

Relations Among Radionuclide Content and Physical, Chemical, and Mineral Characteristics of Columbia River Sediments

GEOLOGICAL SURVEY PROFESSIONAL PAPER 433-M

*Prepared in cooperation with the
U.S. Atomic Energy Commission*



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By J. L. GLENN

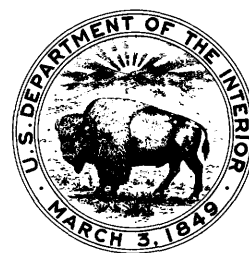
With a section on SAND AND GRAVEL MINERALOGY

By R. O. VAN ATTA

TRANSPORT OF RADIONUCLIDES BY STREAMS

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TRANSPORT OF RADIONUCLIDES BY STREAMS

RELATIONS AMONG RADIONUCLIDE CONTENT AND PHYSICAL, CHEMICAL, AND MINERAL CHARACTERISTICS OF COLUMBIA RIVER SEDIMENTS

By J. L. GLENN

ABSTRACT

The radionuclides discussed in this report were produced by neutron activation of elements in Columbia River water that was used to cool the nuclear reactors in the Hanford area near Pasco, Wash., prior to their final shutdown early in 1971. After return of the low-level radioactive cooling waters to the Columbia River, some radionuclides were attached to sediment particles, and some particles were incorporated in the streambed. This report presents data on radionuclides in size separates of streambed sediments and describes relations among radionuclide content, particle size, cation-exchange capacity, carbon and nitrogen content, and mineralogy. Differences in radionuclide concentrations with particle size and with sample location are evaluated in the framework of simple models for the origin or radionuclides in streambed sediments.

Cation-exchange capacity varies inversely with particle size. For medium sands to clays, the regression of the logarithm of cation-exchange capacity on the logarithm of geometric mean particle diameter is linear and has a regression coefficient of -0.6 . Mean cation-exchange-capacity values for medium sands from seven Columbia River locations are $2.8 (\pm 1.7)$ milliequivalents per 100 grams; mean values for medium to fine clay are $40.8 (\pm 5.1)$ milliequivalents per 100 grams. Mean cation-exchange capacities are higher in coarse and very coarse sands than in medium sands. Very fine sands have cation-exchange capacities that are higher or nearly equal to those of medium and coarse silts. Anomalies in the relation of cation-exchange capacity to particle diameter are traced to the influences of organic matter and mineralogy and to the efficiency of the techniques that were used to prepare size separates.

No statistically significant difference in cation-exchange capacity was noted between locations at the upper and lower ends of the study reach. Cation-exchange capacities in Snake River and in Willamette River size separates generally are slightly higher than cation-exchange capacities in Columbia River size separates.

Nitrogen content also varies inversely with particle size. Mean values in medium to fine clay and in very fine sand are 0.45 percent (about 6 percent organic matter) and 0.04 percent (less than 1 percent organic matter), respectively. High carbon contents in coarse and very coarse sands and high cation-exchange capacities frequently correlate. No longitudinal trends in carbon or nitrogen content are apparent.

Clay minerals make up 70–80 percent of all components in both the <2 -micron and the 2- to 4-micron size separates. The dominant clay minerals are illite, montmorillonite, and mixed-layer clays in roughly equal proportions; chlorite and kaolinite in about 2 to 1 proportions compose 10 percent or less of the average clay-mineral suite. Rough calculations indicate that the mixed-layer clays have average cation-exchange capacities of about 25 milliequivalents per 100 grams. These cation-exchange capacities and the apparent thermal stability of some mixed-layer clays suggest that illite and chlorite layers are abundant in the mixed-layer fraction. Empirical observations and correlations between mineral and cation-exchange-capacity data suggest that the percentages of mineral types are fairly accurate.

The percentages of illite and non-clay components (except organic matter, computed from nitrogen or carbon content) increase and the percentages of montmorillonite, mixed-layer clays, and total clay minerals decrease as particle size increases from less than 2 microns to 2–4 microns. The dominant non-clay components are feldspars, which average 10–15 percent of all components; quartz, which is about 6–12 percent of all components; and organic matter, which averages 4–6 percent of all components.

The mineral suite in the <2 -micron and the 2- to 4-micron separates from Snake River is not appreciably different from that in Columbia River. The Willamette River suite, however, contains more montmorillonite and less illite than does the Columbia River suite. Highly significant differences in mineral assemblage along the Columbia River are not evident, although montmorillonite may increase and quartz may decrease slightly between Pasco, Wash., and St. Helens, Oreg.

Amphibole-group minerals and other non-clay minerals occur in greater amounts as particle size increases from very fine to coarse silt. In the coarse silt separate, clay minerals average less than 15 percent of all components. Within the clay-mineral suite in silt separates, illite and kaolinite plus chlorite increase relative to montmorillonite as particle size increases. Although the two coarsest silt separates were ground prior to X-ray analyses, particle size may have affected estimates of mineral abundance.

Petrographic analyses of sand that was divided into five size separates and gravel that was unsized show that the dominant components are rock fragments, feldspars, and silica-group constituents. Rock fragments average one-third

to one-half of all components in the three finest sand separates and are even more abundant in coarse separates. Nearly two-thirds of all rock fragments are volcanic rocks or volcanic glass. Maturity indices, which are a measure of the susceptibility of sands to weathering, are correspondingly low. More than 25 percent of the feldspar grains and about 15 percent of the rock fragments in medium and fine sand are greater than one-third and one-half altered, respectively. Only the Willamette River, which has higher percentages of rock fragments and lower percentages of potash feldspar and silica-group constituents, appears to have a mineral suite different from the Columbia River suite. No highly significant longitudinal changes in sand-separate mineralogy occur along the Columbia River.

Chromium-51, zinc-65, scandium-46, manganese-54, and cobalt-60, in decreasing order of concentration, are the gamma-emitting radionuclides identified in Columbia River size separates. Fine- to medium-clay separates contain an average of 36 percent of the sum of the zinc-65 concentrations in all separates; fine- and medium-sand separates combined contain less than 2 percent of the sum of the zinc-65 concentrations in all separates. Weighting radionuclide concentrations with results from particle-size analyses shows that the relatively more abundant fine- and medium-sand separates contain nearly 45 percent of the total amount of zinc-65; the relatively less abundant fine- to medium-clay separates contain only 16 percent.

Regression analyses show that the logarithms of radionuclide concentrations in size separates are related to the logarithms of geometric mean particle diameters in size separates. Correlation coefficients of greater than 0.9 indicate that the relations closely fit linear-regression lines. Consistent irregularities in the relation of radionuclide concentrations to geometric mean particle diameters correlate with cation-exchange-capacity variations, organic-matter fluctuations, and (or) mineral changes. A strong tendency for the 2- to 4-micron size separate to flocculate was observed, and flocculation has been suggested to explain relatively low radionuclide contents in the 2- to 4-micron size.

Covariance analyses indicate that regression coefficients for relations of the logarithms of radionuclide concentrations to the logarithms of particle diameters differ significantly at the Pasco location for different radionuclides. No significant difference exists when regression coefficients for the logarithms of zinc-65 concentrations versus the logarithms of particle diameters are compared among sample locations. The pooled regression coefficient for the relation of the logarithms of zinc-65 concentrations to the logarithms of particle diameters is -0.6 and is about equal to the regression coefficient for the relation of cation-exchange capacity to particle diameter. For silt and clay separates, radionuclide content and cation-exchange capacity are related more directly to the total amount of clay minerals than to the particle size.

Between successive downstream locations, radionuclide concentrations in streambed sediments decrease, but not in proportion to distance. Greatest decreases occur between adjacent locations bracketing major tributaries. Zinc-65, manganese-54, cobalt-60, and scandium-46 concentrations at St. Helens, Oreg., are about 1 percent of their concentrations at Pasco, Wash.

Radionuclide-concentration ratios show varying relations to particle size and to sample location. The scandium-46/zinc-65 ratio is an order of magnitude higher in clay than in fine sand, whereas the zinc-65/manganese-54 and zinc-65/cobalt-60

ratios appear to be independent of particle size. The zinc-65/cobalt-60 ratio increases progressively at locations downstream from McNary Dam, but the scandium-46/zinc-65 ratio is nearly constant below McNary Dam.

Radionuclide content is related directly to cation-exchange capacity in medium-sand to clay separates but tends to be independent of cation-exchange capacity in coarse sands. Increases in cation-exchange capacity that are greater than increases in radionuclide content have been attributed to weathering rinds on coarse particles and to organic-matter content.

Two simplified qualitative models have been used to aid interpretation of streambed-sediment and radionuclide data. One model assumes a fixed streambed and reversible uptake-release reactions that are dependent mostly on solute radionuclide concentrations. The second model involves sediment transport and considers irreversible uptake reactions that are dependent mostly on solute radionuclide concentrations. Most data presented in this report favor a model that combines features of the two simplified models and that includes at least partially reversible uptake-release reactions. The degree of reversibility and the rate of uptake determine the relative importance of sediment transport as a factor in interpreting radionuclide concentrations in Columbia River streambed sediments. Results from additional streambed-sediment and radionuclide studies and results from radionuclide-transport determinations can be used to further develop qualitative and quantitative models.

INTRODUCTION

From the early 1940's until early 1971,¹ the Columbia River received radionuclides from water used to cool the nuclear reactors in the Hanford area near Richland, Wash. (fig. 1). Most radionuclides were produced by neutron activation of stable elements in or added to the cooling water. Radionuclide concentrations have been monitored almost continuously since operation of the Hanford reactors was begun, and results from the monitoring program and from related studies are contained in yearly reports (Nelson, 1961, 1962; Wilson, 1963, 1964) by the General Electric Co., one of the prime contractors responsible for operating the Hanford facilities.

With the advent of peaceful uses of atomic energy and with the prospect of increasing reliance on nuclear energy, detailed studies began on the disposition of radionuclides in the Columbia River. Initial studies indicated that nuclides separated naturally into particulate (associated with sediment, both inorganic and organic detritus) and solute phases. Those nuclides that became associated with particulates are incorporated in varying degrees in streambed sediments throughout the Columbia River below Richland, Wash.

¹In early 1971, the last of eight reactors at Hanford that were cooled by once-through flow was shut down. A ninth reactor, which has a recirculating cooling system and, therefore, contributes very little radioactive material to the Columbia River, also was shut down in 1971 but may be started again.

In 1962, the U.S. Geological Survey and the General Electric Co. (later replaced by Battelle-Northwest, Pacific Northwest Laboratories) began studies in cooperation with the U.S. Atomic Energy Commission on the uptake, transport, and release of radionuclides in the reach of the Columbia River between Pasco and Longview, Wash. Results from transport studies through 1965 are included in reports by Perkins, Nelson, and Haushild (1966), Haushild, Perkins, Stevens, Dempster, and Glenn (1966), and Nelson, Perkins, Nielsen, and Haushild (1966).

Some of the first investigations of radionuclides in Columbia River streambed sediments were described by Nielsen (in Kornegay and others, 1963, p. 98–105), who reported on radionuclides in reservoir sediments behind McNary Dam (fig. 1). Additional results of studies of radionuclides in Columbia River streambed sediments between the Hanford reactors and McNary Dam are included in progress reports from the General Electric Co. (Gamertsfelder and Green, 1964; Nelson and others, 1964) and from Battelle-Northwest (Nelson, 1965; Pearce and Green, 1966; Pearce and Compton, 1967; Pearce, 1968, 1969). Nelson, Perkins, Nielsen, and Haushild (1966, p. 148–155) described in some detail the kinds and quantities of radionuclides in streambed sediments above McNary Dam. Detailed surveys of the distribution of sediments and radionuclides in the streambed of the Columbia River from the head of the estuary near Longview, Wash. (fig. 1), to near Richland, Wash., were conducted by the Geological Survey in 1965 and 1966. Results from these surveys are planned to be included in a future report.

Streambed sediments and suspended sediments were collected in 1963 at Pasco, Wash., Hood River, Oreg., and Vancouver, Wash. (fig. 1), where routine sampling stations had been established to implement transport studies, and the sediments were analyzed for mineralogy, CEC (cation-exchange capacity), and carbon content. Results from these analyses, reported by Haushild, Perkins, Stevens, Dempster, and Glenn (1966, p. 43–79), indicated the possible significance of these important sediment characteristics on radionuclide uptake and transport, but the limited spatial distribution of data and the absence of direct measurement of radionuclide levels precluded many positive results.

The present report presents new data from a study of (1) kinds and amounts of radionuclides in streambed sediments and (2) CEC, mineralogy, and nitrogen and carbon contents of streambed sediments. The primary objective of the study was to establish relations among radionuclide content and

other more commonly measured physical, chemical, and mineral attributes of sediments. From this study, some conclusions also are possible relative to the causes of differences in radionuclide concentrations with particle size and with sample location.

SAMPLE COLLECTION AND PREPARATION

Sets of surficial streambed sediment samples were collected at seven locations along the Columbia River between Pasco, Wash., and St. Helens, Oreg. (fig. 1). Additional sets were collected from locations above the mouths of the two major Columbia River tributaries between Pasco and St. Helens—the Snake River and the Willamette River (fig. 1). Throughout this report, sample sites are referred to as locations, and the Columbia River locations are called Pasco, McNary Dam, The Dalles, Hood River, Bonneville Dam, Vancouver, and St. Helens. “Snake River” and “Willamette River” are used to designate locations in tributary streams. Additional samples for only carbon or nitrogen analyses were collected from Columbia River locations near Ilwaco and near Harrington Point, Wash., and from Willow Creek, a small Columbia River tributary near Heppner Junction, Oreg. (fig. 1).

Samples were collected with a standard U.S. Geological Survey streambed sediment sampler that retrieves about a pint of surficial sediment (maximum depth below streambed surface about 1.5 in.) with each cast. Sampling was done between April 21 and May 12, 1966, just prior to the annual spring rise of the Columbia River and its tributaries. The sample-collection procedure consisted of (1) selecting a location where local sediment inflow probably was minimal and where the channel cross section was fairly regular (no islands), (2) measuring the river depth to determine the cross-sectional profile, and (3) collecting 22–32 samples at about 50-yard intervals along a cross section.

In the laboratory, selected samples from each cross section were cored with a small ($\frac{1}{2}$ -in.-diameter) tube to obtain a representative 10- to 20-gram split from each sample. The coring tube, rather than a standard sample splitter or a quartering technique, was used because of the wide range in particle size (coarse sand to clay) among samples and because of the need to avoid drying samples prior to some types of analyses. A minimum of 18 and a maximum of 24 of the available samples from each location were cored. Samples that were not cored generally were from nearshore or shallow zones where contamination by locally derived sediments was possible. The cored portions from a cross section were combined to form a composite sample that was analyzed

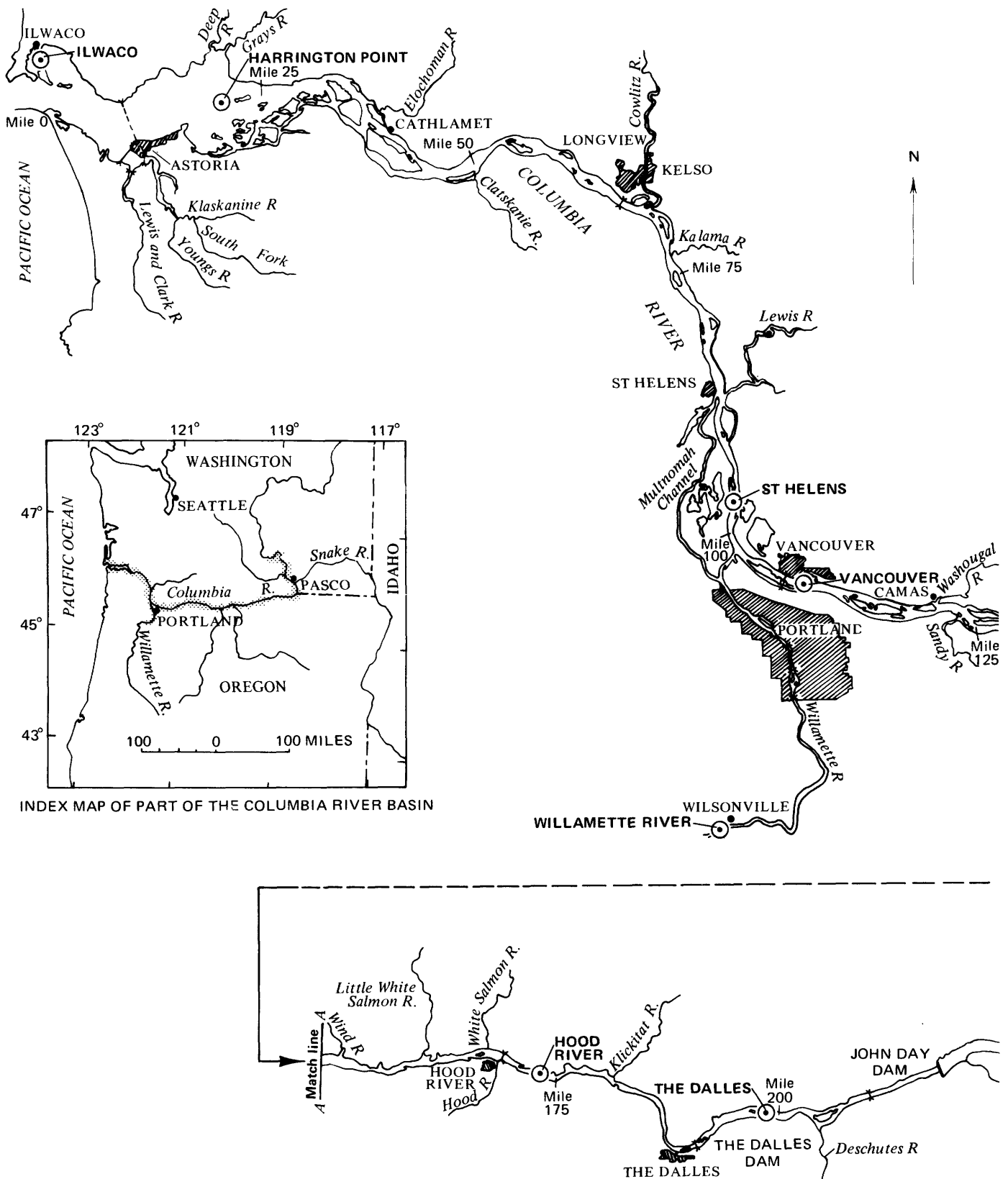
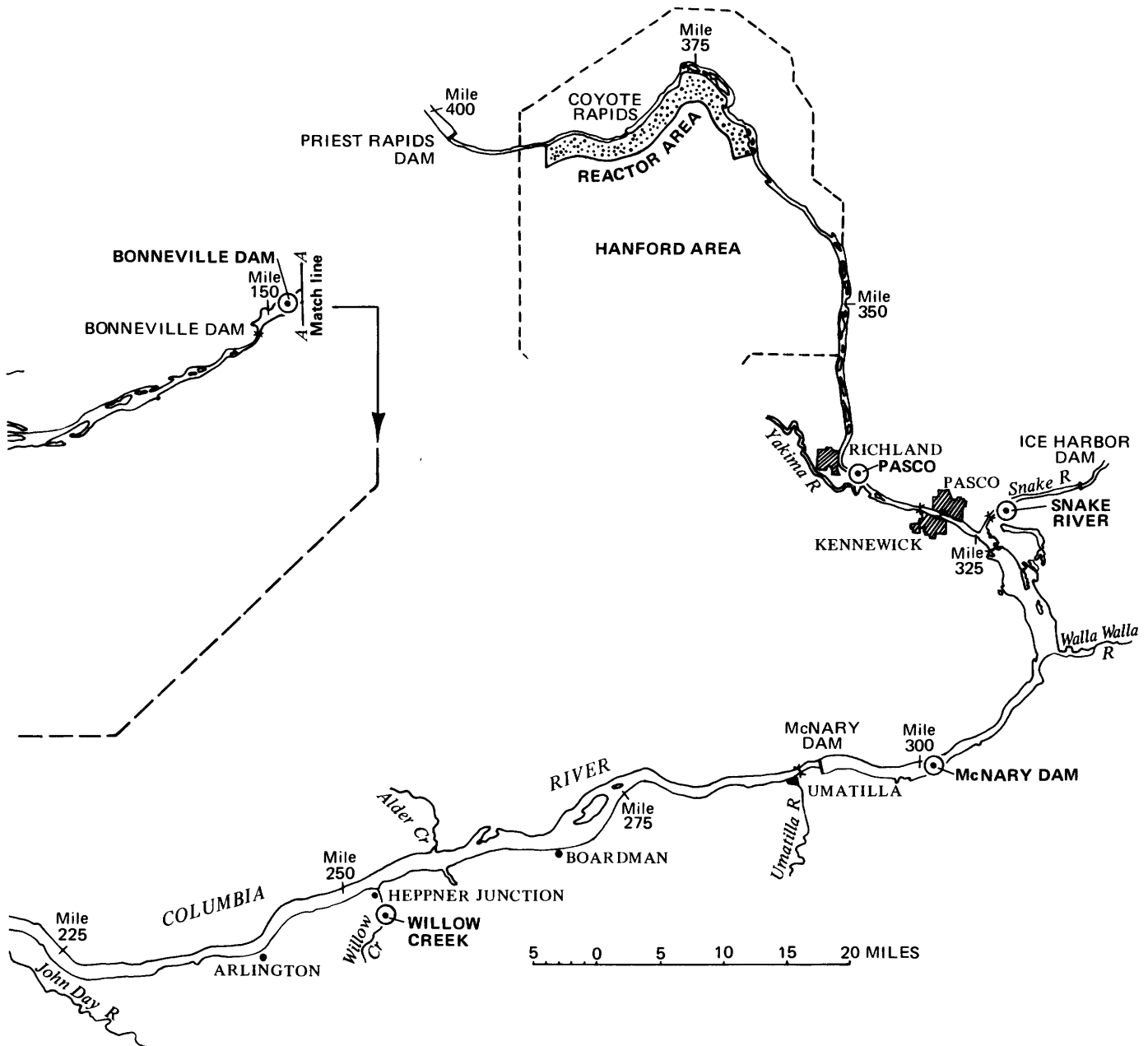


FIGURE 1. — Columbia River study area. Sampling locations are designated by circled dots. (Modified from Haushild and others, 1966.)

EXPLANATION



Sample locations



for particle size by pipette techniques for silt and clay sizes and by visual-accumulation tube for sand sizes. Results from these analyses were used to estimate the distribution of particle sizes in each cross section and to indicate the availability of material in selected size ranges.

Following the particle-size analysis, about equal volumes of sediment were cored from each sample that had been cored previously for the initial composite sample, and this sediment was combined with supplemental amounts of sediment that came from samples appearing to contain certain desired sizes. By a combination of wet-sieve and settling-velocity techniques, the second composite sample from each location was separated into 11 size classes with the following particle-size boundaries (in microns, μ): Class 1, 4,000 to 2,000; class 2, 2,000 to 1,000; class 3, 1,000 to 500; class 4, 500 to 250; class 5, 250 to 125; class 6, 125 to 62; class 7, 62 to 31; class 8, 31 to 16; class 9, 16 to 4; class 10, 4 to 2; and class 11, <2 .

Distilled water (no dispersing agent) and mild physical agitation were employed in preparing the size classes. In an attempt to retain the sediment in as natural a condition as possible, more vigorous chemical and mechanical dispersion techniques, although perhaps better for some aspects of this study, were not employed. Native Columbia River water was not used for various reasons but chiefly because of the possibility that some undeterminable exchange might occur between radionuclides in the water and radionuclides in the sediments.

Particle-size analyses by the pipette method, both with and without vigorous dispersion, were run on a number of fine ($<62\mu$) size separates. When vigorous dispersion was desired, samples were suspended in a 5-percent sodium hexametaphosphate solution and were agitated mechanically in a malted-milk cup for 10 minutes.

ANALYTICAL PROCEDURES

Each size class was divided into two to five splits, the number determined by the amount of sample available and by the amount of sample needed for each prospective type of analysis. A small Jones-type wet splitter was used for silts and clays ($<62\mu$), and a quartering technique was employed for sands ($>62\mu$). If sufficient sample was available, each size class from each Columbia River location was analyzed for (1) radionuclide content, (2) mineralogy, (3) CEC, and (4) nitrogen and carbon content. Samples from tributary streams were not analyzed for radionuclide content.

Advanced multidimensional and multichannel

gamma-ray spectrometry (Perkins, 1965) was used to identify five major gamma-emitting radionuclides in Columbia River sediments. These nuclides and their half lives (Leaderer and others, 1967) are: ^{51}Cr (chromium-51), 27.8 days; ^{65}Zn (zinc-65), 245 days; ^{46}Sc (scandium-46), 83.9 days; ^{54}Mn (manganese-54), 303 days; and ^{60}Co (cobalt-60), 5.26 years. An additional 60 nuclides (Wilson, 1964, p. 11), including some produced during nuclear bomb tests, have been measured in the Columbia River, but the five listed above generally are the most abundant activation products in sediments below Pasco. The major radionuclides, except ^{51}Cr , originated chiefly from exposure to the neutron flux of natural elements in Columbia River water used to cool the reactors in the Hanford area (fig. 1). Chromium-51 occurred chiefly because of the activation of chromium which was added as sodium dichromate to the reactor cooling water to inhibit corrosion. A small amount of some radionuclides probably came from activation of elements in metal pipes that carried water to or through the reactors.

Mineralogy of sand separates ($>62\mu$ sizes) was determined by standard thin-section petrographic techniques supplemented by binocular and petrographic examinations of grains and grain mounts. Thin sections were prepared from approximately 50-gram samples that were well mixed in vials and impregnated with plastic prior to cutting.

Mineralogy of silt and clay classes ($<62\mu$ sizes) was determined by X-ray diffraction using the following instrument settings: Radiation, $\text{CuK}\alpha$; slits, 1–0.006–1; time constant, 1 second; scan rate, 2° per minute; chart speed, 30 inches per hour; power, 40 kilovolts and 20 milliamperes. Pulse-height discrimination circuitry also was employed. To minimize preferred orientation and primary extinction (Klug and Alexander, 1954, p. 290–305), about 1 gram of size classes 7 and 8 material was ground mechanically in alcohol for 30 minutes, dried in a forced-air oven at 60°C , and suspended in water; any remaining $>16\mu$ material was allowed to settle, and the $<16\mu$ material was decanted and used for X-ray analysis. The remaining size classes were analyzed without grinding.

A combination of cation saturations and heat treatments of oriented aggregates on porous tiles (Kinter and Diamond, 1956) was utilized to aid qualitative and quantitative evaluations of mineral composition. The saturations and treatments included (1) potassium saturation and (a) air drying, (b) heating for 1 hour at 110°C , (c) heating for 1 hour at 300°C , and (d) heating for 1 hour at 550°C ; (2) magnesium saturation and (a) air drying, (b) glycerol solvation; and (3) natural cation saturation

(no treatment) and (a) air drying, (b) vapor phase glycol solvation, (c) heating at 300°C for half an hour, and (d) heating at 550°C for half an hour. In addition to the analyses of oriented aggregates, a single trace was run on a random powder of each sample. Naturally saturated (dominantly calcium- and magnesium-saturated) samples routinely were not treated prior to analysis; however, for a few samples, dispersion with 5 percent chlorox was necessary to insure a smooth mount.

Quantitative estimates of the mineral composition of silt and clay size classes were made utilizing the techniques developed by Schultz (1960, 1964). Basically, these techniques rely on relations among weighted sizes (height and (or) area) of reflections from certain basal planes of clay minerals after certain treatments in order to calculate relative amounts of five clay minerals. Because of differences between the Columbia River mineral suite and the suite in the rocks with which Schultz was concerned, two modifications of the relations were necessary. (1) Area-to-height ratios of 7-A (Angstrom) peaks in samples that appeared to contain no contributing 14-A component indicated that a factor of 2.0–2.5 (corresponding to well-crystallized kaolinite, Schultz, 1960, p. 221), rather than 1.4, as used by Schultz, was appropriate for indicating the crystallinity of kaolinite. The 7-A-peak area-to-height ratios for samples containing both 7-A and 14-A peaks also were about 2.0, which indicates that kaolinite and chlorite are of nearly the same crystallinity. (2) Mixed-layer clays in the Columbia River samples tended to be more heat stable than mixed-layer clays for which the Schultz relations were derived. In some cases, complete collapse of Columbia River mixed-layer clays apparently did not occur even after heating to 550°C. More to check the effect than to solve the problem, clay-mineral percentages were calculated using both 300°C–10-A heights and areas (standard Schultz technique) and 550°C–10-A heights and areas (modified Schultz technique).

Random-powder traces and intensity factors are used in the standard Schultz technique to estimate absolute amounts of total clay minerals and non-clay minerals. The only modification of intensity factors derived by Schultz (1964, p. C2) that appeared necessary resulted from differences between X-ray equipment used to analyze Columbia River sediment and X-ray equipment used by Schultz. Analysis of a standard slide on both X-ray units indicated that multiplication of Schultz' intensity factors by 1.3 was necessary.

Cation-exchange capacity was determined by using the radioactive-caesium method (Beetem and others,

1962). Although CEC values are reported to the nearest 0.1 meq per 100 g (milliequivalents per 100 grams), they are not better than 1–3 percent relative nor 1–10 percent absolute (W. A. Beetem, written commun., 1967). Reported results are averages of at least three CEC determinations each on duplicates or triplicates where sufficient sample was available. During processing of some coarse ($>62\mu$) size classes it was noted that, according to fall velocity, not all material was in the indicated size class. Where this was noted, a fall-velocity separation was made, and CEC values are reported for both separates. These CEC values were combined algebraically to give an "as received" CEC of the sample. For a few coarse size classes, some additional dispersion was noted when the samples were treated with 0.5-normal cesium chloride. For these size classes, a second fall-velocity separation was made, and CEC values are reported for both separates.

