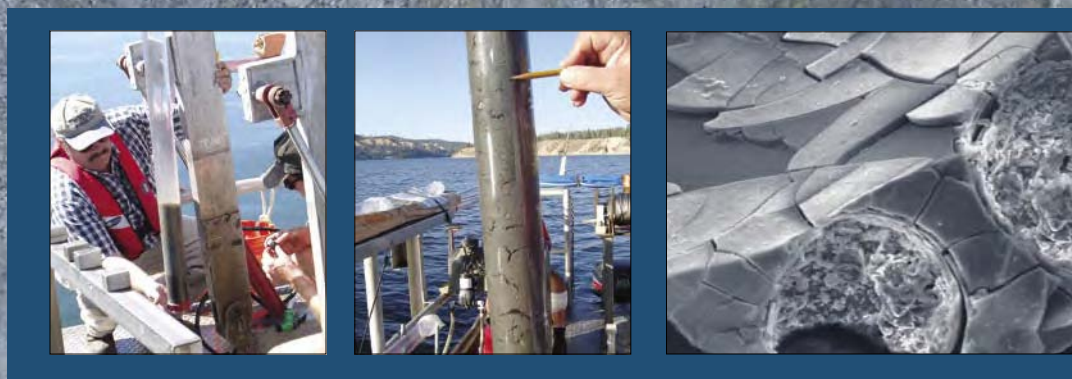


Prepared in cooperation with the Confederated Tribes of the Colville Reservation

Vertical Distribution of Trace-Element Concentrations and Occurrence of Metallurgical Slag Particles in Accumulated Bed Sediments of Lake Roosevelt, Washington, September 2002



Scientific Investigations Report 2004–5090

Cover: Photograph of coring boat preparing to deploy gravity core in Lake Roosevelt at site near Whitestone Mountain, Washington (Photograph taken by Robert Drzymkowski, U.S. Geological Survey, September 10, 2002.)

Inset 1: Retrieval of 40 centimeter sediment core including lacustrine and pre-reservoir soil sediments near Marcus, Washington. (Photograph taken by Robert Drzymkowski, U.S. Geological Survey, September 12, 2002.)

Inset 2: Sediment core collected near Rice, Washington. (Photograph taken by Robert Drzymkowski, U.S. Geological Survey, September 10, 2002.)

Inset 3: Scanning electron microscope (backscatter image) of slag grain. (Photograph taken by J. Stewart Lowther, University of Puget Sound, 2003.)

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By Stephen E. Cox, Peter R. Bell, J. Stewart Lowther, and Peter C. VanMetre

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Contents

Abstract	1
Introduction	1
Purpose and Scope	2
Description of Study Area	2
Previous Studies of Trace Elements in Lake Roosevelt Bed Sediments	5
Acknowledgments	7
Data Collection and Analysis	7
Sample Collection and Processing	8
Isolation and Identification of Slag Particles	9
Accumulated Sediments in Lake Roosevelt.....	10
Description of Cores and Accumulated Sediments	10
Cesium-137 Concentrations and Rates of Sediment Accumulation.....	10
Assignment of Time Stratigraphic Horizons.....	10
Sedimentation Rates	13
Concentrations of Trace Elements in Accumulated Sediments	14
Trace-Element Profiles	15
Patterns of Trace-Element Profiles Within Individual Cores	24
Trace Elements in Pore Water and Sediment	31
Metallurgical Slag in Sediments of Lake Roosevelt.....	34
Relative Impacts of Slag and Liquid Effluent Discharge on Trace-Element Concentrations in Bed Sediment	46
Summary and Conclusions	47
References Cited.....	48

Figures

Figure 1. Map showing location of study area and sediment-core collection sites on Lake Roosevelt and the upper Columbia River, Washington.....	3
Figure 2. Boxplots showing concentrations of selected trace elements in suspended sediment from the Columbia River at Northport, Washington, and in Lake Roosevelt shoreline bank materials	4
Figure 3. Profiles showing vertical distribution of cesium-137 concentrations in sediment cores from Lake Roosevelt, Washington, September 2002	12
Figure 4. Profiles showing vertical distribution of trace-element concentrations in selected sediment cores from Lake Roosevelt, Washington, September 2002	16
Figure 5. Graph showing ratios of cadmium to mercury and zinc to lead in samples from sediment cores from Lake Roosevelt, Washington, September 2002	23
Figure 6. Profiles showing vertical distribution of trace-element concentrations in six sediment cores from Lake Roosevelt, Washington, September 2002	24
Figure 7. Graph showing history of slag and trace elements in liquid effluent discharged to Columbia River by Trail smelter, British Columbia, 1940-2000	30

Figure 8.	Profiles showing vertical distribution of concentrations of dissolved arsenic, cadmium, copper, lead, and zinc in pore waters from sediment core sampling sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington.....	32
Figure 9.	Graphs showing concentrations of arsenic, cadmium, copper, lead, and zinc in whole sediment and leached residual (following extraction with hydroxylamine hydrochloride) from sediment core sampling sites CCR-668 and CCR-705, Lake Roosevelt, Washington, July 2003	33
Figure 10.	Photograph showing black sand beach composed of 70 to 90 percent slag particles deposited near Columbia River gaging station at river mile 743, Washington	35
Figure 11.	Photographs showing slag particles (RS-743) identified in sediment from Lake Roosevelt and the upper Columbia River, Washington	36
Figure 12.	Photographs showing scanning electron microscope (backscatter images) of unweathered slag particles from Lake Roosevelt, Washington	38
Figure 13.	Boxplots showing trace-element concentrations determined by SEM/EDS of slag particle (sample RSS-743) and reported concentrations from previous studies determined by acid digestion and instrumental analysis, Lake Roosevelt, Washington	40
Figure 14.	Boxplot showing trace-element concentrations determined by SEM/EDS of recently deposited slag particles and slag grains from core sediments, Lake Roosevelt, Washington	41
Figure 15.	Photographs showing scanning electron microscopic (backscatter images) of weathered slag particles from Lake Roosevelt, Washington	42
Figure 16.	Boxplot showing trace-element concentrations determined by SEM/EDS of outer surface of slag particles and inner surface exposed by removal of exfoliation flake, Lake Roosevelt, Washington	45

