20.8	40.4	44.3
C381	64	106,000	16	64	2B	15.30	46.7	37.7	42.8
C382	23	5,500	11	24	1B	.60	54.2	35.0	42.8
C383	11	7,500	6	6	3	.045	100.0	22.2	....
C384	48	7,900	7	72	1B	6.28	8.6	3.5	84.7
C385	42	10,900	10	54	1A	2.02	31.2	49.5	13.4
C386	58	9,800	10	42	2A	1.75	75.4	58.8	....
C387	46	14,100	8	26	1B	1.20	85.0	14.2	70.3
C387I	46	14,100	5	24	1B	1.36	75.7	14.7	83.8
C388	66	8,500	8	6	2A	.65	100.0	13.2	83.1
C389	52	6,200	9	9	1A	.84	97.6	11.0	85.0
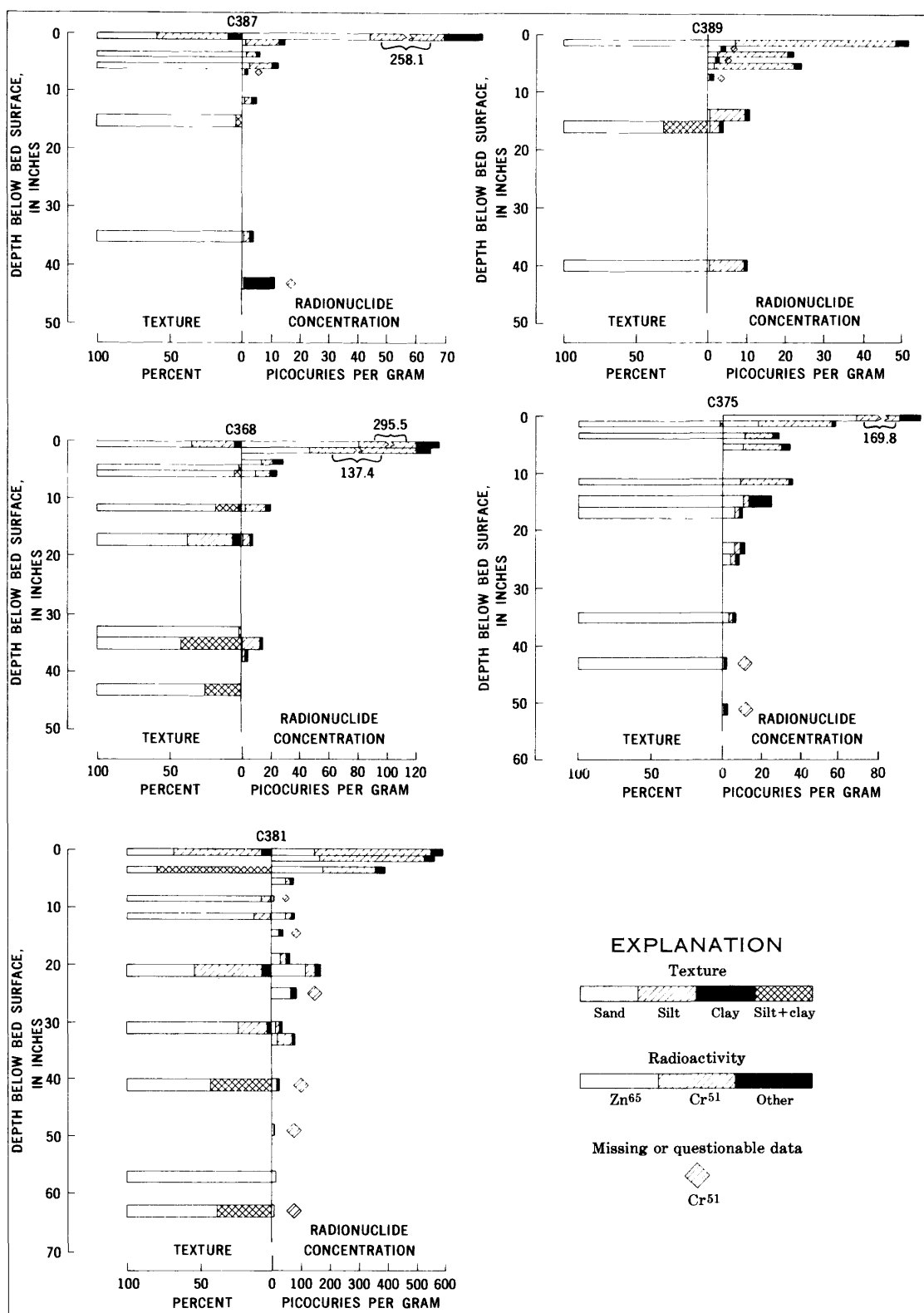
FIGURE 24. — Stratigraphic distribution of radionuclide concentrations and sediment texture in cores from the estuary. The length of the concentration bars denote the total concentration of measured radionuclides less K^{40}.

5. Radionuclides tend to be distributed to greater depths in cores in channels and on slopes than in cores from the flats.
6. As would be expected from the differences in half-life between Cr^{51} (27.8 days) and Zn^{65} (245 days), Cr^{51} is relatively less abundant in the total sediment column than it is in surficial sediments. However, Cr^{51} in cores still averages about twice as abundant as the next most abundant radionuclide, Zn^{65}.

SEDIMENT COMPOSITION AND RADIONUCLIDE CONTENT

In a previous section, possible relations between sediment composition and radionuclide content have been mentioned. The composition of the bed material is characterized by the particle-size distribution, mineralogy, and organic content of the sediment. These characteristics largely fix other variables—such as surface area, cation exchange capacity, and state of aggregation—and can influence the chemical character of surrounding media. Many studies have shown that certain changes in composition usually are accompanied by specific changes in other characteristics of the sediment. For example, it is well known that a decrease in particle size is generally accompanied by increases in surface area and cation exchange capacity, and also quite likely by a change in mineralogy. Differences in almost any aspect of sediment composition will almost certainly result in differences in the quantity of radionuclides associated with the sediment.

Sufficient data were collected during the 1965 survey to evaluate directly the relations between radioactivity and certain statistics that describe particle size distributions. Three such statistics are plotted (fig. 25) against the total concentration of measured radionuclides (less K^{40}). Figure 25 indicates that radioactivity increases as (1) mean size decreases (phi increases), (2) dispersion increases (deviation measure increases), and (3) skewness of the distribution changes from negative to positive.

Considerable scatter exists within the various general relations shown in figure 25. The scatter can be caused by many things, including (1) differences among samples, in any aspect of sediment composition, that are not reflected in the particle-size statistics either because the statistics lack sensitivity or because the variable does not influence the statistics appreciably; (2) errors inherent in both particle size and radionuclide analyses; (3) normal, random variations; and (4) differences among samples in the amount of radionuclides present that are inde-

pendent of sediment composition. Although none of these possible causes can be evaluated adequately with available data, possible trends in lateral and longitudinal variations in radionuclide concentrations in the estuary, suggested in previous sections, imply that a family of curves would be necessary to describe relations between radioactivity and particle size at different locations. To illustrate, the point that represents sample G301--65 in the right-hand part of figure 25 is among the farthest removed from a line that could be drawn to depict an average relation between mean size and the total concentration of measured radionuclides. This sample apparently contains a much lower radionuclide concentration than other samples with a similar mean size. Sample G301--65 was collected (pl. 2) at a lateral position more than 4 miles from the main Columbia River channel and near the mouth of a tributary that contributes sediments with very low radionuclide concentrations. Its position alone, then, is sufficient reason for the relatively low radionuclide concentration. If samples with a wide range of mean sizes were collected from this location and were analyzed for radionuclides, a curve offset somewhat to the right but generally parallel to one for all samples would probably result.

Under comparable conditions, the sorption capacity of sediment for most cations is roughly proportional to the available surface area (Sayre and others, 1963). Surface area, expressed in terms of specific surface, is sometimes approximated from a calculated value (Baver, 1956). By assuming that all particles in a given size range have the same diameter and that all particles in a sample are spheres of specific gravity 2.65, an estimate of specific surface can be obtained from

$$\text{Sp. S.} = \sum_{i=1}^{n} 22.64 \frac{f_i}{D_i} \qquad (1)$$

where
  Sp. S. is the specific surface of a sediment mixture, in square centimeters per gram;
  22.64 is a units-conversion constant;
  D_i is the geometric mean size, in millimeters, of the ith size range;
  f_i is the fraction, by weight, that sediment in the ith size range is of the total sample; and
  n is the total number of size ranges in the mixture.

Specific surface is plotted against Zn^{65} concentration in figure 26 to illustrate the relationship for Columbia River sediments. Because both specific
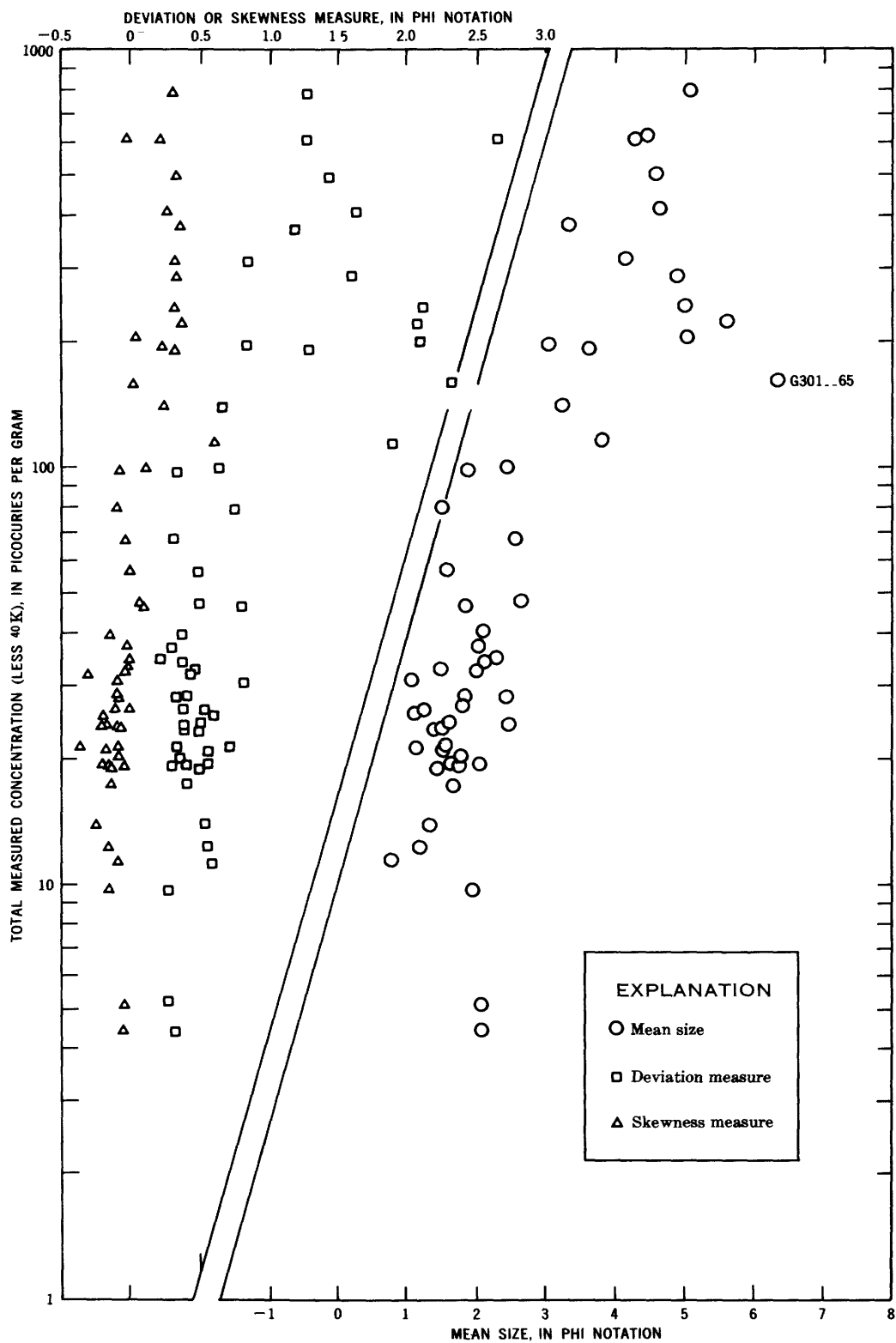
FIGURE 25. — Variation of the total concentration of measured radionuclides (less K^{40}) in surficial sediment with different textural statistics.
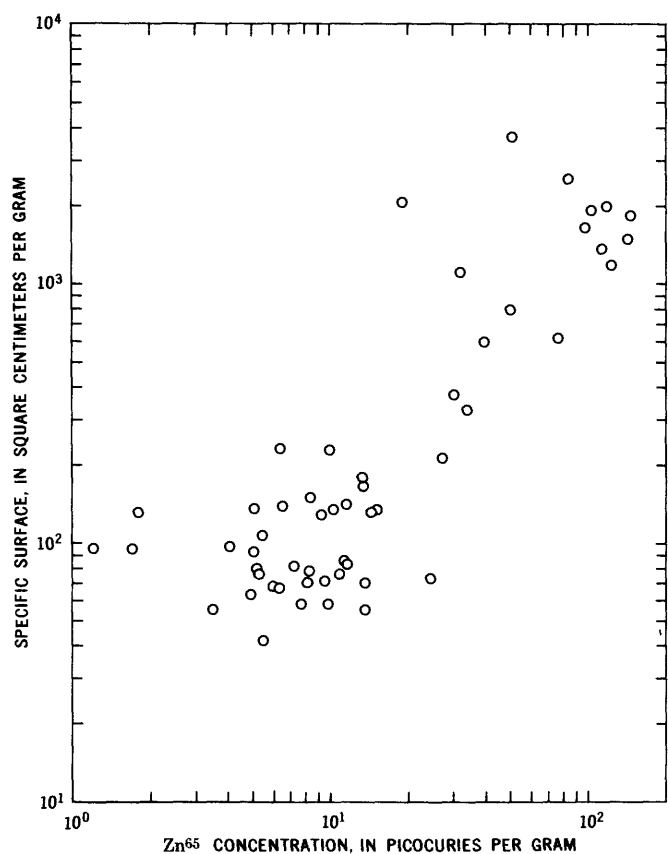
FIGURE 26. — Variation of Zn^{65} concentration in surficial sediment with specific surface.

surface and size statistics are determined from the same particle-size data, similar relations with radio-nuclides should exist — the degree of similarity would depend on how well the particle-size statistics and the specific-surface estimates correlate. Despite the grossness of the specific-surface model, specific surface should be more sensitive to radionuclide content than any single size statistic. Comparison of figure 25 with figure 26, however, suggests that both specific surface and mean size correlate about equally well with radionuclide concentrations. As in figure 25, the largest deviations on the specific-surface plot (fig. 26) appear to reflect principally locational variations in radionuclide content that are not related to physical size of the sediment.

The possibility of locational variations in radio-nuclide concentrations has been mentioned in previous sections. One of the factors that complicates the delineation of any trends is spatial variations in sediment composition that necessitate, for example, comparing radionuclide concentrations in coarse silt at one location with radionuclide concentrations in
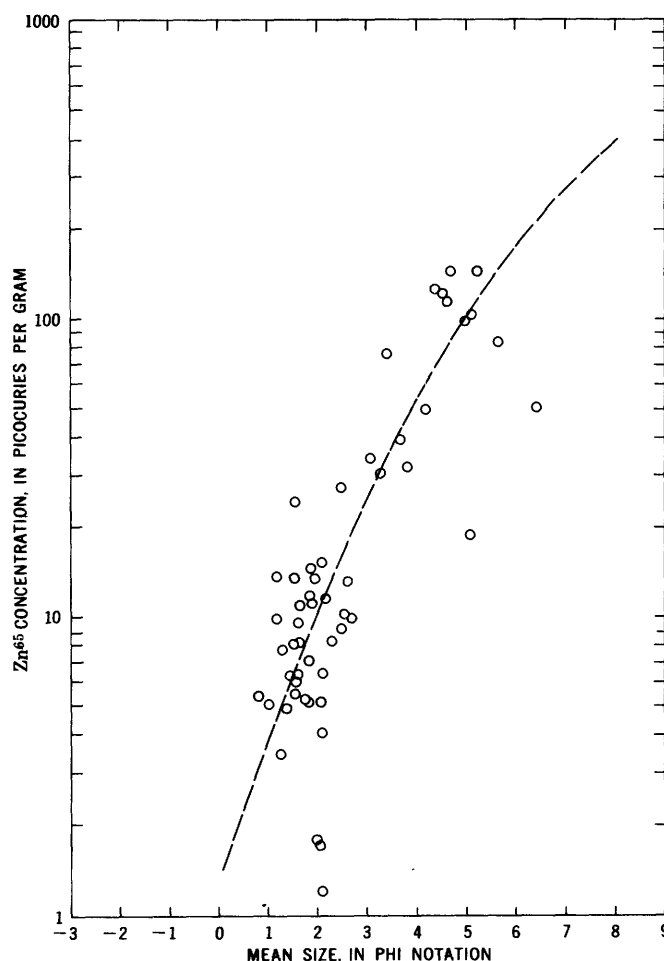
FIGURE 27. — Variation of Zn^{65} concentration in surficial sediment with mean particle size.

sand at another location. This difficulty can be overcome partly by considering the locational variation in radionuclide content associated with only the sediment within an individual size range. Although radionuclide concentrations for individual size separates are not directly available from this survey, they can be approximated from the radionuclide and size analyses of the surficial sediment by utilizing general relations between mean size and radionuclide concentration (figs. 25 and 27). Assume that (1) regardless of location or level of activity, the ratio between the radionuclide concentration of any given narrow size range and the concentration of any other narrow size range in a sediment mixture is constant (the ratio may be different for every different pair of size ranges) and (2) the ratios of concentration between size ranges are defined for total measured radionuclide concentrations (less K^{40}) by an average curve that could be drawn in

figure 25 and by the curve in figure 27 for concentrations of Zn^{65}. These assumptions imply that if radionuclide concentrations associated with each narrow size range in the bed sediment were available from a number of different locations in the estuary, the data would plot as a family of curves parallel to the curves in figures 25 and 27. With these assumptions, for any individual sediment sample

$$C_t = \sum_{i=1}^{n} f_i C_i$$

$$= \sum_{i=1}^{n} f_i a_i C_r$$

$$= C_r \sum_{i=1}^{n} f_i a_i \qquad (2)$$

where

C_t is the concentration of a radionuclide (or radionuclides) in the total sample;

f_i is the fraction, by weight, that the sediment in the ith size range is of the total sample;

C_i is the concentration of a radionuclide (or radionuclides) in the ith size range;

n is the total number of size ranges in the mixture;

C_r is the concentration of a radionuclide (or radionuclides) in a reference size (which may or may not be actually present in the sample); and

a_i is the ratio of the concentration in the ith individual size range to the concentration of the reference size (C_i/C_r).

Values for a_i can be determined from the curves of figures 25 or 27 by selecting for each size range a single size to represent the entire size range — in this analysis the geometric mean is used to represent the size range. If the reference size is taken as that size for which the radionuclide concentration is 1.0 pc/g, then the value of a for each size range equals the concentration at the geometric mean of the size range.