The amount of organic matter was estimated indirectly by appropriate conversion of either nitrogen or carbon percentages. Nitrogen was determined by the Kjeldahl-Gunning-Arnold method for solid samples, and total carbon was measured either by a Leco carbon analyzer or by a modification of a wet-chemical method described by Van Hall, Safranko, and Stenger (1963).

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The investigation of radionuclides in the Columbia River was supported by the Division of Reactor Development and Technology, U.S. Atomic Energy Commission. Collection of samples and preparation of size separates were done by personnel of the Columbia River project under the supervision of W. L. Haushild, whom the authors acknowledge for many useful discussions and much supplemental information. Radionuclide analyses were performed at Battelle Memorial Institute, Pacific Northwest Laboratories, Richland, Wash. Jack L. Nelson ably supervised the analyses of samples and developed the necessary radionuclide calibrations for the small quantities of sample that were available. W. A. Beetem, U.S. Geological Survey, is especially acknowledged for noting the large amount of fines in some coarse size classes and for furnishing all CEC analyses. J. J. S. Yee and N. F. Leibbrand, Geological Survey, performed the carbon and nitrogen analyses. The writers extend their appreciation to E. A. Jenne and L. G. Schultz, Geological Survey, for allowing free access to their laboratories and for sharing their experiences in X-ray analysis. Discussions with Drs. Jenne and Vance Kennedy, Geological Survey, also were most beneficial.

PRESENTATION OF DATA

CATION-EXCHANGE CAPACITY

Results from CEC determinations on sized sediments from the Columbia River and major tributaries are shown in table 1. A comparison of these data with data for streams throughout the continental United States (Kennedy, 1965) indicates that sediments from the Columbia River and major tributaries have CEC values that generally are comparable to CEC values for other stream sediments in western and midwestern areas. The fine- to medium-clay separate (size class 11) from Columbia River locations has CEC values (table 1) that range from 33.4 to 47.8 meq per 100 g. Medium- and fine-sand

separates (size classes 4 and 5) have CEC values that average about 10 percent of average CEC values in fine- to medium-clay separates. In gravel and very coarse sand separates (size classes 1 and 2), however, CEC values increase to about 20 percent of average values in fine- to medium-clay separates. Size separates from tributary locations have slightly higher CEC values than comparable size separates from Columbia River locations.

For the fine- to medium-clay separates, average CEC values reported here of about 41 meq per 100 g (table 1) are lower than average values of about 60 meq per 100 g reported in an earlier study (Hauschild and others, 1966, p. 63-75). Although analytical

TABLE 1.—Cation-exchange capacities (in milliequivalent per 100 grams) of sized sediments from Columbia River and tributary locations

Type of sample (See "Analytical Procedures"):

1. Bulk sample as received for analysis. CEC computed algebraically by combining the results of CEC analyses on type 2 and 3 samples, where available, using the weight percent of material for each type as weighting factors.
2. Bulk sample after material finer than the lower limit of the size class had been removed by decantation.
3. Material finer than the lower limit of the size class.
4. Bulk sample after treatment with cesium chloride followed by decantation and removal of material finer than the lower limit of the size class.
5. Material from type 4 sample that is finer than lower limit of size class.

If type 4 or 5 samples are not listed for >62 μ size classes at a location, or if a dashed line is shown, no analyses were necessary; that is, no additional fines or floating organic matter were present. Size limits (in parentheses) are given in microns.

Location	Type of sample	Size class and limits											Total
		1 (4000- 2000)	2 (2000- 1000)	3 (1000- 500)	4 (500- 250)	5 (250- 125)	6 (125- 62)	7 (62- 31)	8 (31- 16)	9 (16- 4)	10 (4- 2)	11 (<2)	
Columbia River near :													
Pasco.....	1.....	3.0	3.2	9.8	2.9	2.8	3.3	3.5	9.2	18.7	22.3	35.0	113.7
	2.....	3.0	3.2	9.5	2.8	2.7	2.8	.....	.....	.....	22.6	.....
	3.....	6.7	6.7	29.3	18.0	18.1	14.9	.....	.....	.....	20.0	.....
	4.....	2.9	2.9	8.4	2.7	2.6	2.7	.....	.....	.....	.....	.....
	5.....	10.2	10.2	26.4	18.8	19.6	5.9	.....	.....	.....	.....	.....
McNary Dam.....	1.....	12.6	8.5	4.1	2.6	5.0	9.5	5.2	8.7	16.8	31.7	44.8	149.5
	2.....	8.4	5.9	3.9	2.2	4.2	6.3	.....	.....	.....	32.1	.....
	3.....	28.3	53.5	50.6	37.5	32.3	30.0	.....	.....	.....	28.7	.....
	4.....	8.3	5.8	3.9	.....	.....	.....	.....	.....	.....	.....	.....
	5.....	14.0	12.3	3.5	.....	.....	.....	.....	.....	.....	.....	.....
The Dalles.....	1.....	(1)	(1)	23.1	4.3	5.3	9.9	6.0	9.3	17.6	34.4	47.8	157.7
	2.....	(1)	(1)	6.7	3.8	4.8	8.2	.....	.....	.....	34.7	.....
	3.....	(1)	(1)	48.5	25.9	34.3	40.9	.....	.....	.....	32.5	.....
Hood River.....	1.....	13.3	3.5	2.4	2.3	3.1	10.4	5.7	8.0	14.3	32.8	41.7	137.7
	2.....	13.2	3.5	2.3	2.1	2.8	8.1	.....	.....	.....	.....	40.8	
	3.....	14.2	10.3	36.0	29.5	39.6	42.3	.....	.....	.....	.....	42.3	
	4.....	12.5	3.2	.....	.....	.....	.....	.....	.....	.....	.....	.....
	5.....	25.6	107.5	.....	.....	.....	.....	.....	.....	.....	.....	.....
Bonneville Dam.....	1.....	18.4	10.2	3.4	2.1	4.2	9.1	5.9	9.5	17.2	31.6	41.0	152.6
	2.....	14.4	9.5	3.3	2.1	3.7	7.5	.....	.....	.....	32.1	.....
	3.....	53.0	39.5	32.3	10.4	22.3	25.8	.....	.....	.....	22.8	.....
Vancouver.....	1.....	2.0	1.6	2.4	3.0	4.1	8.1	5.1	9.3	18.3	29.6	42.0	125.5
	2.....	2.0	1.6	2.3	2.9	3.8	6.4	5.0	.....	.....	30.0	.....
	3.....	10.5	20.2	21.2	32.0	17.0	36.2	8.4	.....	.....	25.3	.....
	4.....	1.9	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	5.....	9.8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
St. Helens.....	1.....	2.0	2.6	2.6	2.2	3.0	12.6	6.8	10.2	17.1	26.3	33.4	118.8
	2.....	2.0	.....	2.6	2.2	2.8	8.8	.....	.....	.....	27.1	.....
	3.....	.....	.....	8.0	19.0	29.2	38.7	.....	.....	.....	22.0	.....
Mean.....	1.....	8.6	4.9	6.8	2.8	3.9	9.0	5.4	9.2	17.1	29.8	40.8	
Standard deviation.....	1.....	7.1	3.5	7.6	1.7	1.0	2.9	1.0	.7	1.4	4.2	5.1	
Mean.....	(2).....	7.0	4.3	4.2	2.6	3.5	6.8	5.4	9.2	17.1	30.2	40.7	
Standard deviation.....	(2).....	5.6	2.9	2.4	.6	.8	2.0	1.0	.7	1.4	4.1	6.1	
Snake River.....	1.....	11.4	10.9	7.4	3.7	4.2	7.0	5.6	8.7	17.0	30.0	47.6	153.5
	2.....	11.4	10.8	7.0	3.6	4.1	5.7	.....	.....	.....	30.1	.....
	3.....	17.0	12.9	31.7	9.5	17.6	32.5	.....	.....	.....	26.8	.....
	4.....	10.7	10.4	7.0	3.5	.....	.....	.....	.....	.....	.....	.....
	5.....	19.3	21.8	8.2	12.4	.....	.....	.....	.....	.....	.....	.....
Willamette River.....	1.....	6.5	8.0	7.2	9.3	12.0	15.9	12.7	18.0	24.7	34.3	44.6	193.2
	2.....	6.4	7.8	7.0	9.2	11.5	14.4	.....	.....	.....	34.8	.....
	3.....	36.0	30.4	37.2	33.3	34.4	35.9	.....	.....	.....	29.2	.....
	4.....	6.4	7.4	6.9	9.2	11.4	14.4	.....	.....	.....	.....	.....
	5.....	16.3	22.4	23.8	21.0	20.7	25.6	.....	.....	.....	.....	.....

¹Insufficient material for analysis.

²Calculated using CEC data from sample types 4, 2, or 1, in that order of preference.

procedures were different (ammonium chloride method versus radioactive-caesium method) and although caesium is known (Tamura and Jacobs, 1960) to collapse some clay mineral structures (thus preventing free exchange of ions), published data (Beetem and others, 1962, p. B6) suggest that the observed average differences are so great that some other factor is responsible. Differences in mineralogy or carbon content do not appear to be sufficient to cause the difference in CEC.

Variations in CEC among sample locations are shown for selected size classes in figure 2. Data for tributary streams are plotted at the Columbia River mile where the tributary joins the Columbia River, even though the samples were collected some miles up the tributary stream. Statistical comparisons of data from the three uppermost locations (Pasco, McNary Dam, and The Dalles) with data from the three lowermost locations (St. Helens, Vancouver, and Bonneville Dam) indicate that no significant longitudinal trends are present. Although not consistent for all size classes, the available data suggest some reflection in Columbia River size classes of generally high CEC values in tributary-stream size classes. The fact that not all Columbia River size classes had higher values (fig. 2) below a tributary confluence simply may reflect the textural composition of sediments contributed by the tributary.

Relations among CEC, particle size, and an estimate of external specific surface (Sayre and others, 1963; Baver, 1956) are shown in figure 3. CEC data are plotted at the theoretical geometric mean particle diameter (equal to the square root of the product of the upper and lower size class boundaries) of each size class unless otherwise indicated. Inspection of data in figure 3 indicates a regular decrease in CEC with increasing geometric mean particle size or decreasing external specific surface. The three coarsest size classes and size class 6, however, deviate rather greatly from the general trend of the relation. In part, this deviation is the result of incomplete dispersion and separation of silt and clay aggregates or of silt and clay present as semi-permanent coatings on sand particles. The presence of a small amount of fines in a size class that is mainly sand can greatly increase CEC, but their presence will not be reflected in the theoretical geometric mean, which is calculated on the assumption that all particles are distributed in a fixed manner within the boundaries of the size class. In some samples, carbon content (table 5) appears to be related to some deviations; for the coarser separates, however, the deviations also may be related to degree of weathering and to differences in mineralogy (p. M36).

The CEC-particle-diameter relation may be analyzed further by considering results from (1) particle-size distributions of size classes that contain $<62\mu$ sediment (table 2), and (2) type 3 CEC analyses of size classes that contain $>62\mu$ sediment (table 1). These results can be used to give an estimate of the "actual" geometric mean particle diameter in each size class.

Particle-size distributions were determined on both undispersed and dispersed samples. (See "Sample Collection and Preparation.") For size classes 7 and 9, dispersion produced no apparently significant change (table 2) in the size distributions; for size class 10, dispersion resulted in appreciably more $<2\mu$ material and less 16μ - 4μ material, with little change in the amount in the 4μ - 2μ size range. Results for size class 11 were inconsistent but, in general, suggest that rigorous dispersion produced little change. For the analysis that follows, results for samples that were not dispersed are used mainly because more analyses were done in this fashion.

By assuming that all particles between size limits (table 2) have a size equal to the theoretical geometric mean of the size range and by weighting each such geometric mean by the percentage of particles in each size range, a size, called the "actual" geometric mean, can be computed. The average value of the "actual" geometric mean for each $<62\mu$ size class is plotted in figure 3 for comparison with the theoretical geometric mean for each size class.

CEC determinations of type 3 samples (table 1) can be used to estimate the "actual" geometric mean particle diameter of size classes that contain $>62\mu$ -size sediments. To do this, the regression equation for the relation between log CEC (logarithm of the "as received" CEC) and log D (logarithm of the theoretical geometric mean particle diameter) for size classes 7, 8, 9, and 10 was established. The particle diameter of type 3 material was then estimated by finding the diameter equivalent to the CEC of the material. Because organic material is a part of the type 3 material, this procedure results in the maximum deviation between the theoretical and an "actual" particle diameter. Calculations can be made to eliminate the contribution by organic material to the type 3 CEC, but the computations are limited by the necessity of assuming a CEC for the chips and splinters of wood that compose the organic component in $>62\mu$ size classes. The "actual" particle diameter in each $>62\mu$ size class may be calculated as the sum of the percentage of material in the size class times the appropriate theoretical geometric mean particle diameter of the size class plus the percentage of type 3 material times a particle diameter determined from the CEC of the material.

TRANSPORT OF RADIONUCLIDES BY STREAMS

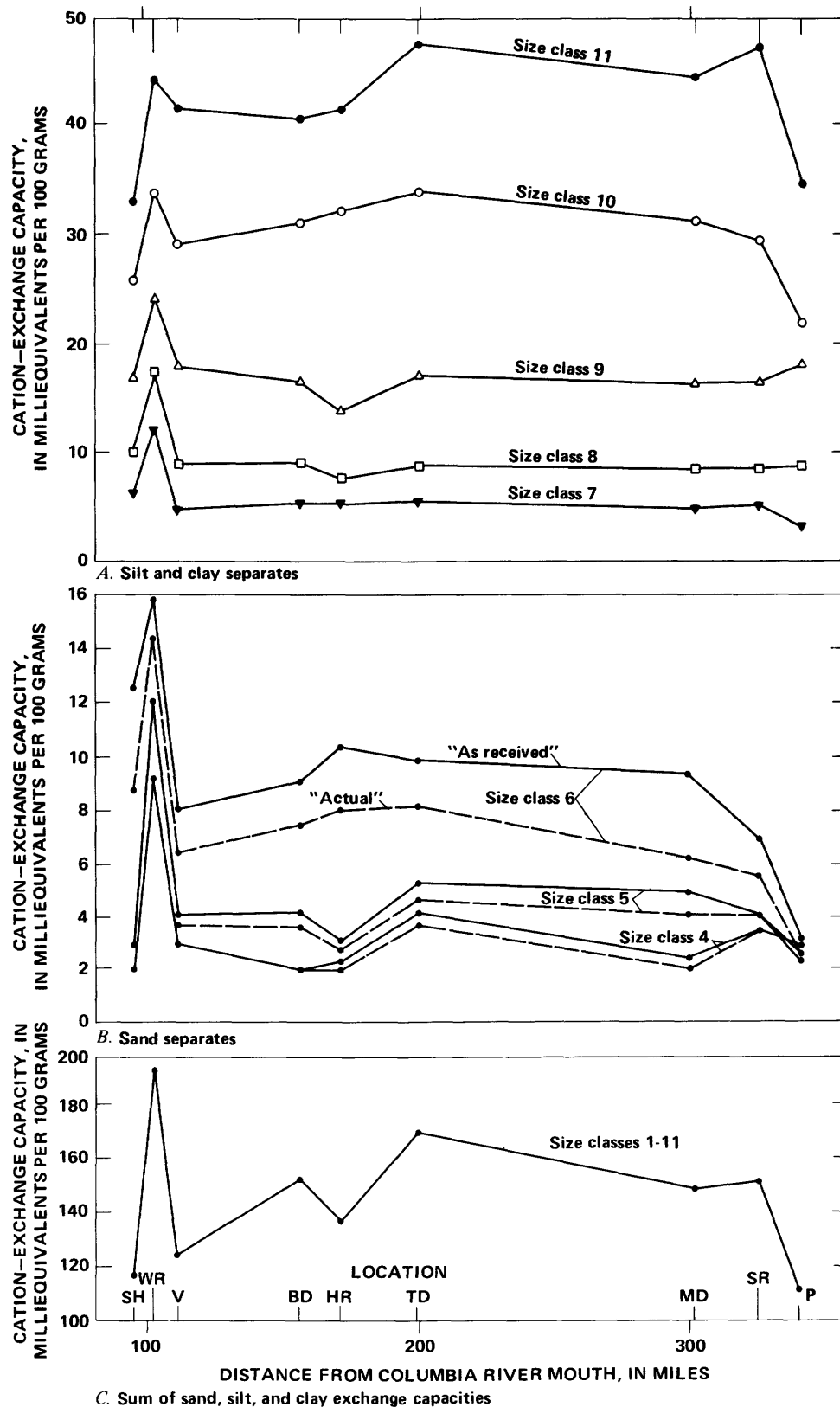


FIGURE 2.—Longitudinal variation of cation-exchange capacity in size classes from the Columbia River and tributaries. Results from tributary streams are plotted as if the samples were obtained near the confluence of the tributary and the Columbia River. Location: SH, St. Helens; WR, Willamette River; V, Vancouver; BD, Bonneville Dam; HR, Hood River; TD, The Dalles; MD, McNary Dam; SR, Snake River; P, Pasco.

Results from determining the average values of the "actual" geometric mean particle diameters of all size classes are plotted in figure 3. The correlation coefficient for the regression relation between log CEC and log " D ," where " D " is the "actual" geo-

metric mean particle diameter, is higher than the coefficient for the relation between log CEC and log D . Thus, the use of an "actual" rather than a theoretical geometric mean results in a more nearly linear relation between CEC and geometric mean

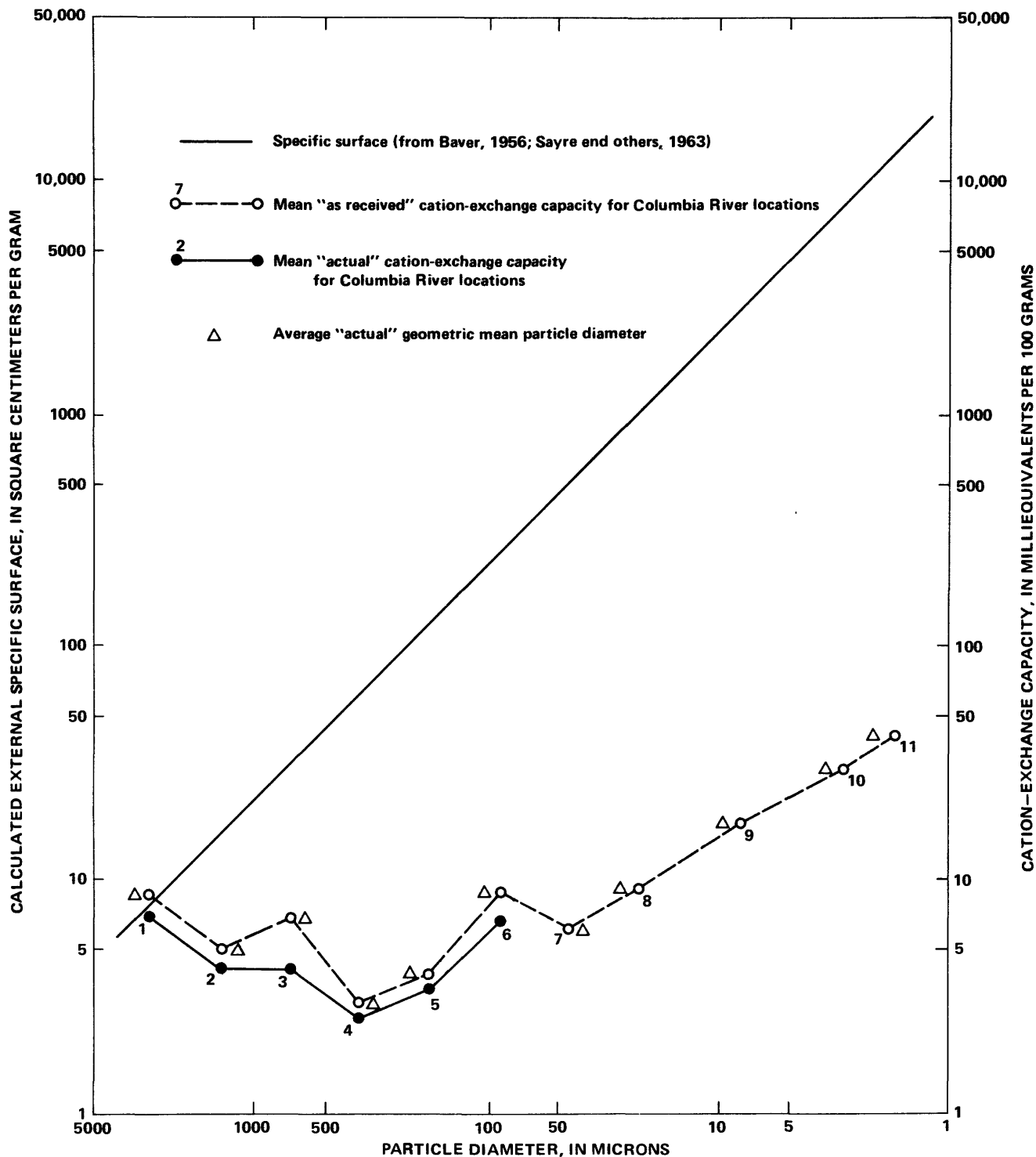


FIGURE 3.— Relations among particle diameter, cation-exchange capacity, and calculated external specific surface. Numbers by data points are size-class numbers.

TABLE 2. — *Particle-size distributions (in percent) of undispersed and dispersed sediments in size classes from Columbia River locations*

[Type of analysis: A, not dispersed mechanically or chemically; B, dispersed mechanically and chemically. Size-distribution limits given in microns]

Designated size class	Location	Type of analysis	Particle size distribution				
			62-31	31-16	16-4	4-2	<2
7.....	Pasco.....	A.....	93.8	4.0	0.7	0.6	0.9
	McNary Dam.....	A.....	92.2	5.3	1.4	.1	1.0
	The Dalles.....	A.....	89.0	8.9	1.3	.1	.7
	Hood River.....	A.....	90.8	7.3	.5	.5	.9
		B.....	86.4	9.5	1.4	1.1	1.6
	Bonneville Dam.....	A.....	92.8	5.2	1.3	.0	.7
	Vancouver.....	A.....	92.5	6.5	.6	.1	.3
	St. Helens.....	A.....	90.8	8.0	.8	.1	.3
8.....	McNary Dam.....	A.....	10.8	83.7	3.7	1.8	.0
	The Dalles.....	A.....	7.4	86.4	4.4	.5	1.3
	Hood River.....	A.....	9.8	84.1	5.5	.2	.4
	Bonneville Dam.....	A.....	12.3	82.7	3.6	.1	1.3
	Vancouver.....	A.....	8.7	85.4	5.2	.2	.5
	St. Helens.....	A.....	9.6	84.7	4.7	.3	.7
9.....	Pasco.....	A.....	.0	22.9	68.1	5.1	3.9
	McNary Dam.....	A.....	.0	11.0	84.6	1.1	3.5
		B.....	.0	7.3	81.5	5.5	5.7
	The Dalles.....	A.....	.0	10.9	82.1	4.0	3.0
	Hood River.....	A.....	.0	.0	90.5	7.6	1.9
	Bonneville Dam.....	A.....	.5	9.1	85.1	2.5	2.8
	Vancouver.....	A.....	.0	8.8	83.7	3.9	3.6
	St. Helens.....	A.....	.0	5.1	87.4	.0	7.5
10.....	McNary Dam.....	A.....	.0	3.7	40.5	46.7	9.1
		B.....	.0	.0	11.6	52.2	36.2
	The Dalles.....	A.....	.0	.0	24.3	60.4	15.3
		B.....	1.0	1.4	2.0	70.6	25.0
	Vancouver.....	A.....	.0	.0	32.0	56.3	11.7
11.....	McNary Dam.....	A.....	.0	.0	.0	34.6	65.4
		B.....	1.1	.2	13.8	10.3	74.6
	The Dalles.....	A.....	.0	.0	.0	30.1	69.9
	Hood River.....	A.....	.0	.0	.5	9.1	90.4
		B.....	.0	.0	.7	10.1	89.2
	Vancouver.....	A.....	.0	.0	.5	19.7	79.8
	St. Helens.....	A.....	.0	.0	.0	6.1	93.9
		B.....	.0	.0	.1	7.9	92.0

particle diameter. Deviations from linearity are still evident, however, and suggest that factors other than particle diameter are affecting CEC. This conclusion is reinforced when mean "actual" CEC values for size classes 1-6 are substituted for mean "as received" CEC values (fig. 3). The mean "actual" CEC is the average of the best estimate (type 4, 2, or 1 CEC values, in that order, table 1) of the CEC of material actually within the size-class boundaries.

Calculation of the regression relation between log CEC and log D also allows estimation of a particle diameter for particles in size class 11. Entering the relation at a CEC value of 40.8, which is the average (table 1) for size class 11, indicates that the material in this class behaves as if it had a particle diameter of about 1.75μ . All data for size class 11 are plotted as if the particle diameter in this class were 1.75μ .

NITROGEN AND CARBON CONTENT

Results from nitrogen and carbon analyses of size separates from the Columbia River and tributaries are shown in tables 3, 4, and 5. The techniques used

for carbon and nitrogen analyses all determine total carbon or total nitrogen (both inorganic and organic). In using factors to convert data on total carbon and total nitrogen to estimates of organic-matter content, it was assumed that all the carbon and (or) nitrogen came from organic matter. Data in Hauschild, Perkins, Stevens, Dempster, and Glenn (1966, p. 75-79) suggest that this assumption results in little error for silt and clay size classes. For sand size classes, however, the error could be large; thus no conversion of total carbon to organic matter was attempted for size classes 1-6.

The use of factors to convert data on carbon and nitrogen content to estimates of organic-matter content has been discussed by Bader (1954, p. 709-710), who concluded that elemental concentrations should be reported. In this report, where a conversion was necessary, 8.1 was used to determine the percentage of carbon from the percentage of nitrogen, and 1.7 (Buckman and Brady, 1960) was used to obtain the percentage of organic matter from the percentage of carbon. Use of 8.1 as the nitrogen-to-carbon factor

for relatively fine grained sediments appears reasonable from the available data (table 4). Visual inspection of organic material in these sediments indicates that it is chiefly brown and flakey or filamentous in appearance. In coarse-grained sediments, where much of the organic material is chips and splinters of wood, a factor of 8.1 may be unrealistic, but it is used in the absence of better information. The factor of 1.7, commonly used by soil scientists, is used here without experimental verification.

Nitrogen data (table 3) indicate increasing

amounts of nitrogen as particle size decreases. An increase on the order of three times occurs between size classes 8 and 9 and between 9 and 10. Comparison of data from size class 6 with data from size class 8 indicates relatively little change in nitrogen content in spite of the difference in particle sizes. For some samples, size class 6 appears to contain more nitrogen than does size class 8. No significant trends with sample location are apparent.

The distribution of nitrogen, hence organic material, in sized sediments may be a function not only

TABLE 3. — Nitrogen data (in percent) for sediments in size classes from Columbia River and tributary locations

[Nitrogen determined by the Kjeldahl-Gunning-Arnold method for solid samples. Size limits (in parentheses) given in microns]

Location	Size class and limits					
	5 (250- 125)	6 (125- 62)	7 (62- 31)	8 (31- 16)	9 (16-4)	10 (4-2)
Columbia River near:						
Pasco.....		0.03			0.34	0.67
McNary Dam.....		.04		0.04	.10	.41
The Dalles.....	0.04	.05		.04	.11	.32
Hood River.....		.06			.08	.42
Bonneville Dam.....		.04			.12	.44
Vancouver.....		.04		.03	.12	.35
St. Helens.....		.04			.08	.28
Mean.....		.04		.04	.14	.36
Standard deviation.....		.000		.001	.008	.014
Harrington Point ¹.....					.35	
Ilwaco ¹.....					.34	
Snake River near Pasco.....		.04		.03	.10	.38
Willow Creek near Heppner Junction ².....					.14	
					.14	
					.14	
Willamette River near Wilsonville.....		.04			.08	.33

¹Results from analyses of two splits from a bed-sediment sample with a median diameter in the indicated size class.

²Results from analyses of three splits from a suspended-sediment sample with a median diameter in the indicated size class.

of particle size but also of the methods of sample preparation. During the wet-sieving process by which coarse size classes were prepared, chips and splinters of wood accumulated in the coarsest (normally size class 1, 2, or 3) and finest (size class 6) sieve-size classes. Similarly, organic material, because of its low density, was concentrated in fine size classes during the decantation process by which the classes were separated.

Carbon and nitrogen data on splits from the same samples are shown in table 4. These data indicate a fairly high degree of analytical precision for both the Leco carbon analyzer (LECO) and the wet-chemical method, but the wet-chemical method consistently gives higher carbon contents than the Leco analyzer. The lower values generally compare more favorably with values reported for size separates from other streams (Malcolm and Kennedy, 1970) and for sediments from oceanic environments adjacent to the Columbia River (Gross, 1969).