Tables

Table 1.	Comparison of mean (N=3) element concentrations in riverbed sediments from upstream and downstream of the smelter at Trail, British Columbia, 1995 and 1999.....	7
Table 2.	Location and depth of six sediment cores and samples of riverine sediment with slag from Lake Roosevelt, Washington, September 10–13, 2002	8
Table 3.	Time horizons and sediment accumulation rates for six cores from Lake Roosevelt, Washington	13
Table 4.	Summary of concentrations of arsenic, cadmium, copper, lead, mercury, and zinc in all analyzed core subsections from Lake Roosevelt, Washington	14
Table 5.	Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002	51
Table 6.	Analytical results for standard reference material and environmental duplicate samples for quality assurance	63
Table 7.	Vertical distribution of concentrations of selected trace elements and major ions in pore water, bulk sediment, and residual sediment from shallow cores from sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington, July 2003	66

Conversion Factors, Datums, Abbreviations, and Acronyms

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter (m ³)	264.2	gallon
gram (g)	0.03527	ounce, avoirdupois
gram per cubic centimeter (g/cm ³)	64,4220	pound per cubic foot
hectare (ha)	2.471	foot
kilogram (kg)	2.205	pound, avoirdupois
meter (m)	3.281	foot
metric ton per day	1.102	ton per day
mile (mi)	1.609	kilometer
millimeter (mm)	0.03937	inch
tonnes (1,000 kg)	1.102	ton (2,000 lbs)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32.$$

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Abbreviations

Abbreviations	Meaning
M	Molar
mg/kg	milligram per kilogram
mL	milliliter
pCi/g	picoCuries per gram

Acronyms

Acronyms	Meaning
CCT	Confederated Tribes of the Colville Reservation
USGS	U.S. Geological Survey

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Vertical Distribution of Trace-Element Concentrations and Occurrence of Metallurgical Slag Particles in Accumulated Bed Sediments of Lake Roosevelt, Washington, September 2002

By Stephen E. Cox, Peter B. Bell, J. Stewart Lowther, and Peter C. VanMetre

Abstract

Sediment cores were collected from six locations in Lake Roosevelt to determine the vertical distributions of trace-element concentrations in the accumulated sediments of Lake Roosevelt. Elevated concentrations of arsenic, cadmium, copper, lead, mercury, and zinc occurred throughout much of the accumulated sediments. Concentrations varied greatly within the sediment core profiles, often covering a range of 5 to 10 fold. Trace-element concentrations typically were largest below the surficial sediments in the lower one-half of each profile, with generally decreasing concentrations from the 1964 horizon to the surface of the core. The trace-element profiles reflect changes in historical discharges of trace elements to the Columbia River by an upstream smelter.

All samples analyzed exceeded clean-up guidelines adopted by the Confederated Tribes of the Colville Reservation for cadmium, lead, and zinc and more than 70 percent of the samples exceeded cleanup guidelines for mercury, arsenic, and copper. Although 100 percent of the samples exceeded sediment guidelines for cadmium, lead, and zinc, surficial concentrations of arsenic, copper, and mercury in some cores were less than the sediment-quality guidelines. With the exception of copper, the trace-element profiles of the five cores collected along the pre-reservoir Columbia River channel typically showed trends of decreasing concentrations in sediments deposited after the 1964 time horizon. The decreasing concentrations of trace elements in the upper half of cores from along the pre-reservoir Columbia River showed a pattern of decreasing concentrations similar to reductions in trace-element loading in liquid effluent from an upstream smelter. Except for arsenic, trace-element concentrations typically were smaller at downstream reservoir locations along the pre-reservoir Columbia River. Trace-element concentration in sediments from the Spokane Arm of the reservoir showed distinct differences compared to the similarities observed in cores from along the pre-reservoir Columbia River.

Particles of slag, which have physical and chemical characteristics of slag discharged to the Columbia River by a lead-zinc smelter upstream of the reservoir at Trail, British Columbia, were found in sediments of Lake Roosevelt. Slag particles are more common in the upstream reaches of the reservoir. The chemical composition of the interior matrix of slag collected from Lake Roosevelt closely approximated the reported elemental concentrations of fresh smelter slag, although evidence of slag weathering was observed. Exfoliation flakes were observed on the surface of weathered slag particles isolated from the core sediments. The concentrations of zinc on the exposed surface of slag grains were smaller than concentrations on interior surfaces. Weathering rinds also were observed in the cross section of weathered slag grains, indicating that the glassy slag material was undergoing hydration and chemical weathering.

Trace elements observed in accumulated sediments in the middle and lower reaches of the reservoir are more likely due to the input from liquid effluent discharges compared to slag discharges from the upstream smelter.