By solving equation 2 for C_r, the concentrations for each size range can be determined from $C_1 = a_1 C_r$, $C_2 = a_2 C_r$, and so forth. Concentrations of Zn^{65} were obtained in this manner for each standard size range from all samples in each cross section for which both the size distribution and the radionuclide content were defined. Whenever concentrations for a size range were available from more than one sample at a cross section, they were combined to give an average concentration for the range. As a
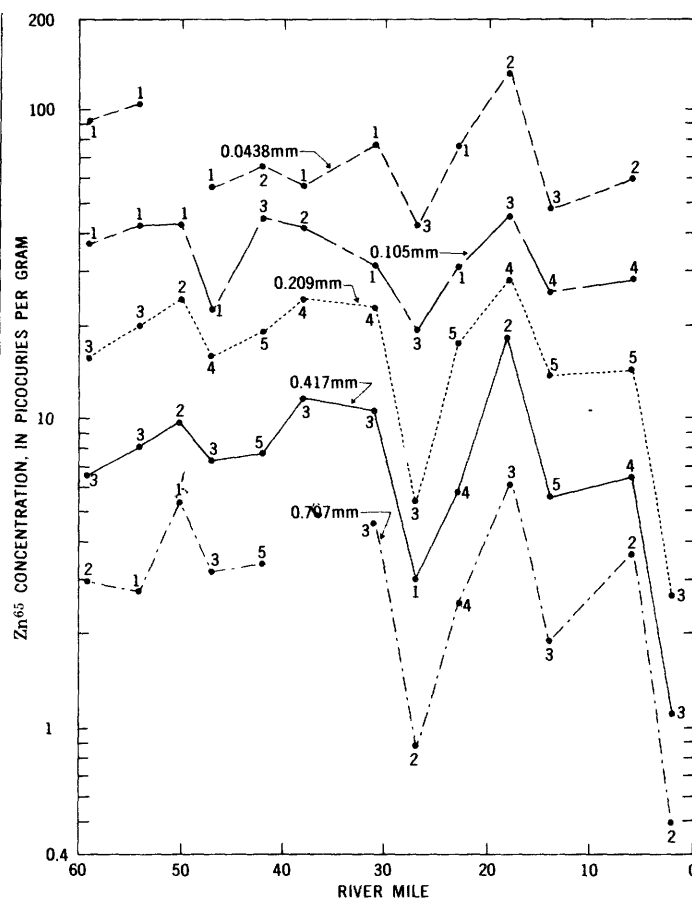
FIGURE 28. — Attenuation of Zn^{65} concentration associated with individual size separates with distance along the estuary. The individual size separates of surficial sediment are identified by the geometric mean size. The number of samples used to determine average value for each point is adjacent to the point.

result, the concentrations are based on different numbers of values from one size range to the next and from one cross section to the next. At each cross section, the concentration of Zn^{65} generally decreased progressively as the size increased, although discontinuities exist in this trend as a result of averaging different numbers of values from one range to another. Despite the shortcomings and inexactness of the procedure, the data suggest that the concentration of Zn^{65} associated with the geometric mean of any particular size range decreases progressively between Longview and the estuary mouth. This trend is shown in figure 28 for geometric means of several size ranges. The individual concentrations at a given river mile should not be given undue significance because they often are based on a very limited amount of data. Some implications that can be inferred from the plots are discussed in a following section of this report.

GENERALIZED QUALITATIVE DESCRIPTION OF THE DISTRIBUTION OF RADIONUCLIDES IN THE ESTUARY

The specific relations and trends presented in the previous sections, together with information on the morphology of the estuary bed during the survey and throughout the year, provide the basis for a generalized qualitative description of the distribution of radionuclides in the estuary.

As a result of the influence of texture on the physicochemical properties of the sediment, radionuclide concentrations and areal distributions of radionuclides are largely determined by the areal distribution of sediment particles. In channels and on some slopes and flats where the flow velocities are relatively high and where active sediment transport occurs at the bed, fine particles are winnowed from the bed, so the sediment is fairly coarse and radionuclide concentrations are low. On most slopes and flats and in some abandoned channels where the flow velocities are generally low or where circulation patterns promote deposition, the bed sediment is relatively fine, and concentrations of radionuclides are highest.

The depth and distribution of radionuclides in estuary environments depend on the previous history of the bed surface; however, percolation of river water in the bed sediments, in situ chemical reactions, and the activities of burrowing organisms and other biota may alter the original depositional patterns. In most areas of the estuary, deposition does not proceed continuously but is intermittent or alternates with scouring periods. The magnitudes and rates at which the depositional and erosional processes occur depend on channel geometry, sediment texture, and local flow characteristics.

In the upper part of the estuary, flow is contained mainly within one or two well-defined channels. In these channels, sandy bottom sediment often is formed into trains of dunes. Depending upon local flow conditions, dunes may have mean heights and lengths as small as 2 and 30 feet or as large as 15 and 600 feet, respectively. The ratios of length to height vary considerably but average about 50; dune heights rarely exceed 20 percent of the channel depth. During times of high flow, dunes achieve maximum height and progress downstream as a result of the erosion of particles on the backslope and deposition on the foreslope. This process causes the bed surface to alternately rise and fall as dunes move by, and it distributes radionuclides vertically throughout the channel bed from the troughs of the dunes to the crests. Usually in a channel dune area, only insignificant amounts of fine sediment remain in the bed sediment and, as a result, the concentrations of radionuclides are low. However, the fine particles often tend to settle in the dune troughs. This deposition creates, at the elevations of the troughs, bands of fine sediment that are approximately parallel to the water surface. Because migrating dunes, even in the same dune area, often have variable crest and trough elevations, the bands of fine sediment occur at various depths in the streambed and thus cause the texture of the sediment and the concentration of the radionuclides to vary stratigraphically.

In areas of actively moving dunes, particles are periodically exposed and buried, so the "age" of the sediment at one elevation may be approximately the same as at every other level in the dune. With this condition, decay does not influence the stratigraphic variations in radionuclide content; however, where particles are trapped in a part of the bed that no longer moves or that moves only very infrequently, the residence time of the particle affects the level of radioactivity. Often small dunes migrate at relatively rapid rates along the backslopes of large dunes. With this condition, the distribution of radionuclides might be fairly uniform vertically throughout the small dunes and then decrease substantially within the body of the large dune.

When the flow is low, little if any sediment transport occurs along the bed. Dune heights appear to reduce somewhat, probably in response to localized scour and deposition; fine material may accumulate at the bed surface, and the radionuclide concentration may increase accordingly.

Around bars, at channel margins, on the insides of bends, and on channel slopes, dunes are relatively small, and the bed sediment is somewhat finer than in the channels, probably as a result of the moderate velocities and the secondary circulation. In such areas radionuclide concentrations are proportionately high.

Where flow is essentially impounded rather than conveyed — such as on wide shallow flats and in sloughs — fine sand, silt, clay, and organic matter tend to accumulate and produce a fine-textured bed. Concentrations of radionuclides in these areas are higher than in areas of coarser sediment. Although deposition is more or less a continuous process on flats and in sloughs, except possibly for an infrequent scouring phase, the net accumulation of sediment with time ordinarily is relatively slow; hence, radionuclides remain fairly close to the surface.

In the estuary below Harrington Point, the flow is less channelized and tends to spread out over vast

shallow flats. Because of moderate velocities and wave action over these flats, the bed remains relatively free of silt and clay. Deposition of fine sediment occurs in large bays and in the remnants of former channels that are closed at the ends. The depth and distribution of the radionuclides follow the same general trends as they do in the upper estuary. However, the bed forms are less well defined, and their migration patterns probably are different because of the tendency for a net flow of zero or an upstream flow to persist at the bed. Bed relief rarely exceeds 3 feet, and the forms tend to be more rounded than the dunes formed upstream.

The influence that saline water in the lower part of the estuary has on concentrations of radionuclides in the sediment is not readily apparent from the available data, principally because of the scarcity of data and the overriding variations in the texture of the sediment. Any effects of flocculation and subsequent settling of sediment that may result from salinity intrusion also are not readily discernible.

RADIONUCLIDE INVENTORY

Information on the areal and stratigraphic distributions of radionuclides in the streambed was used to make an "inventory" of radionuclides in the estuary. Two maps were prepared for the inventory: one shows the distribution of different surficial levels of radioactivity, and the other delineates areas of different stratigraphic distributions of radionuclides. Because in situ count rates provide radioactivity data with the greatest areal density, they were used to prepare the surficial activity-level map. This map divides the estuary bed into divisions in which count rates are estimated to be 10,000 cpm or less, 10,000 to 20,000 cpm, and greater than 20,000 cpm. The ranges of count rates that delineate the divisions were selected to allow maximum use of relations among geomorphic class, particle size, and activity levels. Generally, count rates of 10,000 cpm or less came from channels and flats where flow velocities may be relatively high; rates of 10,000 to 20,000 cpm came from slopes and flats where velocities are moderate; and counts greater than 20,000 cpm came from flats, "dead" channels, and sheltered slopes where velocities are low. These basic relations were utilized to map count-rate divisions between data points in each cross section and to extend cross-section data to all areas between cross sections.

Although surficial activity-level divisions are indicative of the general amounts of radioactivity in the bed, they are only an index to the total depth and stratigraphic distributions of radionuclides. In order to account for variations in radioactivity that result from different vertical distributions, the estuary was divided into sections in which radionuclides were estimated to have one of three different stratigraphic distributions. The boundaries between sections approximately coincide with those separating the geomorphic classes (channels, slopes, and flats) that have been described previously. The radionuclide data from cores generally indicate that stratigraphic distributions differ (p. L35) between geomorphic classes, and the generalized discussion (p. L39–L40) of processes active in each class suggests mechanisms whereby different distributions could result.

A final map was produced by combining the activity-level and stratigraphic maps to form a map with nine kinds of subdivisions, each of which represents areas having a common general level of activity near the surface and a common stratigraphic distribution of radionuclides. The individual areas were measured with a polar planimeter and were summed to give the area of each subdivision.

In order to relate in situ count rates to an actual amount of radionuclides, the relations given in figures 20 and 21 were used. The influence that different stratigraphic distributions of radionuclides had on the computation was introduced by determining from the core samples in each geomorphic class the mean percentage of the total amount of radionuclides in the bed that resided in the upper 8 inches. Percentages were determined on a unit-area basis.

To compute the amount of radionuclides in the bed, the mean amount of radionuclides per unit area in the upper 8 inches in each of the three count-rate divisions was obtained from either figure 20 or 21 by determining the amount that corresponded with the average in situ count rate of all data points included in all the areas encompassed by each count-rate division. Then, for each of the nine combined areal stratigraphic subdivisions, the mean amount of radionuclides in the upper 8 inches was divided by the mean percentage of radionuclides in the upper 8 inches for the stratigraphic class of the subdivision so as to yield the mean amount of radionuclides per unit of surface area in the subdivision. This value was then multiplied by the total area to give the amount of radionuclides in the subdivision, and the amounts from all subdivisions were accumulated to give an overall total. In order to reflect possible longitudinal changes in the amounts of radionuclides, the estuary was divided lengthwise into eight reaches, and the computations

TABLE 10. — *Inventory of measured radionuclides in the estuary*

Longitudinal division	Reach limits (river mile)	Total measured radionuclides — In geomorphic class — Channels (curies)	Total — Slopes (curies)	Total — Flats (curies)	Total — In all geomorphic classes — Amount (curies)	Total — Percent of total in estuary	Zinc–65 — In geomorphic class — Channels (curies)	Zinc — Slopes (curies)	Zinc — Flats (curies)	Zinc — In all geomorphic classes — Amount (curies)	Zinc — Percent of total in estuary	Chromium–51 — In geomorphic class — Channels (curies)	Chrom — Slopes (curies)	Chrom — Flats (curies)	Chrom — In all geomorphic classes — Amount (curies)	Chrom — Percent of total in estuary
Fluvial	55.2–65.8	170	110	180	460	5.3	35	24	46	105	5.1	76	76	118	270	5.1
	46.2–55.2	180	82	65	327	3.7	39	16	14	69	3.4	75	61	47	183	3.5
	34.2–46.2	190	180	290	660	7.5	39	37	74	150	7.3	84	128	191	403	7.6
	27.3–34.2	210	190	500	900	10.3	47	45	120	212	10.3	86	126	328	540	10.2
	23.2–27.3	160	240	500	900	10.3	35	59	120	214	10.4	66	155	334	555	10.5
Transitional	18.1–23.2	440	790	860	2,090	23.9	120	190	210	520	25.3	168	499	592	1,259	23.7
	7.8–18.1	530	1,100	500	2,130	24.4	120	260	120	500	24.3	206	688	349	1,243	23.4
Marine	0–7.8	140	470	670	1,280	14.6	29	90	170	289	14.0	61	336	453	850	16.0
All	0–65.8	2,020	3,162	3,565	8,747	100	464	721	874	2,059	100	822	2,069	2,412	5,303	100

were carried out to provide the amount of radionuclides in each reach.

Three different computations were made. One is of the total amount of measured radionuclides (exclusive of K^{40}), and the other two are of the amounts of Zn^{65} and Cr^{51}. For each computation, average in situ count rates in the three count-rate divisions were determined to be 7,100 cpm, 14,000 cpm, and 53,400 cpm. These average rates represent total amounts of measured radionuclides in the upper 8 inches of 5.2×10^{-7}, 12×10^{-7}, and 35×10^{-7} curies per square foot, respectively (fig. 20). Comparable values for Zn^{65} are 9.3×10^{-8}, 24×10^{-8}, and 102×10^{-8} curies per square foot, and values for Cr^{51} are 42×10^{-8}, 80×10^{-8}, and 220×10^{-8} curies per square foot (fig. 21). Core samples indicated that the percentage of total measured radionuclides in the upper 8 inches in channel areas ranged from 9 to 54 and averaged 36; in slope areas, the percentage ranged from 21 to 99 and averaged 70; and in flat areas, the percentage ranged from 98 to 100 and averaged 99. Comparable percentages for Zn^{65} averaged 32, 72, and 99 and ranged from 6 to 43, 24 to 100, and 99 to 100 for the channels, slopes, and flats, respectively. For Cr^{51}, percentages averaged 66, 74, and 96 and varied from 10 to 97, 26 to 100, and 93 to 100, respectively.

Amounts of radionuclides in each reach of the estuary from the three computations are listed in table 10, and cumulative distributions of radionuclides downstream from CRM 65.8 are shown in figure 29. These data indicate that the total amount of measured radionuclides in the estuary (excluding K^{40}) is about 8,700 curies. Of this amount, about 2,100 curies (24 percent) is Zn^{65}, and 5,300 curies (61 percent) is Cr^{51}. The remaining 1,300 curies (15 percent) is comprised about equally of other activation radionuclides (Sc^{46}, Mn^{54}, Co^{60}) and fallout (Zr^{95}-Nb^{95}, Ru^{106}).

Approximately 15 percent of the total amount of
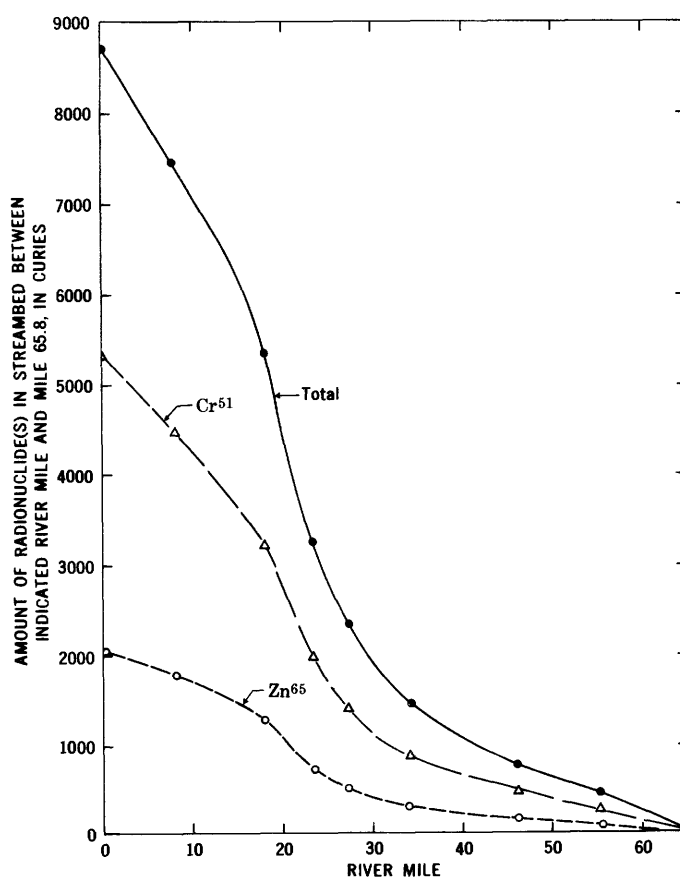
FIGURE 29. — Cumulative distribution of the amounts of total measured radionuclides, Zn^{65}, and Cr^{51} in the bed of the estuary.

measured radionuclides is between CRM 0 and 7.8 (marine environment), 48 percent is between CRM 7.8 and 23.2 (transitional environment), and 37 percent is between CRM 23.2 and 65.8 (fluvial environment). This distribution results primarily from the distribution of surface area, but also reflects differences in mean concentration and in stratigraphic distribution. Approximately 19 percent of the total area of the estuary bed is between CRM 0

and 7.8, 43 percent is between CRM 7.8 and 23.2, and 38 percent is between CRM 23.2 and 65.8. The amount of radionuclides per unit area averages nearly 45 curies per square mile for the entire estuary, about 42 curies per square mile for the fluvial environment, 51 curies per square mile for the transitional environment, and 36 curies per square mile for the marine environment. The distributions of Zn^{65} and Cr^{51} are essentially the same as the distribution of total measured radionuclides; however, proportionately, slightly more Zn^{65} resides in the transitional environment. In the entire estuary, 23 percent of the total amount of measured radionuclides resides in channel areas, 36 percent is in slope areas, and 41 percent is in flat areas.

By weighting the average depth to which radionuclides extend in channels, slopes, and flats with the area of each geomorphic class, it appears that in the fluvial environment radionuclides attain a mean depth of about 2.0 feet; in the transitional environment the depth is 1.8 feet, and in the marine environment it is 1.7 feet.

The accuracies of the computed amounts of radionuclides in the estuary cannot be assessed directly because errors associated with several steps in the computation procedure cannot be evaluated. Proportionately, the individual amounts are consistent with each other. The ratio of the amount of Cr^{51} to the amount of Zn^{65} is 2.5, and the sum of the two amounts is 85 percent of the total amount of measured radionuclides. Similar ratios of radionuclide concentrations in surficial sediments (table 7), adjusted to account for differential decay with depth, show comparable proportions. Additionally, when the mean amount of Zn^{65} per unit area in the upper 8 inches for each count-rate division is obtained from a relation between the amount of Zn^{65} per unit area in the upper 8 inches and the amount of total measured radionuclides (less K^{40}) per unit area in the upper 8 inches (rather than from fig. 21), the computed amount of Zn^{65} in the estuary is virtually unchanged from that shown in table 10. This consistency suggests that the values selected for the amounts of radionuclides per unit area in the upper 8 inches of the bed within the three count-rate divisions probably are reasonably correct.

The influence of mapping errors that could have been introduced when the estuary was divided into areas of common surficial activities and common stratigraphic distributions is indeterminate. However, because the estuary was divided into approximately 700 units, it seems reasonable, barring any consistent bias, that as a result of combining the units into nine subdivisions, mapping errors would not be highly significant.

The mean percentages used to adjust the amount of radionuclides per unit area in the upper 8 inches of the bed to represent the amount of radionuclides per unit area throughout the whole sediment column are another source of error. According to an analysis of the possible error due to these percentages, it can be stated with 90 percent confidence that the computed total amount of radionuclides in the estuary is in error by less than about 25 percent owing to the values used in the computations. The computed possible error reflects the limited number of cores from each geomorphic class and the variance in the percentages of radionuclides in the upper 8 inches determined from the cores (hereafter called adjustment factors).

The analysis is based on the supposition that the percentage error in the amount of radionuclides computed to be in the estuary is the weighted sum of the percentages of error in the amount determined for each geomorphic class; the weighting factor for each class is the fraction that the amount of radionuclides in the class is of the entire amount for all classes. Since the amount of radionuclides in each class is the product of the area of the class and the mean amount of radionuclides per unit area in the class, the percentage error for each class (assuming no error in area) is the same as the percentage error, E, in the mean amount of radionuclides computed to be in a unit area of the class. By definition

$$E = 100\left(\frac{\frac{A_8}{m} - \frac{A_8}{\bar{x}}}{\frac{A_8}{m}}\right) = 100\left(\frac{\bar{x} - m}{\bar{x}}\right)$$

in which

A_8 is the mean amount of radionuclides per unit area in the upper 8 inches of the bed;

m is the percentage that gives the true mean of the amount of radionuclides per unit area throughout the whole sediment column in the class. The value of m is unknown, but it is the same as the mean of the means of all possible samples of the adjustment factor of a given size (that is, it is the population mean); and

$\bar{x}$ is the mean percentage that was used in the inventory computation for a class. The value of $\bar{x}$ is the mean of a sample that includes all available determinations (observations) of adjustment factors in a class.

Although m is unknown and the actual value of E cannot be ascertained, the interval wherein m can

be expected to lie with a specified confidence coefficient and sample size is given (Li, 1964) by

$$\bar{x} - \frac{ts}{\sqrt{N}} < m < \bar{x} + \frac{ts}{\sqrt{N}}$$

in which

t is Student's t, which varies with percentile points of the t-distribution and the sample size;

s is the standard deviation of the sample; and

N is the number of observations in the sample (sample size).

Because $\bar{x} - m$ is a maximum at $\pm ts/\sqrt{N}$, the maximum value of E is defined by

$$E_{\max} = 100 \left(\pm \frac{ts}{\sqrt{N}\bar{x}} \right).$$

When t is taken at the 5-percent point of the t-distribution, calculated values of $E_{\max}$ are 66.9, 17.1, and 7.7 percent for the total amount of radionuclides in channels, slopes, and flats classes, respectively. Weighting these percentages in accordance with the proportion of the amount of radionuclides in each class (p. L42) indicates that the maximum error in the total amount of radionuclides in the estuary which might result from the selected adjustment factors is 24.3 percent, or about 25 percent. The comparable computed maximum errors in the amounts of Zn^{65} and Cr^{51} in the estuary are about 20 and 30 percent, respectively.