Results of carbon determinations on splits that

previously had been analyzed for CEC are shown in table 5. For many samples, an insufficient quantity of material was available (about 1 gram is desired), and the results are only approximate. In addition,

TABLE 4. — Carbon and nitrogen data for sediments from Columbia River and tributary locations

[Carbon determined by LECO (Leco carbon analyzer) and by WCM (wet-chemical method; Van Hall and others, 1963)]

Location	Size class	Percent carbon		Percent nitrogen	Carbon-nitrogen ratio (LECO)
		(LECO)	(WCM)		
Columbia River near:					
McNary Dam.....	11	2.7	3.33	0.41	6.6
St. Helens.....	11	2.3	3.21	.28	8.2
Harrington Point.....	19	3.2	3.54	2.35	9.1
				2.34	9.4
Ilwaco.....	110	3.3	4.41	2.45	7.3
				2.41	8.0
Mean.....					8.1
Standard deviation.....					1.1
Willow Creek near Heppner Junction.....	19	21.2	31.35	3.14	8.6
		21.3	31.35	3.14	9.3
			31.39	3.14	
Willamette River near Wilsonville.....	11	3.1	4.73	.33	9.4

¹See table 3.

²Results from analyses on two splits from the original sample.

³Results from analyses on three splits from the original sample.

TABLE 5. — Carbon data for samples analyzed for cation-exchange capacity

Location	Type of sample ¹	Size class	Weight (grams)	Percent carbon	Remarks
Columbia River near:					
Pasco.....	1	9	0.7937	22.9.....	Complete combustion questionable.
	1	10	.2589	.0	
	3	2	.0548	2.8	
	3	3	.0582	13.2	
	3	5	.0542	3.9	
	3	6	.2345	1.9	
	5	3	.2118	2.2	
McNary Dam.....	1	11	.3703	2,33.6	Woodchips.
	3	3	.0213	38.5.....	
	3	4	.5668	1.5	
	3	5	.1289	7.5	
	3	6	.2908	5.1	
The Dalles.....	3	6	.3578	3.8	
Hood River.....	1	9	.9573	21.0	
	1	10	.9583	1.6	
	1	11	.9697	22.8	
	3	6	.2316	9.4	
Bonneville Dam.....	1	10	.2431	25.1	
	1	11	.2087	24.5	
	3	6	.2798	7.9	
Vancouver.....	3	5	.1529	7.3	
	3	6	.2992	6.7	
St. Helens.....	1	10	.3252	4.5	
	1	11	.8686	2,33.6	
	3	3	.0322	5.4	
	3	4	.0086	19.2	
	3	5	.0364	13.2	
	3	6	.3620	9.6	
	3	10	.0590	.0	
Snake River near					
Pasco.....	1	10	.4262	4.0	
	3	6	.2847	6.4	
Willamette River near Wilsonville.....					
	3	3	.0533	17.2	
	3	6	.3242	4.1	
	5	3	.0508	3.4	
	5	6	.0229	5.4	

¹See table 1 for explanation of sample type.²For comparison with nitrogen content in table 3, divide by 8.1.³For comparison with carbon content of samples not analyzed for CEC, see table 4.

comparison of results from some of these splits with results from splits that had not been used for other analyses (table 3) suggests rather large differences; in general, splits analyzed after determination of CEC contain more carbon than splits that were not analyzed for CEC. The cause of the difference is unknown, but obvious possibilities include nonrepresentative splits and differential losses. A rather large carbon loss (18 percent) with time has been noted by N. F. Leibbrand (written commun., 1967), who made carbon analyses of splits from streambed-sediment samples that were stored wet for a period of up to 1 year after collection. Similar losses were not noted when samples were dried and stored.

Carbon determinations (table 5) on splits that were first analyzed for CEC indicate that many type 3 and 5 samples (table 1) contain large amounts of carbon. Visual inspection of these samples and petro-

graphic analysis (see p. M34) of type 1 samples indicate that most of the carbon is associated with organic rather than inorganic material. The relation between carbon content and CEC of these samples, shown in figure 4, indicates that CEC increases as carbon content increases. There is a suggestion (fig. 4) that the CEC-carbon relation varies with particle size class.

MINERALOGY

CLAY (SIZE CLASS 11)

X-ray-diffraction patterns for clay (size class 11) from the Columbia River and major tributaries are shown in figures 5–7. For the Columbia River, patterns from only the uppermost (Pasco) and lowermost (St. Helens) sampling locations are shown; for intervening locations, the patterns are very similar.

Qualitative aspects of the mineralogy of clays are

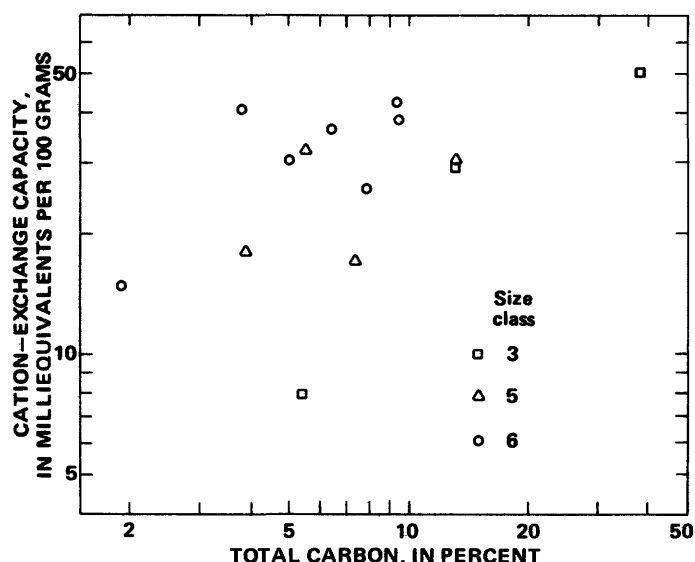


FIGURE 4. — Relation of cation-exchange capacity and carbon content of type 3 samples.

evaluated by analysis of X-ray patterns from random powders and from oriented aggregates. Inspection of powder patterns (fig. 5E) indicates that quartz and feldspar are common constituents. The strongest feldspar peak occurs between 3.21 Å and 3.18 Å, which indicates that plagioclase is more abundant than alkali feldspar. In silt size classes, where feldspar is relatively more abundant and peaks are better defined, peak positions indicate that plagioclase composition is variable but tends to be in the oligoclase to labradorite range. The alkali-feldspar peak, centered around 3.24 Å, often appears as a shoulder or a short, sharp spike on the plagioclase peak in clay-size material; in silt size classes, the alkali-feldspar peak often is masked completely by the plagioclase peak. Although some microcline can be identified in some clay and silt samples, orthoclase appears to be the dominant alkali feldspar.

Clay minerals that are identified from X-ray patterns include montmorillonite, illite, chlorite, kaolinite, mixed-layer clays, and vermiculite. Clay minerals in powder patterns are indicated by peaks (fig. 5E) centered around 14 Å or 12 Å, 10 Å, 7 Å, 4.44 Å, 2.57 Å, and 1.49 Å. The position and characteristics of the initial peak (14 Å or 12 Å) depend on the type of clay and on how well the samples could be dispersed mechanically; for samples that did not disperse, such as the Snake and Willamette River samples (fig. 5E), the addition of a dispersant (5-percent chlorox) produced an initial powder-pattern peak at about 12 Å, or a broad shoulder with many small peaks between 17 Å and 10 Å, if complete dispersion and sodium saturation were not attained.

The powder patterns (060 peaks at about 1.5 Å) indicate that most clay minerals are dioctahedral aluminous varieties. The 14-Å peaks in powder patterns and in traces from oriented aggregates (fig. 5A–D) that consist of natural clay (untreated=undispersed) indicate that most montmorillonitic clays in Columbia River and tributary sediments are calcium-magnesium saturated. Chemical analyses (U.S. Geol. Survey, 1967, p. 25) show that about 75 percent of the common cations in Columbia River water (table 6) are calcium and magnesium.

TABLE 6. — Unweighted mean concentration (in milligrams per liter) and standard deviation of the most abundant constituents in 12 samples of Columbia River water collected near McNary Dam during the period October 1965 through September 1966

[From data in U.S. Geol. Survey, 1967, p. 25]

Chemical constituent	Concentration	
	Mean	Standard deviation
Silica (SiO ₂).....	8.1	3.0
Calcium (Ca).....	23	3.1
Magnesium (Mg).....	5.9	1.4
Sodium (Na).....	7.5	3.8
Potassium (K).....	1.4	.58
Bicarbonate (HCO ₃).....	89	16
Carbonate (CO ₃).....	0	0
Sulfate (SO ₄).....	19	5
Chloride (Cl).....	3.6	2.1

Montmorillonite in well-dispersed samples of “natural” Columbia River clay shows a relatively sharp, slightly asymmetrical peak centered around 14 Å. Upon sodium saturation, the peak shifts to 12 Å where, in most samples, its appearance is much like that of the 14-Å peak. A few samples, notably those from the tributary streams (fig. 5B and C), show broad and asymmetric 12-Å peaks that appear to result, in part, from incomplete sodium saturation. When saturated with potassium (fig. 6), the 14-Å and (or) 12-Å peak shifts toward 10 Å, often with a considerable loss of intensity and symmetry.

Solvation with glycol (fig. 5A–D) and glycerol (fig. 7A–D) results in a montmorillonite peak shift to 17 Å and 18 Å, respectively. Although 8.5-Å or 9.0-Å second-order montmorillonite peaks are present in most solvated samples, other higher-order peaks are rare or shifted from expected positions. The second-order peaks are not defined sharply regardless of the characteristics of the expanded 17-Å or 18-Å peaks. These attributes suggest that “montmorillonite,” as identified both qualitatively and quantitatively in Columbia River and tributary-stream sediments, may include some nonexpanding interlayer material.

Heat treatments for 1 hour at 300°C and 1 hour at 550°C cause progressive collapse of the 17-Å peak (fig. 5A–D) and concomitant increase in the 10-Å

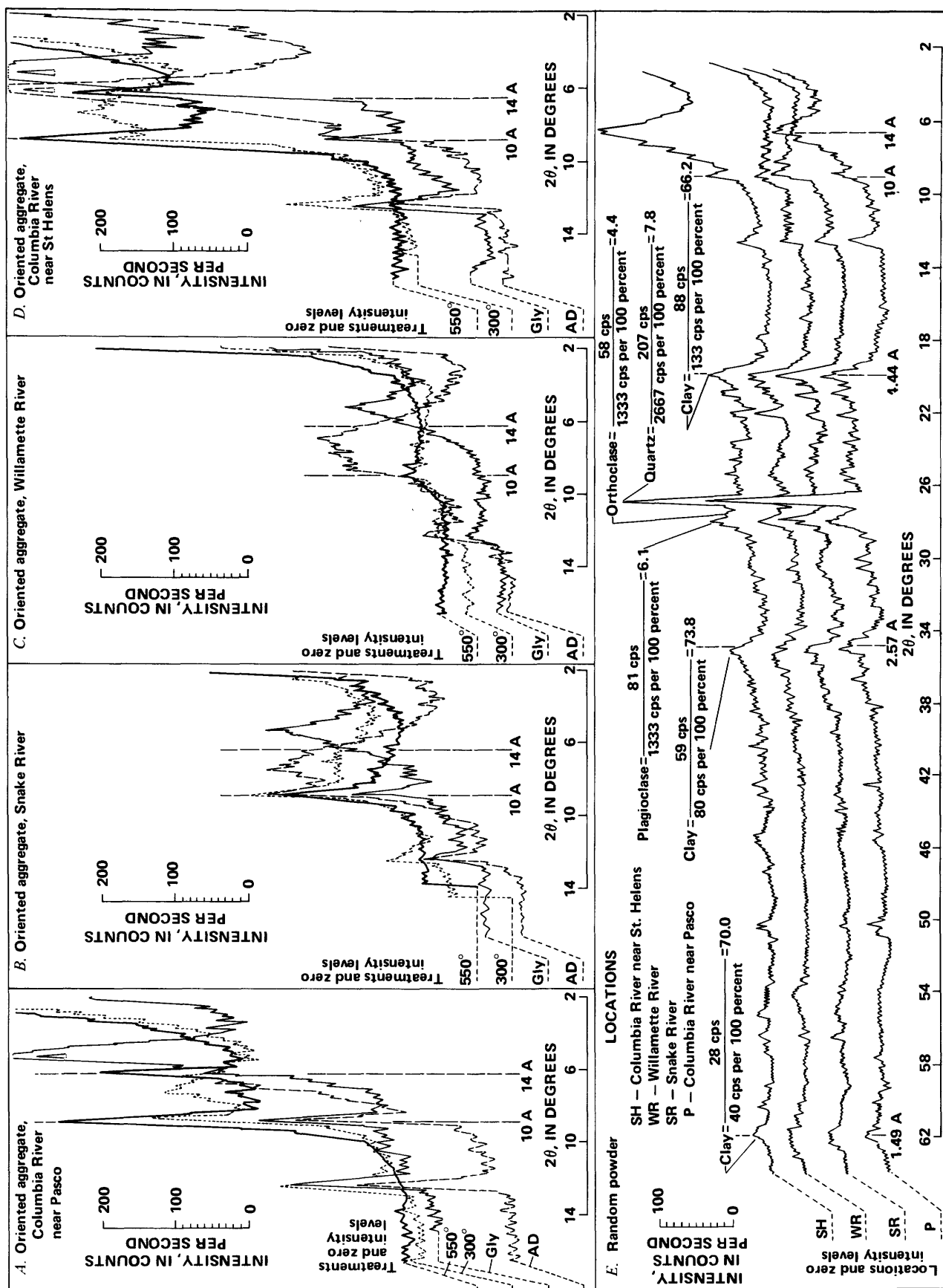


FIGURE 5. — Representative X-ray patterns of undispersed (natural-cation-saturated) sediment from size class 11. Treatments: AD, air dried; Gly, solvated with glycol; 300°, heated at 300° C for 1 hour; 550°, heated at 550° C for 1 hour.

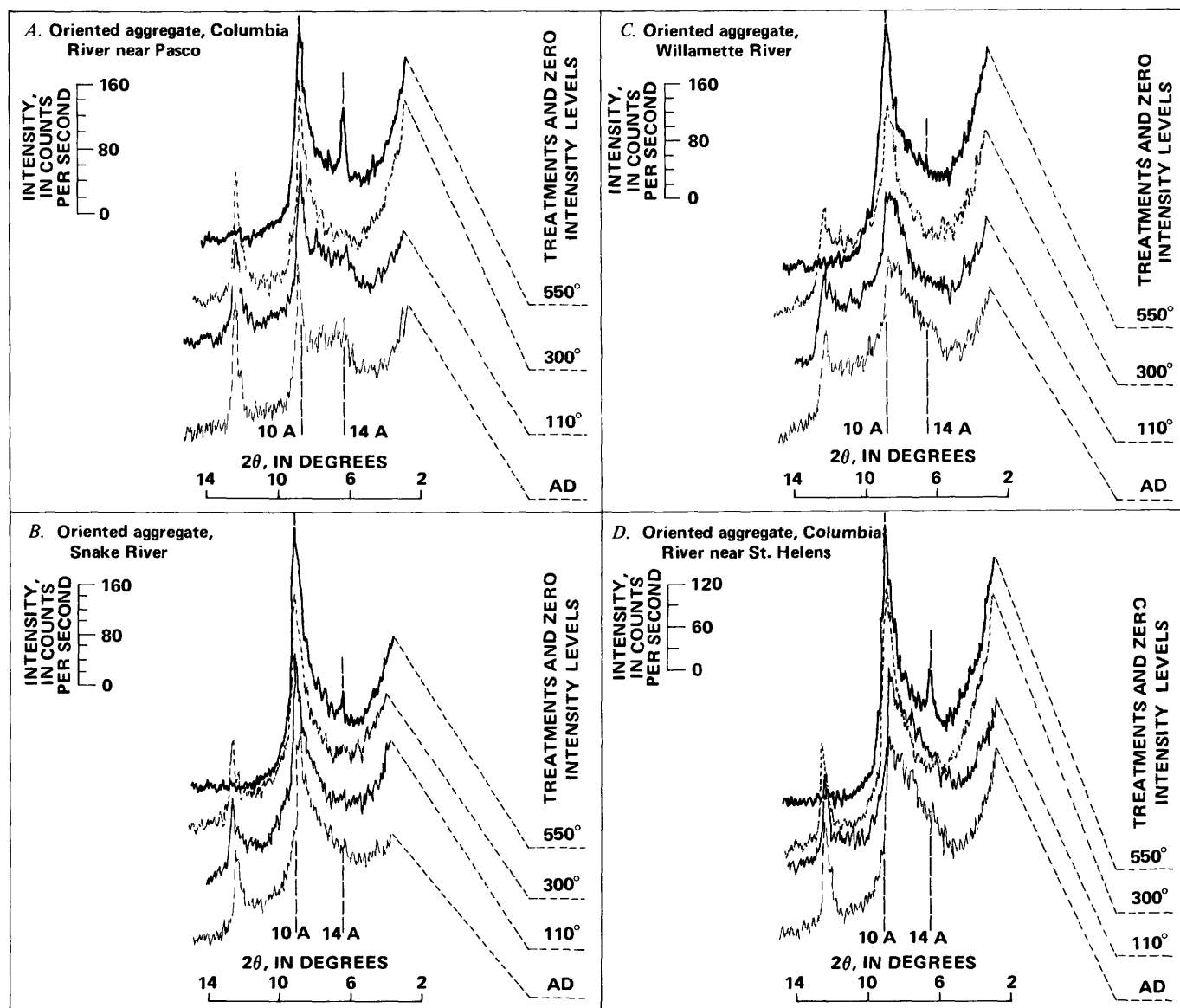


FIGURE 6. — Representative X-ray patterns of potassium-saturated sediments from size class 11. Treatments: AD, air dried; 110°, heated at 110° C for 1 hour; 300°, heated at 300° C for 1 hour; 550°, heated at 550° C for 1 hour.

peak. Similar heat treatments of a potassium-saturated sample (fig. 6) also produce more intense and symmetrical 10-A peaks, which indicates progressive collapse of an expandable clay mineral.

Illite in Columbia River and tributary-stream clays is represented by either a discrete peak or a noticeable shoulder at 10 A in "natural" or solvated samples. The illite portion of the 10-A peak is unaffected by ion saturation or heat treatments that tend to collapse expandable component(s) to 10 A.

Chlorite is identified by a peak near 14 A that is unaffected by ion saturation or solvation but tends to sharpen and become more intense with heat treatments. Heating to 550°C destroys all traces of a 7-A

chlorite-kaolinite peak and, in about half of the samples, results in the development of a sharp, strong 14-A peak. The variability among samples in chlorite response to heat treatments suggests that both stable and less stable "chlorite" layers are present, probably mostly as part of the mixed-layer clay component. Not all analyses of oriented clays prepared for the same sample showed peaks with chlorite characteristics, which indicates that chlorite is present only in small amounts.

Kaolinite was identified in those samples that appeared to contain no chlorite by a 7-A peak that disappeared on heating to 550°C. The presence of kaolinite in two samples that contained chlorite was

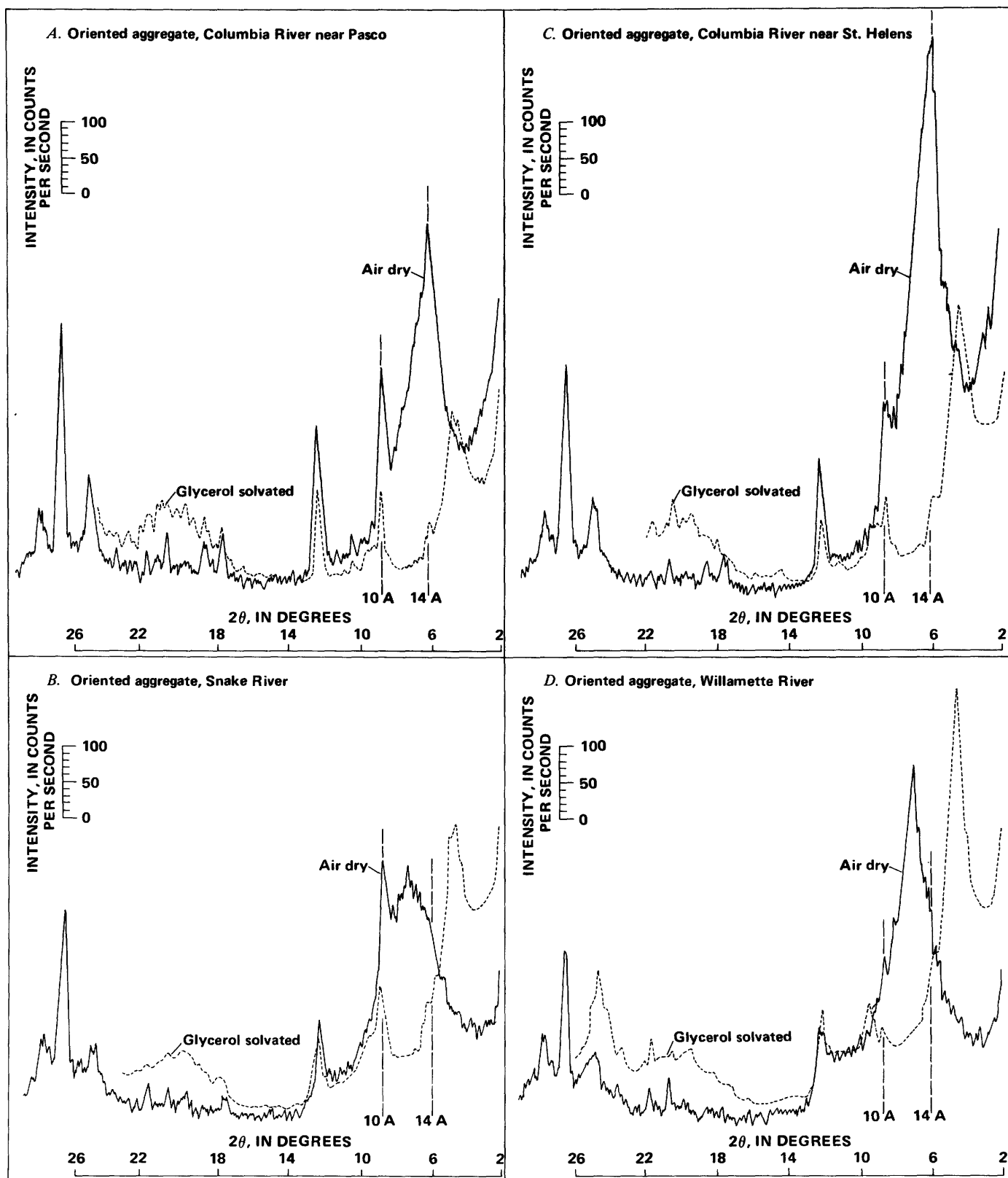


FIGURE 7. — Representative X-ray patterns of magnesium-saturated sediments from size class 11.

indicated by separation of the 002 kaolinite from the 004 chlorite (Biscaye, 1964).

Mixed-layer clays are indicated by broad low reflections between 10 Å and 14 Å in most samples and by incomplete collapse to 10 Å in heated samples. Although it is difficult to be specific about mixed-layer clays, most patterns suggest that illite and chlorite, as well as montmorillonite, layers are present.

Although magnesium-saturated and glycerol-solvated samples (fig. 7) were prepared and analyzed specifically to aid in identification of vermiculite, positive identification of this mineral was limited to two samples that appeared to lack chlorite but still had a peak at about 14 Å. This peak appears as a slight bump on the shoulder of the 18-Å solvation peak; where chlorite is present, the 14-Å peak is more sharply defined (fig. 7).

Estimates of the mineral composition of size class 11 samples from Columbia River and tributary locations are shown in table 7, and the calculation procedure is illustrated in figure 5 for the Columbia River sample from the St. Helens location. In the absence of data on accuracy and precision, numbers have not been rounded. Schultz (1964, p. C14-C20) indicated that accuracy and reproducibility were ± 10 percent for components present in amounts greater than 15 percent; somewhat larger variations are very probable for the Columbia River samples.

Six estimates of the amount of total clay minerals in size class 11 samples are shown in table 7. The first three estimates (cols. 5-7) and their average (col. 8) depend on heights of nonbasal clay peaks at about 4.44 Å, 2.57 Å, and 1.49 Å (fig. 5E) and on intensity factors. The estimate in column 9 is derived by recomputing (normalizing) the average (col. 8) of the percentages of clay minerals determined from

intensity factors so that the total of components in each sample is 100 percent rather than the values shown in column 11. The last estimate (col. 10) is derived by subtracting from 100 the percentages of identified non-clay-mineral components determined from intensity factors (quartz and feldspar) or from independent analyses (organic material). For the Columbia River samples, analyses of variance indicate that (1) the mean total clay-mineral content determined by averaging percentages estimated from intensity factors is significantly less than the mean total clay-mineral content determined by the difference method, and (2) the mean of the normalized total clay-mineral content is not significantly different from the mean of the total clay-mineral content determined by the difference method. These observations suggest that either the intensity factors used to determine total clay-mineral content are high or the sum of non-clay components is low. The presence of amorphous material, which has been noted (Kennedy, 1965, p. D14-D15) in sediments from a Columbia River tributary, or of other unidentified non-clay-mineral components could cause the latter effect.

If it is assumed that the intensity factors for non-clay minerals are correct and that the difference method gives the best answer for the percentage of total clay minerals, new intensity factors for Columbia River clays can be calculated by dividing the observed intensities at 4.44 Å, 2.57 Å, and 1.49 Å by the percentage of total clay minerals that was determined by difference. These calculations suggest that, on the average, the intensity factors derived by Schultz for 4.44-Å and 2.57-Å clay peaks are about 5 percent too high for Columbia River samples; the factor for the 1.49-Å peak is about the correct magnitude.

TABLE 7. — Composition (in percent) of size class 11 samples from Columbia River and tributary locations

Location	Organic material ¹	Quartz	Feldspar		Total clay minerals						Total ⁴
			Plagioclase	Alkali	4.44-Å peak	2.57-Å peak	1.49-Å peak	Average of columns 5-7	Normalized ²	By difference ³	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Columbia River near:											
Pasco.....	9.2	9.6	6.4	4.6	71.4	68.7	75.0	71.7	70.6	70.2	101.5
McNary Dam.....	5.6	5.8	5.6	5.1	66.9	70.0	62.5	66.5	75.1	77.9	88.6
The Dalles.....	5.6	5.4	6.1	5.5	79.7	66.2	⁵ 92.5	72.9	76.3	77.4	95.5
Hood River.....	5.8	5.2	5.8	4.4	72.9	80.0	77.5	76.8	78.4	78.8	98.0
Bonneville Dam.....	7.0	6.2	5.8	4.3	78.2	78.8	82.5	79.8	77.4	76.7	103.1
Vancouver.....	6.2	5.5	6.7	5.2	72.0	75.0	⁵ 62.5	73.5	75.7	76.4	97.1
St. Helens.....	3.9	7.8	6.1	4.4	66.2	73.8	70.0	70.0	75.9	77.8	92.2
Snake River near											
Pasco.....	5.2	5.9	7.4	4.6	72.2	65.0	72.5	69.9	75.2	76.9	93.0
Willamette River near Wilsonville.....											
	4.5	4.7	5.8	4.3	69.9	63.8	77.5	70.4	78.5	80.7	89.7

¹By conversion of data in table 3.

²Average value in column 8 adjusted so that the total of all components in each sample is 100.

³Difference between 100 and the sum of columns 1-4.

⁴Sum of columns 1-4 and 8.

⁵Questionable value. Not used in average.

The total of components (clay minerals, non-clay minerals, and organic material) in the clay size class is shown in column 11, table 7. The average percentage of total clay minerals (col. 8) obtained from Schultz' intensity factors was used to compute the total of all components. A total computed by use of intensity factors has certain advantages (Schultz, 1964, p. C5) in that high or low totals can indicate the presence of undetected components or inaccurate intensity factors. How close these totals are to 100 is an indication of the reliability of the method. When the totals are much less than 100 (Schultz, 1964, p. C5, considers the normal range to be 90 to 105), the presence of amorphous material may be indicated.

Measurements and equations used to calculate relative amounts of five clay minerals in the Pierre Shale were discussed in detail by Schultz (1960, 1964), and results of similar calculations for Columbia River and tributary sediments are shown in

table 8. The absolute mineralogy of clay-size materials is shown in table 9; the percentage of total clay minerals determined by the difference method (col. 10, table 7) was used rather than the percentage determined from intensity factors. Using the difference method makes the total of all components 100 percent and facilitates comparisons among samples.

Results of calculations of the relative and absolute compositions of Columbia River samples are summarized in table 10. These data indicate that the clay-mineral suite consists of about equal amounts of illite, montmorillonite, and mixed-layer clays followed in average abundance by chlorite, plagioclase feldspar, and quartz, with small amounts of alkali feldspar and kaolinite. The Snake River clay-mineral suite does not appear to be greatly different from the Columbia River suite; the Willamette River suite, however, may contain more kaolinite and montmorillonite and less illite than the Columbia River suite.