Introduction

Trace-element contamination is known to be widespread throughout surficial bed sediments of Franklin D. Roosevelt Lake, the reservoir created by the impoundment of the Columbia River behind Grand Coulee Dam. Franklin D. Roosevelt Lake, better known as Lake Roosevelt, was completed in 1941 and has developed into a major economic and recreational resource for the region attracting from 1 to 1.5 million visitors each year. Lake Roosevelt also is a vital cultural resource for The Confederated Tribes of the Colville Reservation (CCT) and The Spokane Tribe of Indians whose combined tribal lands extend along more than one-half of the reservoir's length. The reservoir is used extensively by many tribal members who live near the reservoir.

2 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Trace-element contamination of reservoir sediments was first reported in the mid-1980s (Lowe and others, 1985; Johnson and others, 1988, 1990). Trace elements of concern include arsenic, cadmium, copper, lead, mercury, and zinc. Subsequent studies have shown that trace-element contamination of surficial sediments in the lake and adjacent beach deposits is widespread and follows a general pattern in which concentrations of trace elements typically are larger in the upstream reaches of the reservoir compared to concentrations in downstream reaches (Johnson and others, 1990; Bortleson and others, 1994; Majewski and others, 2003; U.S. Environmental Protection Agency, 2003). Trace-element concentrations in bed sediments range from 4 to 220 times larger than concentrations in background reference sediments. In addition, contamination of sport fish with mercury and other trace elements has resulted in the issuance of a health advisory on the human consumption of several species of popular sport fish (Munn and others, 1995), although the level of sport fish contamination has decreased for some constituents (Munn, 2000).

The primary source of elevated trace-element concentrations in bed sediments of Lake Roosevelt is attributed to the transport of metallurgical wastes discharged to the Columbia River by a smelter at Trail, British Columbia, located 21 km upstream of the International Boundary (Bortleson and others, 1994). The smelter has been in operation since the 1890s and historically has discharged wastes to the Columbia River, much of which are transported and deposited in the quiescent waters of Lake Roosevelt. Although waste discharges have occurred nearly continuously throughout most of Lake Roosevelt's 60 plus years of existence, efforts have been underway at the smelter over the last several decades to reduce trace-element loading to the Columbia River. The reduction in effluent discharges may be reflected in the variations in the concentrations of trace elements present in the accumulated sedimentary record of Lake Roosevelt. Previous information on variations in the vertical distribution of trace elements in the accumulated sediments of Lake Roosevelt is limited. Additional information on variations in concentrations of trace elements in the accumulated sediments could provide a useful record of trace elements entering Lake Roosevelt.

Purpose and Scope

The purpose of this report is to present the results of a study (1) to evaluate the trace-element concentrations within the accumulated bed sediments of Lake Roosevelt; (2) to determine if the potential exists for remobilization of trace elements within the buried sediments; and (3) to evaluate sediment from selected core intervals for the occurrence of metallurgical slag. The study was conducted by the U.S. Geological Survey (USGS) in cooperation with the Confederated Tribes of the Colville Reservation. Sediment cores were collected for the determination of trace-element profiles at six widely spaced locations in Lake Roosevelt in

September 2002; with additional sediments collected in July 2003 for analysis of trace elements in pore water. Sediment cores were sectioned and concentrations of trace elements were analyzed for the individual sections, generating a profile of trace-element concentrations. Selected sediment intervals also were examined for either the occurrence of metallurgical slag particles or the concentration of trace elements in pore water.

Description of Study Area

Lake Roosevelt is in north-central Washington and is the largest reservoir in the State of Washington ([fig. 1](#)). The lake was formed by the impoundment of the Columbia River behind Grand Coulee Dam and, when filled to capacity, the reservoir extends upstream more than 237 km such that back-water conditions extend to near the International Boundary (Ray Smith, U.S. Geological Survey, oral commun., 2004). The entire reservoir covers about 32,700 ha and has a storage volume of about 12.8 billion m³. The maximum water depth in the reservoir is more than 115 m (377 ft), and averages about 35 m (115 ft). Flow from the Columbia River makes up the majority (90 percent) of the inflow to Lake Roosevelt; with another 7 percent of inflow from the Spokane River. Flow in these rivers is highly regulated and depleted of suspended sediment by the numerous dams and reservoirs that have been constructed on upstream reaches. Other sources of river inflow to Lake Roosevelt include the Colville, Kettle, and Sanpoil Rivers and the numerous creeks that drain the uplands surrounding the reservoir.

Bed sediments of Lake Roosevelt vary from armored boulders to silts and clay. To provide a framework for interpreting the sediment chemistry data, Bortleson and others (1994) divided the reservoir along the length of the pre-reservoir river channel into several reaches based predominantly on the physical characteristic and depositional environment. The **lower reach** extends from Grand Coulee Dam to the confluence of the Spokane River and is characterized by a deep wide channel with slowing flowing water covering extensive pre-reservoir shorelands and containing lacustrine sediments, which are influenced by inputs from the Spokane River. The **mid-reach** of the reservoir extends from the confluence of the Spokane River to Marcus Island and is characterized by deep-slowing moving water in a wide irregular channel containing lacustrine sediments. The **upper reach** of the reservoir extends from Marcus Island to about RM 730, which is characterized by a narrowing and shallowing channel with fewer embayments and flooded areas generally lacking lacustrine sediments from the swifter flowing reservoir conditions in the pre-reservoir channel. The transitional reach (Northport Reach) that extends from RM 730 to near the International Boundary where flow conditions transition from impounded slack water of the upper reach of the reservoir to the swift river environment of the free flowing Columbia River contain primarily a cobbly-boulder streambed with sand-size sediments deposited only in protected areas.