Although the maximum probable error in the inventory computations cannot be assessed because several kinds of error cannot be quantified, the error is greater than the maximum error of any single element in the computations. Inasmuch as the adjustment factors alone could contribute up to 25 percent error, the possible error would exceed this value. Also, aside from the statistical errors, the computed amounts of radionuclides may not be representative of the amounts present throughout the whole of 1965 or in subsequent years. As mentioned previously, surficial activity may be somewhat lower in June than at other times of the year, and the general level of activity probably has diminished as a result of the decrease in the number of reactors being operated at Hanford since 1964.

ASPECTS OF SEDIMENT TRANSPORT IN THE ESTUARY

A knowledge of the amounts of radionuclides in the estuary and of the spatial variations in the concentrations of radionuclides can be used to quantify approximately certain sediment-transport phenomena in the estuary. Almost without exception, however, the approximations depend on assumptions about the uptake and (or) release of radionuclides by the particulate matter in the estuary as well as about other considerations. Unfortunately, the validity of most assumptions cannot be verified. Despite this shortcoming, and with the recognition that computations may be grossly in error, we present the following analyses in the belief that some of the techniques and conclusions will be beneficial in interpreting sediment-related processes that directly influence the disposition of radionuclides in the estuary.

RETENTION OF FINE SEDIMENT

In any given reach of the estuary the rate of change in the amount of radionuclides in the reach equals the difference between the net rate of inflow of radionuclides (inflow minus outflow) and the rate of radionuclide decay in the reach. This relation can be expressed for an individual radionuclide as follows

$$\frac{dA}{dt} = (C_s Q_w)_I - (C_s Q_w)_O + (C_f Q_f)_I$$
$$- (C_f Q_f)_O + (C_c Q_c)_I - (C_c Q_c)_O - \lambda A \qquad (3)$$

where

A is the amount of the radionuclide in the reach at any given time, t;

C_s, C_f, C_c are the concentrations of the radionuclide in solution and associated with the fine and coarse sediment,[5] respectively;

Q_w, Q_f, Q_c are the discharges of water and of fine and coarse sediment, respectively;

I, O are subscripts denoting a quantity that is coming in or going out of the reach, respectively; and

λ is the decay coefficient for the radionuclide.

In equation 3,

$$(C_f Q_f)_O \equiv C_{f_O} Q_{f_O} \text{ and } (C_f Q_f)_I \equiv C_{f_I} Q_{f_I}.$$

Thus, by setting

$$\frac{(C_s Q_w)_O}{(C_s Q_w)_I} = k, \ \frac{C_{f_O}}{C_{f_I}} = c$$

and dividing by $(C_f Q_f)_I$, equation 3 becomes

$$\frac{dA}{dt} = (C_f Q_f)_I \left[R_s (1-k) + 1 - c(1-P) \right.$$
$$\left. + R_c - \frac{(C_c Q_c)_O}{(C_f Q_f)_I} - \frac{\lambda A}{(C_f Q_f)_I} \right] \qquad (4)$$

---

[5]Fine sediment is all material, including biota, whose diameter is ≥0.45 micron and <62 microns. Coarse sediment is all material ≥ 62 microns in diameter.

TABLE 11. — *Computation of fraction of fine sediment (P) retained in the estuary*

Year	Percent of total sediment discharge		Percent of total Zn65 discharge		Daily Zn65 discharge (curies per day)	$\dfrac{C_{f_i}}{C_{c_i}}$	R_s	R_c	$(C_fQ_f)_i$ (curies per day)	$\left(\dfrac{\lambda A}{C_fQ_f}\right)_i$	P
	<0.062 mm	>0.062 mm	In solution	On sediment							
1961	[1]70	[1]30	[1]20	[1]80	[2]44	5	0.21	0.09	32.4	0.18	0.10
1962	[1]70	[1]30	[1]20	[1]80	[2]29	5	.21	.09	21.4	.27	.19
1963	[3]80	[3]20	[3]17	[3]83	[2]22	5	.22	.05	17.4	.33	.29
1964	[3]62	[3]38	[3]20	[3]80	[3]18	5	.28	.12	12.8	.45	.35
[4]1965	[3]68	[3]32	[3]19	[3]81	[3]37	5	.26	.09	27.4	.21	.13
[5]1961	[1]70	[1]30	[1]20	[1]80	[2]44	5	.21	.09	32.4	.14	.06
[5]1964	[3]62	[3]38	[3]20	[3]80	[3]18	5	.28	.12	12.8	.36	.26
[6]1961	[1]70	[1]30	[1]20	[1]80	[2]44	5	.21	.09	32.4	.22	.14
[6]1964	[3]62	[3]38	[3]20	[3]80	[3]18	5	.28	.12	12.8	.53	.43

[1]Estimated.
[2]From Foster (1964).
[3]Written communication, Haushild (1968).
[4]January through June.
[5]Based on Zn65 content in bed 20 percent lower than computed amount.
[6]Based on Zn65 content in bed 20 percent higher than computed amount.

where

$$\frac{(C_sQ_w)_l}{(C_fQ_f)_l}=R_s,\quad \frac{(C_cQ_c)_l}{(C_fQ_f)_l}=R_c,\text{ and}$$

$$\frac{Q_{f_l}-Q_{f_O}}{Q_{f_l}}=P,\text{ or }Q_{f_O}=Q_{f_l}(1-P).$$

If equation 4 is applied to the transport and storage of Zn^{65}, it can be reduced with several simplifying assumptions. In the reach between Pasco and Vancouver, the amount of Zn^{65} in the streambed is essentially constant throughout the year (Nelson and others, 1966, fig. 6). If this condition also exists in the estuary, then $\frac{dA}{dt}=0$. Further, the outflow of Zn^{65} in association with coarse sediment probably can be considered negligible. With these assumptions, equation 4 reduces to

$$P=\frac{c+k\,R_s-\left[R_s+R_c+1-\dfrac{\lambda A}{(C_fQ_f)_l}\right]}{c},\qquad (5)$$

in which P is the fraction of the fine sediment inflow that is retained in the estuary.

On the basis of the following assumptions, available data on the transport of Zn^{65} at Vancouver and the computed amount of Zn^{65} in the estuary can be used to approximate the magnitude of P: (1) The transport rate of Zn^{65} and the proportion of Zn^{65} in solution and associated with the particulate matter in transport are not significantly different at Vancouver and Longview (the input station for the estuary) ; (2) the proportion of fine and coarse sediment in transport is essentially the same at Vancouver and Longview; (3) the amount of Zn^{65} in solution and associated with the suspended particulate matter in transport in the estuary at any given time is insignificant relative to the amount of Zn^{65} in the streambed; (4) the ratio of the discharges of Zn^{65} in solution going out of and coming into the estuary, k, is constant; and (5) the ratio of the concentrations of Zn^{65} associated with the fine sediment going out of and coming into the estuary, c, is constant.

In order to test the sensitivity of equation 5, values of P were computed by using transport data from several different years together with constant values of k, c, and the computed amount of Zn^{65} in the estuary. Use of equation 5 in this manner implies that the constant amount of Zn^{65} is maintained wholly by variations in the transport of fine sediment going out of the estuary. This condition probably does not exist, but it may be met sufficiently for practical purposes. A detailed explanation of the variables in equation 5 and their values is given in appendix 6.

Computed values of P along with pertinent basic data for calendar years 1961–64 and the period January 1965 through June 1965 are listed in table 11. Also included in the table are values of P computed for 1961 and 1964 with hypothetical amounts of Zn^{65} 20 percent higher and 20 percent lower than the actual computed amount. During 1963 and 1964, when the mean daily inflows of Zn^{65} associated with the fine sediment and the computed amount of Zn^{65} would have been most nearly in balance, P averaged about 0.32 (32 percent). The mean daily inflow for 1965 is somewhat high because it does not reflect inflow during the second half of the year, which typically is substantially lower than the first half. As a result, the value of P is lower than would have been computed for the whole year. Values of P computed for 1961 and 1962 also probably are low because the actual amount of Zn^{65} at that time very likely was greater than 2,059 curies as a result of the higher inflow of Zn^{65}. Although the computations are not conclusive, they suggest that on an annual basis approximately 30 percent of the fine sediment that enters the estuary is retained there.

The computations show that values of P are relatively insensitive to variations in the transport variables; for a change from 12.8 to 32.4 curies per day (153 percent increase) in the inflow of Zn^{65} associated with fine sediment, the percentage of fine

sediment that must be retained in the estuary to maintain 2,059 curies decreases only from 35 percent to 10 percent. Apparently, variations in the amount of the radionuclide in the bed affects the computed values of P to a much greater degree than do variations in the inflow of Zn^{65} associated with the fine sediment. Still, the hypothetical 20-percent variations in the amount of Zn^{65} in the bed caused the value of P to change on the average only about 0.07.

Given a knowledge of the percent of fine sediment retained in the estuary, equation 5 can be used to estimate the amount in the bed associated with any specified (past or future) Zn^{65} discharge. For instance, by using values of b, c, k, R_c, and R_s as given in appendix 6 and table 5 and by assuming P equals 0.30, the amount of Zn^{65} in 1961 coincident with the annual mean daily Zn^{65} discharge of 44 curies per day would be computed as 4,345 curies.

RADIONUCLIDE CONCENTRATIONS AND SEDIMENT TRANSPORT

Information on the longitudinal attenuation of radionuclide concentrations associated with sediment particles in a given size range (fig. 28) provides the potential for computing the mean rate of transport of the particles in the range. Implicit in the computation are the assumptions that (1) the radionuclide concentration associated with the particles changes only as a result of radioactive decay, (2) the particles present at a downstream location ultimately came from upstream, and (3) the concentration used to portray the level of radioactivity associated with the particles of the size range at any location is representative of the concentration associated with all the particles of the size range that may be transported at that location. If these assumptions hold, the difference in the concentrations between two locations is equal to the decay that occurs during the time the particles are transported from the first to the second location; hence, the mean rate of transport of the size range (mean particle velocity), v_p, can be computed from

$$v_p = LT^{-1} = L\left(\frac{2.303}{\lambda} \log \frac{C_0}{C}\right)^{-1} \qquad (6)$$

where

L is the distance between the two points,

T is the net time required for the particle to move between the two points,

λ is the decay coefficient of the radionuclide, and

C_0 and C are the concentrations of the radionuclide associated with the particles of the size range at the initial

and final locations (or times), respectively.

Computations of v_p for several size ranges were made by using the average attenuation of Zn^{65} in the reach between miles 14 and 59, as defined by regression lines for the data in figure 28. In general, v_p decreased as the geometric mean particle size of the range increased. The regression of the logarithm of v_p on the logarithm of geometric mean particle size was defined to achieve a smooth progression. From this relation, values of v_p of 3,210, 2,920, 2,710, 2,520, and 2,390 feet per day were determined for size ranges having geometric mean particle sizes of 0.0438, 0.105, 0.209, 0.417, and 0.707 mm, respectively.

Throughout most of the reach between miles 14 and 59, the sediment in the channels (where most of the sediment transport occurs) has a mean particle size of approximately 0.250 mm and is formed into dunes of various heights. Of the several size ranges for which velocities were computed, only the finest two ranges are transported at times in significant quantities as suspended sediment. The coarser sediment moves predominantly as bedload. Because so few particles are transported in suspension, the particle velocities computed for most of the sediment seem to be inordinately high. Also, when one considers that tidal action causes the flow in the reach at times to be either upstream or essentially stagnant, the computed particle velocities seem even more unreasonable. Reasonable values of v_p can only be achieved by substantial increases in C_0/C. That is, C_0 must be higher relative to C, or, conversely, C must be lower relative to C_0. The discrepancy between computed and reasonable values suggests that one or more of the underlying assumptions is violated.

Contrary to the first assumption, the possibility exists that radionuclides are exchanged on the sediment particles, so the longitudinal attenuation of concentration may not be intimately related to decay. However, available data for Zn^{65} (Johnson and others, 1967) tend to suggest that only small amounts of this nuclide are released at any time. Also, the general decrease in concentrations of Zn^{65} in solution due to progressive dilution toward the mouth of the estuary minimizes the likelihood of additional uptake. In the lower estuary, the influx of littoral drift may dilute the bed mixture with "uncontaminated" particles and thereby cause radionuclide concentrations to be lower than they would be otherwise. This effect negates the second assumption, but since low values of C promote the computation of more reasonable values of v_p, dilution of this

type cannot be used to explain the discrepancy. Contrary to the third assumption, low values of C_0 could result from sampling surficial sediment that contains significant numbers of particles that have been buried for extended periods of time and have unusually low levels of activity due to decay. This effect could result from the migration of large dunes during the spring freshet, which was occurring during the survey, and is most likely to occur in the highly channelized reaches of the upstream part of the estuary.

The change, with time, in the ratio of the concentrations of two different radionuclides also has been used to estimate particle velocities (Gross and Nelson, 1966). The technique is identical to the one used to estimate deposition rates of sediment (see following section), except that the length dimension refers to distance along the channel rather than depth of deposit. The assumptions (next col.) in both techniques are the same. Using the attenuation of a ratio rather than the attenuation of a single radionuclide has some advantages as well as disadvantages. Perhaps the most obvious advantage of a ratio is that the effects of most types of dilution are minimized, with the result that the ratio attenuation may be more closely related to decay. One disadvantage is that the possible effects of uptake and (or) release must be considered for both radionuclides in the ratio.

Radionuclide concentration ratios for individual size ranges are not available from the data, but the mean ratios for each cross section (table 7) can be utilized to estimate the mean transport rate for the bed-sediment mixture as a whole. Mean Zn^{65}/Co^{60} ratios along the estuary (table 7) attenuate approximately 1.5 times in 54 miles. Accordingly, the mean rate of transport is computed as 1,770 feet per day. Although this mean rate for the whole bed mixture is somewhat lower than the rate for the mean particle size in the estuary (0.208 mm), as estimated from the regression of the logarithm of v_p (from eq 6) on the logarithm of size, it also appears to be high. The general agreement between velocities computed by the two different techniques tends to reinforce the conclusion that the concentrations of radionuclides are influenced by factors in addition to radionuclide decay.

RATES OF DEPOSITION

The relative rates of decay between two abundant radionuclides can be used to estimate rates of aggradation. This technique has been used by various investigators, including Nelson, Perkins, Nielsen, and Haushild (1966), who determined deposition rates for Columbia River sediment in McNary Reservoir.

The fundamental equation characterizing radionuclide decay is

$$A = A_0 e^{-\lambda T}$$

where

A_0 is the amount (or concentration) of a radionuclide at some initial time, $t=0$;

A is the amount (or concentration) of the radionuclide at a later time, $t=T$; and

λ is the decay coefficient for the radionuclide. With two radionuclides,

$$\frac{(A_0)_1}{(A_0)_2} = \frac{A_1 e^{\lambda_1 T}}{A_2 e^{\lambda_2 T}} = \frac{A_1}{A_2} e^{(\lambda_1 - \lambda_2)T}.$$

Hence,

$$T = \left(\frac{2.303}{\lambda_1 - \lambda_2}\right) \log \frac{R_0}{R} \qquad (7)$$

in which

$$R_0 = \frac{(A_0)_1}{(A_0)_2} \text{ and } R = \frac{A_1}{A_2}.$$

When equation 7 is used to determine a deposition rate, R_0 and R pertain to the ratios of concentrations of two radionuclides at an initial bed elevation, d_0, and at a higher elevation, d, respectively, such that $d - d_0 = h$. Hence, equation 7 states, in effect, that the time, T, required to deposit sediment within a depth increment, h, located between two different elevations in the bed is proportional to the difference between the logarithms of the ratios of the concentrations of the radionuclides at each depth. The net deposition rate during the time interval, T, is equal to h/T. Implicit in the use of this technique are the assumptions that (1) the ratios of the concentrations of the radionuclides associated with the sediment at the two elevations were equal at the time of deposit, and (2) the changes in the concentrations of the radionuclides during the time interval are due to decay only.

Data in appendixes 1 and 3 show that radionuclide ratios in the surficial sediment may vary greatly, even within given areas where the sediment texture and in situ gross gamma radioactivity are fairly uniform. The variations probably occur partly because in most places aggradation is not continuous but is interrupted by periods of degradation. As a result of these alternating processes, particularly if they are related to dune movement, "older" particles that have been buried for some time may be reexposed and deposited once again at the bed surface. Thus, the ratio that exists at the bed surface depends on the relative "age" of the particles there at the time of sampling and may be unrelatable in terms of decay to ratios in sediment below the surface. When this is the case, deposition rates computed
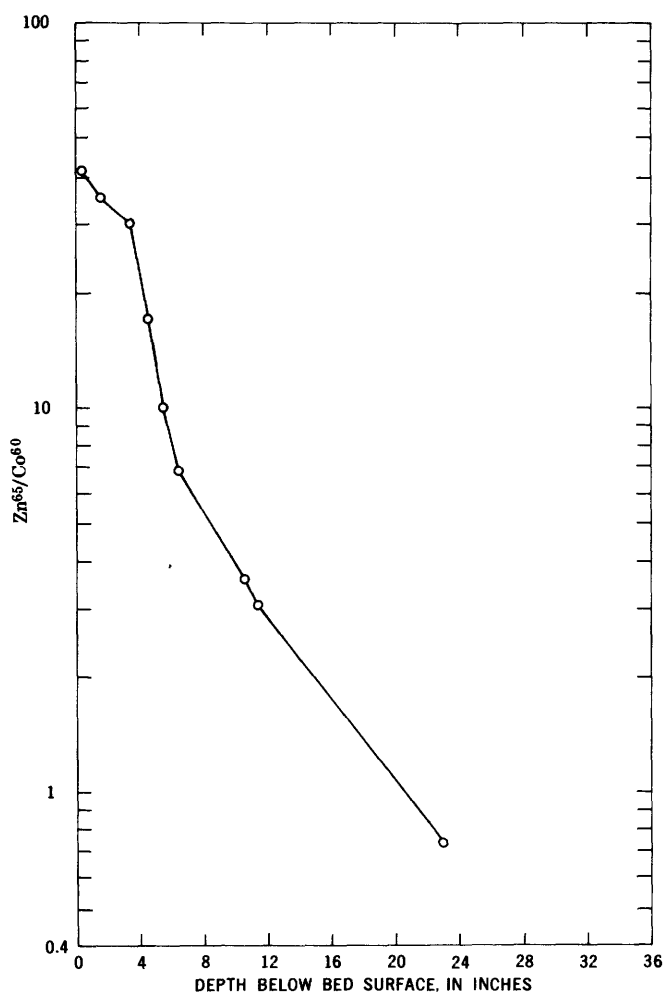
FIGURE 30. — Variation of Zn^{65}/Co^{60} ratio with depth in core C373.

from equation 7 are invalid. Because alternating deposition and erosion are not as likely to occur with fine sediment as with coarse sediment, except possibly at specific locations in the estuary, the most meaningful deposition rates probably can be obtained from cores collected in areas where fine sediment is being deposited more or less continuously.

Of the available cores, C373 seems most likely to satisfy the requirements for a reasonably accurate long-term deposition rate. The sediment is comparatively fine throughout the length of the core, radionuclide ratios change with depth in a consistent manner, and the core was obtained from an area where continuous deposition probably has been occurring. Figure 30 shows the attenuation of the Zn^{65}/Co^{60} ratio with depth for this core. The average deposition rate obtained by weighting the computed rate between each pair of defined points with the length of the depth increment is 5.4 inches per

year for the upper 11.5 inches of the bed. The net deposition rate, determined from the length of time necessary for the ratio at the surface to become equal to the ratio at the 11.5-inch depth, is 3.4 inches per year. The computed rates, of course, apply only to a local area and should not be assumed to represent a general deposition rate for the whole estuary.

CONCLUSIONS

Bed sediment in the Columbia River estuary is predominantly sand ($-1.0 < phi \leqslant 4.0$) ; however, textural characteristics vary appreciably throughout the estuary. Clay-size material ($phi \geqslant 8.0$) is sparse, but significant amounts of silt ($4.0 < phi < 8.0$) are present, and about 25 percent of all surficial sediment samples contain some gravel ($phi \leqslant -1.0$). An "average" sediment sample consists of about 1 percent gravel, 84 percent sand, 13 percent silt, and 2 percent clay.