TABLE 8. — *Relative percentages of five clay minerals in size class 11 samples from Columbia River and tributary locations*
[a, standard Schultz; b, modified Schultz]

Location	Chlorite		Kaolinite		Illite		Montmorillonite		Mixed layer	
	a	b	a	b	a	b	a	b	a	b
Columbia River near:										
Pasco.....	16.4	12.4	4.0	3.0	44.4	28.9	27.4	20.8	7.8	34.9
McNary Dam.....	4.0	3.6	9.0	9.4	51.3	48.4	19.1	17.5	15.7	21.1
The Dalles.....	9.1	5.2	—2	—1	32.2	18.5	37.2	28.7	21.7	47.7
Hood River.....	9.0	6.7	1.6	1.2	25.7	18.8	27.4	26.4	36.3	46.9
Bonneville Dam.....	8.3	5.9	2.3	1.6	32.7	23.3	27.8	22.7	28.9	46.5
Vancouver.....	4.4	4.2	8.2	7.6	44.8	42.1	29.1	26.8	13.5	19.3
St. Helens.....	16.5	9.7	1.8	1.1	26.0	15.3	54.2	59.1	1.5	14.8
Snake River near Pasco.....	1.6	1.9	13.8	16.3	35.1	51.1	17.2	27.6	32.3	3.1
Willamette River near										
Wilsonville.....	6.5	7.2	22.6	25.4	8.7	9.8	42.4	45.6	19.8	12.0

A comparison of the data from modifying the Schultz calculations to account for the stability of mixed-layer clays in Columbia River sediments indicates (table 10) that the effect of the modification is to increase the amount of mixed-layer clays, chiefly at the expense of illite and chlorite.

A summary of textural and compositional variations in clay-size materials from Columbia River and tributary sediments is shown in figure 8. These data demonstrate the complex interrelations that exist among mineralogy, CEC, organic matter, and particle size. The stronger relative relations are

TABLE 9. — *Absolute percentages of clay and non-clay minerals in size class 11 samples from Columbia River and tributary locations*
[a, standard Schultz; b, modified Schultz]

Location	Organic material ¹	Quartz	Feldspar		Chlorite ²		Kaolinite ²		Illite ²		Montmorillonite ²		Mixed layer ²		Total ³
			Plagioclase	Alkali	a	b	a	b	a	b	a	b	a	b	
Columbia River near:															
Pasco.....	9.2	9.6	6.4	4.6	11.5	8.7	2.8	2.1	31.2	20.3	19.2	14.6	5.5	24.5	100
McNary Dam.....	5.6	5.8	5.6	5.1	3.3	2.8	7.0	7.3	40.2	37.7	14.9	13.6	12.3	16.3	100
The Dalles.....	5.6	5.4	6.1	5.5	7.0	4.0	—1	—1	24.9	14.3	28.8	22.3	16.8	36.9	100
Hood River.....	5.8	5.2	5.8	4.4	7.1	5.3	1.3	.9	20.2	14.8	21.6	20.8	28.6	37.0	100
Bonneville Dam.....	7.0	6.2	5.8	4.3	6.4	4.5	1.8	1.2	25.1	17.9	21.3	17.4	22.1	35.7	100
Vancouver.....	6.2	5.5	6.7	5.2	3.4	3.2	6.3	5.8	34.2	32.2	22.2	20.5	10.3	14.7	100
St. Helens.....	3.9	7.8	6.1	4.4	12.8	7.5	1.4	.9	20.2	11.9	42.2	46.0	1.2	11.5	100
Snake River near															
Pasco.....	5.2	5.9	7.4	4.6	1.2	1.5	10.6	12.5	27.0	39.3	13.2	21.2	24.9	2.4	100
Willamette River near															
Wilsonville.....	4.5	4.7	5.8	4.3	5.2	5.8	18.2	20.5	7.0	7.9	34.2	36.8	16.1	9.7	100

¹By conversion of data in table 3.

²Relative percentages from table 8 multiplied by percent total clay from column 10 of table 7.

³Sum of the non-clay minerals plus the percentages of clay minerals from either "a" or "b."

TABLE 10. — *Average percentages of clay and non-clay minerals in size class 11 samples and in size class 10 samples from Columbia River locations*

[Type of calculation: a, standard Schultz; b, modified Schultz]

Component	Type of calculation	Range		Mean		Standard deviation	
		Size class 11	Size class 10	Size class 11	Size class 10	Size class 11	Size class 10
Illite.....	a.....	20.2-40.2	23.0-40.4	28.0	30.5	7.4	7.5
	b.....	11.9-37.7	17.7-35.0	21.3	23.5	9.8	6.1
Montmorillonite.....	a.....	14.9-42.2	12.1-24.4	24.3	17.6	9.5	4.0
	b.....	13.6-46.0	10.4-16.3	22.2	13.6	11.7	1.8
Mixed layer.....	a.....	1.2-28.6	-5.5-22.6	13.8	8.3	9.5	9.8
	b.....	11.5-37.0	8.6-32.0	25.2	22.5	11.2	9.1
Chlorite.....	a.....	3.3-12.8	3.3-18.4	7.4	8.1	3.8	4.9
	b.....	2.8-8.7	3.0-10.4	5.1	5.7	2.3	2.5
Kaolinite.....	a.....	-.1-7.0	.8-5.7	2.9	3.6	2.6	1.8
	b.....	-.1-7.3	.5-4.8	2.6	2.8	2.8	1.5
Plagioclase feldspar.....		5.6-6.7	8.3-11.4	6.1	10.0	.4	1.3
Quartz.....		5.2-9.6	9.9-18.9	6.5	12.4	1.6	3.3
Alkali feldspar.....		4.3-5.5	4.5-6.7	4.8	5.0	.5	.8
Organic material.....		3.9-9.2	.0-7.6	6.2	4.5	1.6	2.6

those between total clay-mineral content and CEC, and between CEC and the percentage of montmorillonite. These relations appear to be improved somewhat when the percentage of total clay minerals is derived by the difference method and the percentage of montmorillonite is calculated by the modified Schultz method, which suggests that these methods give the best results. Organic material, which is calculated from nitrogen content in table 3, is relatively uniform among samples and does not appear to be related to differences in mineralogy or CEC. A relation between percentage less than 2μ and percentage of montmorillonite is suggested by the data.

Highly significant longitudinal trends in mineral abundance are not evident, although montmorillonite appears to increase (fig. 8) and quartz to decrease (table 9) downstream from the Pasco location. Differences in the abundance of some constituents between the Vancouver and St. Helens locations (fig. 8 and table 9) may reflect contributions from the Willamette River. No significant mineralogic differences appear to be related to the Snake River.

The clay mineralogy of $<2\mu$ Columbia River sediments recently was discussed by Knebel, Kelley, and Whetten (1968). These authors, using a "construct" similar to that described on page M30, determined the relative amounts of montmorillonite, illite, and chlorite plus kaolinite. Their data are comparable to data presented here if the mixed-layer clay is considered as "montmorillonite." As is noted in a subsequent section, however, if mixed-layer clay is not identified, then mineralogy and CEC data tend to conflict. Knebel, Kelley, and Whetten (1968), along with Russell (1967), and Russell and Duncan (1968), indicated that very little kaolinite occurs in sedi-

ments of Columbia River origin. Knebel, Kelley, and Whetten (1968, p. 603-604) noted little difference in montmorillonite content between Pasco and Bonneville Dam, although samples from this reach contained more montmorillonite than samples from above Pasco.

SILT (SIZE CLASS 10)

Representative X-ray-diffraction patterns for size class 10 are shown in figures 9 and 10. Comparison of these patterns with those for the clay size class (figs. 5-7) indicates very little qualitative difference in mineralogy. Quantitatively, however, non-clay peaks are more intense and clay peaks are less intense in size class 10.

The Schultz method was used to obtain quantitative data (table 11) for size class 10. Comparison of the average total clay-mineral percentage obtained by intensity factors (col. 8, table 11) with the total clay-mineral percentage obtained by the difference method (col. 9, table 11) suggests that the two techniques give similar average results. The similar results between these techniques in class 10 contrast with the different results in class 11 (p. M19). One explanation for the difference might be more amorphous material in the finer size class.

Kennedy (1965, p. D16-D19) suggested a technique whereby data on CEC and quantitative X-ray mineralogy of clay-size material can be combined with data on CEC of silt-size material to yield an additional estimate of the total clay-mineral content of silt-size material. Estimates for Columbia River and tributary samples are shown in column 10, table 11. These estimates are about 12 percent less than either the average intensity-factor values (col. 8, table 11) or the difference values (col. 9, table 11).

As particle size increases, quantitative differences in clay and non-clay minerals are expected. These differences between class 11 and class 10 affect one of the assumptions in the technique used to estimate

total clay minerals in the silt fraction from CEC data (Kennedy, 1965); namely, that the CEC of clay minerals in the clay fraction (class 11) is the same per unit weight as that of the clay minerals in the

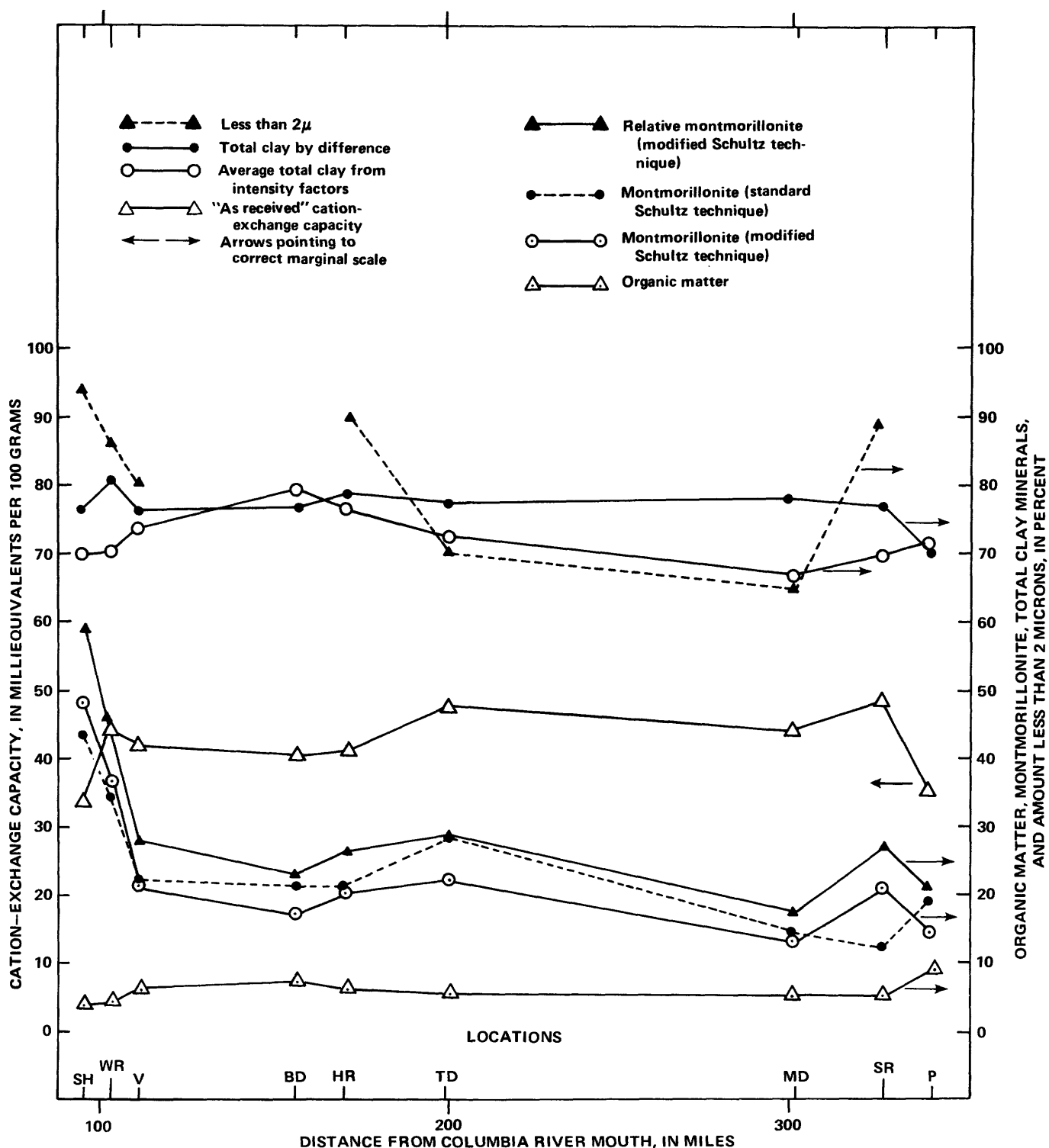


FIGURE 8.—Summary of textural and compositional variations in size class 11. Locations: P, Pasco; MD, McNary Dam; TD, The Dalles; HR, Hood River; BD, Bonneville Dam; V, Vancouver; SH, St. Helens; SR, Snake River; WR, Willamette River.

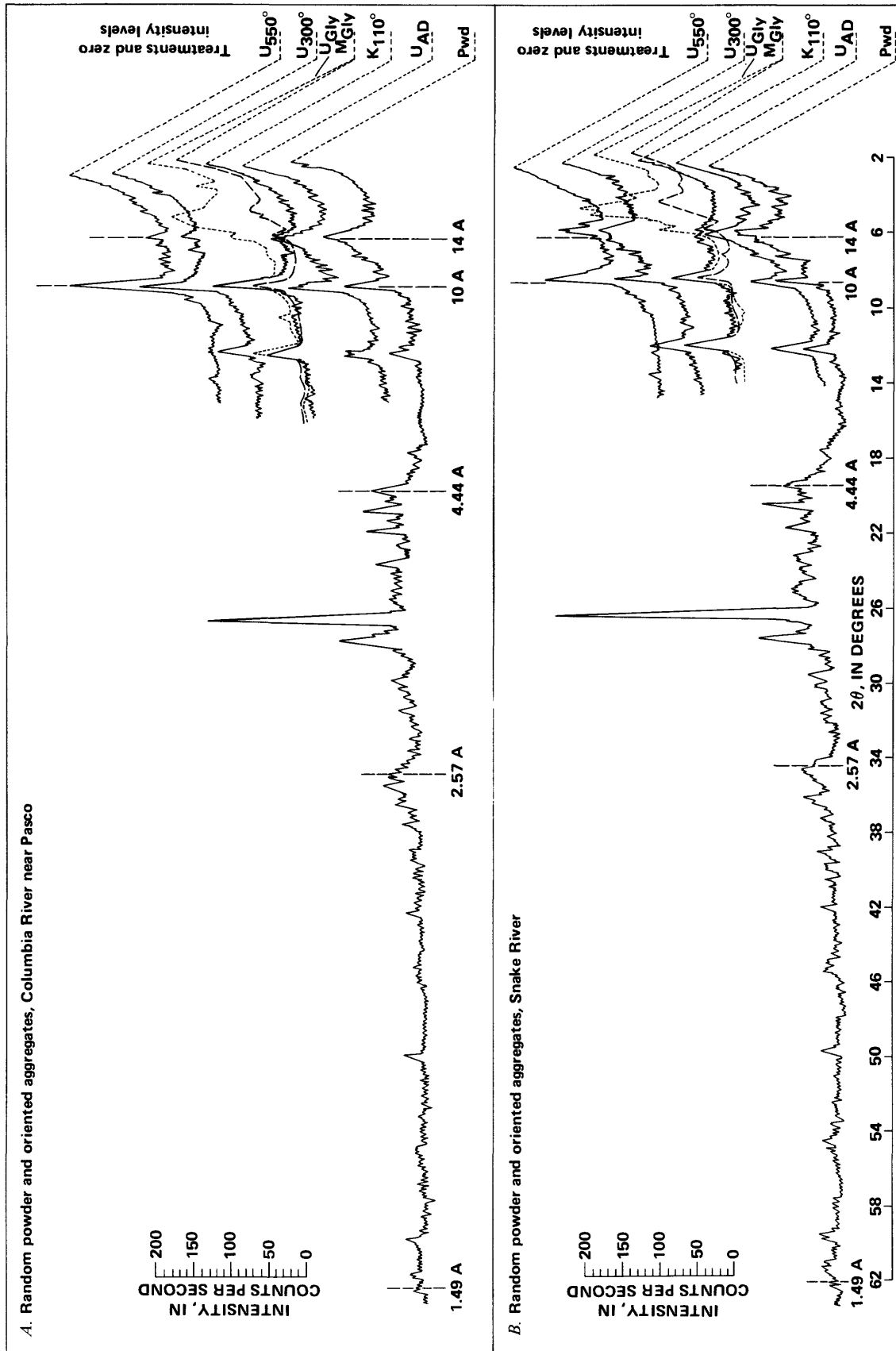


FIGURE 9. — Representative X-ray patterns of size class 10 samples from Columbia River near Pasco and from Snake River. Treatments: Pwd, random powder; UAD, undispersed and air dried; K110°, potassium-saturated and heated at 110° C for 1 hour; MGly, magnesium-saturated and solvated with glycerol; U₅₅₀°, undispersed and solvated with glycerol; U₃₀₀°, undispersed and heated at 300° C for 1 hour; U₅₅₀°, undispersed and heated at 550° C for 1 hour.

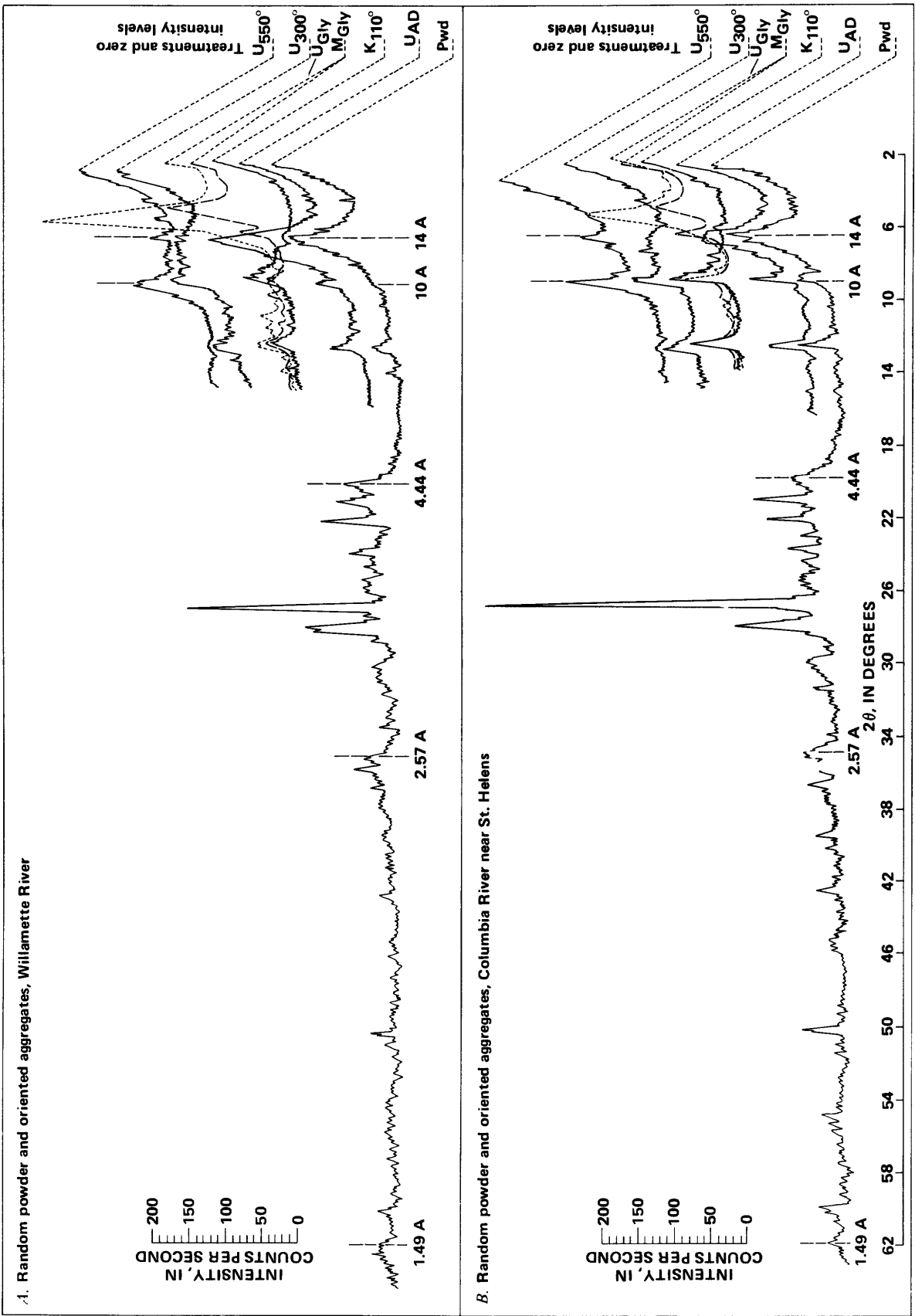


FIGURE 10. — Representative X-ray patterns of size class 10 samples from Columbia River near St. Helens and from Willamette River. Treatments: PwD, random powder; UAD, undispersed and air dried; K_{110°}, potassium-saturated and heated at 110° C for 1 hour; M_{Gly}, magnesium-saturated and solvated with glycerol; U_{Gly}, undispersed and solvated with glycerol; U_{300°}, undispersed and heated at 300° C for 1 hour; U_{550°}, undispersed and heated at 550° C for 1 hour.

TABLE 11. — *Composition (in percent) of size class 10 samples from Columbia River and tributary locations*

Location	Organic material ¹	Quartz	Feldspar		Total clay minerals						Total ¹³
			Plagio- class	Alkali	4.44-A peak	2.57-A peak	1.49-A peak	Average of columns 5-7 (8)	By differ- ence ²	From CEC	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Columbia River near:											
Pasco.....	40.0	14.7	8.3	4.6	60.2	67.5	452.5	63.8	72.4	44.7	91.4
McNary Dam ⁵	4.5	11.6	9.2	5.0	77.4	82.5	460.0	80.0	69.7	55.1	110.3
The Dalles.....	4.4	9.9	10.0	4.8	69.2	71.2	467.5	70.2	70.9	55.7	99.3
Hood River.....	2.7	10.7	10.8	4.5	66.9	70.0	480.0	68.4	71.3	62.0	97.1
Bonneville Dam ⁵	7.3	10.8	8.6	4.9	69.9	86.2	92.5	82.9	68.4	59.1	114.5
Vancouver.....	4.8	10.1	11.4	6.7	66.9	68.8	75.0	70.2	67.0	53.8	103.2
St. Helens.....	7.6	18.9	11.4	4.6	53.4	72.5	65.0	63.6	57.5	63.8	106.1
Snake River near Pasco.....	6.8	10.9	8.8	5.2	57.9	65.0	57.5	60.1	68.3	48.4	91.8
Willamette River near											
Wilsonville.....	(8)	10.4	9.9	4.1	58.6	62.5	62.5	61.2	675.6	62.1	685.6

¹By conversion of data in table 3 or 5.²Difference between 100 and the sum of columns 1-4.³Sum of columns 1-4 and 8.⁴Questionable value. Not used in average.⁵Insufficient sample to fill regular sample holder. Values for non-clay minerals are probably about 10 percent low; values for clay minerals appear high.⁶No organic-material data available.

silt fraction (Kennedy, 1965, p. D16). The differences in clay-mineral composition in class 10 are such that an approximation of the magnitude of the difference, using the average amounts of clay minerals (table 10) and an assumed CEC (see fourth paragraph below) for the clay minerals, indicates about a 20-percent decrease in CEC per unit weight between class 11 and class 10. The 12-percent discrepancy between total clay-mineral estimates from intensity factors and estimates from CEC data is lessened appreciably if the CEC of class 10 material is increased by 20 percent.

Except for two samples, the total of all known or estimated components (col. 11, table 11) is within

the range (90-105 percent) found by Schultz, which suggests that the intensity-factor method is satisfactory. The high calculated totals for the samples from McNary Dam and Bonneville Dam locations may have resulted from having insufficient sample for the standard sample holder; as a result, a smaller holder was used. Results from analyses of two samples using the small as well as the large holder indicated that nonclay minerals consistently are underestimated and clay minerals generally are overestimated when the sample is mounted in the small holder.

The absolute mineralogy of size class 10 samples is shown in table 12 and is summarized in table 10.

TABLE 12. — *Absolute percentages of clay and non-clay minerals in size class 10 samples from Columbia River and tributary locations*

[a, standard Schultz; b, modified Schultz]

Location	Organic material ¹	Quartz	Feldspar		Chlorite ²		Kaolinite ²		Illite ²		Montmorillonite ²		Mixed layer ²		Total ³
			Plagio- clase	Alkali	a	b	a	b	a	b	a	b	a	b	
Columbia River near :															
Pasco.....	0.0	14.7	8.3	4.6	18.4	10.4	5.7	3.2	26.1	17.7	16.6	14.0	5.6	27.1	100
McNary Dam ⁴	4.5	11.6	9.2	5.0	7.6	5.3	2.4	1.7	37.4	26.1	14.6	12.8	7.7	23.8	100
The Dalles.....	4.4	9.9	10.0	4.8	5.0	3.8	2.4	1.9	23.0	18.0	20.2	14.3	19.4	32.0	100
Hood River.....	2.7	10.7	10.8	4.5	6.6	4.3	.8	.5	40.4	25.8	16.7	13.3	6.8	27.4	100
Bonneville Dam ⁴	7.3	10.8	8.6	4.9	6.3	5.8	5.2	4.8	37.5	35.0	18.0	14.2	1.4	8.6	100
Vancouver.....	4.8	10.1	11.4	6.7	3.3	3.0	4.2	3.8	24.8	22.6	12.1	10.4	22.6	27.2	100
St. Helens.....	7.6	18.9	11.4	4.6	9.4	7.5	4.7	3.7	24.5	19.4	24.4	16.3	-5.5	10.6	100
Snake River near Pasco.....	6.8	10.9	8.8	5.2	4.8	4.0	6.5	5.5	39.0	33.2	10.4	8.4	7.6	17.2	100
Willamette River near															
Wilsonville.....	(5)	10.4	9.9	4.1	8.2	6.6	6.9	5.5	11.3	9.1	44.1	39.6	5.1	14.8	100

¹By conversion of data in table 3 or 5.²Relative amounts determined as for size class 11 multiplied by percent total clay from column 9 of table 11.³Sum of the non-clay minerals plus the percentages of clay minerals from either "a" or "b."⁴Insufficient sample to fill regular sample holder. Values for non-clay minerals are probably about 10 percent low; values for clay minerals appear high.⁵No organic-material data available.

Comparing these data with data for size class 11 (tables 9 and 10) shows that quartz, feldspar, illite, chlorite, and kaolinite are more abundant and montmorillonite and mixed-layer clays are less abundant in the fine-silt size. As in size class 11, the modified Schultz as compared with the standard Schultz calculations result in higher mixed-layer-clay percentages and in lower percentages of other minerals, chiefly illite. Also, as in size class 11, the Snake River mineral suite appears to be nearly the same

as that in the Columbia River, whereas the Willamette River mineral suite appears to contain less illite and more montmorillonite than does the Columbia River suite.

Relations among CEC, mineralogy, and organic content in size class 10 are indicated in figure 11. In general, the same relations that were noted for size class 11 can be seen for size class 10.

If certain assumptions are made, CEC and mineralogy data can be combined to test their mutual

compatibility. The necessary assumptions are: (1) CEC values of quartz and feldspar are insignificant relative to those of organic material and clay minerals; and (2) CEC values of kaolinite, illite, chlorite, montmorillonite, and organic material are 8, 30, 30, 100, and 100 meq per 100 g, respectively. Because quartz and feldspar are present in relatively small amounts in clay and fine-silt separates, the first assumption probably introduces no serious error. Although the CEC values of clay minerals

vary (Grim, 1953, p. 129), the assumed values probably are of the correct relative magnitude (Buckman and Brady, 1960, p. 93). The CEC value of 100 for organic material is based on the observation that the organic matter is not strongly altered to humuslike material. Malcolm and Kennedy (1970, p. 158) reported a CEC of 94 meq per 100 g for somewhat similar organic materials that also were obtained from sized river sediments. However, the extremely variable nature of organic material (Buckman and

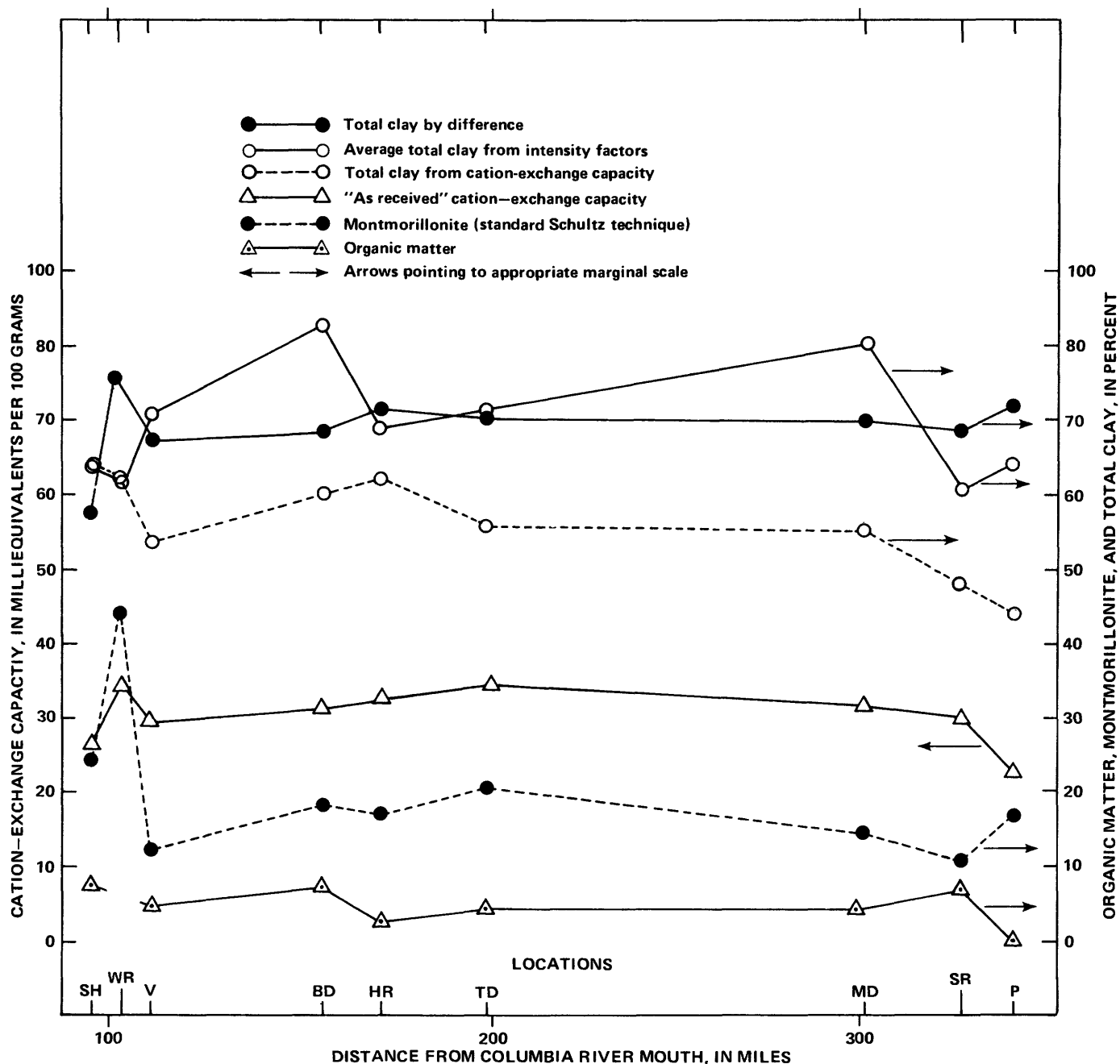


FIGURE 11. — Summary of compositional variations in size class 10. Locations: P, Pasco; Md, McNary Dam; TD, The Dalles; HR, Hood River; BD, Bonneville Dam; V, Vancouver; SH, St. Helens; SR, Snake River; WR, Willamette River.