4 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Sediments deposited in Lake Roosevelt are derived from the upper basin of the Columbia River, tributary streams and rivers, and from landslides and erosion of unconsolidated sediments along the margin of the reservoir. Granulated slag discharged to the Columbia River from the smelter upstream of Lake Roosevelt is a component of sediment that is transported and deposited in Lake Roosevelt. Numerous landslides have occurred along the shores of Lake Roosevelt, primarily in the unconsolidated Pleistocene terrace sediments that occur along 80 to 90 percent of reservoir shoreline (Jones and others, 1961; Kiver and Stradling, 1995; and U.S. Bureau of Reclamation, 2001). Large landslides on the order of 765,000 m³ of material occurred more frequently in the past, particularly in the early years following completion of the reservoir. Between 1941 and 1954, there were more than 500 landslides along the reservoir shoreline that related to the

initial filling of the reservoir and the fluctuating water level in the reservoir (Jones and others, 1961). Landslides continue to occur up to the present (U.S. Bureau of Reclamation, 2001), although they typically are smaller in magnitude and the severity has greatly diminished. Concentrations of trace elements in bank sediments prone to landslides are on the order of western continental averages reported by Shacklette and Boerngen (1984).

Trace-element concentrations in bank material typically were much smaller than concentrations measured in suspended sediment flowing into Lake Roosevelt (Bortleson and others, 1994; Kelly and others, 2001). A comparison of trace-element concentrations in bank sediments adjacent to Lake Roosevelt to trace-element concentrations reported in Columbia River suspended sediment is shown in [figure 2](#).

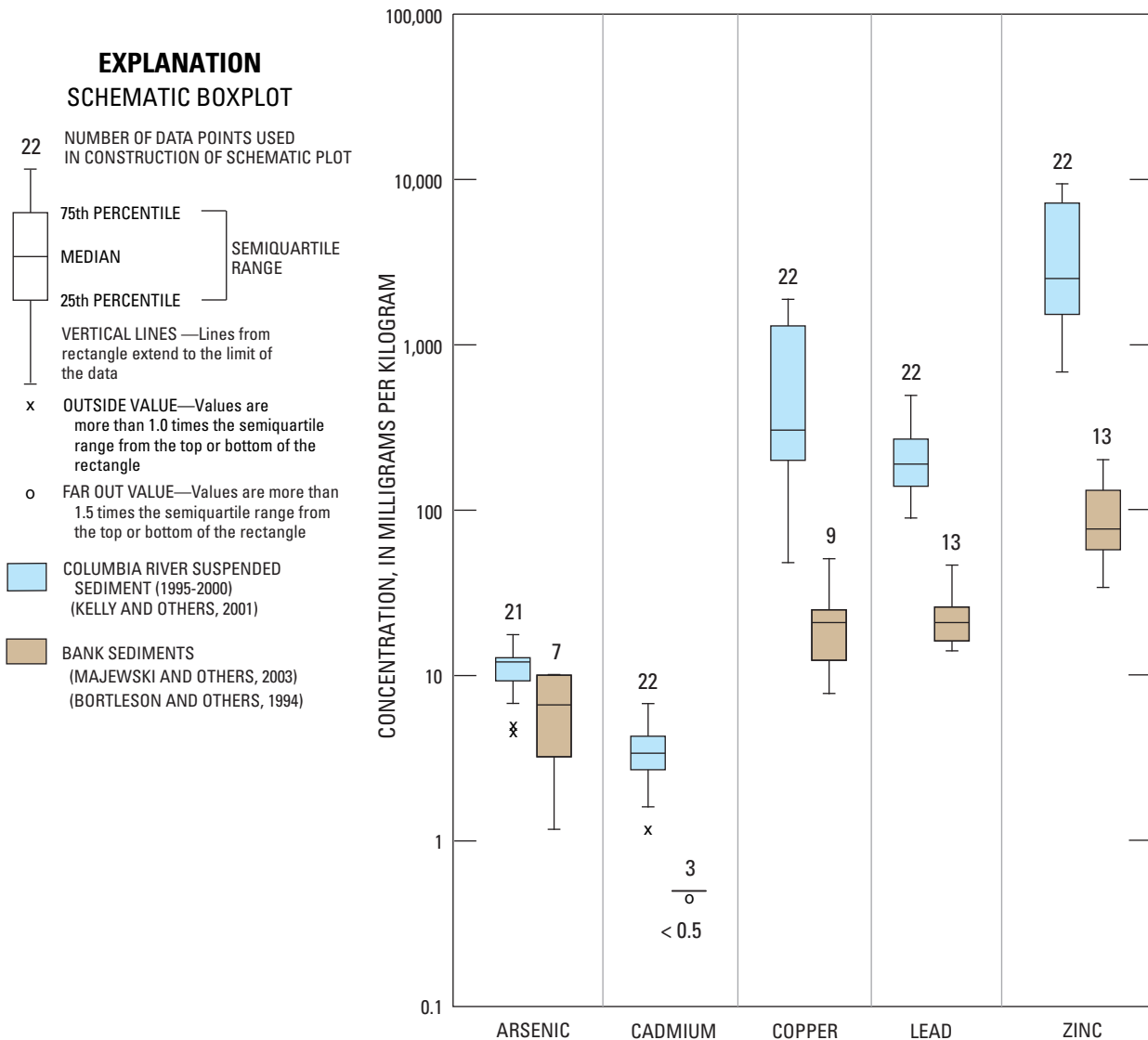


Figure 2. Concentrations of selected trace elements in suspended sediment from the Columbia River at Northport, Washington, and in Lake Roosevelt shoreline bank materials.