Separating the estuary into geomorphic classes called channels, slopes, and flats and grouping samples according to class significantly reduces variability of the data and permits comparisons within cross sections and among cross sections. In the estuary as a whole, channel sediments are coarse ($M_\phi = 1.87$), are moderately well sorted ($\sigma_\phi = 0.75$), and have size distributions that tend to be skewed toward the coarse particles ($\alpha_{1\phi} = -0.02$) ; sediments on flats are fine ($M_\phi = 3.18$), are relatively poorly sorted ($\sigma_\phi = 0.90$), and have distributions skewed toward the fine particles ($\alpha_{1\phi} = 0.17$) ; and slope sediments are intermediate. From the head to the mouth of the estuary, channel sediments appear to become finer, and their size distributions become less negatively skewed; sediments on slopes and flats show no significant trends.

A further separation of the estuary into longitudinal divisions in which the dominant processes are fluvial, transitional, and marine facilitates additional comparisons among samples. Within any given division, channels contain sediments with the coarsest particles, flats generally have sediments with the finest particles and the most positively skewed size distributions, slopes generally have the least skewed size distributions, and sediments in all three classes are moderately well sorted. Channel sediments are finest in the transitional division and are finer and have more positively skewed size distributions in the marine division than in the fluvial division. Slope sediments have the same textural characteristics throughout the estuary but may be slightly better sorted and have size distributions more positively skewed near the estuary mouth. On flats, sediments are finer in the fluvial and marine divisions

than in the transitional division, where extensive sand flats occur. In all classes and divisions, the variations in textural characteristics are large. Elimination of "outlying values" as determined by statistical tests reduces variances but does not affect the previously noted textural trends.

Cores show that sediment texture varies stratigraphically and that strata usually are less than 1 inch thick. At many locations, sand is overlain with a thin fine-grained layer. In channels, sediments are fairly homogeneous stratigraphically, but on slopes and flats stratigraphy often is complex. Sediment color varies with depth from brown and green to gray and black. Organic matter occurs either in layers or as individual fragments. In general, sediments in core segments are finer than sediments in surficial samples. Textural differences between core and surficial samples probably reflect a biased selection of core sites rather than a significant textural difference with depth.

About 60 percent of the estuary had in situ gross gamma count rates of less than 10,000 cpm (background was probably about 2,500 cpm), 19 percent had rates from 10,000 to 20,000 cpm, and 21 percent had rates from 20,000 to 142,000 cpm. Generally, low count rates occurred in channels, whereas count rates varied over a fairly wide range on slopes and flats. Both in situ gross gamma count rates and laboratory gross gamma count rates of surficial sediment samples correlate well with total measured radionuclide concentrations and with Zn^{65} concentrations. In situ count rates also correlate fairly well with the amounts of radionuclides per unit area in the upper 8 inches of the bed.

The radionuclides Cr^{51}, Zn^{65}, Sc^{46}, Ru^{106}, Mn^{54}, Co^{60}, and Zr^{95}-Nb^{95} are 6.2, 2.2, 0.2, 0.1, 0.07, 0.06, and 0.05 times as abundant, respectively, in surficial sediments as naturally occurring K^{40}, which averages about 14 pc/g in estuary sediments that contain little organic material.

Radionuclide concentrations vary greatly throughout the estuary. Generally, concentrations are lowest in channels and highest on slopes and flats. When data from a common division (fluvial, transitional, or marine) are combined, standard deviations generally are so large as to preclude positive conclusions about trends in concentration along the estuary. Ratios, however, suggest changes in the relative amounts of some radionuclides; Cr^{51} appears to increase relative to Zn^{65} toward the mouth of the estuary.

Sediment texture and organic-matter content combine with sample location to influence the concentration of radionuclides associated with the sediment and to contribute to the variance of concentration within samples from common geomorphic classes or from common longitudinal divisions.

The stratigraphic distributions of radionuclides vary considerably within the estuary. On the average, 66 percent of the total amount of measured radionuclides (excluding K^{40}) at core sites is within 8 inches of the bed surface, but at some sites radionuclides extend well below 60 inches. Radionuclides tend to be distributed to greater depths in channels and on slopes than on flats. Highest concentrations typically occur at the surface or a few inches below. Amounts of measured radionuclides (less K^{40}) in the bed ranged from 0.05 to 15 microcuries per square foot and averaged 3.6 microcuries per square foot. Chromium-51 is relatively less abundant in the sediment column than it is in surficial sediments, but overall, it averages about twice as abundant as Zn^{65}.

Sediment texture influences the radionuclide content significantly. Radionuclide concentrations increase as the mean size of sediment decreases, as the sediment becomes less well sorted, and as the skewness of the sediment size distribution changes from negative to positive.

Values of specific surface and of mean size computed from particle-size distributions of sediment samples correlate with concentrations of Zn^{65} about equally well.

Radionuclide concentrations associated with individual size separates were approximated by using radionuclide and size data from surficial samples together with an average relation between mean size and radionuclide concentration. Computations for each cross section suggest that the concentrations of Zn^{65} associated with different size ranges (represented by the geometric mean) decrease progressively between Longview and the estuary mouth.

Data on the surficial and stratigraphic distributions of radionuclides and sediment texture in association with information on streambed morphology provide a framework for a generalized qualitative description of the distribution of radionuclides in the estuary.

At the time of the 1965 survey, in situ count rates of 7,100, 14,000, and 53,400 cpm corresponded to total amounts of measured radionuclides in the upper 8 inches of the bed of 5.2×10^{-7}, 12×10^{-7}, and 35×10^{-7} curies per square foot, respectively. The amounts of measured radionuclides in the upper 8 inches averaged 36 percent of the amount of measured radionuclides in the total sediment column in channels, 70 percent in the total column on slopes, and 99 percent in the column on flats.

The total amount of measured radionuclides in the

estuary (excluding K^{40}) in June 1965 was about 8,700 curies, of which 61 percent was Cr^{51}, 24 percent was Zn^{65}, and 15 percent was other activation products and fallout. This total amount is about one-quarter of the amount that Seymour and Lewis (1964) estimated was in the total system (river, estuary, and ocean) below Vancouver in 1961–63. Approximately 15 percent of the total amount of measured radionuclides was between CRM 0 and 7.8 (marine division), 48 percent was between CRM 7.8 and 23.2 (transitional division), and 37 percent was between CRM 23.2 and 65.8 (fluvial division). The amount of measured radionuclides per unit area averaged nearly 45 curies per square mile for the entire estuary, about 42 curies per square mile for the fluvial division, 51 curies per square mile for the transitional division, and 36 curies per square mile for the marine division. Channels, slopes, and flats contained 23, 36, and 41 percent, respectively, of the total amount of measured radionuclides. The distributions of Zn^{65} and Cr^{51} are essentially the same as the distribution of total measured radionuclides except that, proportionately, slightly more Zn^{65} is in the transitional division.

The computed inventory may not be representative of the inventory throughout 1965 or in subsequent years because of possible seasonal variations in the amounts of radionuclides stored in the bed and reductions in the number of reactors in operation at Hanford.

Computations based on transport rates of Zn^{65} at Vancouver and a mass-balance equation derived from the assumption of a constant amount of Zn^{65} in the bed suggest that on an annual basis approximately 30 percent of the fine sediment that enters the estuary is retained there. The computations are relatively insensitive to errors in the transport data and in the quantity of Zn^{65} in the estuary bed.

Mean particle velocities for individual size separates determined from the attenuation of Zn^{65} concentration downstream along the estuary are somewhat higher than the mean particle velocity for the whole bed mixture determined from the attenuation of the Zn^{65}/Co^{60} ratio. However, overall, the computed velocities seem excessively high. The results reinforce the conclusion that the concentrations of radionuclides in surficial sediments are determined by factors in addition to radioactive decay.

At many core sites, cyclic deposition and erosion preclude accurate computations of deposition rates from the variation of radionuclide ratios with depth. For one core located where conditions appeared to be compatible with the assumptions of the technique, the attenuation of the Zn^{65}/Co^{60} ratio with depth

gave a net deposition rate of 3.4 inches per year for the upper 11.5 inches of the core.

Relatively low sampling densities, lack of replicate samples and analyses, and incomplete information on the morphology and physical-chemical character of environments throughout the estuary have restricted the extent to which the data could be interpreted. However, despite the deficiencies, available data indicate that information on geomorphic expression and sediment composition can be combined with a knowledge of the types and amounts of radionuclides discharged to provide the basis for predicting the probable distribution of radionuclides in rivers and estuaries.

Additional surveys of a similar but more detailed nature should be undertaken to provide data for refining the delineation of significant evironmental divisions within the estuary and for improving the definition of seasonal and long-term trends in the radionuclide inventory.

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APPENDIXES

APPENDIX 1. — *Particle-size statistics of surficial sediment from the estuary*

[Statistics computed according to Inman (1952) and Trask (1932). In situ gross gamma values are in counts per minute]

SAMPLE NC	PHI VALUE AT INDICATED PCT FINER 5	50	95	INMAN VALUES MEAN	SORT	ALPHI	ALPH2	BETA	TRASK VALUES SORT	SKEW	PERCENT GRAVEL	SAND	SILT	CLAY	IN SITU GROSS GAMMA
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 64																
G202---65	2.35	1.71	.00	1.61	.51	-.20	-1.05	1.31	1.249	1.046	1	99			6300
G203---65	2.15	1.43	-.18	1.23	.64	-.32	-.69	.83	1.318	1.143	2	98			9000
G234---65*	2.04	1.26	.00	1.16	.59	-.10	-.41	.71	1.302	1.057	3	97			10300
G205---65	1.92	.81	-.12	.87	.58	.09	.16	.77	1.301	.963	1	99			8200
G207---65	2.80	2.11	1.00	2.07	.42	-.12	-.51	1.14	1.212	1.036		100			10500
G206---65	7.00	3.62	2.16	3.76	1.13	.13	.85	1.14	1.676	.875		63	34	3	84500
G208---65	7.46	3.72	2.50	3.96	1.06	.22	1.19	1.35	1.646	.838		60	36	4	47300
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 59																
G220---65*	2.74	2.28	1.92	2.28	.22	-.00	.24	.89	1.106	1.000		99	1+		8000
G221---65*	2.12	1.46	-.42	1.18	.68	-.40	-.89	.85	1.366	1.256	3	97			6100
G210---65*	14.00	5.78	4.08	7.08	2.51	.52	1.30	.98	2.693	.520		4	74	22	4100
G211---65*	2.08	1.36	.71	1.36	.39	-.00	-.01	.64	1.201	1.001		100			8000
G212---65*	2.41	1.72	.78	1.66	.49	-.11	-.25	.66	1.253	1.025		100			8300
G218---65	6.69	2.94	1.50	3.53	1.37	.43	.85	.90	1.745	.698		75	22	3	13000
G219---65	2.10	1.30	.27	1.24	.54	-.11	-.22	.68	1.284	1.033		100			8200
G217---65*	2.21	.61	-2.54	-.47	2.09	-.52	-.37	.14	2.385	2.041	26	73	1+		6600
G216---65	1.95	1.07	.00	1.04	.62	-.05	-.15	.57	1.359	.995	2	98			6600
G215---65*	2.13	1.12	-6.06	-.99	2.72	-.77	-1.13	.51	1.625	1.514	22	78			5400
G214-1-65*	2.10	1.38	-1.00	1.14	.70	-.35	-1.18	1.20	1.300	1.204	5	95			8700
G213---65*	2.31	1.58	.83	1.57	.44	-.04	-.03	.69	1.225	1.015		100			6300
G222---65*	10.46	4.21	2.63	4.65	1.65	.27	1.41	1.37	2.165	.781		45	49	6	41300
G223---65*	9.33	4.82	3.22	5.26	1.65	.27	.88	.86	2.116	.785		28	62	10	59800
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 54																
G225---65	6.46	2.89	1.76	3.34	1.20	.37	1.02	.96	1.720	.767		77	20	3	21800
G226---65*	2.04	1.03	-2.18	.73	1.00	-.31	-1.10	1.12	1.561	1.174	11	89			5800
G227---65*	3.07	2.56	1.68	2.49	.38	-.18	-.49	.83	1.191	1.060		100			8500
G228---65*	3.10	2.63	2.08	2.62	.30	-.06	-.13	.68	1.149	1.010		100			9900
G229---65	7.64	4.84	3.05	4.24	.87	.23	1.49	1.62	1.501	.880		50	45	5	73200
G232---65	3.09	2.47	2.00	2.50	.31	.08	.24	.75	1.156	.977		99	1+		11800
G231---65	2.35	1.64	.39	1.55	.56	-.16	-.49	.76	1.301	1.054		100			8400
G230---65*	10.13	3.36	.49	3.69	2.21	.15	.88	1.19	2.872	.854	1	62	30	7	8000
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 50																
G233---65*	-.54	-3.12	-5.00	-2.97	1.29	.11	.27	.73	1.858	.846	94	5	1+		4100
G235---65	1.84	1.13	-1.00	.99	.59	-.24	-1.20	1.40	1.306	1.108	5	95			7000
G234---65	2.19	1.44	.20	1.31	.58	-.21	-.41	.71	1.299	1.083		100			7600
G236---65*	3.10	2.02	.88	2.00	.66	-.04	-.05	.68	1.353	1.030		100			7900
G237---65	2.46	1.84	1.06	1.83	.38	-.02	-.20	.83	1.189	.998		100			9000
G238---65*	2.64	2.02	1.56	2.07	.33	.16	.26	.64	1.166	.954		100			8600
G239---65	2.90	2.28	1.75	2.30	.32	.05	.13	.82	1.148	1.000		99	1+		10600
G240---65*	3.06	2.47	1.77	2.43	.40	-.09	-.13	.62	1.205	1.032		100			8500
G241---65	4.64	3.14	2.40	3.24	.54	.18	.70	1.07	1.252	.976		89	10	1	22700
G242---65	2.72	2.25	1.78	2.25	.22	-.00		1.10	1.109	1.000		100			6300
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 47																
G244---65	1.77	.87	-.42	.84	.56	-.04	-.34	.94	1.304	1.019	3	97·			6700
G245---65	1.88	1.08	-.18	.97	.57	-.19	-.41	.80	1.297	1.097	2	98			6000
G246---65*	2.14	1.60	.96	1.57	.35	-.07	-.14	.67	1.176	1.019		100			7500
G247---65*	2.42	1.49	.77	1.51	.45	.04	.24	.82	1.236	.982		100			10200
G248---65	1.84	.83	-.20	.84	.58	.03	-.01	.77	1.308	.988	1	99			6580
G249---65*	2.07	1.36	.12	1.33	.47	-.08	-.57	1.10	1.217	.994	2	98			7500
G250---65	2.38	1.69	1.14	1.66	.34	-.09	-.36	.81	1.177	1.022		100			9308
G251---65	2.84	2.27	1.56	2.27	.32	-.01	-.22	1.00	1.149	1.000		100			6980
G252---65*	4.84	3.08	2.50	3.25	.66	.25	.89	.77	1.318	.926		86	13	1	30000
G243---65	2.93	2.21	1.60	2.20	.33	-.03	.17	1.04	1.151	1.000		99	1+		7500
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 42																
G266---65*	1.84	1.20	.60	1.21	.37	.81	.04	.67	1.188	1.000		100			
G265---65	2.80	1.29	.18	1.20	.54	-.16	-.37	.70	1.273	1.841		100			4700
G264---65	1.69	.76	-.80	.75	.61	-.01	-.51	1.03	1.333	1.005	4	96			4500
G261---65	2.39	1.54	.31	1.45	.64	-.15	-.30	.61	1.355	1.081		100			10100
G262---65*	12.70	4.80	3.22	5.30	1.48	.34	2.13	2.20	1.870	.723		21	70	9	9600
G263---65	3.15	2.41	1.81	2.44	.36	.07	.17	.83	1.183	.979		99	1+		
G259---65	2.37	1.82	.82	1.80	.36	-.07	-.63	1.13	1.178	1.004		100			8000
G260---65	10.94	4.90	2.75	5.16	1.36	.19	1.43	2.01	1.727	.842		18	72	10	92500
G255---65*	3.25	1.78	.65	1.85	.80	.09	.22	.64	1.469	.955		99	1+		52600
G256---65	2.41	1.83	1.25	1.83	.35	.01	.01	.67	1.176	.998		100			6800
G257---65	2.70	2.03	.00	1.96	.47	-.15	-1.45	1.89	1.242	1.062	3	97			7400
G258---65	3.71	2.60	1.72	2.65	.50	.09	.23	1.00	1.249	.982		97	3+		13900
G253---65*	12.40	5.33	3.50	5.81	1.67	.29	1.57	1.67	2.086	.736		13	75	12	142000
G254---65*	10.94	4.46	1.32	4.47	2.67	.00	.62	.80	4.182	1.471		44	46	10	19200
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 38																
G267---65	7.00	2.55	1.57	3.41	1.35	.63	1.28	1.01	1.563	.659	1	76	20	3	5600
G268---65	2.20	1.28	.08	1.22	.68	-.09	-.21	.56	1.389	1.049	1	99			4200
G269---65*	2.15	1.44	.92	1.49	.36	.13	.26	.70	1.182	.962		100			7000
G270---65	6.62	2.46	1.78	3.43	1.38	.70	1.27	.76	1.876	.416		75	22	3	2300
G271---65	5.69	1.72	.10	1.99	1.25	.21	.94	1.24	1.772	.797	1	90	7	2	5700
G272---65	2.69	2.11	1.15	2.06	.37	-.13	-.50	1.08	1.182	1.035		99	1+		9400
G273---65	2.21	1.36	.21	1.31	.53	-.11	-.29	.88	1.255	1.006	1	98	1+		5900
G274---65	2.93	2.12	1.50	2.12	.38	.01	.26	.87	1.195	.997		99	1+		11600
G275---65	2.29	1.74	.50	1.68	.42	-.14	-.81	1.13	1.205	1.010		100			6800
G278---65	3.50	2.76	2.16	2.78	.36	.06	.20	.85	1.163	1.000		9A	2+		12800
G277---65*	2.21	-1.12	-3.00	-.83	2.17	.13	.34	.20	3.582	.785	51	49			5900
G276---65*	9.60	4.34	2.50	4.90	1.62	.34	1.05	1.19	2.035	.664	1	40	51	8	23600
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 31																
G287---65	2.50	1.73	.17	1.65	.56	-.14	-.70	1.08	1.291	1.043		100			9400
G286---65	3.15	2.31	1.60	2.35	.46	.09	.16	.69	1.228	.978		99	1+		7200
G285---65*	2.53	1.91	1.31	1.93	.36	.05	.02	.72	1.179	.987		100			7600
G284---65	4.69	3.02	1.50	2.96	.59	-.11	.12	1.70	1.291	1.047		92	7	1	30700
G282---65	2.60	1.57	.10	1.50	.76	-.09	-.28	.65	1.435	.995	1	99			14700
G281---65	2.95	1.63	.65	1.87	.75	.32	.23	.53	1.474	.766		100			8500
G280---65	1.75	.83	-.47	.78	.60	-.09	-.32	.85	1.329	1.041	2	98			5700

See footnotes at end of table.