Brady, 1960, p. 143), the resulting large differences in CEC, and the indirect method of determining the organic-matter content indicate that considerable error may arise from assumptions involving organic material.

The test procedure involves determining the difference between the "as received" CEC (table 1) and a CEC calculated by summing the products of (1) the percentages of the individual clay minerals times the assumed CEC values of the minerals, and (2) the percentage of organic material (tables 9 and 12) times the assumed CEC value of organic material. Dividing the difference by the percentage of mixed-layer clays (tables 9 and 12) in a sample yields an estimate of the CEC of the mixed-layer clays. Because the mixed-layer clay appears to be mostly illite and chlorite with some montmorillonite (p. M19), this estimate should range around 30 meq per 100 g. If much higher or much lower values are calculated, either (1) mineralogy and CEC data are incompatible or (2) a basic assumption is incorrect.

Mixed-layer-clay CEC values that are reasonable can be computed for most size class 10 and 11 samples. In general, the mineral abundance estimates from the modified Schultz calculations give higher and perhaps more reasonable estimates of mixed-layer-clay CEC. At Pasco and St. Helens locations, computed mixed-layer-clay CEC values are low, and at McNary Dam location, the computed CEC values seem to be high. Although there is no way to determine exactly where the error(s) lie, at both Pasco and St. Helens, CEC values (table 1) are below average; at St. Helens and McNary Dam locations, the percentage of montmorillonite (tables 9 and 12) also may be in error. Visual inspection of the oriented aggregate for St. Helens location suggests that the aggregate is especially thin, a condition which Schultz (1964, p. C12) indicated can result in overestimation of montmorillonite abundance. A particularly thick oriented aggregate from McNary Dam location could cause the computed low percentage of montmorillonite (table 9), which, in turn, could result in computed CEC values for mixed-layer clays that appear high. For those samples that appeared to give reasonable CEC values for mixed-layer clays, the values ranged from 14 to 40 meq per 100 g and averaged about 25 meq per 100 g. These CEC values suggest that illite and chlorite layers are abundant in the mixed-layer component.

SILT (SIZE CLASSES 7, 8, AND 9)

Representative X-ray-diffraction patterns for size classes 7, 8, and 9 are shown in figure 12. Inspection of the powder patterns and comparison of the pow-

der patterns with those for size classes 10 and 11 indicate both qualitative and quantitative mineralogic differences. Probably the most conspicuous additional peak that is not a quartz or feldspar peak is centered around 8.4 Å. This peak and a peak at 2.82 Å indicate the presence of amphibole-group mineral(s) (Biscaye, 1965, p. 807). Hornblende and pyroxene-group minerals have been identified (Whetten and others, 1969, p. 1160; Kulm and others, 1968; Glenn, 1965; also table 19 of this report) as abundant constituents in Columbia River sands, and their presence in silt size classes is to be expected.

Quantitative estimates of the composition of size classes 7, 8 and 9 are shown in table 13. These estimates were derived from intensity factors that had been used previously for non-clay minerals and from an intensity factor (127) slightly lower than had been employed previously for total clay minerals. The factor of 127 was used because data presented for size class 11 samples (p. M19 of this report) indicate that Schultz' factors for total clay minerals were about 5 percent too high for these samples. Small peaks, and in some cases, interfering peaks from non-clay minerals, prevented determination of an average total clay content from peaks at 4.44 Å, 2.57 Å, and 1.49 Å; thus, total clay was estimated from the intensity of only the 4.44-Å peak. A total clay content determined by the difference method is not valid for size classes 7, 8, and 9 for two reasons: (1) Strong plagioclase-feldspar peaks generally tend to mask the desired alkali-feldspar peak, and no consistent quantitative relation could be established with any other feldspar peak; and (2) other non-clay minerals, such as amphibole-group minerals, cannot be evaluated quantitatively.

If the total of known components (quartz, plagioclase, total clay, and organic materials) is subtracted from 100, the result is an estimate of the percentage of unidentified minerals; the result also is an indicator of the reliability of the analyses. If the difference is negative and if peaks for alkali feldspar and (or) amphibole are present, then the abundance of some component(s) is overestimated. Although some low differences and a negative value (table 13) were calculated for some samples that contained amphibole and alkali feldspar, most samples gave apparently realistic differences.

A second and perhaps better indication of the relative reliability of quantitative data for quartz and plagioclase is gained by plotting the abundances of these minerals for each size class at each location (fig. 13). These plots indicate, in general, that the same relative differences between locations frequently occur in all size classes. The same relative

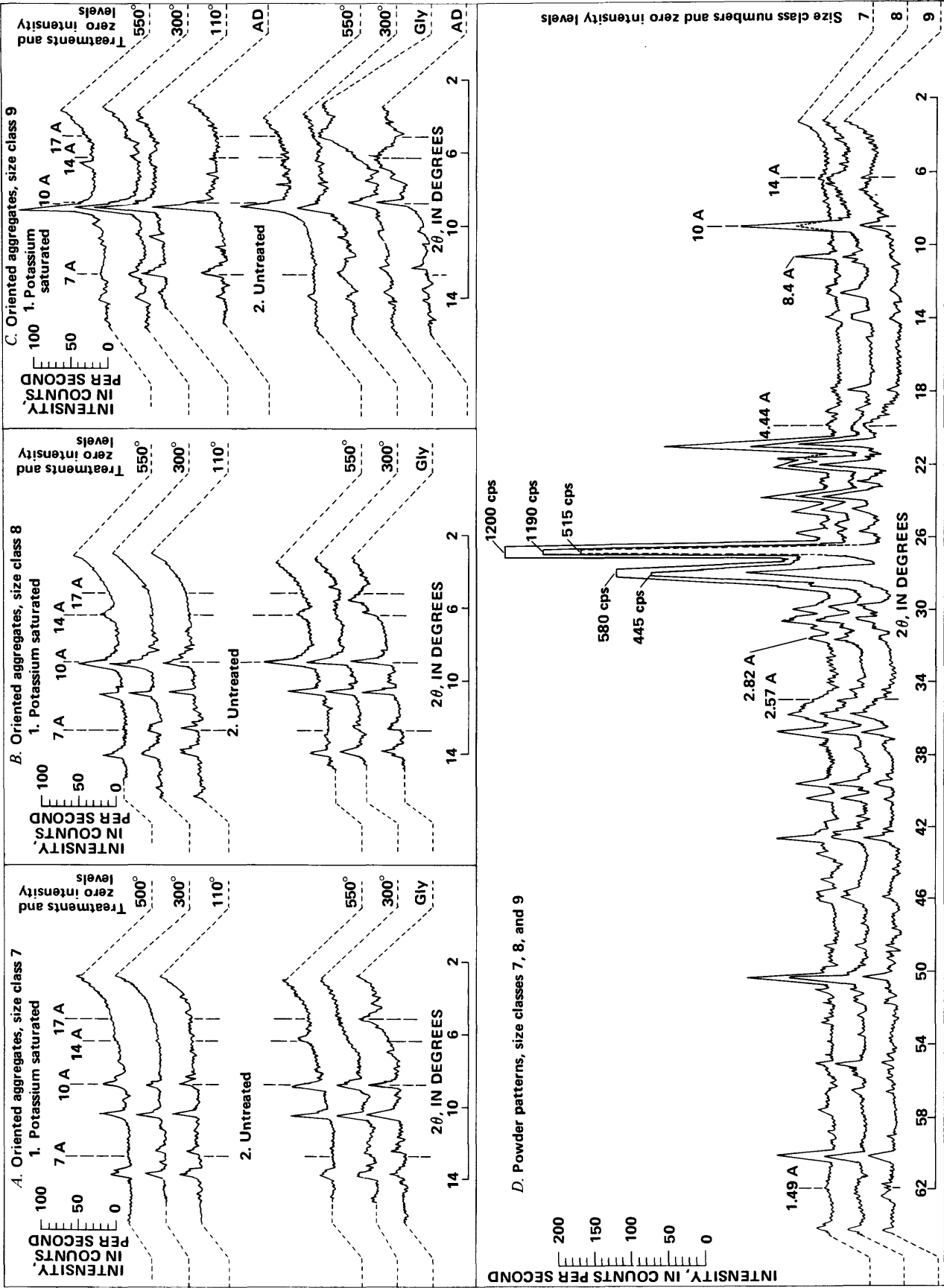


FIGURE 12. — Representative X-ray patterns of size class 7, 8, and 9 samples from Columbia River near Bonneville Dam. Treatments: AD, air dried; Gly, solvated with glycol; 110°, heated at 110° C for 1 hour; 300°, heated at 300° C for 1 hour; 550°, heated at 550° C for 1 hour.

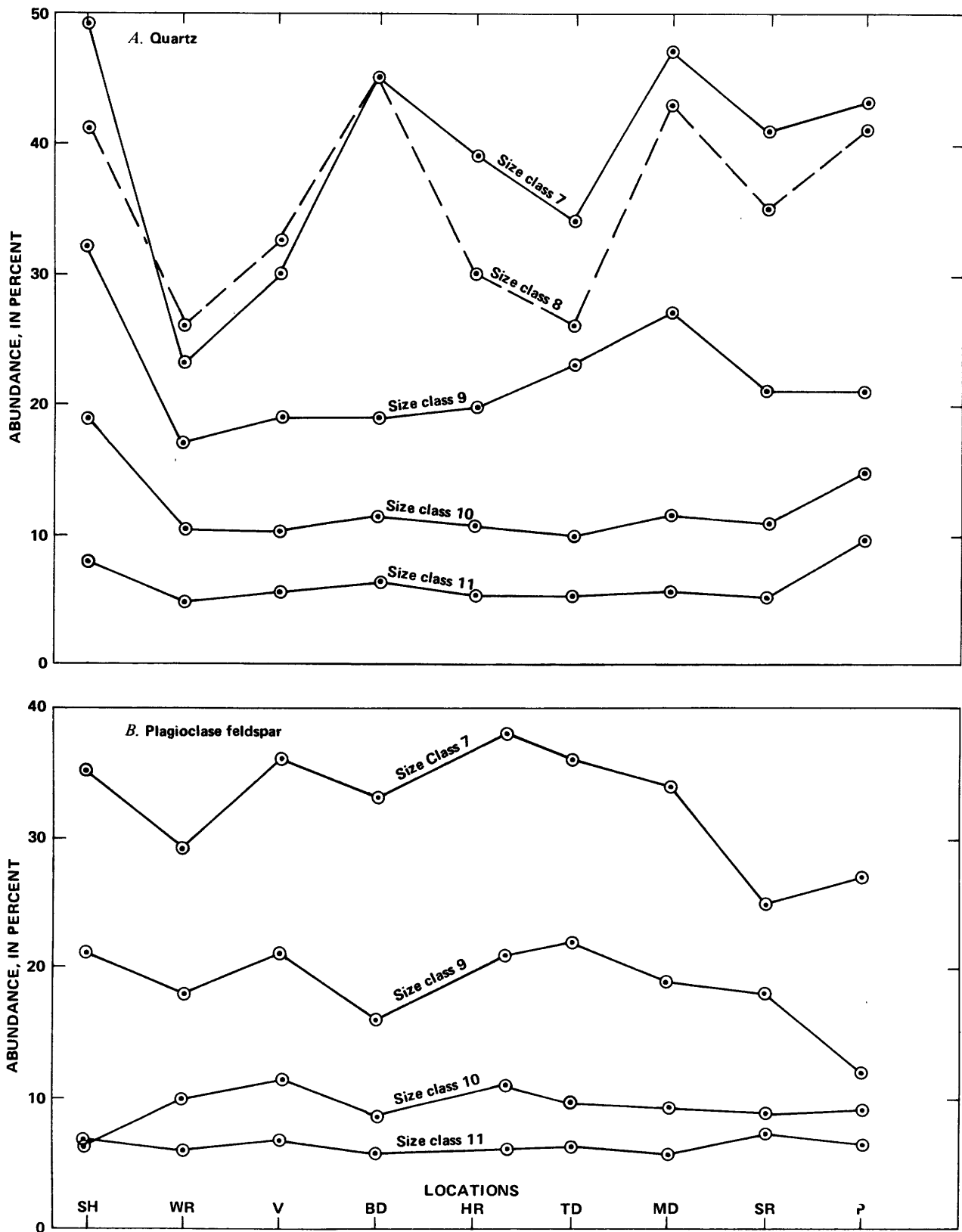


FIGURE 13. — Variation in quartz and plagioclase-feldspar abundance with particle size and sample location. Plagioclase feldspar in class 8 is similar to that in class 9 and is not plotted. Locations: P, Pasco; MD, McNary Dam; TD, The Dalles; HR, Hood River; BD, Bonneville Dam; V, Vancouver; SH, St. Helens; SR, Snake River; WR, Willamette River.

TABLE 13. — *Composition (in percent) of size class 7, 8, and 9 samples from Columbia River and tributary locations*

[Leaders (....) indicate no data]

Location	Size class	Organic material ¹ (1)	Quartz (2)	Plagio- clase (3)	Total clay ² (4)	Other minerals ³ (5)	Clay minerals					
							Montmorillonite		Illite		Kaolinite+Chlorite	
							Relative (6)	Absolute (7)	Relative (8)	Absolute (9)	Relative (10)	Absolute (11)
Columbia River near:												
Pasco.....	7.....	(4)	43	27	12	18	.....				
	8.....	(4)	41	22	20	17	.....				
	9.....	5	21	12	55	7	.....				
McNary Dam.....	7.....	(4)	47	34	16	3	10	2	64	10	26	4
	8.....	0	43	33	26	-2	16	4	70	18	14	4
	9.....	1	27	19	43	10	19	8	68	29	13	6
The Dalles.....	7.....	(4)	34	36	16	14	20	3	67	11	13	2
	8.....	0	26	28	20	26	21	4	66	13	13	3
	9.....	2	23	22	43	10	32	14	54	23	14	6
Hood River.....	7.....	(4)	39	38	12	11	12	1	72	9	16	2
	8.....	(4)	30	36	28	6	20	6	65	18	15	-4
	9.....	1	20	21	41	17	.....				
Bonneville Dam.....	7.....	(4)	45	33	13	9	15	2	71	9	14	2
	8.....	(4)	45	29	21	5	21	4	67	14	12	3
	9.....	2	19	16	41	22	30	12	59	24	11	5
Vancouver.....	7.....	(4)	30	36	9	25	27	2	55	5	18	2
	8.....	0	35	35	21	9	29	6	58	12	13	3
	9.....	2	19	21	43	15	30	13	61	26	9	4
St. Helens.....	7.....	(4)	44	30	21	5	28	6	55	12	17	3
	8.....	(4)	41	28	17	14	37	6	44	8	19	3
	9.....	1	32	21	37	9	49	18	37	14	14	5
Snake River near Pasco.....	7.....	(4)	41	25	16	18	22	3	67	11	11	2
	8.....	(4)	35	23	20	22	28	6	62	12	10	2
	9.....	1	21	18	41	19	29	12	58	24	13	5
Willamette River near												
Wilsonville.....	7.....	(4)	23	29	21	27	.....				
	8.....	(4)	26	33	37	4	58	21	40	15	2	1
	9.....	1	17	18	45	19	73	33	27	12	0	0

¹By conversion of data in table 5. Rounded to nearest percent.²Calculated by using only the 4.44-A peak height and an intensity factor equal to 127.³Calculated from 100 minus the sum of columns 1-4.⁴Not analyzed. Organic content probably very low.

differences should occur if quartz and feldspar at all locations were derived from the same primary source or from primary sources in which quartz and feldspar have similar particle-size distributions. For quartz, in particular, the primary source or sources seem to be mostly in the upper Columbia River basin or in deposits originally derived from the upper Columbia River basin (Haushild and others, 1966, p. 60-61). Hence, quantitative data for quartz in all size classes would be expected to show the same relative differences between locations.

Clay minerals (fig. 12) in size classes 7, 8, and 9 consist chiefly of an expandable 14-A component (montmorillonite), a 10-A component (illite), and a 7-A component (kaolinite and chlorite). Mixed-layer clays, such as were identified in size classes 10 and 11, are not as common in 7, 8, and 9 sizes; and where present, the clays do not have the thermal stability that was noted in 10 and 11 sizes. Montmorillonite, which collapses in potassium-saturated samples only after heat treatments in size classes 10 and 11, collapses more readily in size classes 7, 8,

and 9. However, its collapsed spacing is slightly greater than 10 Å, and the peak height is not greatly different from the 10-Å peak height due to illite alone. The occurrence of a 7-Å peak in some samples that lack any 14-Å peak after heating to 550°C indicates that kaolinite is present. In a few other samples, 7-Å peaks remained and the 14-Å peaks were accentuated after heating to 550°C; this suggests that chlorite composition may be slightly different in coarse-silt sizes than in clay sizes.

Calculations of relative amounts of clay minerals in 7, 8, and 9 sizes by the Schultz technique give results that indicate that peak areas and heights cannot be measured accurately or with sufficient precision to permit use of the Schultz relations. In general, and particularly for size classes 7 and 8, in which all peaks are very small, the relative amount of illite is overestimated, and in many cases illite is computed to represent more than 100 percent of a sample.

Because the Schultz technique gave unreasonable results, relative amounts of illite, montmorillonite,

kaolinite plus chlorite—the most abundant clay minerals in size classes 7, 8, and 9—were estimated by means of a “construct” described by Biscaye (1965, p. 808–809) and similar to that of Johns, Grim, and Brindley (1954). The procedure consists of weighting and summing peak areas as follows: For montmorillonite, one times the 17-A glycol peak area; for illite, four times the 10-A glycol; and for chlorite plus kaolinite, two times the 7-A glycol. The weighting factors (Johns and others, 1954; Weaver, 1961, p. 149) permit a direct comparison between relative amounts of these clay minerals. To obtain the relative amount of each mineral, the weighted peak area of each mineral is divided by the sum of the weighted peak areas.

For some samples, the relative amounts of each mineral determined by both the “construct” and the Schultz method were compared. This comparison indicated that both methods give nearly the same ratio of kaolinite-plus-chlorite:illite:montmorillonite, even though the Schultz relations often indicated that more than 100 percent of a sample was illite. For size classes 10 and 11, however, the “construct” results in percentages of montmorillonite that are incompatible with other data, notably CEC data. This incompatibility results from the substantial amount of mixed-layer clay in these classes.

An estimate of the absolute amount of each clay mineral in size classes 7, 8, and 9 is obtained by multiplying the percentage of total clay minerals (column 4, table 13) by the relative amount. Both the relative and absolute amounts indicate that illite is the dominant clay mineral. There is some indication that the relative amounts of illite and of kaolinite plus chlorite are higher in coarser silt as compared with finer silt and clay, whereas the relative amount of montmorillonite is lower. Muscovite occurs in substantial amounts in Columbia River sands; therefore, a relatively large 10-A component is expected in coarser silt as compared with finer sizes. In terms of absolute amounts, however, all clay minerals decrease with increasing particle size because the total clay-mineral content decreases markedly.

DISCUSSION: QUANTITATIVE X-RAY MINERALOGY

As has been indicated previously, the peak intensity, and hence the computed relative abundance, of a mineral is not solely dependent on the amount of a mineral that is present in a sample. The available data can be used to examine two possible effects—particle-size differences and mineral interferences—on intensity determinations and abundance estimates.

The average 1.82-A quartz-peak intensities for size classes 9–11 from Columbia River locations are plotted against the geometric mean particle diameter of each class in figure 14 along with similar data from Gordon and Harris (1955, 1956) as cited in Brown (1961, p. 506–507). Gordon and Harris' data show the effect on the 1.82-A quartz-peak intensity when only particle size is changed. A comparison of their data with data for Columbia River size classes suggests that the increase in 1.82-A intensity between size class 11 and size class 9 may not reflect solely increasing amounts of quartz. In fact, because the slope of the Columbia River data is not greatly different from the slope of Gordon and Harris' data, the reported increase in quartz could be due to a change in particle size alone. For size classes 7 and 8, the relation of intensity to particle diameter cannot be established directly because the sediments were ground (see “Analytical Procedures”) prior to X-ray analyses. If the diameters of the mechanically

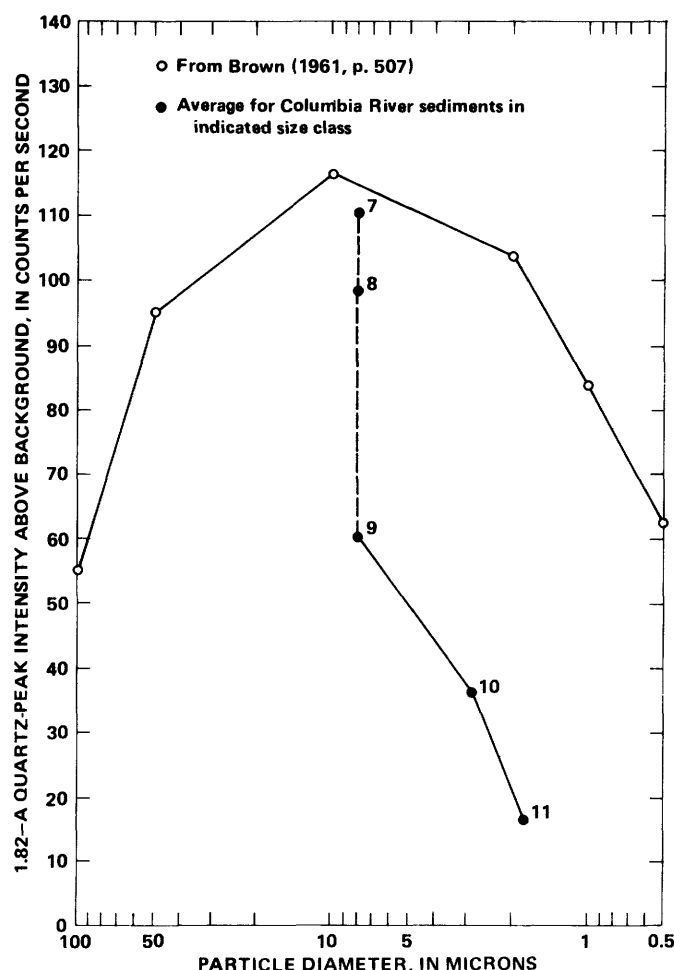


FIGURE 14. — Relation between particle diameter and 1.82-A quartz-peak intensity. Numbers adjacent to Columbia River data points are size-class numbers.

ground 7 and 8 sizes are not significantly different from the geometric mean particle diameter of size class 9, which is reasonable when grinding times and conditions are considered, then the increase in intensity in classes 7 and 8 probably reflects increasing amounts of quartz.

The second effect, that of mineral interferences, relates to the use of the 3.34-A quartz-peak intensity as an indication of quartz abundance. Because of the large amount of 10-A clay minerals in Columbia River sediments, a strong 003 reflection from these clay minerals could contribute significantly to a

3.34-A peak, particularly if a completely random orientation was not attained in powder mounts. Because these clay minerals have only weak or very weak (Brown, 1961, p. 238-239) reflections in the 1.82-A region, the 1.82-A peak and the 4.26-A peak have been used (Biscaye, 1965, p. 807) to estimate the abundance of quartz.

A plot of 3.34-A peak intensity versus 10-A peak intensity in powder patterns from Columbia River locations is shown in figure 15. These data indicate that no highly significant relation exists between these intensities either among particle size classes regardless of location. The absence of a significant correlation suggests that the intensity of the 003 reflection from 10-A components does not affect significantly the 3.34-A intensity from quartz.

SAND (SIZE CLASSES 2-6) AND GRAVEL (SIZE CLASS 1)

By R. O. VAN ATTA

The availability of sand and gravel size classes and the type of analysis on each class are indicated in table 14. Generally, precise quantitative and qualitative examinations were limited to the three finest sand size classes; however, thin sections and loose grains from all available size classes were examined with binocular and petrographic microscopes, and some estimates of the identity and abundance of constituents were made.

Determination of relative abundance of components in the three finest sand classes was made by point counting the constituents in thin sections. The method of preparing thin sections of these size classes generally left so little void space that point counting was acceptable. An automatic point counter

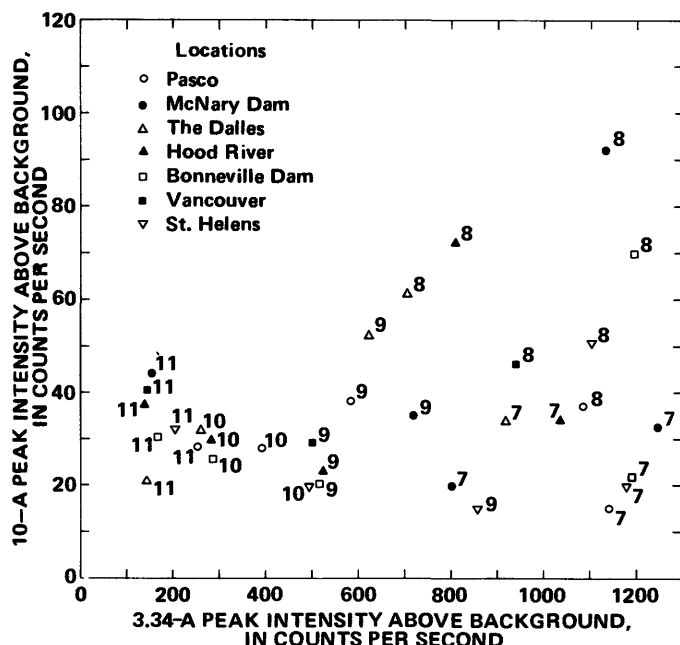


FIGURE 15. — Plot of 10-A peak intensity versus 3.34-A peak intensity for random powders of samples from Columbia River locations. Numbers adjacent to data points are size-class numbers.

TABLE 15. — Composition (in percent) of size class 4, 5, and

[Numbers under locations are size classes. Type of percent:

Component	Type of percent	Pasco			Snake River			McNary Dam		
		4	5	6	4	5	6	4	5	6
Rock fragments.....	A	39	37	25	46	43	34	49	31	28
Volcanic.....	B	49	....	....	48	....	....	59	....	....
Sedimentary.....	B	29	....	....	31	....	....	21	....	....
Metamorphic.....	B	15	....	....	6	....	....	6	....	....
Felsic.....	B	6	....	....	3	....	....	13	....	....
Glassy.....	B	1	....	....	12	....	....	2	....	....
Altered ¹	B	11	6	....	13	13	....	8	15	....
Feldspars.....	A	27	34	26	20	23	23	15	31	33
Plagioclase.....	A	67	62	73	40	65	70	73	58	73
Potash.....	A	33	38	27	60	35	30	27	42	27
Altered ¹	B	48	39	....	40	28	....	40	31	....
Silica group.....	A	30	22	27	26	26	23	27	27	20
Opauques and femags.....	A	3	6	21	3	5	16	4	9	17
Glass.....	A	1	1	1	5	3	4	5	2	2
Heavy minerals.....	C	....	....	25	....	....	12	....	....	11
Maturity index ³		0.45	0.31	0.53	0.39	0.39	0.40	0.42	0.44	0.33

¹Percentage of altered grains within the component.

²Glass included as part of the rock-fragment component for this sample only.

³Ratio of silica group (stable components) to rock fragments, feldspar, and glass (unstable components).