The reported concentrations of trace elements in suspended sediment were determined from 22 discharge-weighted samples collected between 1995 and 2000 at Northport (Kelly and others, 2001). For the trace elements of concern, the greatest difference was in the concentration for zinc, which was roughly 30 times larger in suspended sediment than in bank sediments. Concentrations of cadmium, copper, and lead were about 10 times larger in suspended-sediment samples than concentrations in samples of bank sediments. The concentrations of arsenic were the most similar; the concentration in suspended sediment was only about two times as large as arsenic concentrations in samples of bank sediments. Mercury concentrations in suspended sediment were not reported by Kelly and others (2001), however, Bortleson and others (1994) reported a median concentration of mercury in five discharge-weighted suspended-sediment samples of 1.7 mg/kg, which is roughly 30 times larger than the concentrations in typical bank deposits (<0.05 mg/kg). From these data, the episodic addition of bank sediments to relatively consistent input of suspended sediment transported to Lake Roosevelt by the Columbia River will dilute the concentration of trace elements in the resulting bed sediments. Thus landslides, particularly in the upper part of the reservoir, tend to dilute concentrations of arsenic, copper, cadmium, lead, mercury, and zinc in sediments carried to the reservoir by the Columbia River.

Most of Lake Roosevelt is situated within the Okanogan Highland of north-central Washington, an area that extends about 250 km north into British Columbia, in which extensive geologic processes have resulted in a mountainous and highly mineralized region containing many precious and base metal deposits (Washington State Department of Natural Resources, 2003). Geologically, this region is composed of some of the oldest and most mineralized geologic units in Washington. In the area east of Lake Roosevelt, the repeated folded metasedimentary rocks of the Kootenay Arc contain hydrothermal ore deposits, particularly lead and zinc, many of which have been developed. Lead and zinc ores typically occur as the minerals galena and sphalerite that were deposited in veins, open space fillings, or as replacement bodies in limestone and dolomite deposits. Mills (1977) describes 98 separate deposits in Stevens County alone, many of which also were reported to contain minor amounts of silver. Numerous similar sites also occur in the Kootenay Arc region of British Columbia although the Sullivan Mine that produced much of the ore for the Trail smelter was characterized as a sedimentary-exhalative deposit (Lydon, 2000). Other trace elements often associated with lead deposits composed of galena include antimony, copper, arsenic, and bismuth; elements associated with zinc deposits composed primarily of sphalerite include copper, tin, arsenic, silver, mercury, iron, manganese, and cadmium (Levinson, 1974). Precious metal deposits to the west of Lake Roosevelt also have been developed particularly in the area around Republic. In addition to gold and silver, there are deposits containing copper, cobalt, bismuth, and molybdenum.

Metallurgical and mining wastes have been discharged to streams of the upper Columbia River (Orlob and Saxton, 1950). The Trail smelter was originally built as a copper smelter in 1896 and was converted to smelt lead and zinc in 1909 (G3 Consulting, Ltd., 2001). Lead and zinc production have been nearly continuous since that time and the facility has developed into one of the worlds largest integrated metallurgical complexes. Annual production in 2000 was 273,000 metric tonnes of refined zinc and 91,000 tonnes of refined lead, with smaller quantities of silver, gold, cadmium, bismuth, and many other associated metal products (Teck-Cominco, 2002). Historically, waste materials from this facility, including slag and process waste water, were discharged directly to the Columbia River. Between the late 1970s and late 1990, the metallurgical complex was extensively modernized to improve production efficiency and reduce the discharge of slag and effluent to the Columbia River. Effluent treatment was installed in 1981 and was upgraded through the 1990s. The operation of the phosphate fertilizer plant was discontinued in 1994. The routine discharge of slag to the Columbia River was discontinued in 1995 after which time reported slag discharge has been limited to periods when disruption in the smelting process have resulted in upset conditions at the smelter when the release of waste material has occurred.

Previous Studies of Trace Elements in Lake Roosevelt Bed Sediments

Initial assessment of the extent of trace-element contamination in Lake Roosevelt bed sediment (Johnson and others, 1988, 1990) showed that elevated concentrations of trace elements were widespread throughout Lake Roosevelt and that the concentrations of trace elements decreased along the longitudinal axis from upstream to downstream. They attributed the source of the elevated trace elements to the discharge of smelter wastes to the Columbia River at Trail. This source had been previously identified by British Columbia Ministry of Environment (1976, 1979) and Environment Canada (Sheehan and Lamb, 1987; Sigma Engineering Ltd., 1987; and Smith, 1987; NORECOL Environmental Consultants Ltd., 1989,) as a source of metals contamination of water, sediment, and biota in the reach of the Columbia River immediately upstream of the International Border.

A comprehensive follow-up study was conducted in 1992 by the U.S. Geological Survey (Bortleson and others, 1994) that determined trace-element concentrations in sediment from Lake Roosevelt and its tributaries, including the upstream reach of the Columbia River extending to reservoirs in Canada. The results of that study confirmed and greatly extended previous findings and conclusions. The overarching conclusion was that although other possible sources of trace elements were present within the region and may have a localized influence on trace-element concentrations in the sediments of Lake Roosevelt, the primary source of the

widespread elevated trace-element concentrations in the bed sediments of Lake Roosevelt was the waste discharged to the Columbia River from the Trail smelter. This conclusion, based on the distribution of elevated trace-element concentrations in bed sediments and the hydrology of the reservoir-river system, was the only adequate explanation of the persistent and widespread distribution of trace elements in the bed sediments throughout Lake Roosevelt and the upstream reach of the Columbia River and the differences in the patterns of specific trace-element concentrations.