APPENDIX 1. — *Particle-size statistics of surficial sediment from the estuary—*
Continued

SAMPLE NO.	PHI VALUE AT INDICATED PCT FINER			INMAN VALUES					TRASK VALUES'		PERCENT				IN SITU GROSS GAMMA
	5	50	95	MEAN	SORT	ALPH1	ALPH2	BETA	SORT	SKEW	GRAVEL	SAND	SILT	CLAY	GAMMA
G279---65	5.00	3.05	1.61	2.97	.59	-.13	.44	1.88	1.283	1.057		91	8	1	7700
G283---65	9.00	4.07	2.59	4.57	1.45	.35	1.19	1.21	1.769	.861		48	46	6	80700
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 27															
G288---65*	2.56	.55	-3.00	-.44	2.56	-.39	-.30	.09	3.855	2.594	36	64			9300
G289---65*	2.12	1.56	.84	1.52	.39	-.12	-.21	.66	1.196	1.039		100			5200
G290---65	2.65	2.10	1.50	2.07	.33	-.08	-.07	.77	1.161	1.020		100			7100
G291---65	8.00	4.03	2.57	4.31	1.29	.22	.98	1.11	1.764	.915		49	46	5	106000
G292---65	4.12	2.98	2.33	3.01	.41	.08	.59	1.19	1.210	.971		94	6+		29900
G293---65*	14.00	4.78	3.35	5.27	1.37	.36	2.84	2.88	1.760	.737		19	71	10	137000
G294---65	2.56	1.53	.44	1.52	.67	-.01	-.05	.58	1.390	.983		100			6700
G295---65	2.46	1.89	1.25	1.90	.33	-.04	-.10	.84	1.164	.990		100			6600
G296---65	2.74	2.02	.72	1.53	.47	-.19	-.62	1.16	1.239	1.080	2	97	1+		5500
G297---65	3.50	2.70	2.14	2.73	.37	.06	.31	.84	1.178	.999		97	3+		12700
G298---65	2.73	2.12	1.50	2.11	.36	-.04	-.03	.70	1.182	1.009		100			5300
G299---65*	11.87	4.85	3.15	5.63	2.07	.38	1.28	1.10	2.633	.607		33	53	14	38500
G300---65	3.00	1.92	.65	1.85	.61	-.12	-.16	.94	1.305	1.030	1	98	1+		6800
G301---65*	11.06	6.27	2.00	6.35	2.36	.03	.11	.92	2.649	.943	1	15	63	21	18800
G302---65	5.46	2.56	1.94	2.80	.62	.40	1.86	1.86	1.317	.826		90	8	2	19900
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 23															
G315---65	2.41	1.80	.39	1.72	.46	-.17	-.86	1.19	1.205	1.005		100			6200
G316---65	2.32	1.81	.63	1.73	.42	-.21	-.80	1.00	1.204	1.026	1	99			5600
G317---65	8.46	3.33	2.26	4.36	1.87	.55	1.08	.66	2.380	.404		63	31	6	15300
G318---65	2.43	1.97	1.37	1.94	.31	-.07	-.21	.72	1.156	1.021		100			8600
G319---65*	2.14	1.48	.22	1.35	.53	-.25	-.57	.80	1.265	1.096	2	98			4800
G320---65	2.56	1.98	1.37	1.98	.34	-.02	-.06	.76	1.171	1.005		99	1+		6800
G321---65*	9.60	4.78	3.22	5.23	1.41	.32	1.15	1.26	1.798	.764		21	71	8	55900
G322---65	2.83	1.85	1.05	1.88	.51	.08	.19	.74	1.263	.971		99	1+		15700
G323---65*	2.74	2.17	.91	2.03	.46	-.30	-.76	1.00	1.197	1.062		99	1+		9600
G324---65	2.42	1.85	1.22	1.86	.32	.03	-.11	.84	1.161	.994		100			5900
G309---65	5.00	2.81	2.15	3.08	.70	.39	1.09	1.04	1.322	.880		87	12	1	19700
G307---65*	14.00	4.75	3.32	5.17	1.31	.32	2.99	3.09	1.713	.785		20	72	8	56100
G306---65	4.80	3.16	2.50	3.23	.47	.15	1.03	1.43	1.206	1.001		89	10	1	22500
G305---65	2.26	1.57	.42	1.54	.50	-.06	-.46	.85	1.267	1.019		99	1+		5600
G304---65	2.82	2.20	1.41	2.17	.37	-.09	-.23,	.90	1.170	1.009		99	1+		8000
G303---65	7.46	2.74	1.63	3.12	.93	.40	1.95	2.15	1.348	.923	2	82	12	4	12300
G308---65	4.00	2.58	1.22	2.52	.70	-.10	.04	.99	1.349	1.075		95	4	1	15200
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 18															
G334---65*	9.87	4.31	2.44	5.01	2.13	.33	.87	.74	2.773	.643		45	45	10	38200
G335---65	2.65	2.19	1.66	2.17	.25	-.07	-.12	.99	1.115	1.000		99	1+		17000
G336---65	2.65	1.79	-1.28	1.51	.84	-.33	-1.32	1.34	1.474	1.215	6	94			5500
G338---65	2.13	1.06	.00	1.07	.65	.01	.00	.63	1.353	1.001	2	98			4800
G337---65	3.85	2.37	1.15	2.44	.65	.11	.20	1.08	1.320	.934		96	4+		15200
G325---65	2.42	1.86	.88	1.82	.39	-.10	-.53	.84	1.193	1.014		100			5300
G326---65	2.60	2.07	1.53	2.05	.31	-.04	.00	.73	1.153	1.011		100			3800
G314---65	2.35	1.74	.80	1.70	.42	-.10	-.38	.84	1.204	1.008		100			5400
G313---65	2.23	1.52	.13	1.45	.51	-.13	-.67	1.05	1.260	1.049	1	99			6300
G312---65	2.20	.93	-1.00	.97	.90	.04	-.37	.78	1.550	.935	5	95			5000
G311---65	8.00	4.03	3.05	4.40	1.01	.36	1.44	1.48	1.538	.804		49	46	5	9100
G310---65	7.46	3.43	1.94	3.74	1.40	.22	.91	.97	1.970	.843		64	32	4	13300
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 14															
G343---65	2.68	2.20	1.68	2.19	.22	-.04	-.07	1.23	1.106	1.000		99	1+		7300
G344-1-65*	8.49	2.62	1.29	3.80	1.90	.62	1.19	.89	2.203	.404		72	23	5	18900
G344-2-65	9.87	4.94	2.15	5.03	2.11	.04	.51	.83	2.816	1.122		35	55	10	18900
G345---65	6.00	2.11	1.08	2.35	.81	.30	1.76	2.04	1.401	.879		91	7	2	28700
G346---65*	3.00	2.28	1.76	2.30	.29	.10	.36	1.10	1.133	1.000		98	2+		11900
G347---65	3.28	2.58	2.04	2.57	.32	-.02	.25	.94	1.161	1.006		99	1+		10800
G348---65	2.24	1.12	-.47	1.04	.80	-.10	-.29	.70	1.477	1.041	2	97	1+		4300
G349---65	2.88	2.24	1.67	2.25	.30	.00	.10	1.02	1.139	1.000		100			5300
G332---65	5.28	2.84	1.72	3.04	.85	.23	.77	1.09	1.463	.900		86	13	1	25500
G331---65	2.17	1.37	.54	1.37	.50	-.01	-.03	.84	1.262	1.005		100			6600
G330---65*	10.94	4.67	2.64	4.91	1.87	.13	1.13	1.21	2.433	1.018		36	54	10	43800
G329---65	2.93	2.14	1.62	2.15	.33	.04	.40	.95	1.171	.993		98	2+		8500
G328---65	2.94	2.25	1.73	2.27	.32	.05	.27	.89	1.149	1.000		99	1+		6000
G327---65*	3.12	2.49	2.03	2.54	.33	.15	.24	.65	1.166	.957		100			8900
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 6															
G352---65	6.69	3.21	1.86	3.64	1.30	.33	.82	.86	1.910	.680		66	32	2	15000
G353---65*	12.40	4.23	2.72	5.31	2.10	.51	1.58	1.30	2.674	.447		46	42	12	14000
G351---65	6.62	3.86	3.00	4.15	.86	.33	1.10	1.10	1.497	.808		58	39	3	33800
G350---65*	11.41	4.25	3.13	4.88	1.39	.46	2.18	1.98	1.795	.671		43	49	8	33500
G354---65*	12.93	5.28	1.79	5.95	2.09	.32	1.00	1.67	2.381	.673		18	66	16	9400
G356---65*	11.37	5.11	2.20	5.60	3.06	.16	.55	.50	4.331	1.095		38	42	20	5000
G355---65*	9.60	2.46	1.61	3.90	1.80	.80	1.75	1.22	1.278	.853		81	11	8	5800
G357---65	4.62	2.16	1.58	2.23	.43	.18	2.19	2.52	1.189	.993		93	6	1	13900
G358---65	2.79	2.14	1.69	2.14	.26	-.02	.37	1.09	1.128	1.002		97	2	1	8200
G359---65	2.60	2.06	1.53	2.05	.31	-.03	.02	.73	1.154	1.008		99	1+		8800
G360---65	2.38	1.53	.57	1.55	.49	.05	-.11	.84	1.259	.977		100			6000
G361---65	2.50	1.88	1.30	1.90	.34	.07	.06	.75	1.171	.985		98	2+		11400
G362---65	5.46	1.34	.55	1.56	.54	.42	3.09	3.55	1.209	.915		92	6	2	5200
G363---65	3.00	1.59	.62	1.59	.48	-.00	.46	1.49	1.241	1.013		96	4+		21500
G364---65	5.00	1.97	.57	2.03	.76	.08	1.08	1.92	1.371	.986	1	93	4	2	6300
G365---65	2.42	2.11	1.69	2.09	.21	-.10	-.23	.72	1.098	1.024		100			7900
FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 2															
G339---65	9.00	2.31	1.71	3.81	1.85	.81	1.64	.97	1.270	.860		79	15	6	6700
G340---65*	2.53	2.05	1.50	2.03	.31	-.07	-.12	.65	1.155	1.014		100			4300
G341---65	2.44	2.03	1.57	2.02	.26	-.06	-.10	.65	1.131	1.014		100			
G342---65	2.40	2.01	1.50	1.97	.27	-.13	-.21	.65	1.136	1.033		99	1+		5000
MISCELLANEOUS SAMPLES FROM NEAR ASTORIA (COLUMBIA RIVER MILE 15)															
G 62---64	3.39	2.32	1.00	2.29	.56	-.06	-.22	1.15	1.258	.983		98	2+		
G 63---64	2.95	2.29	1.61	2.29	.38	.01	-.02	.75	1.186	.996		100			
G 64---64	6.62	2.39	1.32	2.76	1.00	.37	1.58	1.66	1.424	.874		86	11	3	
G 95---64	2.35	1.52	.39	1.48	.48	-.08	-.31	1.03	1.253	1.035		100			
G 96---64*	9.56	5.33	3.90	5.65	1.58	.39	.89	.79	2.062	.632		7	81	12	
G101---64	3.13	2.46	2.03	2.52	.32	.18	.37	.72	1.159	.952		99	1+		
G107---64	6.00	3.35	2.20	3.55	1.02	.19	.73	.86	1.628	.875		71	27	2	
G109---64	2.50	2.09	1.50	2.05	.29	-.16	-.32	.71	1.139	1.031		100			
G135---64	6.64	2.26	1.56	2.31	.41	.13	4.46	5.15	1.160	1.000	1	90	5	4	
G139---64	6.00	3.61	2.27	3.79	.83	.22	.64	1.26	1.410	.916		71	26	3	

* HIGHER ORDER STATISTICS FOR THIS SAMPLE MAY BE IN ERROR
+ SILT PLUS CLAY
‡ ALL STATISTICS FOR THIS SAMPLE MAY BE IN ERROR

APPENDIX 2. — *Particle-size statistics of selected segments of cores from the estuary*

[Statistics computed according to Inman (1952) and Trask (1932)]

SAMPLE NO	PHI VALUE AT INDICATED PCT FINER 5	50	95	INMAN VALUES MEAN	SORT	ALPHI	ALPH2	BETA	TRASK VALUES SORT	SKEW	PERCENT GRAVEL	SAND	SILT	CLAY
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 64														
C383--0-1*	10.39	6.97	4.30	7.14	1.91	.09	.19	.60	2.522	.914		3	66	31
C383--1-1*	10.39	6.88	1.19	6.86	2.15	-.01	-.51	1.14	2.729	1.011		9	61	30
C383-10-1												1	99+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 54														
C384--0-1*	2.61	1.83	.70	1.74	.58	-.15	-.30	.64	1.311	1.060		100		
C384--3-1*	2.35	1.59	.73	1.59	.53	.00	-.09	.54	1.305	.967		100		
C384--5-1*	2.38	1.59	.68	1.55	.51	-.08	-.12	.68	1.263	1.035		100		
C384-46-2	2.92	2.39	1.73	2.39	.33	-.01	-.19	.81	1.167	1.002		100		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 50														
C385--0-1*	5.85	2.48	1.90	2.56	.40	.20	3.47	3.90	1.206	.930		92	8+	
C385--1-1	2.83	2.33	1.78	2.33	.29	-.00	-.12	.75	1.146	1.000		100		
C385-11-1*	2.62	2.20	1.66	2.19	.27	-.05	-.23	.79	1.125	1.000		100		
C385-22-2*	2.56	2.14	1.63	2.12	.28	-.06	-.14	.69	1.133	1.007		100		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 47														
C386--1-1	2.43	1.65	.51	1.57	.57	-.14	-.34	.65	1.314	1.047		100		
C386--3-1	2.40	1.66	.62	1.63	.51	-.05	-.29	.75	1.280	1.007		100		
C386--5-1*	2.46	1.79	.95	1.75	.46	-.08	-.19	.64	1.241	1.018		100		
C386-26-2	2.53	1.85	1.27	1.88	.35	.08	.11	.75	1.171	.986		100		
C386-28-2*	2.58	2.01	1.33	1.99	.37	-.07	-.16	.68	1.190	1.025		100		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 42														
C382--0-1	4.00	1.32	.18	1.32	.66	-.00	1.17	1.91	1.340	.988	1	94	4	1
C382--1-1	2.13	1.27	.26	1.23	.57	-.06	-.13	.65	1.302	1.021	1	99		
C382-11-1	2.00	1.12	.07	1.09	.61	-.05	-.14	.57	1.353	1.002	2	98		
C382-12-2*	2.13	1.42	.56	1.37	.47	-.11	-.20	.63	1.248	1.046		100		
C382-20-2	2.16	1.22	.08	1.17	.57	-.09	-.15	.85	1.258	1.040	2	98		
C381--0-1*	8.73	4.64	3.06	4.79	1.23	.13	1.02	1.29	1.822	.924		32	61	7
C381--3-1*	6.21	4.75	3.25	4.75	.89	-.00	-.02	.67	1.514	1.000		20	80+	
C381--8-1*	4.36	3.02	2.29	3.02	.44	-.00	.69	1.33	1.230	1.001		94	5	1
C381-11-1	5.37	3.34	2.68	3.44	.47	.21	1.46	1.85	1.223	.943		87	12	1
C381-20-2*	8.77	4.18	2.90	4.61	1.32	.33	1.25	1.22	1.920	.712		46	47	7
C381-30-2	6.83	3.46	2.70	3.86	.85	.48	1.55	1.44	1.315	.872		77	20	3
C381-40-2*	5.59	3.78	2.72	3.97	.90	.22	.42	.59	1.548	.858		58	42+	
C381-56-2*	3.46	2.90	2.36	2.91	.33	.02	.04	.65	1.168	.995		100		
C381-62-2*	7.72	3.39	2.42	4.53	1.60	.59	1.05	.66	2.098	.456		62	38+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 38														
C380--0-1*	5.60	2.65	1.93	2.83	.63	.28	1.77	1.92	1.277	.952		89	9	2
C380--1-1	3.28	2.53	1.85	2.54	.41	.02	.08	.76	1.209	.391		100		
C380--5-1	2.90	2.19	1.50	2.20	.44	.02	.03	.61	1.234	.990		100		
C380-10-1	4.59	2.76	2.09	2.89	.58	.22	.99	1.17	1.302	.932		93	6	1
C380-14-2*	3.18	2.54	1.87	2.54	.39	.01	-.03	.69	1.199	.996		100		
C380-34-2*	2.85	2.32	1.89	2.33	.28	.06	.19	.74	1.129	1.000		100		
C380-44-2*	3.09	2.46	1.87	2.47	.37	.04	.07	.65	1.189	.987		100		
C379--1-1	5.63	2.91	2.16	3.09	.68	.27	1.46	1.57	1.340	.912		88	10	2
C379--2-1*	4.00	2.77	2.22	2.83	.39	.14	.85	1.26	1.171	1.000		95	5+	
C379--3-1*	8.00	3.30	2.42	4.06	1.35	.57	1.42	1.07	1.648	.672		72	23	5
C379--5-1*	7.55	3.27	2.38	3.89	1.19	.52	1.43	1.18	1.485	.801		75	21	4
C379-11-1	3.29	2.56	1.73	2.53	.44	-.08	-.11	.77	1.227	1.030		100		
C379-22-2	3.33	2.72	2.15	2.72	.33	-.00	.05	.78	1.159	1.000		100		
C379-26-2*	7.55	3.15	2.34	3.85	1.22	.57	1.47	1.13	1.529	.720		75	21	4
C379-34-2*	4.42	3.34	2.50	3.40	.58	.10	.21	.66	1.305	.960		85	15+	
C379-42-2	3.59	2.78	2.22	2.82	.38	.10	.32	.78	1.184	.992		98	2+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 31														
C376--4-1	3.59	2.73	2.14	2.77	.41	.10	.32	.76	1.202	.996		98	2+	
C376--5-1	3.50	2.66	2.12	2.70	.38	.11	.40	.81	1.190	.985		99	1+	
C376--8-1	3.28	2.58	2.11	2.62	.33	.11	.34	.76	1.171	.971		100		
C376-11-1*	3.25	2.72	2.25	2.73	.29	.01	.09	.72	1.145	1.000		100		
C376-31-2	3.56	2.79	2.08	2.79	.48	.01	.07	.53	1.284	1.008		99	1+	
C376-33-2*	3.59	2.46	1.97	2.64	.47	.38	.69	.70	1.240	.855		98	2+	
C376-45-2	3.13	2.44	2.00	2.49	.32	.16	.35	.73	1.157	.959		100		
C375--1-1	3.50	2.66	1.58	2.61	.52	-.10	-.22	.83	1.258	1.047		98	2+	
C375--3-1*	2.83	1.48	.66	1.64	.66	.25	.41	.65	1.326	.906		100		
C375-11-1*	2.63	1.41	.64	1.50	.55	.16	.47	.84	1.283	.936		100		
C375-14-2	3.00	1.55	.10	1.65	.91	.11	.00	.59	1.507	.882	3	97		
C375-16-2*	2.94	1.80	.87	1.89	.68	.13	.15	.53	1.382	.928		100		
C375-34-2	3.24	2.02	.62	1.98	.83	-.05	-.11	.58	1.527	1.049		100		
C375-42-2*	3.06	1.31	.15	1.60	1.03	.28	.29	.41	1.687	.735	2	98		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 27														
C378--0-1*	6.81	4.98	3.11	4.97	1.12	-.01	-.01	.65	1.684	1.000		19	81+	
C378--2-1*	9.14	5.25	3.41	5.61	1.51	.23	.67	.89	1.757	.958		14	76	10
C378--4-1*	9.13	5.40	3.50	5.81	1.55	.26	.61	.84	1.864	.837		11	78	11
C378--5-1*	8.75	4.57	2.94	5.04	1.68	.28	.76	.73	2.154	.818		38	54	8
C378--6-1	8.03	3.82	2.67	4.42	1.32	.46	1.15	1.03	1.841	.615		57	38	5
C378--8-1	5.33	2.80	2.06	2.86	.54	.13	1.65	2.12	1.269	.958		92	6	2
C378-11-1	3.33	2.68	2.00	2.68	.40	-.01	.04	.73	1.199	1.006		100		
C378-34-2	3.46	2.87	2.23	2.89	.33	.05	-.07	.85	1.165	.989		100		
C378-46-2*	3.03	2.19	.94	2.12	.77	-.08	-.28	.34	1.461	1.071		100		
C378-56-2*	2.50	1.39	.59	1.46	.55	.12	.29	.73	1.287	.949		100		
C377--1-1*	6.00	3.18	2.43	3.42	.71	.34	1.45	1.51	1.307	.926		83	15	2
C377--2-1*	6.00	3.08	2.31	3.53	.93	.49	1.16	.98	1.411	.795		79	20	1
C377--3-1	3.74	2.93	2.22	2.96	.41	.07	.11	.84	1.211	.977		98	2+	
C377--8-1	3.89	2.89	2.25	2.92	.44	.08	.41	.87	1.224	.975		96	4+	
C377-15-1*	9.30	4.73	2.94	5.32	1.98	.30	.71	.61	2.554	.751		37	52	11
C377-27-2*	4.74	3.06	2.31	3.11	.51	.09	.91	1.40	1.252	.983		92	7	1
C377-51-2*	5.02	3.02	2.19	3.24	.76	.30	.76	.85	1.342	.924		84	16+	

See footnotes at end of table.