TABLE 14. — *Types of analyses performed on size class 1-6 samples from Columbia River and tributary locations*

[Types of analyses: A, point count; B, altered feldspar; C, altered rock fragments; D, heavy minerals; E, qualitative]

Size class	Types of analyses	Pasco	Snake River	McNary Dam	The Dalles	Hood River	Bonneville Dam	Vancouver	Willamette River	St. Helens
1.....	E.....	X	(1)	(1)	(1)	X	X	X	X	X
2.....	E.....	(1)	(1)	(1)	(1)	X	X	X	X	X
3.....	E.....	X	X	X	(1)	X	X	X	X	X
4.....	A.....	X	X	X	X	X	X	X	X	X
	B.....	X	X	X	(2)	(2)	(2)	(2)	(2)	X
	C.....	X	X	X	X	X	X	X	X	X
5.....	A.....	X	X	X	X	X	X	X	X	X
	B.....	X	X	X	X	X	X	X	X	X
	C.....	X	X	X	X	X	X	X	X	X
6.....	A.....	X	X	X	X	X	X	X	X	X
	B.....	X	(2)	(2)	(2)	(2)	(2)	(2)	(2)	X
	D.....	X	X	X	X	X	X	X	X	(2)

¹No sample available from this location.²Sample available but not analyzed.

was utilized, and traverses were spaced to provide complete coverage of the thin section when 500 points were counted. In four thin sections, counts of 500 points were compared with counts of 1,000 points; percentages varied no more than a few tenths of a percent, so counting 500 points each for all thin sections appeared reasonable. Percentages determined from point counts are volume percentages, and no effort was made to convert them to weight percentages.

The degree to which grains are altered is one of the mineralogic aspects that undoubtedly affects the quantity of radionuclides sorbed by sand and gravel. Special grain counts were made of altered and unaltered feldspars and of altered and unaltered rock fragments in some size classes (table 14). Feldspar and rock-fragment grains were counted as unaltered if less than one-third and one-half, respectively, of a grain were clouded or obscured with alteration products. The use of one-third and one-half, rather

than some other proportions, represents an arbitrary decision that significant differences in radionuclide content might exist if the degree of alteration were greater than these proportions. Only grains in size classes 4 and 5, where both feldspars and rock fragments are abundant, were inspected for degree of alteration.

Staining techniques (Gabriel and Cox, 1929; Rosenblum, 1956) were used to determine plagioclase and potash feldspar in size classes 4, 5, and 6. Heavy-mineral separations, using tetrabromoethane (specific gravity 2.95 at 20°C), were made on size class 6 sediment, and the relative abundance of heavy minerals was determined by grain counts or was estimated by inspection of grain mounts.

Qualitative and quantitative mineralogic data for the three finest sand size classes are shown in table 15. Six major components were identified, and their volumetric abundance was determined. The component "rock fragments" includes all polymineralic

6 samples from Columbia River and tributary locations

A, by volume; B, by number; C, by weight. Tr., trace]

The Dalles			Hood River			Bonneville Dam			Vancouver			Willamette River			St. Helens		
4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
46	37	36	47	36	44	46	42	30	58	37	36	75	60	48	60	31	32
59	....	....	78	....	....	63	....	....	....	72	....	85	....	....	....	58	....
13	....	....	8	....	....	7	....	....	....	11	....	11	....	....	....	19	....
6	....	....	3	....	....	22	....	....	....	4	....	2	....	....	....	15	....
9	....	....	6	....	....	6	....	....	....	0	....	2	....	....	....	3	....
13	....	....	5	....	....	2	....	....	....	13	....	Tr.	....	....	....	....	....
11	20	....	16	17	....	12	14	....	20	17	....	22	20	....	13	23	....
24	29	20	23	26	20	24	21	20	17	33	22	9	18	17	24	32	25
75	72	80	43	77	80	46	62	65	65	61	68	89	94	94	75	72	76
25	28	20	57	23	20	54	38	35	35	39	32	11	6	6	25	28	24
....	16	....	....	16	....	....	21	....	....	21	....	....	17	....	26	30	....
20	17	15	24	28	12	27	24	18	17	17	18	11	13	18	10	18	19
10	9	24	4	8	22	2	12	24	7	11	15	4	7	16	4	16	18
(²)	8	5	2	2	2	1	1	8	1	2	9	1	2	1	2	3	6
....	....	20	....	....	23	....	....	17	....	....	10	....	....	14	....	....	....
0.29	0.26	0.27	0.34	0.45	0.19	0.39	0.38	0.36	0.23	0.24	0.31	0.13	0.17	0.28	0.12	0.29	0.33

grains; the "silica group" includes not only quartz but also quartzite, chert, and other dominantly siliceous materials, including chalcedony. "Opakes and femags" are essentially the abundant heavy minerals; the opakes are magnetite, ilmenite, hematite, and pyrite; the femags (ferromagnesian minerals) are chiefly amphibole- and pyroxene-group minerals.

Rock fragments are the most abundant component (table 15) in size classes 4, 5, and 6 from Columbia River and tributary locations. For Columbia River locations, the percentage of rock fragments (table 16) ranges from an average of 33 percent in class 6 to 49 percent in class 4. Grain counts of class 4 and 5 samples (table 16) indicate that volcanic rocks are by far the most abundant constituent of the rock-fragment component; on the average, volcanic rocks (table 16) are about four times as abundant as the next most common constituent. The groundmass of most volcanic rocks is vitrophyric and contains abundant phenocrysts of plagioclase feldspar. The phenocryst composition indicates an intermediate-to-basic (andesitic-to-basaltic) composition for most volcanic rocks.

Sedimentary, metamorphic, and felsic rocks, in that order, are the most abundant rock types after volcanic rocks (table 16). Chert and various types of sandstone (table 17) are relatively widespread sedimentary rock types, claystone is not infrequent, and carbonate or other chemical or organic rock types are rare. Metamorphic rocks are dominantly quartzite and some schist and are rarely gneiss, phyllite, or hornfels. The felsic rocks include those with quartz, potash, and (or) plagioclase feldspar and with more or less equigranular texture. Most felsic rocks would probably be called microgranites or granodiorites.

Feldspar is the second most abundant component in most samples of the three finest sand classes (table 15); soda-lime varieties generally tend to be about twice as abundant as potash varieties (table 16). A rough idea of the proportion of various feldspars can be seen from the data in table 18. Orthoclase is the dominant potash feldspar, although microcline is widespread. The soda-lime species are prevailingly intermediate to basic (closer to An₅₀ than to An₁₀ or An₁₀₀) in composition.

Silica-group constituents are the third most abundant component in size classes 4, 5, and 6. Although quartz is the dominant constituent in this group, it is nearly always subordinate to feldspar. In many samples, chert and quartzite make up 20–25 percent of the silica group; chalcedony is a very minor but widespread constituent. Relative to other components, silica-group constituents exhibit a higher de-

TABLE 16. — Average composition (in percent) of size class 4, 5, and 6 samples from Columbia River locations

[Unless otherwise indicated, averages include data for all Columbia River locations. Type of percent: A, by volume; B, by number]

Component	Type of percent	Size class			
		4	5	6	4, 5, and 6
Rock fragments.....	A.....	49	36	33	39
Volcanic.....	B.....	61	65	.....	.....
Sedimentary.....	B.....	16	15	.....	.....
Metamorphic.....	B.....	10	10	.....	.....
Felsic.....	B.....	8	1	.....	.....
Glass.....	B.....	5	9	.....	.....
Feldspars.....	A.....	22	29	24	25
Plagioclase.....	A.....	64	66	71	68
Potash.....	A.....	36	34	29	32
Silica group.....	A.....	22	22	18	21
Opakes and femags.....	A.....	5	10	20	12
Glass.....	A.....	2	3	5	3

¹Averages for types of rock fragments are for data from Columbia River locations near Pasco, McNary Dam, The Dalles, Hood River, and Bonneville Dam.

²Averages for types of rock fragments are for data from Columbia River locations near Vancouver and St. Helens.

TABLE 17. — Sedimentary rock types in size class 4, 5, and 6 samples from Columbia River and tributary locations

[Types identified are designated by the letter "I"]

Rock type	Pasco	Snake River	McNary Dam	The Dalles	Hood River	Bonneville Dam	Vancouver	Willamette River	St. Helens
Chert.....	I	I	I	I	I	I	I	I	I
Wacke.....	I	I	I	.....	.....	I	.....	I	I
Claystone.....	I	I	I	.....	.....	I	.....	I	.....
Quartz arenite ¹.....	.....	I	I	.....	.....	.....	.....	.....	.....
Arkose or arenite.....	I	I	.....	.....	.....	I	.....	.....	.....
Carbonate ².....	.....	.....	I	.....	.....	I	.....	.....	.....
Diatomite.....	I	.....	.....	.....	.....	.....	.....	.....	.....

¹Could be metaquartz.

²Could be vein calcite or from amygdulites.

TABLE 18. — Feldspar in size class 4, 5, and 6 samples from Columbia River and tributary locations

[Relative abundance: (X), present; X, abundant; [X], dominant; Tr., trace; (?), probably present]

Location	Potash varieties			Soda-lime varieties		
	Orthoclase	Sandine	Microcline	An ₀ -An ₁₀	An ₁₀ -An ₅₀	An ₅₀ -An ₁₀₀
Pasco.....	X	(X)	(X)	.....	X	(X)
Snake River.....	X	(X)	.....	.....	X	[X]
McNary Dam.....	X	.....	X	.....	X	X
The Dalles.....	X	(X)	(X)	(X)	[X]	(X)
Hood River.....	(X)	.....	(X)	.....	[X]	(X)
Bonneville Dam.....	X	.....	(X)	(X)	.....	(X)
Vancouver.....	X	.....	(X)	(X)	X	X
Willamette River.....	Tr.	.....	Tr.	.....	X	[X]
St. Helens.....	X	.....	(X)	(?)	X	(X)

gree of rounding, although they seldom are better than subrounded. Some quartzite and chert fragments are well rounded, a condition which suggests that they represent at least second-cycle weathering products.

Opaque and ferromagnesian minerals are generally relatively minor components in the three finest sand classes (tables 15 and 16). Although ore minerals (magnetite and ilmenite) and ferromagnesian minerals are by far the most abundant constituents, less than an estimated 2 percent of accessory minerals also are found. Preliminary estimates of the composition of the opaque-ferromagnesian component in size class 6 are shown in table 19. These data, al-

TABLE 19. — *Opaque and ferromagnesian constituents in size class 6 samples from Columbia River and tributary locations*

[Relative abundance: VC, very common; C, common; S, scarce; VS, very scarce; R, rare; VR, very rare; (X), present; [X], dominant; (?), probably present. Abundance estimates for Pasco, Snake River, and Willamette River are based on the system of Milner (1962) and are not comparable with estimates from other locations]

Constituent	Pasco	Snake River	McNary Dam	The Dalles	Hood River	Bonneville Dam	Vancouver	Willamette River
Opaques:								
Magnetite.....	C	VC	(X)	(X)	(X)	(X)	(X)	VC
Ilmenite.....	VC	C	(X)	(X)	(X)	(X)	(X)	VC
Leucoxene.....	R	....	....	(X)	....	....	(X)	VR
Hematite.....	....	VS	(X)	(X)	(X)	....	(X)	VS
Pyrite.....	....	VR	(?)	(X)	....	(X)	(X)	....
Pyroxene group:								
Augite.....	C	VC	(X)	(X)	....	....	(X)	C
Pigeonite.....	....	....	....	....	....	....	(X)	....
Hypersthene.....	VC	VC	(X)	(X)	(X)	[X]	(X)	....
Aegirine.....	....	....	....	....	....	(X)	....	....
Amphibole group:								
Hornblende.....	VC	VC	(X)	(X)	(X)	(X)	[X]	S
Lamprobolite.....	....	....	....	(X)	(?)	(?)	(X)	....
Biotite ¹.....	....	S	(X)	(X)	....	....	....	....
Olivine.....	....	VS	(?)	(?)	(X)	(X)	(X)	....
Rutile.....	....	....	....	....	(X)	(X)	(X)	....
Sphene.....	S	C	(X)	....	(X)	(X)	(X)	....
Apatite.....	C	S	(X)	(X)	(X)	(X)	(X)	VS
Zircon.....	R	VS	(X)	(X)	(X)	(X)	(X)	R
Epidote.....	S	C	(?)	(X)	(X)	(X)	(X)	R
Zoisite.....	....	....	....	....	(?)	(X)	....	(?)
Clinzoisite.....	VR	(?)	....	....	(?)	....	....	....
Monazite.....	....	....	(X)	....	(X)	....	....	....
Kyanite.....	....	....	....	....	....	....	(X)	....
Tourmaline.....	VR	VR	....	....	....	....	....	VR
Staurolite.....	....	....	(X)	....	....	....	....	....
Garnet.....	S	S	(X)	(X)	(X)	(X)	(X)	VR
Glaucophane.....	....	VS	(X)	....	....	....	....	....
Limonite.....	....	....	....	....	(X)	....	(X)	....
Andalusite.....	....	....	(X)	....	....	....	....	....

¹Specific gravity less than 2.96. Probably present due to entrapment.

though not complete, suggest that the opaques (magnetite and ilmenite), the pyroxenes (augite and hypersthene), and the amphiboles (hornblende) are the abundant major constituents; garnet, epidote, apatite, and sphene are widespread accessory minerals.

Volcanic glass (table 15) is a conspicuous and ubiquitous minor component in the three finest sand classes from Columbia River and tributary streams. When compared with other types of rock fragments (table 15), volcanic glass is almost as abundant as felsic rocks and may represent as much as 13 percent of all rocks. In addition to individual glass fragments, whose abundance is indicated in table 15, many mineral grains exhibit a fringe of volcanic glass; thus, available data probably indicate the minimum amount of glass in a sample.

Several distinct forms of volcanic glass are found: brown, clear; colorless, clear; colorless, with many microlites; opaque, choked with magnetite; micro-vesicular, with aligned tubules; microvesicular, with "swiss-cheese" texture; sideromelane; palagonitic glass; and clear, with a dust of magnetite(?). The opaque glass compares almost identically with tholeiite glass taken from the eruption products of Kilauea Iki, Hawaii.

Data in tables 15 and 16 indicate some fairly consistent differences in the rock and mineral suite as particle size varies. The most evident difference is the increase in rock fragments as particle size increases (table 16). This trend continues in size

classes 3 and 2, where nearly all samples are dominantly rock fragments. In class 1, which contains gravel-size material, available samples contain exclusively rock fragments.

Other major components decrease as particle size increases. Opaque and ferromagnesian minerals, which average 20 percent of all components in class 6, average only 5 percent (table 16) in class 4. Volcanic glass also appears to be more abundant in fine size classes. Feldspar and silica-group constituents, however, do not vary significantly in abundance as particle size differs.

Available data (table 15) indicate that a fairly large percentage of feldspar is more than one-third altered. An average of about 25 percent of feldspar grains in class 5 at Columbia River locations show greater than one-third alteration, and perhaps slightly higher percentages in class 4 are altered. Feldspar-alteration products consist mainly of sericite, chlorite, and undetermined "clay," some of which may be montmorillonite. In many samples, almost totally unaltered feldspar was commonly found along with some grains so badly altered that they were difficult to recognize. Feldspar phenocrysts in rock fragments often are surprisingly fresh, although in numerous samples the enclosing matrix is badly altered.

A significant percentage of the rock fragments (table 15) is more than one-half altered; the average percentage in size classes 4 and 5 is about 15 percent. The dominant alteration product(s) is a red-

dish to yellowish material that is apparently some form of iron oxide. Volcanic rock and glass, the relatively unstable components of the rock-fragment suite, tend to be more severely altered than do other rock types.

Although the above data represent at least one measure of the significance of alteration, many rock fragments as well as mineral grains that are less than one-half or one-third altered exhibit well-formed peripheral alteration bands or weathering rinds. These rinds are often very sharply defined in coarse and medium sand grains, and even though they may be thin, their position around the exterior of a grain indicates that they could affect significantly CEC values and radionuclide concentrations. Inspection of the thin section for size class 3 from the Pasco location indicates that the anomalously high CEC (table 1) and radionuclide values (table 21; fig. 16) are related to well-developed weathering rinds. Although much of the weathering product in this thin section is red or yellow, its other optical characteristics suggest that it is an iron-stained clay.

The maturity index represents a ratio of the chemically and mechanically stable component (silica group) to the chemically and mechanically unstable components (rock fragments, feldspar, and glass). The lower the value of this ratio, the more susceptible are the sands to weathering processes; hence, the more likely the sands are to contribute to anomalous CEC values and (or) high radionuclide concentrations.

The maturity index for Columbia River and tributary sands (table 15) is very low and averages about 0.33 for the three finest sand size classes. This value is about one-third as high as the average value of a similar ratio (Pettijohn, 1957, p. 508) computed for major types of sandstone. The relatively large percentage of unstable volcanic detritus is the main factor in the low ratio for Columbia River and tributary-stream sands. The maturity index does not appear to reflect differences in the mineral and rock suite that have been related to particle size.

No highly significant differences (table 15) in the rock and mineral suite apparently occur in the part of the Columbia River between Pasco and St. Helens. Of the two major tributaries along this part of the river, only Willamette River sediments have an apparently different rock and mineral suite. The major differences between the Columbia River suite and the Willamette River suite (table 15) are higher percentages of rock fragments and lower percentages of potash feldspar and possibly silica-group constituents in the tributary stream sediments. The

percentage of rock fragments of volcanic origin increases slightly between Pasco and St. Helens, and the percentage of the silica-group constituents decreases. A slight decrease in the maturity index between the two locations may be a response to the apparent changes in these two components.

The mineralogy of bulk samples (sand-, silt-, and clay-size material) from the Columbia River has been described by Whetten (1966), Whetten, Kelley, and Hanson (1969), and Kelley and Whetten (1969). Whetten (1966, p. 1057), from bulk-sample mineral and chemical analyses, concluded that Columbia River sediments were comparable to graywacke sandstone in that the sediments contained a large percentage of unstable constituents. Whetten, Kelley, and Hanson (1969, p. 1161) reported an increase in the abundance of rock fragments (particularly volcanic rock fragments) and a decrease in the abundance of quartz and potash feldspar between McNary and Bonneville Dams. Similar longitudinal trends were suggested by Haushild, Perkins, Stevens, Dempster, and Glenn (1966, p. 47-58) and are supported partly by data in this report. Kelley and Whetten (1969, p. 1169), using discriminate-function analysis, noted no statistically significant change in bulk-sample mineralogy in the reach of the Columbia River between McNary and Bonneville Dams; heavy minerals, however, did allow a distinction between reservoirs along the reach.

Data reported by Haushild, Perkins, Stevens, Dempster, and Glenn (1966) for $>62\mu$ -size material cannot be compared directly with data presented here for sand size classes with relatively narrow class limits. Despite some apparent differences that probably reflect mostly particle-size effects, their data are generally compatible with data presented here.

RADIONUCLIDE CONTENT

Radionuclides associate with sediments by numerous mechanisms, including some that are reversible (Kelley, 1948) and some that are irreversible (Morton, ed., 1965). Because an average of about 15 gallons of distilled water was used to separate the particle size classes at each location, chemical and radiochemical analyses were made of filtered (using cellulose acetate filters with a 0.45μ pore size) distilled water that had been used to process samples from Pasco and McNary Dam locations. Because of decay and of low concentrations of other radionuclides, only ^{65}Zn could be determined accurately in the distilled water. Laboratory tap water also was analyzed chemically for comparative purposes, and the results from all analyses are shown in table 20.

If all the ^{65}Zn in the distilled water came from

TABLE 20.— *Chemical and radiochemical analyses of water used to prepare size separates of Columbia River sediments*[Abundance of all constituents except ^{65}Zn is in milligrams per liter; ^{65}Zn has units of picocuries]

Constituent	Laboratory tap water	Distilled water			Pasco size separates	McNary Dam size separates
		before preparing separates	after preparing Pasco separates	after preparing McNary Dam separates		
Silica (SiO_2)	9.3	0.1	(1)	2.5	-----	-----
Iron (Fe)	.39	(1)	(1)	.1	-----	-----
Manganese (Mn)	.09	(1)	(1)	.0	-----	-----
Calcium (Ca)	2.8	.0	(1)	1.1	-----	-----
Magnesium (Mg)	1.5	.0	(1)	.4	-----	-----
Sodium (Na)	2.2	.4	(1)	.4	-----	-----
Potassium (K)	.4	.0	(1)	.4	-----	-----
Zinc-65 (^{65}Zn)	(2)	(2)	311,224	3703	4143,858	467,436

¹Not determined.²Not determined but probably very low.³Represents the ^{65}Zn content leached from the total weight of the sediment.⁴Calculated as the sum of the products of the weight of sediment processed in each size class times the ^{65}Zn concentration of the sediment in each size class. Represents the ^{65}Zn content in the total weight of the sediment that was exposed to distilled water.

constituents (inorganic and organic) in the sediments, then about 7 percent of the available ^{65}Zn was released from sediments obtained at the Pasco location, and about 1 percent, from sediments obtained at the McNary Dam location (table 20). Small amounts of some stable constituents (table 20) also were removed.

Nishita and Essington (1966) reported that only insignificant amounts of ^{65}Zn are released when calcareous sediments are leached with distilled water or with artificially prepared irrigation water. Johnson, Cutshall, and Osterberg (1967, p. 99–102) found that only small amounts (less than 3 percent) of ^{65}Zn were removed from Columbia River sediments by leaching with sea water. They also noted that essentially no ^{51}Cr or ^{46}Sc was released, although some ^{54}Mn was removed. These observations indicate that the use of distilled water to prepare size separates should have resulted in little loss of radionuclides from Columbia River sediments.

Results from radionuclide analyses of size classes from seven Columbia River locations are shown in table 21. Because of insufficient amounts of material and because of some delay prior to analysis, radionuclide data were not obtained for all size classes (indicated by dashed leader lines in table 21), and some values are questionable. Data for ^{51}Cr (table 21), the radionuclide with the shortest half life and lowest gamma energy of the five nuclides determined, were affected most. For this reason, ^{51}Cr data mostly are ignored. In general, however, most relations discussed in subsequent pages for other radionuclides also are valid for ^{51}Cr . (See fig. 16.)

Inspection of the data in table 21 indicates that the highest radionuclide concentrations are found in fine size classes; for all locations, the ^{65}Zn concentration in size class 11 averages about 36 percent of the

TABLE 21.— *Radionuclide content (in picocuries per gram) in sized sediments from Columbia River locations*

[Leaders (....) indicate no data are available]

Size class	Pasco	McNary Dam	The Dalles	Hood River	Bonneville Dam	Vancouver	St. Helens
Chromium-51							
1.....	50	-----	-----	28	-----	22	14
2.....	-----	-----	-----	17	42	<2	6
3.....	156	5	-----	15	12	<2	12
4.....	81	10	13	17	10	12	21
5.....	116	21	8	20	22	30	29
6.....	248	50	40	54	35	91	-----
7.....	-----	29	25	44	24	73	84
8.....	1,070	-----	26	35	27	136	5
9.....	-----	239	-----	73	-----	-----	128
10.....	-----	261	-----	-----	27	609	310
11.....	-----	-----	559	-----	83	455	415
Zinc-65							
1.....	63.7	-----	-----	56.6	-----	4.7	4.1
2.....	-----	-----	-----	19.7	35.1	8.7	5.0
3.....	528	22.2	-----	31.7	23.6	17.7	6.8
4.....	241	53.3	32.1	30.6	20.8	12.7	9.4
5.....	303	134	47.5	44.3	41.4	25.8	11.5
6.....	440	270	108	121	69.8	68.4	-----
7.....	860	205	74	112	61.4	58.3	20.8
8.....	1,650	307	122	168	91.0	98.8	29.0
9.....	5,540	381	338	310	147	191	42.1
10.....	3,305	982	746	173	432	428	80.0
11.....	7,210	1,670	862	778	429	450	91.6
Manganese-54							
1.....	28.1	-----	-----	3.9	-----	0.3	<0.2
2.....	-----	-----	-----	1.2	5.4	.4	<2
3.....	68.3	1.4	-----	1.3	2.2	.9	.3
4.....	21.4	2.6	2.5	1.4	1.3	.6	.5
5.....	19.8	5.1	4.0	2.2	1.8	1.0	.4
6.....	19.5	9.5	7.6	6.8	3.4	1.9	-----
7.....	58.0	4.1	2.3	3.3	1.7	1.1	.4
8.....	63.6	6.9	6.6	5.9	2.8	2.0	.7
9.....	316	21.1	19.7	14.7	8.6	5.0	2.4
10.....	254	90.6	84.8	9.2	35.2	26.7	8.5
11.....	342	62.9	54.6	185.2	29.1	17.6	4.8
Cobalt-60							
1.....	20.1	-----	-----	1.2	-----	<0.2	<0.2
2.....	-----	-----	-----	.4	1.7	.7	.3
3.....	57.6	2.5	-----	.5	.8	1.3	<2
4.....	21.8	5.2	2.0	.6	.8	.5	.4
5.....	27.6	10.5	2.2	1.3	1.5	.8	<2
6.....	24.5	16.4	4.2	2.8	2.8	1.5	-----
7.....	20.6	8.0	1.8	2.1	1.5	.9	.3
8.....	52.6	10.8	3.5	3.2	2.2	1.7	<2
9.....	191	8.5	7.4	4.7	3.6	1.3	.7
10.....	136	44.5	29.1	3.5	16.0	11.1	2.6
11.....	216	50.5	19.7	17.3	13.4	8.2	1.4
Scandium-46							
1.....	3.2	-----	-----	0.7	-----	0.3	<0.2
2.....	-----	-----	-----	<2	<2	<2	<2
3.....	18.2	<2	-----	<2	<2	<2	<2
4.....	9.0	<2	.5	.5	.4	.4	<2
5.....	11.5	1.0	.4	<2	<2	.4	<2
6.....	23.6	5.7	3.0	2.3	.9	1.0	-----
7.....	227	4.4	1.1	1.1	.4	.6	<2
8.....	253	5.7	5.2	3.2	1.6	1.5	<2
9.....	1,160	22.6	4.2	16.9	6.0	<2	2.3
10.....	810	127	86.7	6.8	55.3	42.2	8.6
11.....	2,070	231	145	143	77.3	69.4	17.0

TABLE 22. — *Distribution of particle size and of ^{65}Zn in a composite sample from each Columbia River location*

[Distribution: A, particle size, percent by weight in each size class; B, ^{65}Zn , percent in each size class of the total amount in the composite sample. Size class limits (in parentheses) given in microns]

Location	Distri- bution	Size class and limits										
		1 (4000- 2000)	2 (2000- 1000)	3 (1000- 500)	4 (500- 250)	5 (250- 125)	6 (125- 62)	7 (62-31)	8 (31-16)	9 (16-4)	10 (4-2)	11 (<2)
Columbia River near:												
Pasco.....	A	4.9	0.0	0.1	24	58	12	0.5	0.2	0.2	0.0	0.1
	B	1.0	.0	.2	18.3	55.6	16.7	1.4	1.0	3.5	.0	2.3
McNary Dam.....	A	.0	.0	1	5	11	13	13.9	17.2	26.2	1.9	10.8
	B	.0	.0	.0	.6	3.4	8.1	6.6	12.2	23.1	4.3	41.7
The Dalles.....	A	.1	.0	.0	2.9	25	18	17.9	15.0	13.8	1.3	6.0
	B	.0	.0	.0	.5	6.9	11.3	7.7	10.6	27.3	5.6	30.1
Hood River.....	A	.2	.8	9	46	34	1	2.4	2.7	2.5	.4	1.0
	B	.2	.4	5.1	24.7	26.4	2.1	4.7	7.9	13.7	1.2	13.6
Bonneville Dam.....	A	.3	.0	3.7	54	29	2	2.7	3.0	3.2	.2	1.9
	B	.0	.0	2.1	26.1	28.0	3.2	2.3	6.3	10.9	2.1	19.0
Vancouver.....	A	2.8	3.2	27	48	18	0	0	.5	.4	.0	.1
	B	.6	1.7	27.3	34.7	26.1	.0	.0	2.8	4.5	.0	2.3
St. Helens.....	A	6.3	2.7	27	47	13	2	1	.5	.3	.1	.1
	B	3.5	1.2	20.6	50.3	17.2	.0	2.4	1.2	1.2	1.2	1.2
Average.....	B	.8	.5	7.9	22.3	23.4	5.9	3.6	5.9	12.0	2.0	15.7

sum of the ^{65}Zn concentrations in all size classes; the ^{65}Zn concentration in size classes 4 and 5 averages less than 2 percent of the sum of the ^{65}Zn concentrations in all size classes.

A significantly different perspective of the distribution of radionuclides is gained, however, when results of particle-size analyses (table 22) of composite cross-section samples are combined with results of radionuclide analyses of size separates. If the particle-size analyses fairly represent the actual distributions of particle sizes in the cross sections, then their combination with radionuclide concentrations reveals that, at five of the seven locations, more of the ^{65}Zn is associated with sand size classes than with silt or clay size classes. On the average, size class 11 contains only about 16 percent (table 22) of the total amount of ^{65}Zn , whereas size classes 4 and 5 contain about 22 and 23 percent, respectively. This results principally from the relative abundance of 125- to 500-micron sizes in Columbia River sediments.

The relative order of radionuclide abundance in Columbia River sediments varies among particle size classes and among sample locations (table 23). Chromium-51 and ^{65}Zn , not necessarily in that order,

are the most abundant radionuclides in all classes and at all locations. The general order of the remaining radionuclides, however, depends somewhat on particle size with ^{46}Sc tending to become relatively more abundant than ^{60}Co as particle size decreases. Overall, available data indicate that the decreasing order of radionuclide abundance is ^{51}Cr , ^{65}Zn , ^{46}Sc , ^{54}Mn , and ^{60}Co .