All trace elements of concern, including arsenic, cadmium, copper, lead, mercury, and zinc, are known to be components of the liquid effluent or slag discharged to the Columbia River by the Trail smelter (British Columbia Ministry of Environment, 1976; 1979). The concentrations of these trace elements in bed sediments were all highly elevated at locations downstream of the area of smelter waste discharge, however, the distributional pattern of elevated trace elements in the sediments of Lake Roosevelt varied among trace elements reflecting depositional grain-size and mode of trace-element input. The most notable pattern was simultaneous presence of slag particles and very large concentrations of copper and zinc in bed sediments of the upper and transitional reaches of Lake Roosevelt and the upstream reach of the Columbia River. Slag, which was reported to contain 0.5 to 1 percent copper and 2 to 3 percent zinc, could be easily identified in sand-size fractions by its unique morphology and physical characteristics. In sediment samples from the International Boundary, in which slag was estimated to compose 48 percent of sediment grains, the concentrations of copper and zinc were 3,000 and 15,000 mg/kg, respectively, while slag in bed sediments 24 km farther downstream was estimated to comprise 5 percent of the sand-sized fraction and the concentrations of copper and zinc were 670 and 4,100 mg/kg, respectively. In the transitional reach of the reservoir near Northport, bed sediments contained substantial percentages of sand-sized particles and the very large concentrations of copper and zinc were attributed to the presence of slag particles in these sediments. Other trace elements noted to follow distributional patterns similar to slag were antimony, arsenic, barium, chromium, iron, and manganese.

Bortleson and others (1994) also reported that concentrations of cadmium, lead, and mercury were larger in bed sediments farther downstream in the mid and lower reaches of the reservoir where depositional areas are predominated by silt-size particles. Cadmium, lead, and particularly mercury are present in slag in very small concentrations compared to copper and zinc but are prevalent in the liquid effluent discharged by the Trail smelter. The presence of these trace elements in bed sediments of Lake Roosevelt was attributed to the sorption of trace elements from the water column onto suspended-sediment particles, which are subsequently deposited in the downstream quiescent

waters of the mid and lower reaches of Lake Roosevelt. Because sorption is related to the surface area of particles, a proportionally greater mass of trace elements is sorbed to smaller sized sediment particles. Thus, concentrations of these trace elements were larger in the downstream reaches of Lake Roosevelt that were dominated by fine colloidal silt and clay sized lacustrine sediments.

Additional information on previous studies of the water quality of Lake Roosevelt and trace-element contamination of bed sediments in Lake Roosevelt have been reviewed and summarized in Derewetzky and others (1994) and U.S. Environmental Protection Agency (2000; 2003).

The effects of the Trail-smelter discharge on water, sediment, and biota in the Columbia River receiving water was evaluated in a study conducted by the smelter between 1995 and 1999 (G3 Consulting, Ltd., 2001). The intent of that study was to document the effects from modernization of the smelter process and improved waste-management practices implemented in the mid-1990s on trace-element loading to the Columbia River from the Trail smelter effluent discharge. This study examined trace-element concentrations in water, sediment, and biota at locations upstream and downstream of the effluent discharge zone of the Trail-smelter complex in the spring and autumn of 1995 and 1999 (G3 Consulting, Ltd., 2001). Results from this study clearly demonstrated the large influence that slag and liquid effluent discharges have had on the trace-element concentrations in water and sediment of the Columbia River, and thus Lake Roosevelt.

Very large increases in trace-element concentration in sediment immediately downstream of the effluent and slag discharge from the smelter were observed during the 1995 sampling prior to completion of the last phases of an extensive modernization of the lead smelting facility. As shown in [table 1](#), the measured concentrations of nearly all 29 trace elements measured were often many fold higher in bed-sediment samples collected downstream of the smelter complex than the concentrations measured in samples of similar material collected from a background reference site 8 km upstream of the smelter complex. Although the measured concentrations of trace elements in sediment collected at the upstream reference site did not change substantially between 1995 and 1999, except for iron, the trace-element concentrations in sediments at sites downstream of the metallurgical complex were much smaller in 1999 than in 1995. These decreases in concentrations were attributed to implementation of the new lead smelter and discontinuing the practice of discharging slag to the Columbia River (G3 Consulting, Ltd., 2001). Considering that historical discharges of slag and liquid effluent were substantially larger than occurred in 1995, these results demonstrate a minimum level of influence that Trail smelter discharge had on sediment chemistry in the Columbia River down stream of smelter and subsequently Lake Roosevelt throughout most of its existence.

Table 1. Comparison of mean (N=3) element concentrations in riverbed sediments from upstream and downstream of the smelter at Trail, British Columbia, 1995 and 1999.

[Modified from Appendix 3.1.4, G3 Consulting Ltd., 2001. mg/kg, milligram per kilogram]

Element	Upstream reference site		Downstream monitoring site	
	1995	1999	1995	1999
Major element (mg/kg)				
Aluminum	2,820	3,290	15,700	8,600
Calcium	1,690	1,840	49,800	21,800
Iron	5,160	14,900	181,000	80,000
Magnesium	2,020	1,850	5,700	3,580
Manganese	129	146	4,840	1,870
Titanium	281	298	1,230	641
Trace elements (mg/kg)				
Antimony	0.15	0.187	56	87.2
Arsenic	1.14	1	41.8	23.5
Barium	29.4	24.6	3,260	920
Beryllium	<.2	.14	1.4	4
Bismuth	.05	.055	.838	.218
Boron	6.47	5	147	24
Cadmium	.17	.147	4.1	1.19
Chromium	8.73	16.6	265	58.6
Cobalt	2.43	2.51	192	35.6
Copper	10.1	13.2	3,740	1,100
Germanium	<.1	.09	34.5	9.6
Gallium	1.55	2.22	35.3	10.2
Indium	<.05	.02	23.9	9.23
Lead	8.48	8.29	312	237
Lithium	7.72	5.21	21.3	7.67
Mercury	<.05	<.02	.05	.02
Molybdenum	.21	.15	68.8	16.1
Nickel	7.05	7.3	26.4	12.9
Selenium	<1	<.05	1.3	1
Silver	.12	.076	12.7	5.48
Strontium	22.5	22.8	732	195
Tellurium	<.2	<.01	.261	.06
Thalium	<.05	.04	.353	.215
Thorium	4.04	8.81	4.38	4.22
Tin	.24	.248	44	68.7
Tungsten	.59	.24	20	4.16
Uranium	.49	.68	7.16	2.34
Vanadium	13.3	28.7	54.5	28
Zinc	58.1	40.3	21,400	5,660