APPENDIX 2. — *Particle-size statistics of selected segments of cores from the estuary* — Continued

Column groups: PHI VALUE AT INDICATED PCT FINER (5, 50, 95); INMAN VALUES (MEAN, SORT, ALPHI, ALPH2, BETA); TRASK VALUES (SORT, SKEW); PERCENT (GRAVEL, SAND, SILT, CLAY)

SAMPLE NO	5	50	95	MEAN	SORT	ALPHI	ALPH2	BETA	SORT	SKEW	GRAVEL	SAND	SILT	CLAY
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 23														
C369--1-1*	9.44	4.98	2.29	5.32	1.90	.18	.47	.88	2.141	.956		27	62	11
C369--4-1*	8.85	3.94	2.10	4.69	1.87	.40	.82	.81	2.274	.536		52	40	8
C369--5-1	6.55	3.17	2.00	3.21	.75	.06	1.48	2.04	1.375	1.002		85	12	3
C369-11-1	3.44	2.46	1.35	2.45	.62	-.00	-.10	.69	1.327	.986		100		
C369-18-2	3.64	2.30	1.10	2.34	.67	.05	.10	.90	1.337	.965		97	3+	
C369-22-2	4.00	2.94	2.11	2.97	.56	.05	.20	.68	1.303	.986		95	5+	
C369-34-2*	5.60	3.43	2.41	3.75	.98	.33	.59	.63	1.587	.770		68	32+	
C369-40-2*	4.96	3.64	2.72	3.76	.69	.17	.36	.63	1.391	.906		67	33+	
C373--1-1	7.48	3.74	2.73	4.23	1.14	.44	1.20	1.08	1.688	.676		60	36	4
C373--5-1	5.68	3.31	2.66	3.42	.52	.22	1.67	1.93	1.249	.944		86	12	2
C373--7-1	3.67	3.12	2.58	3.11	.31	-.03	.03	.76	1.154	1.007		99	1+	
C373-10-1*	4.73	3.43	2.78	3.62	.57	.33	.57	.71	1.294	.854		78	22+	
C373-34-2	3.95	3.28	2.69	3.31	.31	.08	.12	1.02	1.141	1.000		96	4+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 18														
C370--1-1	2.31	1.39	.08	1.30	.72	-.13	-.27	.55	1.410	1.085	2	98		
C370--9-1*	2.15	1.03	-1.29	.97	.78	-.06	-.78	1.20	1.459	1.030	7	93		
C370-18-2*	2.22	1.42	.60	1.43	.51	-.01	-.04	.60	1.268	.997		100		
C370-26-2*	2.85	2.19	.36	2.00	.59	-.31	-.99	1.12	1.263	1.094	1	99		
C370-34-2	2.91	1.92	-2.35	.86	1.56	-.68	-1.05	.69	1.554	1.488	15	85		
C368--0-1	8.00	3.53	2.61	4.23	1.32	.53	1.34	1.04	1.770	.592		65	30	5
C368--4-1	3.74	2.98	2.31	2.99	.40	.02	.11	.79	1.205	.994		98	2+	
C368--5-1*	4.00	3.09	2.43	3.12	.44	.07	.29	.80	1.222	.982		95	5+	
C368-11-1*	6.00	3.14	2.39	3.46	.78	.41	1.37	1.32	1.250	.987		82	16	2
C368-16-2*	8.36	3.57	2.50	4.32	1.46	.52	1.28	1.01	1.911	.562		63	31	6
C368-32-2*	3.76	3.08	2.43	3.06	.37	-.05	-.03	.70	1.189	1.014		99	1+	
C368-34-2*	5.35	3.81	2.70	3.89	.86	.09	.25	.54	1.506	.947		58	42+	
C368-42-2*	4.93	3.42	2.56	3.60	.71	.26	.45	.68	1.381	.855		75	25+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 14														
C371--0-1*	8.85	2.90	1.61	4.24	2.33	.57	1.00	.56	3.253	.289		57	35	8
C371--1-1	2.44	2.01	1.26	1.94	.33	-.21	-.48	.79	1.165	1.065		100		
C371-16-2	4.00	1.99	1.29	1.98	.36	-.03	1.83	2.61	1.181	1.010		95	5+	
C371-26-2*	14.00	2.20	.36	5.24	3.97	.77	1.25	.72	2.276	.429	1	74	25+	
C371-40-2	4.00	1.91	1.00	1.87	.48	-.08	1.22	2.10	1.251	1.028		95	3	2
C371-44-2*	9.58	2.43	1.63	4.11	2.13	.79	1.49	.86	2.360	.274		71	20	9
C371-44-2	6.55	2.36	1.63	2.47	.47	.23	3.66	4.20	1.228	.931		90	7	3
C367--0-1	7.39	2.24	1.32	2.62	.90	.43	2.35	2.38	1.313	.923	1	86	9	4
C367--1-1	2.50	1.99	1.00	1.88	.42	-.25	-.57	.80	1.213	1.095		100		
C367--8-1*	5.85	2.08	1.16	2.04	.47	-.10	3.02	3.99	1.240	1.041		92	8+	
C367-11-2*	2.40	1.89	.93	1.84	.41	-.12	-.48	.88	1.205	1.028		100		
C367-23-2*	2.46	1.79	.66	1.70	.51	-.18	-.45	.73	1.248	1.030		99	1+	
C367-35-2	4.00	1.74	1.04	1.78	.49	.09	1.61	2.03	1.260	.977		95	3	2
C367-37-2	7.23	2.16	1.13	2.31	.63	.23	3.19	3.82	1.245	1.012		87	9	4
C367I-0-1*	9.06	2.73	1.69	4.10	2.10	.65	1.26	.75	2.669	.298		65	27	8
C367I-2-1	2.50	1.92	.80	1.83	.45	-.21	-.60	.87	1.227	1.063		100		
C367I11-2*	2.56	1.97	.86	1.86	.46	-.25	-.58	.85	1.230	1.094		100		
C366--0-1*	8.32	4.08	2.24	4.24	1.78	.09	.67	.71	2.536	1.055		50	44	6
C366--1-1*	8.65	5.00	3.29	5.07	1.11	.06	.87	1.41	1.632	1.000		17	76	7
C366--2-1*	8.80	5.08	3.00	5.30	1.35	.16	.61	1.15	1.701	1.000		17	75	8
C366--3-1	7.60	4.75	3.41	4.80	.96	.05	.78	1.17	1.609	1.000		23	73	4
C366--5-1												2	98+	
C366--9-2$	6.76	5.24	3.72	5.24	.92	-.00	-.00	.65	1.541	1.000		9	91+	
C372--0-1	4.55	2.52	2.03	2.61	.39	.23	1.95	2.21	1.202	.923		94	4	2
C372-11-1*	3.09	2.59	2.12	2.60	.30	.02	.04	.64	1.150	.995		100		
C372-22-2	3.13	2.48	1.90	2.50	.35	.06	.09	.77	1.176	.982		100		
C372-34-2	3.06	2.48	2.06	2.52	.29	.13	.27	.70	1.146	.966		100		
C372-38-2*	7.69	2.66	2.04	3.02	.76	.48	2.91	2.72	1.243	.959		85	15+	
C372-52-2	3.60	2.92	2.26	2.91	.41	-.04	.01	.64	1.212	1.015		99	1+	
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 6														
C388--1-1*	10.33	5.68	1.70	5.44	3.01	-.08	.11	.43	3.074	.746		21	59	20
C388--3-1*	11.66	7.07	1.79	7.15	2.71	.03	-.13	.82	3.596	.953		12	51	37
C388--5-1*	10.86	5.70	3.91	6.58	1.98	.45	.85	.76	2.334	.509		6	74	20
C388-34-2												2	98+	
C389--1-1	2.48	2.14	1.71	2.13	.22	-.07	-.23	.75	1.100	1.000		100		
C389-15-2$	14.00	2.35	1.66	7.96	6.04	.93	.91	.02	8.936	.019		70	33+	
C389-39-2	2.50	2.15	1.71	2.13	.23	-.06	-.18	.73	1.106	1.000		100		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 2														
C387--0-1*	9.32	4.37	2.06	4.46	2.07	.04	.64	.76	2.759	1.047		42	49	9
C387--3-1	2.79	2.32	1.81	2.32	.27	.03	-.07	.84	1.129	1.000		100		
C387--5-1*	2.67	2.21	1.66	2.20	.29	-.04	-.15	.72	1.141	1.000		100		
C387-14-2	4.00	2.57	1.70	2.81	.69	.34	.40	.66	1.395	.803	1	94	5+	
C387-34-2*	2.68	2.31	1.93	2.31	.23	-.00		.64	1.113	1.000		100		
C387I-0-1*	9.65	4.63	2.35	4.86	1.86	.12	.74	.96	2.164	1.020		35	55	10
C387I-3-1*	2.67	2.24	1.74	2.24	.27	-.01	-.13	.75	1.130	1.000		100		
C387III-1*	2.65	2.21	1.66	2.20	.28	-.05	-.20	.77	1.132	1.000		100		

* HIGHER ORDER STATISTICS FOR THIS SAMPLE MAY BE IN ERROR
+ SILT PLUS CLAY
$ ALL STATISTICS FOR THIS SAMPLE MAY BE IN ERROR

APPENDIX 3. — *Measured radionuclide concentrations and computed totals and ratios of radionuclides in surficial sediment from the estuary*

[Less-than values or totals including less-than values are indicated by * ; questionable values are indicated by A]

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 64										
G202---65	6300	.3	10.9	.4	.2 *	12.2 A	.2 *	.2 *	9.91			40		
G383---65	7500	.2 *	.4	.2 *	.2 *	2.3 *	.2 *	.2 *	11.4	15.1 *	3.7 *			
G204---65	10300	.2	13.7	.3	.3	10.8	.2 *	.2 *	11.9	37.6 *	25.7 *	70	.02	.788
G209---65	52300	2.2	87.12	1.8	7.60	164.4	6.22	1.5	15.6	286.50	270.90	40	.0879	1.887
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 59										
G220---65	8000	.4	8.38	.2 *	.2 *	25.2	.2 *	.2 *	10.7	45.48*	34.78*	20		3.01
G219---65	8200	.59	7.66	.3	.45	16.7	.45	.2 *	11.5	37.85*	26.35*	13	.059	2.18
G214-1-65	8700	.2	9.91	.3	.59	9.91	.2 *	.2 *	9.73	31.04*	21.31*	50	.060	1.00
G214-3-65		.2 *	10.9	.2	.2 *	10.8	.2 *	.2 *	11.1	33.8 *	22.7 *			.991
G222---65	41300	6.04	143.2	3.1	14.1	242.3	3.4	2.7	21.0	435.84	414.84	23.7	.0985	1.692
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 54										
G225---65	21800	1.3	77.07	2.5	14.1 A	280.6	2.6	2.7	16.2			59		3.641
G227---65	8500	.2	10.3	.2	.4	12.6	.2 *	.2 *	12.9	37.0 *	24.1 *	50	.04	1.22
G231---65	8400	.3	9.50	.4	.1	9.91	.68	.2 *	9.37	30.46*	21.09*	30	.01	1.04
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 50										
G237---65	9000	.2 *	11.8	.2	.2 *	14.0	.2 *	.2 *	11.7	38.5 *	26.8 *			1.19
G385---65	10900	.3	12.6	.4	.2 *	2.3 *	.54	.2	15.4	31.94*	16.54*	40		
G240---65	8500	.3	9.19	.3	.2	18.0	.3	.2 *	12.8	41.29*	28.49*	30	.02	1.96
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 47										
G246---65	7500	.2	8.06	.3	.2 *	12.2	.3	.2 *	10.5	31.96*	21.46*	40		1.51
G247---65	10200	.2 *	13.6	.4	.4	17.6 A	.3	.2 *	9.77			40	.03	
G386---65	9800	.3	11.6	.50	.2 *	2.3 *	.81	.2 *	11.9	27.81*	15.91*			
G258---65	9300	.2 *	11.3	.2	.4	15.3	.4	.2 *	13.2	41.2 *	28.0 *		.04	1.35
G252---65	30800	.59	30.4	.99	2.6	105.9	.2 *	.63	14.4	155.71*	141.31*	52	.086	3.48
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 42										
G265---65	4700	.2 *	3.5	.2 *	.2	7.66	.2 *	.2 *	10.2	22.36*	12.16*		.06	2.2
G259---65	8000	.2 *	7.21	.3	.4	11.7	.2 *	.2 *	10.0	30.21*	20.21*		.06	1.62
G255---65	52600	.3	14.4	.54	.4	30.6	.2 *	.2 *	10.6	57.24*	46.64*	50	.03	2.12
G258---65	13900	.3	9.86	.2	.2	36.0	.90	.2 *	12.0	59.66*	47.66*	30	.02	3.65
G254---65	19200	3.0	119.3	4.82	15.7	466.7	5.32	2.5	18.8	636.14	617.34	40	.13	3.912
G254-A-65		.4	20.3	1.2	.2 *	21.2	.90	.2 *	1.1	45.50*	44.40*	50		1.04
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 38										
G272---65	9400	.2 *	15.2	.4	.4	23.9	.2 *	.2 *	13.4	53.9 *	40.5 *		.03	1.57
G274---65	11600	.2 *	11.7	.4	.4	21.2	.2 *	.2 *	12.1	46.4 *	34.3 *		.03	1.81
G275---65	6800	.2 *	5.32	.3	.45	10.8	.2 *	.2 *	9.05	26.52*	17.47*		.08	2.03
G276---65	23600	3.8	97.61	2.5	6.31	171.6	4.2	2.7	25.1	313.82	288.72	26	.06	1.758
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 31										
G287---65	9400	.2 *	8.29	.3	.3	9.91	.2 *	.2 *	10.8	30.20*	19.40*		.04	1.20
G282---65	14700	.4	24.4	.68	.81	53.15	1.0	.2 *	11.2	91.84*	80.64*	60	.033	2.18
G280---65	5700	.2 *	5.45	.3	.45	4.50	.2 *	.2 *	9.28	20.58*	11.30*		.083	.826
G283---65	80700	2.7	113.0	3.8	13.5	359.9	5.23	2.1	20.3	520.53	500.23	42	.119	-3.185
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 27										
G289---65	5200	.2 *	6.04	.2	.4	14.9	2.0	.3	12.6	36.64*	24.04*		.07	2.47
G291---65	106000	2.3	123.8	4.82	22.2	451.8	5.00	2.5	25.4	637.82	612.42	54	.179	3.649
G299---65	38500	4.1	83.78	2.1	6.67	119.8	5.63	2.2	22.3	246.58	224.28	20	.0796	1.430
G301---65	18800	1.8	50.41	1.8	4.91	96.40	4.0	1.5	14.2	175.02	160.82	28	.0974	1.912
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 23										
G316---65	5600	.3	5.32	.2 *	.2 *	13.1	.2 *	.2 *	11.5	31.02*	19.52*	20		2.46
G319---65	4800	.2	4.91	.2 *	.2 *	7.66	.4	.2 *	10.2	23.97*	13.77*	20		1.56
G323---65	9600	.45	6.53	.3	.2 *	24.3	.54	.2	12.9	45.42*	32.52*	15		3.72
G307---65	56100	2.7	147.3	5.77	19.0	607.0	5.77	3.0	23.7	814.94	791.24	55	.129	4.126
G305---65	5600	.2 *	5.54	.2 *	.2 *	16.7	.86	.2 *	8.74	32.64*	23.90*			3.01
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 18										
G334---65	36000	2.7	102.5	3.7	9.82	120.3	2.5	2.6	17.1	262.22	245.12	38	.0958	1.174
G337---65	15200	.63	27.1	1.0	1.4	68.47	.63	.2	13.6	113.03	99.43	43	.052	2.53
G326---65	3800	.4	4.1	.2 *	.2 *	14.0	.4	.2 *	11.5	31.0 *	19.5 *	10		3.4
G313---65	6300	.4	6.44	.2 *	.3	10.8	.68	.2 *	10.6	29.62*	19.02*	20	.05	1.68
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 14										
G344-1-65	18900	.90	19.0	.68	2.7	90.09	2.2	.3	13.3	129.17	115.87	21	.14	4.74
G344-2-65		1.9	32.1	.81	5.18	161.30	2.8	1.1	20.2	225.39	205.19	17	.161	5.02
G344-8-65		1.8	2.8	1.5	.2 *	17.10	2.0	.90	15.7	42.00*	26.30*	1.6		6.1
G347---65	10800	.59	13.2	.59	.68	51.80	.54	.2 *	13.6	81.20*	67.60*	22	.052	3.92
G348---65	4300	.2 *	5.14	.4	.2 *	24.80	.2 *	.2 *	11.0	42.14*	31.14*			4.82
G332---65	25500	.72	34.1	1.4	3.4 A	156.80	1.2	.50	16.0			47		4.60
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 6										
G352---65	15000	1.2	39.5	.50	3.6	142.8	3.5	.90	16.8	208.80	192.00	33	.091	3.62
G351---65	33800	1.6	50.00	.3	4.59	254.1	4.1	.81	17.2	333.10	315.90	31	.0918	5.090
G359---65	8800	.2	5.09	.50	.50	30.6	.2 *	.2 *	13.4	50.69*	37.29*	30	.098	6.01
G361---65	11400	.68	13.5	1.4	1.8	80.18	1.4	.2 *	10.5	109.66*	99.16*	20	.13	5.94
G363---65	21500	.3	6.44	.4	1.1	47.75	.63	.2	13.0	69.82	56.82	20	.17	7.41
				FOLLOWING SAMPLES FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 2										
G340---65	4300	.2 *	1.2	.2 *	.2 *	2.3 *	.2 *	.2 *	11.7	16.2 *	4.5 *			
G341---65		.2 *	1.7	.3	.2 *	2.3 *	.3	.2 *	12.0	17.2 *	5.2 *			
G342---65	5000	.2 *	1.8	.2 *	.2 *	6.76	.2 *	.2 *	12.5	22.06*	9.56*			3.8
				MISCELLANEOUS SAMPLES FROM NEAR ASTORIA (COLUMBIA RIVER MILE 15)										
G 62---64		.90	16.3	1.7	1.6	144.1						18	.098	8.84
G 63---64		.4	9.82	.81	.86	73.87						20	.088	7.52
G 64---64		1.4	44.2	3.8	5.23	522.5						32	.118	11.8
G 95---64		.45	3.4	.86	.45	12.1						7.6	.130	3.6
G 96---64		5.59	129.7	5.14	11.2	788.3						23.2	.0864	6.078
G101---64		2.0	17.7	2.3	1.2	71.62						8.8	.068	4.05
G107---64		2.3	44.4	2.5	3.6	375.7						19	.081	8.46
G109---64		.68	7.25	.63	.72	44.5						11	.099	6.14
G135---64		.90	12.7	1.1	1.7	79.28						14	.13	6.24
G139---64		2.6	44.8	2.6	2.3	298.6						17	.051	6.67

APPENDIX 4. — *Measured radionuclide concentrations and computed totals and ratios of radionuclides in selected segments of cores from the estuary*

[Less-than values or totals including less-than values are indicated by *; questionable values are indicated by A]