Relations between radionuclide concentrations and geometric mean particle size at three locations are shown in figure 16. As expected, radionuclide concentrations increase as particle diameters decrease, although the increase is not always regular. Part of the irregularity is undoubtedly statistical; however, for many locations and radionuclides, consistent irregularities exist and suggest causes in addition to usual statistical variations.

Three typical irregularities in the relations of radionuclide concentrations to particle diameters are illustrated by data in figure 16B. For convenience, the irregularities are called (1) coarse separates deviation, (2) size class 6 deviation, and (3) size class 10 deviation. The coarse separates deviation normally shows disproportionately high radionuclide concentrations in one or more coarse separates (size classes 1, 2, or 3); in some cases, minimum radionuclide concentrations occur in size class 4 rather than in size class 1 where concentrations might be expected to be lowest. The size class 6 deviation at five of six possible sample locations indicates more radionuclides in this class than in size class 7 and usually more radionuclides than in size class 8. The size class 10 deviation is somewhat variable (compare fig. 16A and B with fig. 16C), but, in general, radionuclide concentrations are low in size class 10 relative to those in size classes 9 and 11.

TABLE 23. — *Relative order of radionuclide abundance in selected size classes from Columbia River locations*

Size class	Location	Relative order				
1.....	Pasco.....	^{65}Zn	> ^{51}Cr	> ^{54}Mn	> ^{60}Co	> ^{46}Sc
	Hood River.....	^{65}Zn	> ^{51}Cr	> ^{54}Mn	> ^{60}Co	> ^{46}Sc
	St. Helens.....	^{51}Cr	> ^{65}Zn	> ^{54}Mn	= ^{60}Co	= ^{46}Sc
5.....	Pasco.....	^{65}Zn	> ^{51}Cr	> ^{60}Co	> ^{54}Mn	> ^{46}Sc
	Hood River.....	^{65}Zn	> ^{51}Cr	> ^{54}Mn	> ^{60}Co	> ^{46}Sc
	St. Helens.....	^{51}Cr	> ^{65}Zn	> ^{54}Mn	> ^{60}Co	= ^{46}Sc
8.....	Pasco.....	^{65}Zn	> ^{51}Cr	> ^{46}Sc	> ^{54}Mn	> ^{60}Co
	Hood River.....	^{65}Zn	> ^{51}Cr	> ^{54}Mn	> ^{60}Co	= ^{46}Sc
	St. Helens.....	^{65}Zn	> ^{51}Cr	> ^{54}Mn	> ^{60}Co	= ^{46}Sc
11.....	Pasco.....	(1)	> ^{65}Zn	> ^{46}Sc	> ^{54}Mn	> ^{60}Co
	Hood River.....	(1)	> ^{65}Zn	> ^{46}Sc	> ^{54}Mn	> ^{60}Co
	St. Helens.....	^{51}Cr	> ^{65}Zn	> ^{46}Sc	> ^{54}Mn	> ^{60}Co

¹Probable position of ^{51}Cr from inspection of data in table 21.

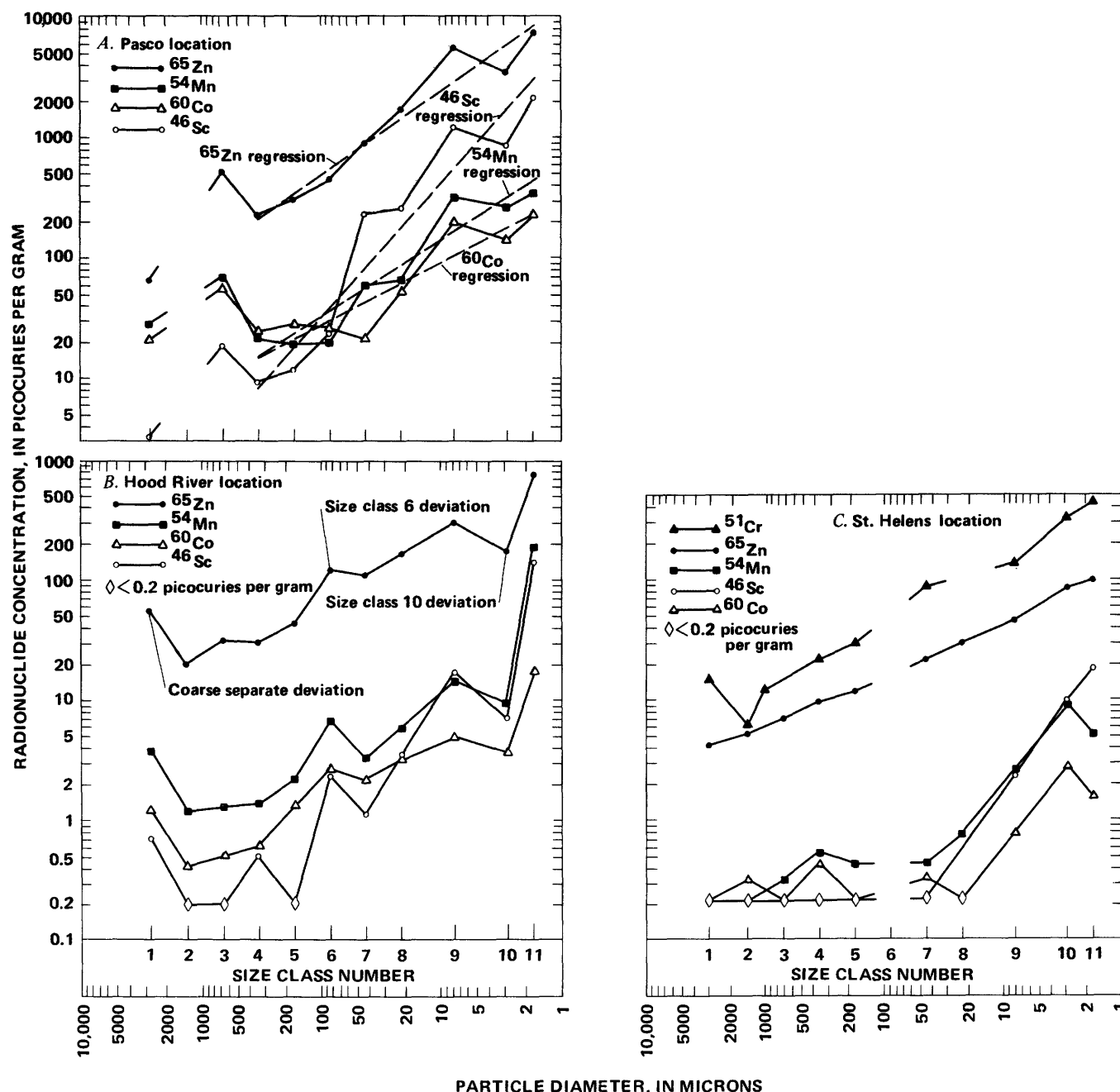


FIGURE 16.—Relations between radionuclide concentration and particle diameter.

Explanations for the most commonly observed irregularities are available from particle-size, CEC, carbon-nitrogen, and mineralogy data. The coarse separates deviation is closely allied with anomalies in CEC and particle-size data (table 1; fig. 3) that show that average CEC increases rather than decreases between size class 3 and size class 1. These anomalies have been related to fines (p. M9), to carbon content (p. M13), and (or) to mineralogy (p. M36). The size class 6 deviation also corresponds with an anomaly in the CEC-particle-diameter rela-

tion that is attributed to fines (p. M9) and to nitrogen (organic-matter) content (p. M13). However, even after organic material and fines apparently were removed more completely, CEC data (table 1) show that size class 6 has higher CEC values than size class 7. These higher CEC values suggest a possible mineralogic difference between classes. Although such a difference could not be evaluated directly because the methods of determining mineralogy (X-ray versus optical) varied between class 6 and class 7, more rock fragments and weathered

particles capable of sorbing radionuclides might be expected in size class 6 than in size class 7.

No completely satisfactory explanation has been found for the size class 10 deviation. Particle-size analyses (table 2) suggest that this size class may contain a high percentage of particles that tend to naturally occur as flocs. If this is true, the opportunity for particles on the inside of a floc to attract a radionuclide would be limited, and radionuclide concentrations would be lower than expected. CEC data (table 1) for size class 10 show an anomaly that may or may not be compatible with the floc explanation; namely, particles that were finer than those in the indicated size class (sample type 3, table 1) had lower CEC values than did particles in the indicated size (sample type 2, table 1). An explanation of this phenomenon, other than sample number error, which is considered unlikely, remains to be determined.

Regression, variance, and covariance analyses are useful tools for quantifying the relations between radionuclide concentrations and particle diameters, as well as for indicating the significance of differences in relations among radionuclides and among locations. Because of lack of data for coarse grain sizes at some locations (table 21), the only radionuclide data that were considered in establishing regression relations were data from size classes 4–11. It should be noted, however, that in many cases, using data from the coarse separates results in little difference in the correlation coefficients of the relations.

Linear-regression techniques were used to define relations between the logarithms of radionuclide concentrations of each size class and the logarithms of the geometric mean particle diameters of each size class. Because multiple observations of radionuclide concentration in each size class from each location are not available, the linearity of the relations at a location cannot be established directly by statistical techniques. However, if a "location" is defined as the Columbia River, the available radionuclide concentrations can be grouped by size classes and the linearity of the relation between radionuclide concentration and particle size can be established (Li, 1964, p. 336–339). Indirectly, this analysis suggests that a linear relation could exist at each location between the logarithms of the radionuclide concentrations and the logarithms of the geometric mean particle diameters.

Regression equations that describe the relations between the logarithms of ^{65}Zn , ^{46}Sc , ^{54}Mn , and ^{60}Co concentrations of each size class and the logarithms of the geometric mean particle diameters of each size class at the Pasco location are shown in table 24.

TABLE 24. — Regression equations for the relations between radionuclide concentration and particle size at Columbia River locations

[^{65}Zn , concentration of ^{65}Zn , in picocuries per gram of sediment; D , geometric mean particle diameter of the sediments in each size class, in microns; r , correlation coefficient; SE , standard error of estimate, in log units]

Location	Regression equation	r	SE
Pasco.....	Log $^{65}\text{Zn}=4.03739-0.66379(\log D)$	0.91	0.16492
	Log $^{54}\text{Mn}=2.74559-0.62150(\log D)$	.95	.18788
	Log $^{60}\text{Co}=2.42137-0.47956(\log D)$	.91	.19799
	Log $^{46}\text{Sc}=3.69146-1.06759(\log D)$	.96	.29698
McNary Dam.....	Log $^{65}\text{Zn}=3.24811-0.53877(\log D)$	.96	.14797
The Dalles.....	Log $^{65}\text{Zn}=3.07603-0.62633(\log D)$	.98	.12288
Hood River.....	Log $^{65}\text{Zn}=2.82532-0.48456(\log D)$	.91	.20100
Bonneville Dam.....	Log $^{65}\text{Zn}=2.76724-0.54510(\log D)$	.98	.10392
Vancouver.....	Log $^{65}\text{Zn}=2.87776-0.64838(\log D)$	.96	.15811
St. Helens.....	Log $^{65}\text{Zn}=2.06811-0.44155(\log D)$	.99	.02881

In addition, equations are given for the relation between $\log ^{65}\text{Zn}$ and $\log D$ at all Columbia River locations. The high correlation coefficients and the low standard errors of estimate for these equations indicate a close relation between radionuclide concentration and particle diameter.

Inspection of the regression equations (table 24), as well as of the data in figure 16A, suggests that not all radionuclide concentrations are related similarly to particle diameters; that is, the slopes (regression coefficients) of the regression lines are not all equal. A covariance analysis (Li, 1964, p. 393–399) applied to data from the Pasco location indicates that relations between radionuclide concentrations and particle diameters at that location have statistically different regression coefficients at the 5-percent significance level (probability of rejecting a true hypothesis).

Regression relations and covariance analyses are useful also in establishing the significance of among-location differences in the slopes of regression lines for the same radionuclide. Inspection of the data in figure 16 suggests, for example, that the slope of the regression of $\log ^{65}\text{Zn}$ versus $\log D$ decreases between Pasco and St. Helens. Covariance analyses show, however, that statistically no differences (5-percent significance level) in slope exist when the data from all locations are considered. When data from the upper three locations are pooled and are compared with pooled data from the lower three locations, covariance indicates no statistically significant (5-percent significance level) difference in the slope of the relation of $\log ^{65}\text{Zn}$ to $\log D$.

With a theoretical, simplified model that assumes that sediment particles are spherical, the relation of the logarithm of specific surface to the logarithm of particle diameter has a slope of -1.0 (Sayre and others, 1963, p. 16). Because the sorption capacity of sediments is roughly proportional to specific surface (Sayre and others, 1963, p. 15), the slope of a regression line for the relation of the logarithm of

radionuclide concentration to the logarithm of particle diameter also is expected to be about -1.0 if particle diameter is the only or dominant variable controlling both specific surface and radionuclide concentration.

Statistical tests (Li, 1964, p. 317-322) show that the observed slopes of the regression lines for $\log {}^{65}\text{Zn}$ versus $\log D$ are generally significantly less than -1.0 ; at all locations, the pooled slope estimate is about -0.6 . A very similar slope was determined for the regression of $\log \text{CEC}$ versus $\log D$. (See p. M9 and fig. 2.) Thus, the explanation that is suggested for differences between observed and expected relations must accommodate the relations of both CEC and radionuclide concentration to geometric mean particle diameter. The applicability of the theoretical specific-surface model is open to question; however, refining the model by considering different shapes for fine particles could result only in a steeper theoretical slope if a linear relation were assumed.

Three possibilities are suggested as causes of the deviations between expected and observed relations. The possibilities are the effects of (1) flocculation, (2) inclusion of fines, and (3) variations in mineral composition. If sediments in fine size classes were naturally present as flocs, the concentration of a radionuclide in these classes could be low because of a possible shielding effect. This explanation, however, does not appear reasonable for the $\log \text{CEC}$ - $\log D$ relation because equilibration times were long and samples were mechanically agitated during equilibration. The inclusion of small amounts of fines in coarse and medium size classes could greatly increase CEC or radionuclide concentrations without changing appreciably a weighted geometric mean particle diameter. This explanation is reasonable for both the CEC and the radionuclide-concentration versus particle-diameter relations; however, it does not explain all deviations in the CEC versus geometric-mean-particle-diameter relation. Hence, it seems unlikely that inclusion of fines can explain all deviations in the relation between radionuclide concentration and geometric mean particle diameter.

It has been shown previously (p. M21 and M31) that differences in particle size are accompanied by differences in mineralogy. One of the more obvious mineralogic differences is the decrease in the amount of total clay minerals as particle size increases. When the regression equation for the relation of the logarithms of the amounts of the total clay minerals (as indicated by the average intensity of the 4.44-A peak at all locations) to the logarithms of geometric mean particle diameters for classes 7-10 is determined,

the regression coefficient, or slope of the relation, also is about -0.6 . This suggests that both CEC and radionuclide content may be related intimately to mineralogic content that is related in turn to particle size.

Differences in radionuclide concentration along the Columbia River can be evaluated with data from particle size classes. The percentage difference between adjacent locations and between Pasco location and each location downriver are shown in table 25. For ${}^{65}\text{Zn}$, the differences in clay (size class 11) and in medium sand (size class 4) are shown as well as the difference in the average amount of ${}^{65}\text{Zn}$ in the eight finest size classes (size classes 4-11). Zinc-65 concentrations in the clay size class were determined both from actual analyses (type A radionuclide concentration, table 25) shown in table 21 and from regression equations (type B radionuclide concentration, table 25) presented in table 24. Some available radionuclide concentrations and some computed percentage differences are not shown in table 25 because they provide little additional information.

Inspection of the data in table 25 indicates that radionuclide concentrations in the clay size class at St. Helens are about 1 percent of comparable concentrations at Pasco. The decrease is only slightly different if regression-determined values are substituted for actual measured values. Cobalt-60, ${}^{46}\text{Sc}$, and ${}^{54}\text{Mn}$ in the clay size class appear to decrease somewhat differently than ${}^{65}\text{Zn}$ in the same size class, but the difference is probably not statistically significant. A slight increase in ${}^{65}\text{Zn}$ concentration between Bonneville Dam and Vancouver (table 25) probably reflects usual statistical variations rather than any real change.

From Pasco to St. Helens, ${}^{65}\text{Zn}$ in the medium-sand size class decreases less than ${}^{65}\text{Zn}$ in the clay size class decreases. The average concentration of ${}^{65}\text{Zn}$ in the eight finest size classes, as might be expected, decreases between Pasco and downstream locations in a manner intermediate between decreases in the clay and the medium-sand sizes.

Data in table 25 and figure 17 very convincingly demonstrate where largest decreases in radionuclide concentrations occur and, indirectly, suggest reasons for varying rates of decrease. Per mile of river, the largest decreases are between Pasco and McNary Dam locations and between Vancouver and St. Helens locations. Pasco and McNary Dam locations bracket a major water- and sediment-contributing stream, the Snake River; Vancouver and St. Helens locations also are separated by a major water- and sediment-contributing stream, the Willamette River.

TABLE 25. — *Percentage difference in radionuclide concentrations between Columbia River locations*

[Type of radionuclide concentration: A, from radionuclide analysis of size class 11; B, from regression equation at geometric mean for size class 11; C, from radionuclide analysis of size class 4; D, average of concentrations for size classes 4–11 from radionuclide analyses]

Location	Type of radionuclide concentration	Radionuclide concentration, in picocuries per gram				Percent difference in radionuclide concentration							
		⁶⁵ Zn	⁶⁰ Co	⁴⁶ Sc	⁵⁴ Mn	Between adjacent locations				Between Pasco and indicated location			
						⁶⁵ Zn	⁶⁰ Co	⁴⁶ Sc	⁵⁴ Mn	⁶⁵ Zn	⁶⁰ Co	⁴⁶ Sc	⁵⁴ Mn
Pasco	A	7210	216	2070	342								
	B	7620											
	C	241											
	D	2443											
McNary Dam	A	1670	50.5	231	62.9	—77	—77	—89	—82	—77	—77	—89	—82
	B	1310				—83				—83			
	C	53.3				—78				—78			
	D	500				—80				—80			
The Dalles	A	862	19.7	145	54.6	—49	—61	—37	—13	—88	—91	—93	—84
	B	839				—36				—89			
	C	32.1				—40				—87			
	D	291				—42				—88			
Hood River	A	778	17.3	143	(¹)	—10	—12	—1	(¹)	—89	—92	—93	(¹)
	B	510				—39				—93			
	C	30.6				—5				—87			
	D	217				—25				—91			
Bonneville Dam	A	429	13.4	77.3	29.1	—45	—23	—46	(¹)	—94	—94	—96	—92
	B	431				—49				—94			
	C	20.8				—32				—91			
	D	162				—26				—93			
Vancouver	A	450	8.2	69.4	17.6	+5	—39	—10	—40	—94	—96	—97	—95
	B	525				+22				—93			
	C	12.7				—39				—95			
	D	167				+3				—93			
St. Helens	A	91.6	1.4	17.0	4.8	—80	—83	—76	—73	—99	—99	—99	—99
	B	90.3				—83				—99			
	C	9.4				—26				—96			
	D	37.4				—82				—98			

¹Questionable value.

Radionuclide ratios provide an insight into the relative differences in ratio components among particle sizes and among locations. Plots in figure 18 show that some ratios behave differently among locations, as well as among particle sizes. The ⁴⁶Sc/⁶⁵Zn ratio increases greatly as particle size decreases; other ratios increase only slightly or change erratically as particle size decreases. The ⁶⁵Zn/⁶⁰Co ratio shows no statistically significant difference between Pasco and McNary Dam locations. When ⁶⁵Zn/⁶⁰Co ratios at upstream locations are compared with ratios at downstream locations, ratios at downstream locations usually are highest. This indicates that ⁶⁵Zn associated with sediment increases relative to ⁶⁰Co along the river. The ⁴⁶Sc/⁶⁵Zn ratio, unlike the ⁶⁵Zn/⁶⁰Co ratio, is statistically significantly higher at Pasco than at McNary Dam; below McNary Dam the ratio appears to be more or less constant. When compared with the ⁴⁶Sc/⁶⁵Zn and ⁶⁵Zn/⁶⁰Co ratios, the ⁶⁵Zn/⁵⁴Mn ratio is intermediate; that is, it generally increases downstream from Pasco, as does the ⁶⁵Zn/⁶⁰Co ratio, and tends to change little below McNary Dam, as does the ⁴⁶Sc/⁶⁵Zn ratio.

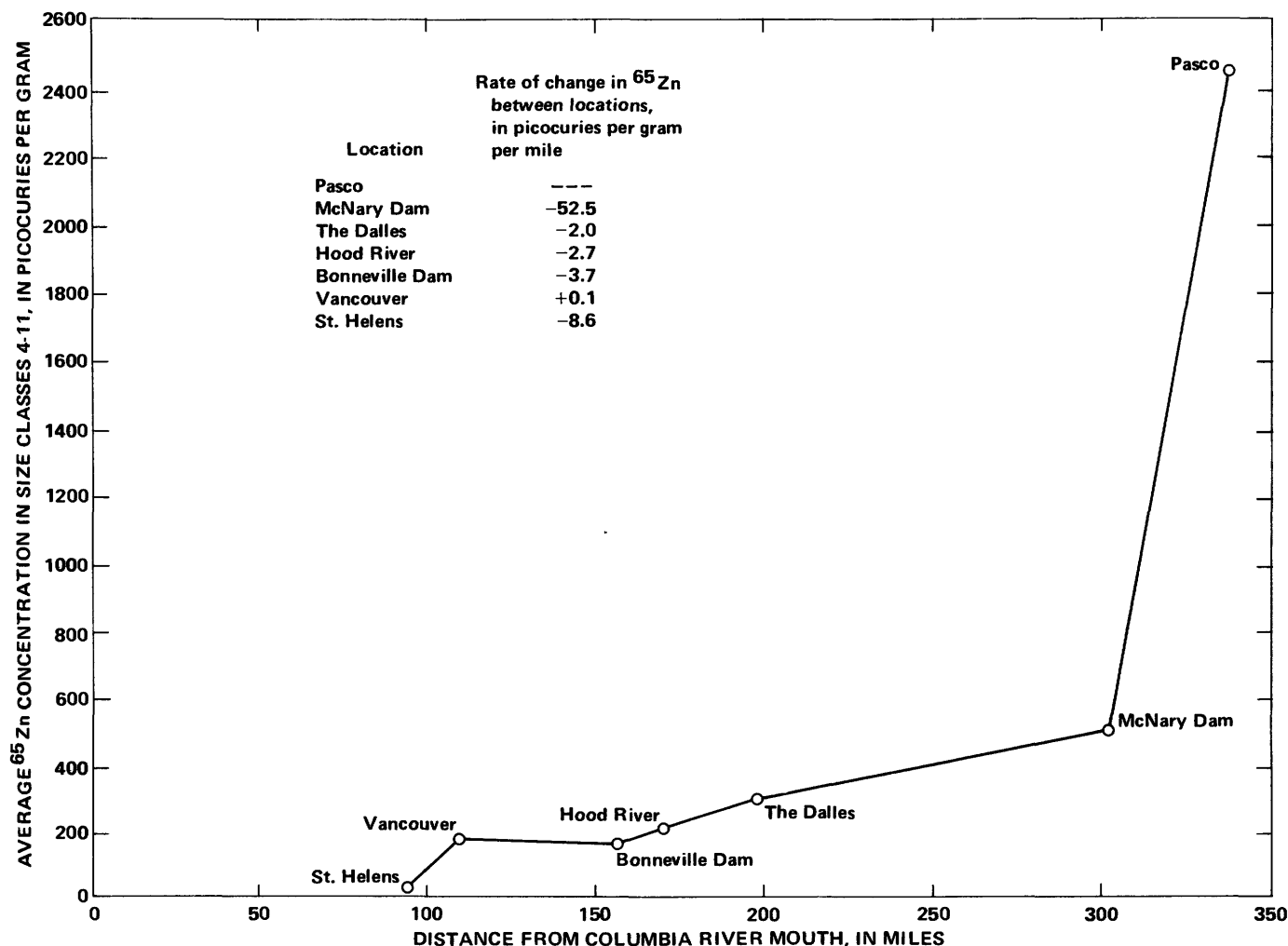
The ⁵⁴Mn/⁶⁰Co ratio has been plotted in figure 18D to illustrate differences in a ratio that does not have ⁶⁵Zn as one of the ratio components. In general, this ratio may increase slightly with decreasing particle size, but it shows no consistent difference with sample location.

The relation between CEC and radionuclide con-

centration is illustrated in figures 19 and 20. With noticeable deviations, direct relations are evident for most radionuclide concentrations and CEC values of clay, silt, and some fine to very fine sand size classes. For medium- to coarse-sand classes, however, radionuclide concentrations frequently are more or less independent of CEC. Although the exact reasons for the independence are unknown, it probably reflects differences in the location and (or) mechanism of ion sorption on coarse particles as compared with silt or clay particles. In this connection, Malcolm and Kennedy (1970, p. 156) noted that ion exchange rates for coarse particles are much slower than for fine particles.

Data indicate that some radionuclides respond differently, if erratically, to changes in CEC. For example, ⁶⁰Co and ⁵⁴Mn are frequently more abundant in size class 10 than in size class 11 (fig. 19) even though the CEC in size 10 is much less than that in size 11. At most locations, ⁶⁵Zn and ⁴⁶Sc also tend to be higher in size 10 than might be expected from the difference in CEC although their concentrations in size class 11 generally are greater than in size 10. Again, no good explanation can be given for these observations.

As indicated previously (p. M9 and M39), size class 6 has higher than expected CEC and radionuclide concentrations. The CEC-⁶⁵Zn relation (fig. 20, McNary Dam and Vancouver locations) and other CEC-radionuclide relations (tables 1 and 21) indi-

FIGURE 17. — Change in average ^{65}Zn concentration in size classes 4-11 along the Columbia River.

cated that the high CEC is not accompanied by a proportionately high radionuclide concentration. Quite commonly, the CEC in some coarse separates (for example, fig. 20, Pasco location, size class 3) also is disproportionately higher than the radionuclide concentration.

When "actual" CEC values (p. M12) are plotted against radionuclide concentrations, many size class 6 (for example, fig. 20, McNary Dam location) and some coarse separates discrepancies are eliminated, although CEC values and radionuclide concentrations in size class 6 are still higher than in size class 7. The elimination indicates that the high CEC but low radionuclide content in the "as received" size class 6 sediment is due principally to the inclusion of materials that contribute unequally to CEC and radionuclide content.

Both organic matter and fines could contribute unequally by virtue of having different CEC:radionuclide-content ratios than other materials indige-

nous to a size class. Because of differences in the nature of exchange sites and exchange mechanisms between organic and inorganic materials, it is possible that organic material would tend to take up less nuclides than inorganic material even though both had the same exchange capacity. Thus, where both are present in a sample, as they are in the "as received" Columbia River samples, radionuclide concentrations might tend to be lower than expected. More likely, however, the discrepancies arise from the nature of fines associated with coarse particles. If the fines are principally weathering rinds or compacted clays that were removed or dispersed during sample preparation for CEC analyses, then the discrepancies would be explained because radionuclides would probably only be associated with the surface layers of such materials. Regardless of its origin, any type of weathering product or clay layer could result in less increase in measured radionuclide concentrations than in measured exchange capacity.

TRANSPORT OF RADIONUCLIDES BY STREAMS

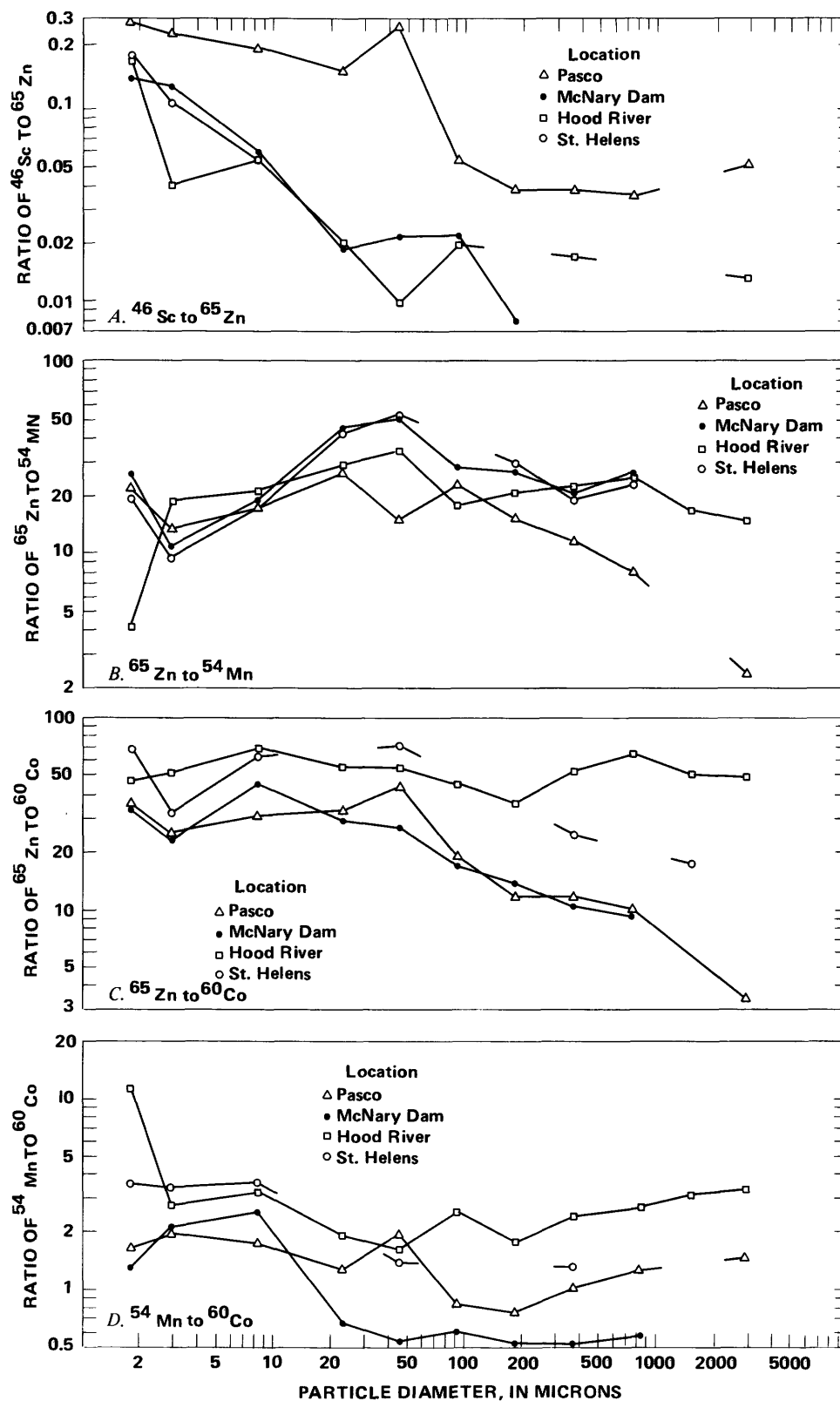


FIGURE 18.—Variations in radionuclide ratios with particle diameter and sample location along the Columbia River.