Acknowledgments

This study was conducted with the assistance of many individuals and organizations. We thank Patti Bailey and the Confederated Tribes of the Colville Indian Reservation for their assistance in planning and conducting this study; Greg Behrans of the U.S. Bureau of Reclamation at Grand Coulee Dam for map coverages and information on landslides; Brian Hicks of the Colville Tribe and Louis Wynn of the Spokane Tribe for archaeological support of field activities; Rick Sanzalone of the U.S. Geological Survey, Geologic Materials Laboratory for conducting the partial extraction of trace-element experiment and oversight of laboratory analysis. Technical review of previous drafts of this report were provided by Don Hurst of the Confederated Tribes of the Colville Indian Reservation and Lauri Balistrieri, Gilbert Bortleson (retired), Anthony Paulson, and Gary Turney of the U.S. Geological Survey.

Data Collection and Analysis

Sediment cores were collected from near the pre-reservoir river channel where the accumulation of reservoir sediment was thought to be thickest and least likely to be disturbed by the seasonal fluctuation in water level in the reservoir. Other considerations for site selection included avoiding the presence of large landslides along the margins of the reservoir and consultations with tribal archaeologists to avoid possible disturbances of submerged ancestral tribal areas. Lacustrine sediments were not found in pre-reservoir channel at the most upstream site, consequently, the core for this area was collected away from the pre-reservoir channel toward the left bank of the reservoir on what is likely a submerged terrace.

Five sediment cores were collected from the lower and mid reaches of the reservoir and one sediment core was collected from the Spokane Arm of the reservoir. The locations of these sediment cores were determined using a Global Positioning System (GPS) to determine latitude and longitude ([table 2](#)) and are shown in [figure 1](#). Core designations were assigned using the nearest river mile (RM). Cores collected along the pre-reservoir Columbia River channel include CCR-624 in the lower reach of the reservoir, and CCR-643, CCR-668, CCR-692, and CCR-705 in the mid-reach of the reservoir. Core CSA-8 was collected from the Spokane Arm of the reservoir. Sites of continuously accumulating sediments

8 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

could not be identified in the upper and Northport reaches of the reservoir. The three most upstream cores were in areas where previously reported concentrations of trace elements typically were high. These sediment cores were selected to determine if the concentrations of trace elements varied within the accumulated sediments of Lake Roosevelt. The other three sediment cores were collected farther downstream in the reservoir to determine if sediment concentrations might indicate the combined influence of inflow from both the Columbia and Spokane Rivers. These cores were collected from: (1) in the Spokane Arm of the reservoir outside of the general influence of inflow from the Columbia River (CSA-8), (2) in the mainstem of the reservoir upstream of the confluence with the Spokane Arm (CCR-643), and (3) downstream of the confluence of the Spokane Arm and the mainstem Columbia River (CCR-624).

Sediment samples with readily identifiable slag particles were collected at three sites, designated RSS-685, RSS-724, and RSS-743 (table 2 and fig. 1). Slag particles from these samples were used to characterize slag particles in Lake Roosevelt. Sediments in samples from the RSS-724 and RSS-743 sites were collected from beach deposits immediately adjacent to the reservoir and the Columbia River. Sediments in samples from the RSS-685 site were collected from beneath the reservoir sediments at a site where attempts to collect a sediment core to determine trace-element profiles was

unsuccessful as less than 20 cm of lacustrine sediments were recovered. The slag containing sand underlying the lacustrine silts were interpreted to be a fluvial deposit of the pre-reservoir Columbia River.

Sediment cores used to develop trace-element profiles were collected using a Benthos gravity core with a diameter of 6.5 cm. The gravity core was suspended from a pontoon boat capable of collecting cores from depths as much as 120 m. The gravity cores were collected in September 2002. Because pore water could not be obtained from the gravity cores as originally planned, resampling of the three upstream sites was conducted in July 2003 using a box core with a 14×14-cm cross section. GPS coordinates were used to locate the original sampling sites.

Sample Collection and Processing

At each site where gravity cores were collected, several attempts were made to obtain undisturbed cores greater than 50 cm in length and that also encountered the pre-reservoir sediments. The least disturbed core with the greatest thickness of lacustrine sediments was selected for subsampling and analysis (fig. 1 and table 2). After collection, cores were subsampled by pushing the top of the core up through the plastic core liner and slicing the core into sections that were 2 to 5 cm thick. Sediment samples were packed on

Table 2. Location and depth of six sediment cores and samples of riverine sediment with slag from Lake Roosevelt, Washington, September 10–13, 2002.