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 64														
G383---65	7500	.2 *		.2 *	.2 *	2.3 *	.2 *	.2 *	11.4	15.1 *	3.7 *			
C383---0-1		.2 *	.68	.2 *	.2 *	2.3 *	.2 *	.2 *	9.46	13.44*	3.98*			
C383--1-1		.2 *	1.7	.2 *	.2 *	2.3 *	.45	.2 *	11.3	16.55*	5.25*			
C383- 3-1		.2 *	.4 *	.2 *	.2 *	2.3 *	.2 *	.2 *	9.95	13.65*	3.70*			
C383--5-1		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	10.7	14.2 *	3.5 *			
C383--7-1		.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	12.6					
C383-10 1		.2 *	.2 *	.2 *	.2 *		.95	.2 *	13.4					
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 54														
G384---65	7900	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C384--0-1		.2 *	2.5	.2 *	.2 *	18.9	1.8	.2 *	10.9	34.9 *	24.0 *			7.6
C384--1-1		.2 *	1.3	.2	16.2	.68	.2	11.6	30.58*	18.98*				12
C384--3-1		.2 *	.90	.2	.2 *	9.46	1.1	.2 *	11.1	23.36*	12.26*			11
C384--5-1		.2 *	1.5	.2	.2 *	17.1	1.1	.2 *	11.2	31.7 *	20.5 *			11
C384-11-1		.2 *	1.1	.2	.2 *	18.5	.81	.2	13.1	34.31*	21.21*			17
C384-34-2		.3	.77	.2	.54	45.5	.90	.2 *	15.0	63.41*	48.41*	3	.70	59
C384-46-2		.4	1.2	.2 *	.2 *		.90	.2	14.2			3		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 50														
G385---65	10900	.3	12.6	.4	.2 *	2.3 *	.54	.2	15.4	31.94*	16.54*	40		
C385--0-1		.4	25.4	.45	.4	30.2	1.5*	.95	15.9	75.20	59.30	60	.02	1.19
C385--1-1		.59	12.3	.2	.2 *	2.3 *	8.96	1.3	21.8	47.65*	25.85*	21		
C385--3-1		.2	13.3	.3	.2 *	2.3 *	.77	.3	14.9	32.27*	17.37*	70		
C385--5-1		.2	12.8	.4	.2 *	2.3	1.0	.2	14.8	31.9 *	17.1 *	60		.18
C385-10-1		.2 *	12.9	.3	.2 *		.72	.59	14.2					
C385-11-1		.63	12.5	.4	.2 *	2.3 *	9.23	1.2	20.4	46.86*	26.46*	20		
C385-12-1		.5	9.46	.2 *	.2 *		10.0	2.5	17.2			19		
C385-22-2		.2 *	2.2	.2 *	.2 *		.2 *	.81	14.8					
C385-34-2		.2 *	2.9	.2	.2 *	2.3 *	.77	.2 *	14.9	21.67*	6.77*			
C385-40-2		.2 *	1.4	.2 *	.2 *		.2 *	.4	6.44					
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 47														
G386---65	9800	.3	11.6	.5	.2 *	2.3 *	.81	.2 *	11.9	27.81*	15.91*	40		
C386--0-1		.2 *	6.53	.2 *	.2 *	2.3 *	.68	.81	10.6	21.52*	10.92*			
C386--1-1		.3	9.5	.3	.2 *	2.3 *	.2 *	.3	11.6	24.70*	13.10*	30		
C386--3-1		4.3 A	110.9 A	4.4 A	.2 A	2.3 A	14.4 A	4.5 A	131.2 A					
C386--5-1		.2 *	6.08	.2	.2 *	2.3 *	.86	.2 *	11.1	21.14*	10.04*			
C386--8-1		.2 *	3.0	.2 *	.2 *		.4	.4	9.37					
C386-11-1		.2 *	1.5	.2 *	.2 *	2.3 *	.63	.2	11.1	16.33*	5.23*			
C386-22-2		.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	10.6					
C386-34-2		.2 *	.54	.2 *	.2 *	2.3 *	1.2	.2 *	10.5	15.34*	4.84*			
C386-46-2		.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	11.9					
C386-56-2		.2 *	.2 *	.2 *	.95		.68	.72	8.38					
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 42														
G382---65	5500	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C382--0-1		.3	4.59	.2 *	.2 *	25.7.	.99	.2 *	10.5	42.68*	32.18*	20		5.60
C382--1-1		.2 *	2.7	.2 *	.2 *	9.46	.77	.2 *	8.15	21.88*	13.73*			3.5
C382--2-1		.2 *	2.6	.2 *	.2 *		.81	.2 *	11.4					
C382--3-1		.2 *	1.7	.2 *	.2 *	2.3 *	.90	.2 *	8.51	14.21*	5.70*			
C382--4-1		.2 *	1.8	.3	.2 *		.81	.2 *	10.4					
C382--5-1		.2 *	2.8	.2 *	.2 *	2.3 *	.2 *	.2 *	8.56	14.66*	6.10*			
C382--6-1		.2 *	3.2	.2 *	.54	25.2 A	1.2	.2	10.9				.17	
C382--7-1		.2 *	3.7	.2	.3	3.6	.4	.2 *	10.2	18.8 *	8.6 *		.08	.97
C382--8-1		.3	3.6	.2 *	.3	2.3 *	.95	.2 *	8.87	16.72*	7.85*	10	.08	
C382-11-1		.2 *	4.2	.2 *	.2 *	2.3 *	.2 *	.2 *	8.11	15.61*	7.50*			
C382-20-2		.2 *	.68	.2 *	.2 *		.2 *	.2 *	9.55					
G381---65	106000	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C381--0-1		2.5	148.1	5.77	17.1	402.7	4.55	2.8	20.3	603.82	583.52	59	.115	2.719
C381--1-1		3.0	164.1	5.50	17.5	359.9	4.50	3.6	20.5	578.60	558.18	55	.107	2.193
C381--3-1		2.7	173.6	4.4	15.4	183.3	2.7	3.4	20.8	406.3	385.5	64	.0887	1.056
C381--5-1		1.1	49.91	1.1	3.0	16.7	3.3	1.4	14.0	90.51	76.51	45	.060	.335
C381--8-1		.54	7.03	.3	.2 *		.2 *	1.2	13.5			13		
C381-11-1		3.3	45.86	1.7	1.3	20.3	1.8	1.8	20.0	96.06	76.06	14	.028	.443
C381-14-1		2.2	23.4	.5	.2 *		1.2	3.2	16.1			11		
C381-18-2		2.6	29.1	1.6	.50	18.9	2.4	1.8	18.4	75.30	56.90	11	.017	.649
C381-20-2		7.84	115.9	3.1	.95	32.4	6.49	4.3	26.3	205.48	170.98	14.8	.0082	.280
C381-24-2		5.27	63.33	1.4	.2 *		6.53	6.71	22.3			12.0		
C381-30-2		3.3	12.0	.3	.2 *	12.2	1.8	1.3	16.3	47.4 *	31.1 *	3.6		1.02
C381-32-2		5.41	18.3	.2 *	.2 *	49.55	2.3	1.9	25.2	103.06*	77.86*	3.38		2.71
C381-40-2		5.32	13.5	.2 *	.2 *		.2 *	2.9	25.0			2.54		
C381-48-2		.99	1.3	.2 *	.2 *		.2 *	1.5	14.4			1.3		
C381-56-2		.3	.2 *	.2 *	.2 *	2.3 *	7.39	.72	16.9	28.21*	11.31*			
C381-62-2		.50	.3	.2 *	.2 *		.2 *	1.4	12.6			.6		
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 38														
G380---65	10500	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C380--0-1		.50	28.9	.86	1.3	56.76	.3	.45	14.5	103.57	89.07	58	.045	1.96
C380--1-1		.4	12.7	.2	.2 *	21.6	.86	.3	11.7	47.96*	36.26*	30		1.70
C380--3-1		.3	15.3	.45	.2 *	10.4	.50	.2	12.8	40.15*	27.35*	50		.680
C380--5-1		.2	11.1	.2 *	.2 *	9.91	.2 *	.2 *	11.8	33.81*	22.01*	60		.893
C380-10-1		.54	26.0	.72	2.2		1.1	2.0	14.5			48	.085	
C380-11-1		.4	20.0	.50	.2 *	39.6 A	.2 A	.4	16.3			50		
C380-22-2		.45	16.5	.4	.68		.72	.72	16.5			37	.041	
C380-34-2		.3	2.9	.2 *	.2 *	.2 *	.2 *	.2 *	10.5	14.7 *	4.2 *	10		
C380-44-2		.2 *	2.3	.2 *	.2 *		1.1	.86	14.3					
G379---65	34900	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C379--0-1		1.1	37.9	1.2	1.4	2.3 *	2.3	1.3	15.6	63.1 *	47.5 *	34	.037	
C379--1-1		.90	11.8	.50	.2 *	2.3 *	.3	.54	12.1	28.64*	16.54*	13		
C379--2-1		.3	16.2	.68	.2 *	2.3 *	.2 *	.3	11.7	31.88*	20.18*	50		
C379--3-1		.81	36.7	1.1	1.1	2.3 *	.77	.95	12.7	56.43*	43.73*	45	.030	
C379--4-1		.4	4.59	.3	.2 *		.45	.54	14.5			10		
C379--5-1		.77	12.2	.59	.2 *	2.3 *	.77	.68	11.1	28.61*	17.51*	16		
C379--7-1		.72	10.6	.54	.2 *		1.2	1.5	12.5			15		
C379-11-1		1.1	2.4	.2 *	.2 *	2.3 *	9.68	1.5	18.9	36.28*	17.38*	2.2		

APPENDIX 4. — *Measured radionuclide concentrations and computed totals and ratios of radionuclides in selected segments of cores from the estuary* — Continued

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
C379-22-2		.2	.2 *	.2 *	.2 *		.4	.2	13.5					
C379-24-2		.45	.2 *	.2 *	.2 *	2.3 *	8.42	.99	18.6	31.36*	12.76*			
C379-26-2		.4	.4	.2 *	.2 *	33.3	.54	.72	13.9	43.66*	35.76*	1		80
C379-28-2		.2	.2 *	.2 *	.2 *	29.7	.2 *	.50	13.5	44.70*	31.20*			
C379-34-2		.2 *	.2 *	.2 *	.3	10.8	.86	.2	13.6	26.36*	12.76*			

FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 31

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G376---65	25400		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									16	.075	3.29
C376--0-1		2.0	32.0	1.3	2.4	105.4	2.4	1.4	15.6	162.5	146.9	16	.075	3.29
C376--1-1		1.5	24.8	1.4	1.8	64.86	1.5	.45	13.2	109.51	96.31	17	.073	2.62
C376--2-1		1.0	25.6	1.4	1.4		.2 *	1.9	13.6			26	.055	
C376--3-1		1.9	21.8	1.0	2.1	54.05	2.1	.99	15.9	98.84	82.94	11	.050	2.43
C376--4-1		1.7	12.9	.4 •	.2 *		1.6	1.8	16.1			7.6		
C376--5-1		1.5	6.40	.2 *	.2 *	24.8	1.4	.95	11.9	47.35*	35.45*	4.3		3.87
C376--8-1		.3	1.3	.2 *	.2		.2 *	.2	13.5			4	.2	
C376-11-1		.2 *	.2 *	.2 *	.2	35.6	.4	.2 *	12.1	49.1 *	37.0 *			
C376-29-2		.3	.2 *	.2 *	.2 *		9.68	2.2	15.2					
C376-31-2		.4	.2 *	.2 *	.2 *	2.3 *	7.61	.86	18.0	29.77*	11.77*			
C376-33-2		.2 *	.2 *	.2 *	.2 *	20.7	.2	.2 *	11.1	33.0 *	21.9 *			
C376-43-2		.2 *	.2 *	.2 *	.2 *	5.86	.2 *	.2 *	11.7	18.76*	7.06*			
C376-45-2		.2 *	.2 *	.2 *	.2 *	4.50	.45	.2 *	12.1	18.05*	5.35*			

G375---65	7400		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									63	.105	2.462
C375--0-1		1.1	68.96	.81	7.12	169.8	3.6	3.4	14.8	269.59	254.79	63	.105	2.462
C375--1-1		.50	18.6	.3	.2 *	37.8	.63	.4	14.1	71.93*	57.83*	36		2.10
C375--3-1		.4	11.2	.3	.59	14.9	.68	.2	11.7	39.97	28.27	30	.053	1.33
C375--5-1		.4	11.3	.2 *	.77	19.8	1.3	.4	9.14	43.31*	34.17*	30	.068	1.75
C375-11-1		.4	9.28	.4	.59	24.8	.2 *	.2 *	10.9	46.77*	35.87*	20	.064	2.67
C375-14-2		.81	10.8	.4	.2 *	2.3 *	8.83	1.4	16.3	41.04*	24.74*	13		
C375-16-2		.4	6.13	.2 *	.2 *	2.3 *	.86	.2 *	10.9	21.19*	10.29*	20		
C375-22-2		.72	6.31	.2 *	.2 *	2.3 *	1.0	.4	11.4	22.53*	11.13*	8.8		
C375-24-2		.3	4.3	.2 *	.2 *	2.3 *	.95	.2 *	11.8	20.25*	8.45*	10		
C375-34-2		.53	3.3	.2 *	.2 *	2.3 *	.2	.2 *	12.9	19.80*	6.90*	6.6		
C375-42-2		.2 *	.2 *	.2 *	.2 *		.54	.2 *	12.7					
C375-50-2		.2 *	.4	.2 *	.2 *		.3	.86	13.4					

FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 27

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G378---65	130000		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									60	.116	1.807
C378--0-1		2.3	137.6	4.64	15.9	248.6	2.6	3.4	20.5	435.54	415.04	60	.116	1.807
C378--1-1		3.1	167.4	6.17	28.1	339.2	4.4	4.0	22.9	575.27	552.37	54	.168	2.026
C378--2-1		5.36	185.4	6.53	23.5	277.0	5.14	3.9	24.2	531.03	506.83	34.6	.127	1.494
C378--3-1		3.1	173.9	4.77	24.4	263.5	4.0	2.8	25.0	501.47	476.47	56	.140	1.515
C378--4-1		3.7	219.9	5.18	22.7	250.0	5.45	4.68	26.3	537.91	511.61	59	.103	1.137
C378--5-1		2.0	101.2	2.1	8.38	73.42	2.6	2.7	17.3	209.70	192.40	51	.0828	.7250
C378--6-1		.54	19.4	.2	.2 *	2.3 *	1.1	.95	12.7	37.39*	24.69*	36		
C378--8-1		.4	5.68	.2 *	.2 *		.81	.90	11.1			10		
C378-11-1		.4	5.32	.2 *	.2 *	2.3 *	.63	.2 *	9.91	19.16*	9.25*	10		
C378-34-2		.2 *	.3	.2 *	.2 *	2.3 *	.2 *	.2 *	10.9	14.5 *	3.6 *			
C378-44-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	10.2	13.7 *	3.5 *			
C378-46-2		.2 *	.3	.2 *	.2 *	2.3 *	.2 *	.2 *	10.1	13.7 *	3.6 *			
C378-48-2		.2 *	.3	.2 *	.2 *	2.3 *	.2 *	.2 *	10.9	14.5 *	3.6 *			
C378-56-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.63	.2 *	10.4	14.33*	3.93*			
C378-58-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	8.96	12.46*	3.50*			

G377---65	98900		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									32	.139	4.385
C377--0-1		1.8	58.24	1.8	8.11	255.4	1.9	2.2	18.4	347.85	329.45	32	.139	4.385
C377--1-1		.99	14.4	.50	1.8	71.62	.54	.50	15.4	105.75	90.35	15	.12	4.97
C377--2-1		1.3	37.1	1.3	4.77		2.4	2.3	14.3			29	.129	
C377--3-1		.72	1.2	.2 *	.2 *	4.50	.59	.2 *	13.2	20.81*	7.61*	1.7		3.7
C377--4-1		.81	2.0	.2 *	.2 *		.2 *	.90	13.5			2.5		
C377--5-1		2.7	.99	.2 *	.2 *	2.3 *	1.4	.2	3.6	11.59*	7.99*	.37		
C377--7-1		.68	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	5.54	9.52*	3.38*			
C377--8-1		.4	.3	.2 *	.2 *	2.3 *	.2 *	.3	7.48	11.38*	3.90*	.7		
C377-11-1		.3	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	5.0	8.6 *	3.6 *			
C377-15-1		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	.2 *	3.7 *	3.5 *			
C377-16-1		.2 *	.2 *	.2 *	.2 *	2.3 *	6.85	.3	11.7	21.95*	10.25*			
C377-17-1		.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	11.9					
C377-21-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	8.87	12.37*	3.50*			
C377-27-2		.3	.2 *	.2 *	.2 *	2.3 *	6.89	.45	15.4	25.94*	10.54*			
C377-29-2		.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	12.8					
C377-51-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	8.38	11.88*	3.50*			

FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 23

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G369---65	56700		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									48	.120	3.565
C369--0-1		1.9	90.72	3.6	10.9	323.4	4.3	2.3	19.4	456.52	437.12	48	.120	3.565
C369--1-1		2.4	102.0	4.0	14.9	331.1	5.14	3.7	20.1	483.34	463.24	43	.146	3.246
C369--2-1		2.2	93.69	3.1	7.12		1.6	3.7	15.3			43	.0760	
C369--3-1		.77	28.5	.90	1.3	35.6	3.6	.86	11.8	85.13	71.53	37.	.04606	1.250
C369--4-1		1.2	16.3	.63	.2 *		.2 *	.90	11.8			14.		
C369--5-1		.68	3.8	.2 *	.2 *	9.91 A	.4	.3	12.9			5.60		
C369--8-1		.3	1.3	.2 *	.2 *	13.1 A	1.1	.2 *	12.8			4.		
C369-11-1		.2	.68	.2 *	.2 *	7.66A	.54	.2 *	13.0			3.		
C369-22-2		.2 *	.2 *	.2 *	.2 *	14.9 A	.2 *	.2 *	14.6					
C369-34-2		.2 *	.2 *	.2 *	.2 *	8.56A	.2 *	.2 *	12.3					

G373---65	88600		NO SURFICIAL BED SAMPLE AT THIS CORE SITE									41.	.134	4.006
C373--0-1		3.1	128.4	5.09	17.2	514.4	4.2	3.2	21.9	697.49	675.59	41.	.134	4.006
C373--1-1		2.0	70.63	2.6	12.0	274.8	1.8	2.1	19.7	385.63	365.93	35.	.170	3.891
C373--3-1		1.8	53.51	1.8	3.7	202.3	2.2	1.8	14.3	281.41	267.11	30.	.069	3.731
C373--4-1		1.8	30.6	1.0	1.3	43.7	1.2	1.2	15.5	96.3	80.8	17.	.042	1.43
C373--5-1		1.5	15.4	.50	.54	23.9	1.7	1.4	15.4	60.34	44.94	10.	.035	1.55
C373--6-1		.99	6.80	.2 *	.2 *	24.8	.99	.72	12.7	47.40*	34.70*	6.9		3.65
C373-10-1		3.0	10.7	.2 *	.2	34.2	.95	1.2	20.5	70.95*	50.45*	3.6	.02	3.20
C373-11-1		2.0	6.08	.2 *	.2 *	25.7	.90	.81	19.0	54.89*	35.89*	3.0		4.23
C373-22-2		.99	.72	.2 *	.2 *		.2 *	.95	11.9			.73		
C373-34-2		.4	2.7	.2 *	.2 *	15.3	1.20	.99	13.6	34.59*	20.99*	7		5.7
C373-44-2		.1	.2 *	.2 *	.2 *		.2 *	.2 *	9.64					

FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 18

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G 6---65			NO SURFICIAL BED SAMPLE AT THIS CORE SITE									22	.053	3.60
C 6--0-1		1.4	30.4	1.3	1.6	109.5						22	.053	3.60

APPENDIX 4. — *Measured radionuclide concentrations and computed totals and ratios of radionuclides in selected segments of cores from the estuary* — Continued

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	RADIONUCLIDE CONCENTRATION (PC/G)										RATIOS		
		CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
C 6--1-1	1.4	25.4	.90	.54	13.9							18	.021	.547
C 6--2-1	.90*	3.4	.90*	.90*	42.3									12
C 6--3-1	.90*	.90*	.90*	.90*	32.7									
C 6--4-1	.45*	.77	.45*	.54	20.8								.70	27
C 6--5-1	.90*	1.0	.90*	.90*	39.4									39
C 6--7-1	.45*	.68	.45*	.45*	26.7									39
C 6-12-1	.45*	.90	.45*	.45*	21.4									24
C 6-17-1	.45*	.68	.45*	.45*	22.1									32
C 6-21-1	.45*	.59	.45*	.45*	16.4									28
C 6-26-1	.45*	.59	.45*	.45*	19.9									34
C 6-32-2	.45*	.54	.45*	.45*	12.5									23
C 6-40-2	.45*	.68	.45*	.45*	25.4									37
C 6-44-2	.45*	.45*	.45*	.45*	26.7									
C 6-50-2	.45*	.90	.45*	.45*	27.0									30
C 6-58-2	.45*	.72	.45*	.45*	21.4									30
G370---65	4900	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C370--0-1	.2 *	6.49	.3	.4	24.8	.4	.2 *	11.8	44.59*	32.79*			.06	3.82
C370--1-1	.2 *	4.86	.2	.2 *	22.5	.59	.2 *	9.95	38.70*	28.75*				4.63
C370--3-1	.2 *	4.1	.2 *	.2 *	9.01	.2	.2 *	9.46	23.57*	14.11*				2.2
C370--5-1	.2 *	4.55	.2 *	.2 *	7.66	.45	.2 *	9.5	22.96*	13.46*				1.68
C370-11-1	.2 *	3.8	.2 *	.2 *	4.1	.90	.2 *	10.3	19.90*	9.60*				1.1
C370-18-2	.2 *	4.1	.2 *	.2 *		.2 *	.2 *	7.16						
C370-26-2	.2 *	.2 *	.2 *	.2 *		.2 *	.2 *	9.28						
C370-34-2	.2 *	.2 *	.2 *	.2 *	2.3 *	.2 *	.2 *	12.2	15.7 *	3.5 *				
G368---65	31200	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C368--0-1	2.41	81.94	3.7	6.67	295.5	2.9	1.9	19.6	414.61	395.01		34	.0814	3.606
C368--1-1	1.8	46.76	1.5	3.3	137.4	1.9	1.4	16.1	213.16	194.06		26	.071	2.938
C368--3-1	1.6	14.5	.4	.2 *	8.56	1.9	.86	16.9	44.92*	28.02*		9.1		.590
C368--5-1	1.7	9.59	.2 *	.2 *	10.8	.99	.86	15.6	39.94*	24.34*		5.6		1.13
C368-11-1	1.9	2.5	.2 *	.2 *	14.9	.72	.4	16.2	37.02*	20.82*		1.3		6.0
C368-16-2	.63	.59	.2 *	.2 *	5.41	.72	.2	14.5	22.45*	7.95*		.94		9.2
C368-34-2	.2 *	.2 *	.2 *	.2 *	12.6	.90	.2 *	12.1	26.60*	14.50*				
C368-36-2	.4	.2 *	.2 *	.2 *	2.3 *	.4	.2 *	11.9	15.8 *	3.9 *				

FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 14

SAMPLE NUMBER	INSITU GROSS GAMMA	CO60	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G371---65	14400	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C371--0-1	1.3	58.60	.90	7.52	190.5	5.95	5.0	16.3	286.07	269.77	45	.128	3.251
C371--1-1	.2	2.8	.2 *	.2 *	10.8	.72	.2 *	10.5	25.62*	15.12*	10		3.9
C371--3-1	.2	3.3	.2 *	.2 *	3.2	.68	.2 *	11.0	18.98*	7.98*	20		.97
C371--5-1	.3	3.6	.3 *	.2 *	10.4	.54	.2 *	11.7	27.24*	15.54*	10		2.9
C371-10-2	.4	4.50	.2 *	.2 *		.2 *	.2 *	9.41			10		
C371-16-2	.45	7.93	.2	.99	18.0	.81	.2 *	11.3	39.88*	28.58*	18	.12	2.27
C371-26-2	1.2	42.5	.72	5.05	89.64	2.4	1.2	16.2	158.91	142.71	35	.119	2.11
C371-40-2	.4	10.8	.54	1.1	22.5	.72	.2 *	12.5	48.76*	36.26*	30	.10	2.08
C371-44-2	1.4	60.72	1.5	9.59	119.4	2.6	1.8	16.6	213.61	197.01	43	.158	1.966
C371-46-2	.81	30.3	.68	2.6	17.1	.2 *	1.5	14.1	67.29*	53.19*	37	.086	.564
G367---65	29900	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C367--0-1	.86	20.6	.81	1.5	78.38	1.7	.2	12.5	116.55	104.05	24	.07300	3.800
C367--1-1	.3	5.05	.3	.2 *	18.0	.3	.2 *	12.5	36.85*	24.35*	20		3.560
C367--2-1	.3	4.73	.3	.4	20.7	.2 *	.2 *	12.9	39.73*	26.83*	20	.08000	4.380
C367--3-1	.3	5.05	.2	.3	20.7	.2 *	.2 *	12.7	39.65*	26.95*	20	.06000	4.100
C367--4-1	.3	5.63	.2	.4	12.2	1.1	.2 *	11.8	31.83*	20.03*	20	.07000	2.170
C367--5-1	.3	5.14	.4	.2 *	15.3	.2 *	.2 *	12.8	34.54*	21.74*	20		2.980
C367--7-1	.45	14.6	.59	1.0		.2 *	.5	10.1			32	.06800	
C367--8-1	.68	19.3	.81	2.4	84.23	1.0	.5	18.6	127.52	108.92	28	.12000	4.360
C367--9-1	.4	4.0	.2 *	.2 *		.2 *	.2 *	10.5			10		
C367-11-2	.2 *	3.6	.2 *	.2 *	2.3 *	.2 *	.2 *	10.5	17.4 *	6.9 *			
C367-17-2	.45	2.6	.2 *	.2 *		.2 *	.2 *	9.32			5.8		
C367-23-2	.2 *	2.1	.2 *	.2 *	10.8 A	.2 *	.2 *	14.3					
C367-29-2	.63	2.1	.2 *	.2 *		.4	.68	9.91			3.3		
C367-35-2	.3	3.1	.2 *	.2 *	5.41A	1.2	.2	11.5			10		
C367-37-2	.4	.86	.2 *	.2 *		.2 *	.2 *	11.6			2		
G367I--65	29900	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C367I-0-1	1.5	41.8	.99	3.6	100.0	4.77	6.62	16.3	175.58	159.28	28	.086	2.39
C367I-1-1	.3	7.43	.4	.54	28.8	1.0	.2 *	12.1	50.77*	38.67*	20	.073	3.88
C367I-2-1	.2 *	4.0	.2	.2 *	8.56	.45	.2 *	11.9	25.71*	13.81*			2.1
C367I-3-1	.3	3.6	.2 *	.2 *	7.21	.2 *	.2 *	11.2	23.11*	11.91*	10		2.0
C367I-5-1	.2 *	4.55	.2	.2 *	11.7	.2 *	.2 *	13.0	30.25*	17.25*			2.57
C367I-8-1	.50	3.5	.2 *	.2 *		8.78	1.8	17.1			7.0		
C367I11-2	.2 *	4.4	.2 *	.2 *	14.0	.2	.2 *	11.7	31.1 *	19.4 *			3.2
C367I13-2	.3	3.6	.2 *	.2 *		.2 *	.54	9.10			10		
G366---65	44200	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C366--0-1	2.0	52.75	1.2	6.22	258.1	2.8	1.8	18.9	343.77	324.87	26	.118	4.893
C366--1-1	2.6	38.2	1.0	1.4	41.9	3.2	1.8	17.7	107.8	90.1	15	.037	1.10
C366--2-1	3.2	63.65	1.1	3.4	79.73	6.22	2.9	19.1	179.30	160.20	20	.053	1.253
C366--3-1	2.6	27.4	.86	.95	41.4	3.6	4.2	19.1	100.11	81.01	11	.035	1.51
C366--4-1	2.1	39.9	.81	2.6	77.48	4.4	1.4	17.3	145.99	128.69	19	.065	1.94
C366--5-1	2.7	67.12	1.0	3.8	81.53	6.62	2.3	22.5	187.57	165.07	25	.057	1.215
C366--6-1	2.7	70.14	.95	3.2	66.22	3.5	3.0	20.0	169.71	149.71	26	.046	.9440
C366--7-1	3.2	74.55	1.3	2.9	65.32	5.63	2.3	23.0	178.20	155.20	23	.039	.8760
C366--8-1	2.7	72.39	1.2	4.0	103.2	5.95	2.3	21.7	213.44	191.74	27	.055	1.426
C366--9-1	3.2	83.56	.99	4.64	107.2	12.3	4.4	21.3	237.59	216.29	26	.0555	1.283
G 3---65		NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C 3--0-1	.90*	11.1	.90*	1.3	58.11								.12	5.24
C 3--1-1	.59	8.65	.45*	.45*	81.53							15		9.43
C 3--2-1	.45	3.6	.45*	.81	105.4							8.0	.22	29
C 3--3-1	.45*	4.3	.45*	.59	34.14								.14	22
C 3--4-1	.90*	4.77	.90*	.90*	49.10									10.3
C 3--5-1	.50	4.50	.45	.45	77.03							9.0	.10	17.0
C 3--6-1	.54	4.4	.50	.45*	14.7							8.1		3.3
C 3-10-1	.90	9.37	.77	.77	14.5							10	.082	1.55
C 3-14-1	.50	3.0	.45*	.45*	8.33							6.0		2.8
C 3-33-3	.45*	.99	.45*	.45*	8.02									8.1
C 3-39-3	.45*	1.1	.45*	.45*	26.8									24
C 3-45-3	.45*	.63	.45*	.45*	6.26									9.9
C 3-60-3	.45*	.86	.45*	.45*	17.3									20

APPENDIX 4. — *Measured radionuclide concentrations and computed totals and ratios of radionuclides in selected segments of cores from the estuary* — Continued

SAMPLE NUMBER	INSITU GROSS GAMMA (CPM)	RADIONUCLIDE CONCENTRATION (PC/G)										RATIOS		
		C060	ZN65	MN54	SC46	CR51	RU106	ZRNB95	K40	TOTAL	TOTAL LESS K40	ZN/CO	SC/ZN	CR/ZN
G372---65	7600	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C372--0-1		.2 *	4.2	.2 *	.2 *	14.9	.2 *	.2 *	10.2	30.3 *	20.1 *			3.5
C372--1-1		.3	12.6	.68	.4	23.4	1.4	.2 *	13.7	52.68*	38.98*	40	.03	1.86
C372--3-1		.2	3.6	.2 *	.3	25.7	1.2	.2 *	15.3	46.7 *	31.4 *	20	.08	7.1
C372--5-1		.2 *	.2 *	.2 *	.2 *	25.7	1.2	.2 *	14.6	42.5 *	27.9 *			
C372-11-1		.2 *	.2 *	.2 *	.2 *	6.76	.2 *	.2 *	14.9	22.86*	7.96*			
C372-22-2		.2 *	.2 *	.2 *	.2 *			.2 *	.2 *	10.6				
C372-32-2		.2 *	.2 *	.2 *	.2 *			.2 *	.2 *	11.8				
C372-34-2		.4	.2 *	.2 *	.2 *	2.3 *	8.20	.54	19.3	31.34*	12.04*			
C372-36-2		.2 *	.2 *	.2 *	.2 *			.2 *	.2 *	12.0				
C372-52-2		.2 *	.2 *	.2 *	.2 *			.2 *	.2 *	10.6				
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 6														
G388---65	8500	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C388--0-1		.2 *	3.8	.2 *	.68	32.0	.81	.3	14.4	52.39*	37.99*		.18	8.4
C388--1-1		.50	15.8	.4	2.2	90.09	1.6	.2 *	14.4	125.19*	110.79*	32	.14	5.70
C388--2-1		.2	10.5	.2 *	.4		.95	1.7	11.1			50	.04	
C388--3-1		.2	4.82	.2 *	.59	33.8	.72	.2 *	13.2	53.73*	40.53*	20	.12	7.01
C388--5-1		.2 *	.2 *	.2 *	.2 *	7.66	.2 *	.2 *	10.4	19.26*	8.86*			
C388-11-1		.2 *	.2 *	.2 *	.2 *	4.95	1.1	.2 *	11.9	18.95*	7.05*			
C388-34-2		.2 *	.2 *	.2 *	.2 *	13.5	.2 *	.2 *	10.7	25.4 *	14.7 *			
C388-58-2		.2 *	.2 *	.2 *	.2 *	4.50	.72	.2 *	11.5	17.72*	6.22*			
G389---65	6200	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C389--1-1		.3	7.34	.4	1.2	41.4	1.1	.2 *	10.5	62.44*	51.94*	20	.16	5.64
C389--2-1		.2	3.0	.2 *	.2 *			.2 *	.2 *	8.20			10		
C389--3-1		.4	2.7	.3	.3	17.6	.99	.1	10.9	33.29	22.39	7	.1	6.5
C389--4-1		.3	1.8	.2 *	.2 *			.2 *	.2 *	9.14			6		
C389--5-1		.3	1.4	.2 *	.3	20.3	1.1	.2 *	9.86	33.66*	23.80*	5	.2	14
C389--7-1		.2 *	.2 *	.2 *	.2 *			.2 *	.2 *	9.86				
C389-13-2		.2 *	.2 *	.2 *	.2 *	9.01	.54	.2 *	12.6	23.15*	10.55*			
C389-15-2		.2 *	.2 *	.2 *	.2 *	2.3 *	.3	.2 *	12.3	15.9 *	3.6 *			
C389-39-2		.2 *	.2 *	.2 *	.2 *	8.56	.54	.2 *	11.4	21.50*	10.10*			
FOLLOWING CORE(S) FROM CROSS SECTION NEAR COLUMBIA RIVER MILE 2														
G387---65	14100	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C387--0-1		.99	43.9	.4	6.62	258.1	3.4	1.5	17.9	332.81	314.91	44	.151	5.88
C387--1-1		.2 *	1.1	.2 *	.3	11.3	1.2	.2 *	14.0	28.5 *	14.5 *		.3	10
C387--3-1		.2 *	1.1	.2 *	.2 *	3.6	.2 *	.2 *	14.0	19.7 *	5.7 *			3.3
C387--5-1		.2 *	2.5	.2 *	.4	7.66	.90	.2 *	14.2	26.26*	12.06*		.2	3.1
C387--6-1		.3	.59	.2 *	.2 *			.2~*	.2 *	11.5			2		
C387-11-1		.2 *	.90	.2 *	.2	2.3 *	.54	.2 *	13.2	17.74*	4.54*		.2	
C387-34-2		.2 *	.2 *	.2 *	.2	2.3 *	.2 *	.2 *	12.7	16.2 *	3.5 *			
C387-42-2		.4	.2 *	.2 *	.2 *		9.05	1.3	19.0					
G387I--65	14100	NO SURFICIAL BED SAMPLE AT THIS CORE SITE												
C387I-0-1		.59	41.6	.77	5.95	272.1	2.1	1.3	15.0	339.41	324.41	71	.143	6.54
C387I-1-1		.54	.2 *	.2 *	.2 *	2.3 *	7.88	.68	15.9	27.90*	12.00*			
C387I-3-1		.2	.90	.2 *	.2 *	5.86	.3	.2 *	15.0	22.86*	7.86*	4		6.5
C387I-5-1		.2 *	1.3	.2 *	.2 *	2.3 *	.3	.2 *	12.1	16.8 *	4.7 *			
C387I11-1		.3	3.0	.2 *	.3	12.2	1.1	.3	11.1	28.5 *	17.4 *	10	.1	4.1

APPENDIX 5. — DETERMINATION OF THE AMOUNT OF RADIONUCLIDES PER UNIT AREA BELOW THE BED SURFACE

Data on the vertical variation of radionuclides and sediment texture can be used to determine the distribution and total amount of a radionuclide or radionuclides throughout the entire column of bed sediment. The computation is carried out on the basis of a unit area and is made from

$$A_d = K \sum_{i=1}^{n} \gamma_i R_i h_i$$

where

A_d is the amount of a radionuclide (or radionuclides) per unit area between the bed surface and any depth, d, below the surface;

γ_i is the specific weight of sediment, in situ, in the ith depth increment below the bed surface, expressed in the units of weight per unit volume;

R_i is the concentration of the radionuclide (or radionuclides) in the ith depth increment below the bed surface, expressed in the units of amount per unit weight;

h_i is the height of the ith depth increment below the surface;

n is the number of depth increments between the bed surface and depth, d, and

K is an appropriate units-conversion constant.

In the computations, values of R_i were taken from appendix 4, and values of γ_i were determined from figure 31 by using median values given in appendix 2. The curve in figure 31 is a relation between particle size and specific weight that was defined by Hembree, Colby, Swenson, and Davis (1952) from reservoir deposits. Data obtained by the U.S. Army Corps of Engineers (1960, pls. 307–308) from estuary samples are plotted in the figure for comparison. Although the points scatter considerably, the curve for the reservoir deposits appears to represent the average relationship for the estuary samples reasonably well. For depth increments for which R_i and γ_i were not defined, values were determined by proration between known values.

In most cores, the total depth to which radionuclides extended was not precisely defined by the radionuclide analyses. In order to estimate the total
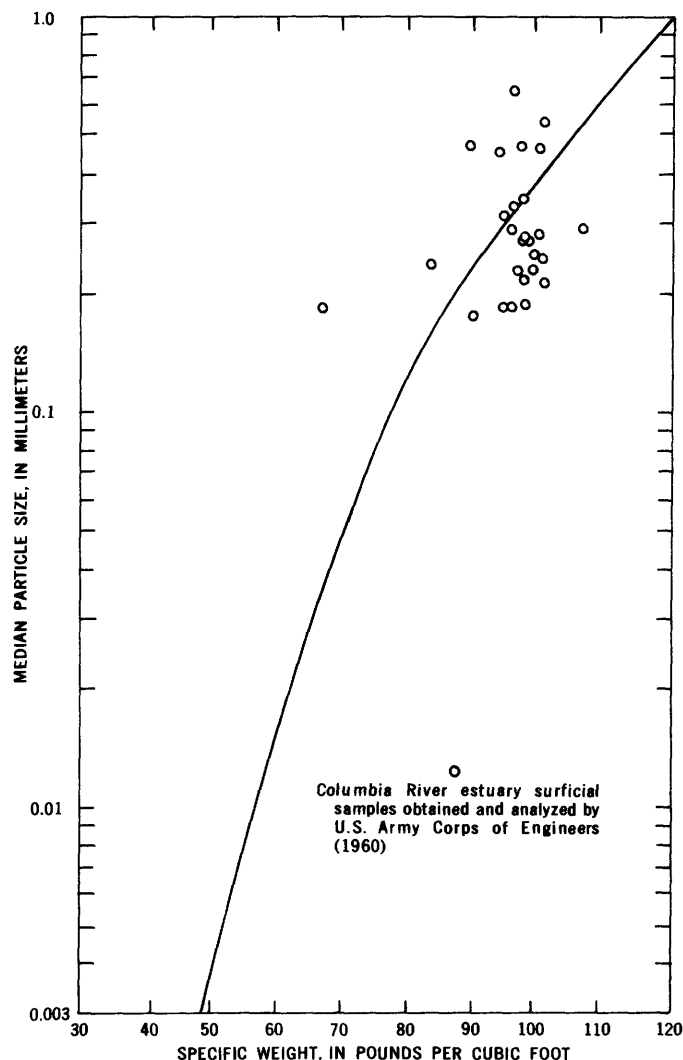

FIGURE 31. — Relation between specific weight of sediment in situ and median particle size (from Hembree and others, 1952). Data from estuary samples are plotted for comparison.

depth and the amount of radionuclides in the whole sediment column, values of A_d and d were plotted by increments to define the attenuation of radionuclide concentrations with depth; the amount and total depth were taken as the values of A_d and d, respectively, where the slope of the curve, dA_d/dd, equaled zero.

APPENDIX 6. — EXPLANATION OF VARIABLES USED IN THE COMPUTATION OF THE FRACTION OF FINE SEDIMENT RETAINED IN THE ESTUARY

Radionuclide and sediment transport data presented by Haushild, Perkins, Stevens, Dempster, and Glenn (1966) and Foster (1964) for the Columbia River at Vancouver together with other data can be used to obtain values of the variables and constants required to compute P, the fraction of fine sediment retained in the estuary, from equation 5. Transport-related variables are evaluated as follows: Equating the total discharge of Zn^{65} associated with sediment to its component parts gives

$$R_n r_p = p_f Q_s C_f + p_c Q_s C_c.$$

If $\dfrac{C_f}{C_c} = b$, then $C_c = \dfrac{R_n r_p}{Q_s (p_c + b p_f)}$

where

C_f and C_c are the concentrations of Zn^{65} associated with fine and coarse sediment, respectively;

R_n is the total discharge of Zn^{65};

r_s and r_p are the fractions of the discharge of Zn^{65} that are transported in solution and in association with the sediment, respectively;

Q_s is the total sediment discharge; and

p_f and p_c are the fractions of the total sediment discharge, by weight, that are fine and coarse sediment, respectively.

Thus, the discharge of Zn^{65} associated with the coarse sediment, $C_c Q_c$, is

$$C_c Q_c = \frac{p_c Q_s R_n r_p}{Q_s (p_c + b p_f)} = \frac{p_c R_n r_p}{p_c + b p_f}.$$

Similarly, the discharge of the Zn^{65} associated with the fine sediment, $C_f Q_f$, is

$$C_f Q_f = \frac{p_f b R_n r_p}{p_c + b p_f}.$$

Also (see definitions on p. L44),

$$R_s = \frac{(C_s Q_w)_1}{(C_f Q_f)_1} = \frac{R_n r_s}{\dfrac{p_f b R_n r_p}{p_c + b p_f}} = \frac{r_s (p_c + b p_f)}{r_p b p_f}$$

and

$$R_c = \frac{(C_c Q_c)_1}{(C_f Q_f)_1} = \frac{\dfrac{p_c R_n r_p}{p_c + b p_f}}{\dfrac{p_f b R_n r_p}{p_c + b p_f}} = \frac{p_c}{b p_f}.$$

The value of b can be approximated from several different kinds of data by representing the Zn^{65} concentrations of the coarse and fine parts of the total sediment load with the concentrations associated with a characteristic size in each part, such as the median size. A review of particle-size analyses of suspended sediment at Vancouver (Haushild and others, 1966, p. 151) suggests that the median sizes of the coarse and fine sediment in transport are slightly larger than 0.125 and 0.008 mm, respectively. Unpublished data from size separates of bed sediment collected for mineralogical analyses 6 miles below the confluence of the Columbia and Willamette Rivers show that concentrations of Zn^{65} are about 15 and 44 pc/g, respectively, for these median sizes. Interpolation and extrapolation at mile 60 on the graph in figure 28 give concentrations of about 40 and 200 pc/g for the median sizes, respectively. Comparable concentrations from figure 27 are about 24 and 170 pc/g. Although values of b computed from each pair of concentrations differ, an average ratio of about five appears to be reasonable.

The findings of Johnson, Cutshall, and Osterberg (1967) indicate that approximately 3 percent of the Zn^{65} associated with the fine particulate matter might be displaced in the presence of sea water. Assuming this is the case, c (p. L43) equals 0.97. If the leached Zn^{65} remained in solution, then k (p. L43) should equal about 1.15 because the Zn^{65} associated with the fine particulate matter in transport is about five times greater than that in solution.

The factor λA equals 5.82 curies per day and comes directly from the product of 0.00283 day^{-1} (the decay coefficient of Zn^{65}) and 2,059 curies (the amount of Zn^{65} computed to be in the estuary bed).