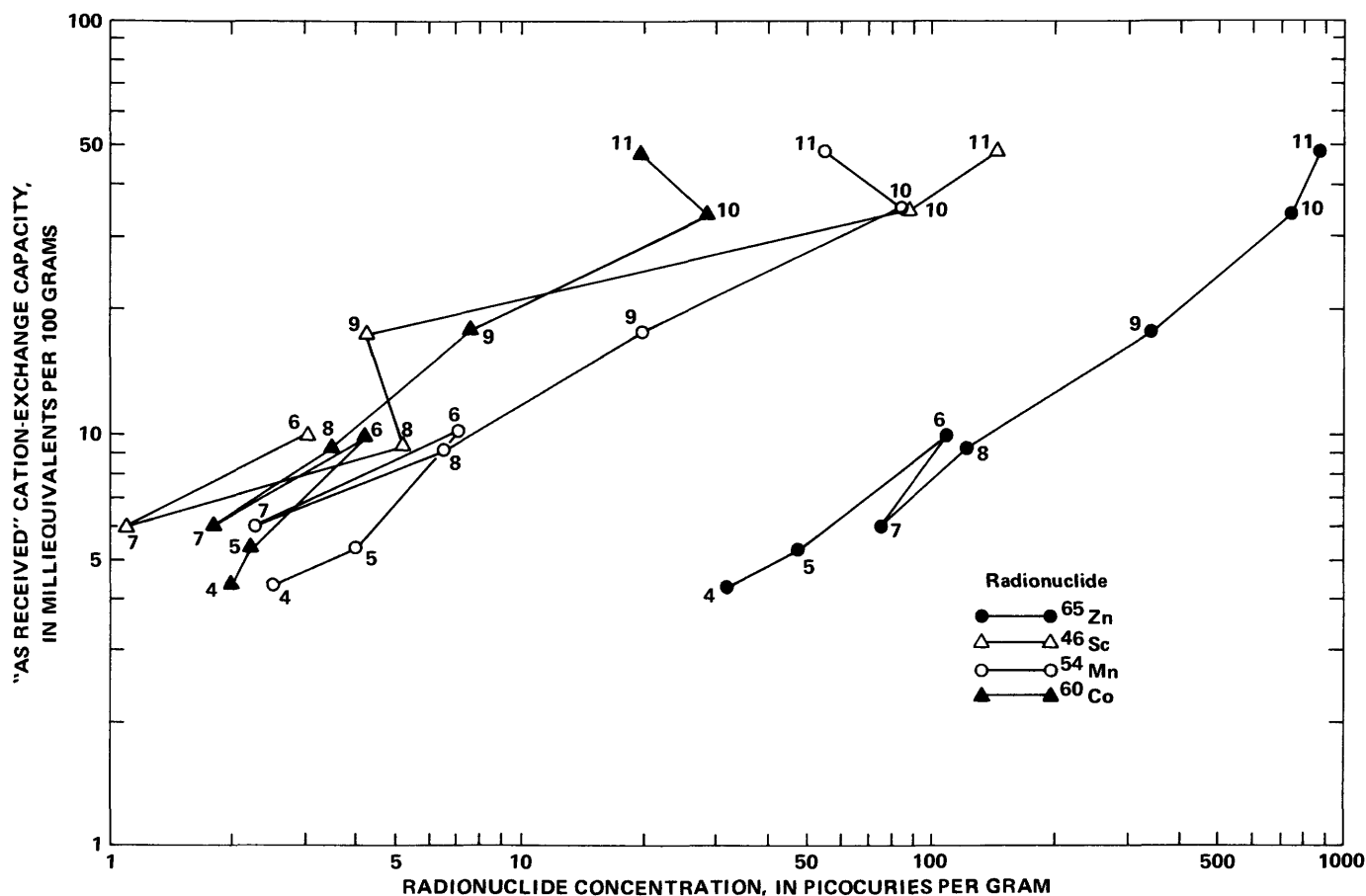


FIGURE 19. — Variation in radionuclide concentrations with "as received" cation-exchange capacities. Data are for size classes from The Dalles location. The number beside each data point is the size-class number.

However, the fact that size class 6 sediments have higher CEC and radionuclide contents than size class 7 sediments, even after removal of organic matter and fines, indicates that a fundamental compositional difference must exist between these two classes.

INTERPRETATION OF RADIONUCLIDE DATA

The presentation of radionuclide data has been limited purposefully to detailing observations in various forms. In order to interpret these observations, a model that describes at least qualitatively the origin of radionuclides in streambed sediments must be developed. Some necessary elements for a model are available, and some elements can be inferred from data presented here; but detailed studies on radionuclide transport phenomena are needed.

The discussion which follows considers very briefly (1) the composition and release of radionuclides to the Columbia River, (2) the uptake of ions by sediments, (3) two simplified models for the origin of radionuclides in streambed sediments, and (4) the compatibility of these models with data presented here. An anticipated future report, which would in-

clude results from additional studies of radionuclides in bottom sediments and results from radionuclide-transport determinations, also will include a more detailed evaluation of the origin of radionuclides in streambed sediments.

Radionuclides in the Columbia River resulted principally from neutron activation of stable elements (Zn, Co, Sc, and Mn) that occur naturally in Columbia River water or of elements (Cr) that were added to inhibit corrosion. With the exception of ⁵¹Cr, therefore, radionuclide concentrations in reactor effluents should be less than stable-element concentrations in ambient waters. National security requires that the absolute concentrations of radionuclides in plutonium-production reactors be classified; relatively, however, ⁵¹Cr is probably initially about 17 times as abundant as ⁶⁵Zn, which, in turn, is probably much more abundant than ⁵⁴Mn, ⁶⁰Co, or ⁴⁶Sc (Nelson, 1961, p. 9–11). From data on stable-element concentrations in the Columbia River above the reactor-effluent outfalls (Silker, 1964, p. 541), Zn is about 12,800, and 10,000 times as abundant as Mn, Co, and Sc, respectively.

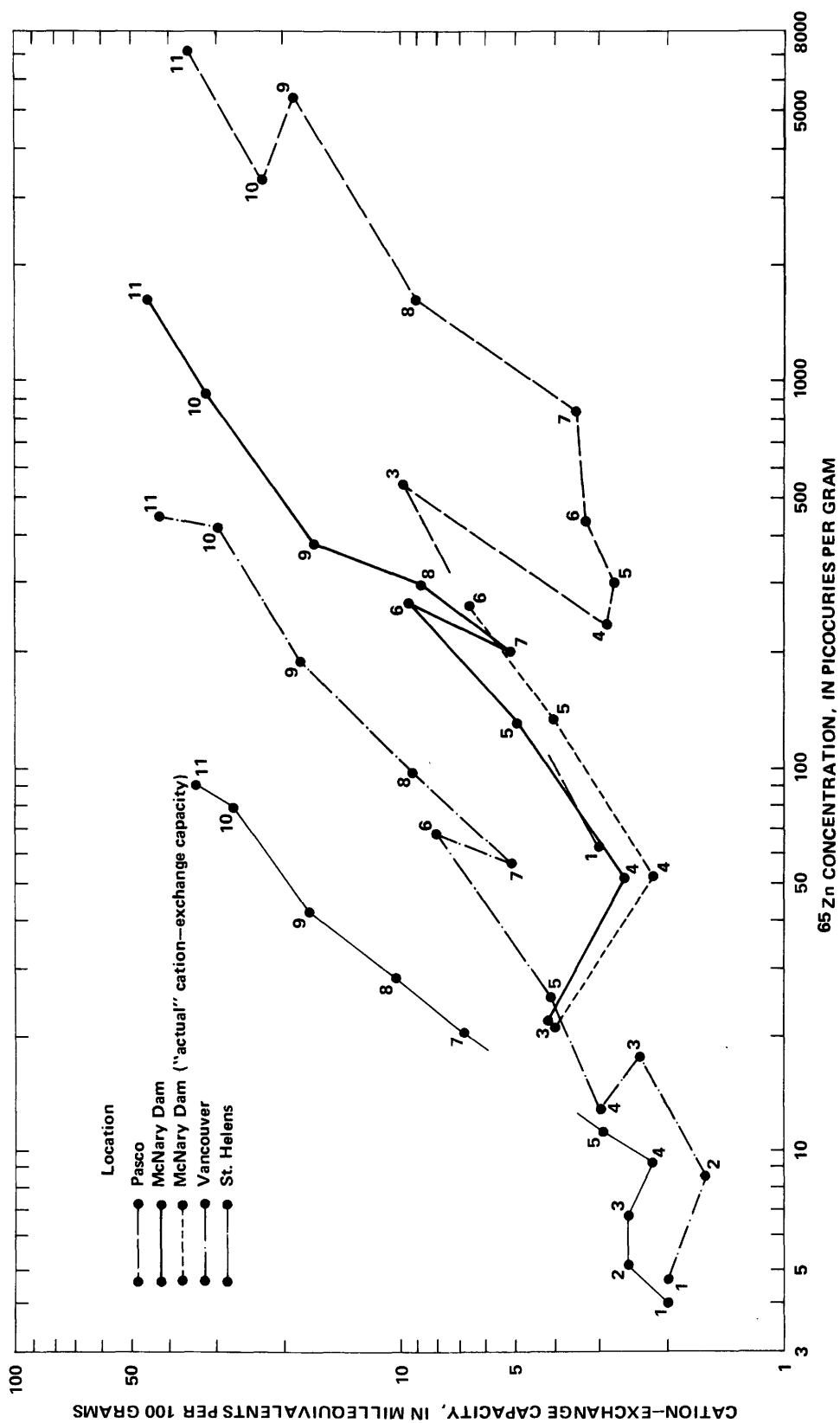


FIGURE 20. — Relation between ^{65}Zn concentration and "as received" and "actual" cation-exchange capacity in size classes from four Columbia River locations. The number beside each data point is the size-class number.

The reactor-effluent radionuclides are initially mostly in the solute phase (Nelson, in Pearce and Green, 1966, p. 89-90). Scandium-46, however, does have a high initial particulate component (68 percent), and about 16 percent of the ^{65}Zn is initially in a particulate phase. The solute-phase radionuclides are not all in a form amenable to immediate uptake by sediment. Chromium-51 and ^{46}Sc both have large percentages (Nelson, in Pearce and Green, 1966, p. 89; Nelson and others, 1966, p. 157-158) of anionic forms that probably are not sorbed readily. Zinc-65, ^{60}Co , and ^{54}Mn in the solute phase are chiefly cationic forms initially, and hence probably are sorbed readily. The percentage of the solute-phase radionuclides that is cationic decreases irregularly downstream from the reactor outfalls.

During the period of reactor operations, radionuclides were released to the Columbia River at mid-channel point sources along about a 12-mile-long reach (Nielsen, in Kornegay and others, 1963, p. 91) adjacent to the Hanford area (fig. 1). The rate of release (Perkins and others, 1966, p. 243-247) had been fairly constant for several years preceding the collection of samples for this study. Annual variations in solute radionuclide concentrations that were related to Columbia River discharge variations (Haushild and others, 1966; Perkins and others, 1966) were large, and low concentrations that accompanied high Columbia River discharges may have been experienced for as long as 2 months during a year. Mean or near-mean solute concentrations should have prevailed at most sampling locations for several months prior to the time samples were collected for this study.

In the Columbia River, periods of relatively greater sediment transport alternate with periods of lesser movement. During the low-flow period that preceded collection of samples for this study, only suspended sediments $<62\mu$ in size were in transport at Pasco, Wash., Umatilla, Oreg., and Vancouver, Wash. (fig. 1). At Vancouver, a very small amount of $>62\mu$ bedload also was being moved during the low-flow period. During the high-flow period that followed sample collection, sediment particles as large as 500μ were transported at most Columbia River locations.

Data on the composition of radionuclides in the Columbia River indicate that, as a result of some type of sorption mechanism(s), sediments remove trace levels of radionuclides from essentially continuous releases of radionuclides that are initially mostly in a solute phase. For stable elements present in high concentrations and for some stable elements present in low concentrations, soil scientists have

investigated sorption-desorption reactions. Concentration gradients, characteristics of stable elements and of sediments, and many other perhaps less important factors have been indicated as controlling the reactions. Both reversible and irreversible reactions have been observed. The amount of sorption has been observed in laboratory experiments to reach limiting values that presumably reflect the combination of all controlling influences.

Investigations with stable elements and with radionuclides (Tamura and Jacobs, 1960; Rowe and Gloyna, 1964; Yousef and Gloyna, 1964; Jenne and Wahlberg, 1968) have indicated the importance of selective and often irreversible sorption by some sediment components when ions are present in trace-level concentrations. Stable elements and radionuclides of the same species generally are regarded as having similar sorption-desorption reactions.

The preceding discussion provides background information that must be considered in any model that attempts to portray qualitatively or quantitatively the origin of radionuclides in Columbia River streambed sediments. A relatively simple model might consider these sediments as being noncumulative and immobile (no deposition or erosion and transport) and as having the same characteristics (CEC and mineralogy) at any location. Under these conditions and after any extended period of continuous and constant radionuclide release, the concentration of radionuclides associated with surficial sediments presumably would attain a steady-state value that is determined mostly by the concentrations of radionuclides, of their stable elements, and of other competing ions in the ambient-water column. This simple solute-concentration-dependent model has built-in implications relative to the nature of sorption-desorption reactions. If radionuclide sorption in this model were not reversible, the radionuclide concentrations in streambed sediments would decrease owing to decay after steady-state concentrations were reached. Decay might be compensated partly by additional uptake of radionuclides while stable ions or decay products from previously sorbed radionuclides are released.

Before discussing a model that considers sediment transport, it is interesting to evaluate data presented here in terms of the simple solute-concentration-dependent model described above. First, the longitudinal attenuation of radionuclide concentrations in streambed sediments should be a function of the decrease in solute radionuclide concentrations that occurs along the river owing to dilution and dispersion; according to data shown in figure 17, the attenuation approximates a relation that might be

predicted from dilution-dispersion data. The magnitude of the total attenuation and of the attenuation between locations bracketing major sources of dilution (tributary streams), however, is much greater than the decrease that can be calculated from water- and sediment-discharge data in Haushild, Perkins, Stevens, Dempster, and Glenn (1966) and in Roden (1967). Because radionuclide content is not a conservative property, the overall magnitude of the longitudinal attenuation would be greater than predicted from dilution-dispersion considerations alone, but decay during transport between closely spaced locations should be relatively unimportant. The decrease along the river in the percentage of the solute-phase radionuclides that is cationic (Nelson, in Pearce and Green, 1966; Nelson and others, 1966) also could result in greater total attenuation, but this decrease is apparently unrelated to tributary inflow.

Some streambed sediments obviously are not immobile, and sediment transport must be considered in any model that describes the origin of radionuclides in Columbia River streambed sediments. Many observations that are presented in the preceding section of this report can be interpreted as solely transport related, particularly if sorption is considered to occur rapidly (Kennedy and Brown, 1966; Malcolm and Kennedy, 1970) and irreversibly. Under these conditions, the concentration of radionuclides in streambed sediments at any location downstream from the point below the effluent outfalls where sorption attains steady-state values is no longer only a function of radionuclide and competing ion concentrations in the ambient-water column. Rather, after an extended period of exposure, the radionuclide concentration is a function of particle travel-time and of dilution due to incorporation of tributary sediments that have radionuclide concentrations that are commensurate with lower radionuclide levels in the ambient waters below a tributary confluence.

Radionuclide content has been related to particle size and to mineral and chemical characteristics of sediments. However, even if these characteristics were invariant, or varied in such a manner that all sizes initially had the same radionuclide concentration, decay during transport of fine and coarse particles might produce some observed relations. Decay during transport, rather than changes in composition, could result in the observed decrease in radionuclide concentration with increasing particle size, and differential decay during transport also could account for the particle-size dependency of the $^{46}\text{Sc}/^{65}\text{Zn}$ ratio. Decay plus dilution by tributary sediments could produce a downstream attenuation

in radionuclide concentration. From data in Haushild, Perkins, Stevens, Dempster, and Glenn (1966) for the 1963 water year, Snake River sediments alone could effect a maximum dilution of about 60 percent.

Several lines of evidence indicate that the transport model as described above is inadequate even if uptake reactions could be shown to be irreversible. First, the transport rate would have the same functional relation to particle diameter as radionuclide concentrations have to particle diameter. Because clay and silt sizes probably are transported at nearly the same rate, differences in radionuclide concentration between fine-sediment size classes are not solely a function of traveltime. If traveltime were significant in determining radionuclide concentrations, nuclides with varying decay coefficients also would exhibit different relations to particle diameter; observed relations, however, are generally similar. Because of varying decay coefficients, radionuclide ratios and percentage changes between locations also would be functions of particle diameter and distance in a model based on sediment transport alone. Only the $^{46}\text{Sc}/^{65}\text{Zn}$ ratio, which is discussed later, is a function of particle size, and the percentage change with distance bears little apparent relation to radionuclide decay. Finally, because of several intervening dams, it is unlikely that sediment particles in coarse size classes ever travel from Pasco to St. Helens; thus, the radionuclide content of these classes obviously is not related in any simple way to sediment transport.

Much of the discussion of models and radionuclide content has stated or implied connotations relative to radionuclide sorption and (or) desorption. Radionuclide ratios can provide information on changes in radionuclide concentrations that imply sorption, desorption, or radionuclide decay. Unfortunately, how the ratios are interpreted often depends on how the radionuclides are assumed to originate in sediments. The $^{46}\text{Sc}/^{65}\text{Zn}$ ratio presents some interesting contrasts in this respect. The ratio is higher at Pasco than at downstream locations, where it has nearly constant values, and it is greater in fine than in coarse particles. The difference in ratio between Pasco and McNary Dam locations could be due to differential decay during transport or to greater ^{65}Zn uptake relative to ^{46}Sc uptake between locations. Because the $^{46}\text{Sc}/^{65}\text{Zn}$ ratio remains constant below McNary Dam, decay effects must be offset by sorption of additional ^{46}Sc or by desorption of ^{65}Zn .

The particle-size dependency of the $^{46}\text{Sc}/^{65}\text{Zn}$ ratio could be due to differential transport rates of fine

and coarse particles, or it could indicate selective sorption of ^{46}Sc over ^{65}Zn by components in fine sizes (or the reverse in coarse sizes). Another possibility is indicated by data (Nelson, in Pearce and Green, 1966, p. 89–90) that show a large percentage of particulate ^{46}Sc in reactor effluent. If this particulate ^{46}Sc is chiefly in fine particles, which seems likely, then the observed particle-size-dependent $^{46}\text{Sc}/^{65}\text{Zn}$ ratio could be produced.

The general increase in $^{65}\text{Zn}/^{60}\text{Co}$ ratio at successive locations downstream from the Pasco location also indicates continued sorption of ^{65}Zn and (or) desorption of ^{60}Co . Neither relative decay during transport nor dilution could cause this increase; thus, at least partly reversible sorption and (or) desorption reactions apparently occur to some extent throughout the Columbia River.

It is not possible with data presented here, or presently available, to combine the two simplified models and to obtain a general qualitative model that fits all observations. Most data presented in this report favor at least partially reversible sorption reactions dependent mostly on solute radionuclide concentrations and on physical, chemical, and mineral characteristics of sediments. Under these conditions, transport of sediments would be of secondary importance as a control of streambed-sediment radionuclide concentrations. During the annual high-flow period, however, and for a time thereafter until a steady state between solute and streambed-sediment radionuclide concentrations is reestablished, sediment transport may be very important. Sediment movement also would be important in those instances where high sediment concentrations or rapid deposition produce a shielding effect that prevents interchange between radionuclides in solute and sediment phases.

The magnitude of the radionuclide attenuation between locations bracketing tributaries remains a problem regardless of the origin of radionuclides in streambed sediments—no explanation satisfactorily accounts for as much decrease as the data indicate. Resident sediments in the streambed below a tributary confluence and sediments entering from a tributary presumably attain a radionuclide concentration commensurate with that in the mixed waters from the tributary and from the mainstream. Sediments in a mainstream above a tributary confluence presumably have radionuclide concentrations that are commensurate with concentrations in the mainstream only. When the sediments are mixed, the resulting unit-weight radionuclide concentrations will decrease. To the extent that uptake is reversible, the mainstream sediments may tend to lose some radio-

nuclides, and they may attain a concentration that is about equal to that attained by resident or tributary sediments. It is not readily apparent, however, how the overall decrease can exceed the decrease in solute radionuclide concentrations unless there is a shielding effect or the radionuclides are no longer amenable to sorption by sediments.

CONCLUSIONS

On the basis of information in this report, the following conclusions can be drawn:

1. Cation-exchange capacity (CEC). CEC increased irregularly as particle size decreased. Mean values for medium sands from Columbia River locations were $2.8 (\pm 1.7)$ meq per 100 g; mean values for medium to fine clay were $40.8 (\pm 5.1)$ meq per 100 g. For medium sands to clays, the regression of the logarithm of CEC on the logarithm of particle diameter was linear and had a regression coefficient of -0.6 .

Mean CEC values are higher in coarse and very coarse sands than in medium sands; very fine sands have CEC values that are higher or nearly equal to those of medium and coarse silts. Irregularities in the relation of CEC to particle diameter were traced to the influences of occluded fines in coarse separates, to organic matter, and to mineralogy.

No statistically significant difference in CEC values of the various size separates was noted between locations at the upper and lower ends of the study reach. CEC values in Snake and Willamette Rivers size separates generally are slightly higher than CEC values in comparable Columbia River size separates, although the influence of higher CEC in tributary-sediment size separates was not reflected similarly in all Columbia River size separates.

2. Nitrogen and carbon content. Nitrogen content increases as particle size decreases. Mean values in medium to fine clay and in very fine sand are 0.45 percent (about 6 percent organic matter) and 0.04 percent (less than 1 percent organic matter), respectively. No longitudinal trends in nitrogen content are apparent. High carbon contents in coarse separates and high CEC values frequently correlate.
3. Mineralogy. Clay minerals make up 70–80 percent of all components in both the $<2\mu$ and the 2μ – 4μ size separates. The dominant clay minerals are illite, montmorillonite, and mixed-layer clays in roughly equal proportions; chlorite and kaolinite in about 2 to 1 proportions compose 10 percent or less of the average clay-mineral

suite. The percentages of illite and non-clay components (except organic matter) increase and the percentages of montmorillonite, mixed-layer clays, and total clay minerals decrease as particle size increases from $<2\mu$ to $2\mu-4\mu$. The dominant non-clay components are feldspars, which average 10–15 per cent of all components; quartz, which is about 6–12 percent of all components; and organic matter, which averages 4–6 percent of all components.

Mixed-layer clays have average CEC values of about 25 meq per 100 g. These CEC values and the apparent thermal stability of the mixed-layer clays suggest that illite and chlorite layers are abundant in the mixed-layer fraction.

The mineral suite in $<2\mu$ and $2\mu-4\mu$ separates from the Snake River is not appreciably different from that in the Columbia River. The Willamette River suite, however, contains more montmorillonite and less illite than does the Columbia River suite. Highly significant differences in mineral abundance along the Columbia River are not evident, although montmorillonite may increase and quartz may decrease slightly between Pasco and St. Helens.

Amphibole-group minerals and other non-clay minerals occur in increasing amounts as particle size increases from very fine to coarse silt. In the coarse silt separate, clay minerals average less than 15 percent of all components. Within the clay-mineral suite in silt separates, illite and kaolinite plus chlorite increase relative to montmorillonite as particle size increases. Although the two coarsest silt separates were ground prior to X-ray analyses, particle size may have affected estimates of mineral abundance.

Petrographic analyses of sand that was divided into five size separates and gravel that was unsized show that the dominant components are rock fragments, feldspars, and silica-group constituents. Rock fragments average one-third to one-half of all components in the three finest sand separates and are even more abundant in coarser separates. Nearly two-thirds of all rock fragments are volcanic rocks or volcanic glass. Maturity indices are correspondingly low. More than 25 percent of the feldspar grains and about 15 percent of the rock fragments in medium and fine sand are greater than one-third and one-half altered, respectively. Only the Willamette River, which has higher percentages of rock fragments and lower percentages of potash feldspar and silica-

group constituents, appears to have a mineral suite different from the Columbia River suite. No highly significant differences in sand-separate mineralogy occur along the Columbia River.

4. Radionuclide content. Chromium-51, ^{65}Zn , ^{46}Sc , ^{54}Mn , and ^{60}Co , in generally that order of decreasing concentration, are the gamma-emitting radionuclides identified in Columbia River size separates. Zinc-65 concentrations in clay separates average 36 percent of the sum of the ^{65}Zn concentrations in all size separates; fine and medium sands combined contain less than 2 percent. Weighting radionuclide concentrations with results from particle-size analyses shows that the relatively more abundant fine and medium sands contain nearly 45 percent of the total amount of ^{65}Zn ; the relatively less abundant clay separate contains only 16 percent.

Consistent irregularities in the relation of radionuclide concentrations to particle diameter correlate with variations in CEC, nitrogen-carbon content, and (or) mineralogy. Flocculation has been suggested to explain relatively low radionuclide contents in the $2\mu-4\mu$ size.

Regression analyses show that the logarithms of radionuclide concentrations of size separates are related to the logarithms of geometric mean particle diameters of the separates. High correlation coefficients and low standard errors of estimate indicate that the relations closely fit linear regression lines.

Covariance analyses indicate that regression coefficients for relations of the logarithms of radionuclide concentrations to the logarithms of particle diameters differ significantly at the Pasco location for different radionuclides. No significant difference exists in regression coefficients for the relations of the logarithms of ^{65}Zn concentrations to the logarithms of particle diameters at different sample locations. The pooled regression coefficient for the relation of the logarithms of ^{65}Zn concentrations to the logarithms of particle diameters is -0.6 and is about equal to the regression coefficient for the relation of the logarithms of CEC to the logarithms of particle diameter. For silt and clay separates, radionuclide content and CEC are related more directly to the difference in the total amount of clay minerals than to the difference in particle size.

Between successive downstream locations, radionuclide concentrations decrease, but not in proportion to distance or to half life. Greatest

decreases occur between adjacent locations bracketing major tributaries. Zinc-65, ^{54}Mn , ^{60}Co , and ^{46}Sc concentrations at St. Helens, Oreg., are about 1 percent of their concentrations at Pasco, Wash.

Radionuclide ratios show varying relations to particle size and to sample location. The $^{46}\text{Sc}/^{65}\text{Zn}$ ratio is an order of magnitude higher in clay than in fine sand, whereas the $^{65}\text{Zn}/^{54}\text{Mn}$ and $^{65}\text{Zn}/^{60}\text{Co}$ ratios appear to be independent of particle size. The $^{65}\text{Zn}/^{60}\text{Co}$ ratio increases progressively at locations downstream from McNary Dam, but the $^{46}\text{Sc}/^{65}\text{Zn}$ ratio is nearly constant below McNary Dam.

Radionuclide content is directly related to CEC in medium-sand to clay size separates but tends to be independent of CEC in coarse sands. Increases in CEC that are greater than increases in radionuclide content have been attributed to weathering rinds on coarse particles and to organic-matter content.

Two simplified qualitative models have been used to aid interpretation of radionuclide data for streambed sediments. One model assumes a fixed streambed and reversible sorption-desorption reactions that are dependent mostly on concentrations of radionuclides, of their stable elements, and of other competing ions in ambient water. The second model involves sediment transport and considers irreversible rapid sorption reactions that are dependent mostly on solute concentrations in water that is not necessarily ambient. Most data presented in this report favor a model that combines features of the two simplified models and that includes at least partly reversible uptake-release reactions. The degree of reversibility and the rate of uptake determine the relative importance of sediment transport as a factor in interpreting radionuclide concentrations in Columbia River streambed sediments. Results from additional streambed-sediment and radionuclide studies and results from radionuclide-transport determinations can be used to further develop qualitative and quantitative models.

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