[Core and riverine sediment sample designation indicates nearest Columbia River mile as shown on 7.5-minute USGS quadrangle maps. Locations of sediment cores and riverine sediment samples are shown in figure 1. Latitude and longitude are given in degrees, minutes, and seconds. Abbreviations: cm, centimeter; m, meter; ft, foot]

Core and riverine sediment sample designation	Length of core (cm)	Latitude (° ' ")	Longitude (° ' ")	Depth of water (m)	Elevation of upper surface of core (ft)	Length of subsection interval (cm)	Number of subsection intervals
Core along Impounded Columbia River							
CCR-624	46	47 53 42	118 32 27	87.5	998	3	16
CCR-643	57	47 57 18	118 21 07	74.7	1,040	3	19
CCR-668	164	48 11 40	118 11 31	66.8	1,067	5	33
CCR-692	38	48 30 26	118 10 51	45.7	1,136	2	19
CCR-705	49	48 38 14	118 05 09	19.5	1,222	2	19
Core along Impounded Spokane River							
CSA-8	90	45 56 02	118 12 03	34.4	1,172	3	28
Riverine Sediment with Slag							
RSS-685	–	48 24 39	118 12 14	165	–	–	–
RSS-724	–	48 49 12	118 56 08	0	–	–	–
RSS-743	–	48 58 15	117 38 50	0	–	–	–

ice and shipped to the laboratory to be freeze-dried prior to submission for chemical analysis. Elemental concentrations were determined on concentrated-acid digests using a mixture of hydrochloric-nitric-perchloric-hydrofluoric acids and analyzed by inductively-coupled plasma/mass spectrometry (ICP/MS) or, in the case of mercury, cold-vapor atomic-absorption spectrometry. Total organic carbon in the cores was determined as the difference between total carbon and carbonate carbon. These laboratory analyses were conducted at the USGS laboratory in Denver, Colorado, using the procedures described by Arbogast (1996).

Quality-assurance and control procedures were incorporated into the study to assure that the resulting data were of a known and acceptable quality. Potential for contamination was minimized by using clean field procedures including dedicated core liners for each core. Equipment used for subsampling the cores into individual sections was thoroughly cleaned between each section using a non-phosphate soap and water. After washing, the equipment was thoroughly rinsed first with tap water followed by additional rinsing with deionized water. A variety of quality-control samples, generated in the laboratory and the field, were used including blanks, and replicate and standard reference materials. For each core submitted to the laboratory as a series of individual sections, an environmental replicate and the standard reference sample also were submitted as blind-quality assurance samples. The standard reference materials used as blind QA samples submitted from the field included the National Institute of Standards and Technology's Buffalo River Sediment number 2704 and National Research Council of Canada's PACS-2. The alert criteria for the analysis of the standard reference material was 80 to 120 percent of the certified concentration.

Pore-water and sediment samples were collected from the three upstream sites (CCR-668, CCR-692, and CCR-705) using a 14-cm box core. The box core was subsampled at three horizons; the surface to 1 cm depth, and the intervals from 1 to 2 cm, and 9 to 11 cm. Core subsampling was done immediately after the sampler was returned to the boat deck minimizing exposure to the atmosphere. The sectioned samples were placed in polyethylene bags, which were flushed and purged with pure nitrogen gases to remove oxygen before sealing then placed in a second polyethylene bag that also was purged with nitrogen before sealing. Exposure time to the atmosphere typically was less than 5 minutes. Samples were returned to mobile laboratory and transferred to 100 mL polyethylene centrifuge tubes. The headspace in the centrifuge tubes was purged with nitrogen and sealed with polyethylene film and spun in a centrifuge for 30 minutes. The pore water was decanted from the centrifuge tube, filtered using 0.45 micron filter, and acidified with ultra-pure nitric acid. The sediment was frozen with dry ice and a portion was sent to the laboratory for analysis along with the pore-water

samples. Pore-water samples were analyzed for trace-element concentrations by ICP/MS. Corresponding sediment samples were analyzed for trace elements as described above for the determination of trace-element profiles. Splits of four of the sediment samples, two each from CCR-668 and CCR-705, were treated for 30 minutes at 50°C with 0.25 M solution of hydroxylamine hydrochloride to remove trace elements sorbed to the sediment surface and in iron and manganese hydroxide coatings on sediment surfaces (Chao and Zhou, 1983). The residual sediment after leaching was then analyzed for trace elements in the same manner as the untreated sediment samples.

Cs-137 concentrations were measured by gamma counting and reported as picoCuries per gram (pCi/g). In the laboratory, sediment samples for elemental analysis were weighed, frozen, freeze-dried, weighed again, and then ground to a fine powder. Wet and dry weights were determined and used along with an assumed density of solids of 2.5 g/cm³, to estimate porosity and bulk density used to calculate mass accumulation rates in the cores. As a check on assumed densities, measured densities were determined for 20 percent of samples from volumes of homogenized wet sediment, which were weighed, dried, and then weighed again so that bulk density and the density of solids could be calculated. Measured densities were about 2.2 to 2.5 g/cm³ and were not sufficiently different from the assumed density to warrant individual analysis.

Isolation and Identification of Slag Particles

Samples from selected intervals of the cores used to determine trace-element profiles were examined for slag-like particles. Intervals were selected based on elevated concentrations of trace elements identified in the analysis of slag samples, which included zinc, copper, antimony, and silver. Chemical and physical characteristics of relatively unweathered slag particles were determined from slag particles isolated in sample RSS-743 collected from a sand bar in the Columbia River (RM 743), about 1.5 km downstream of the International Boundary. Slag particles were more weathered in samples from RSS-724 and RSS-685 sites. Slag was characterized using a petrographic microscope and a Noran 660 SSI scanning-electron microscope equipped with an energy-dispersive X-ray spectrometer (SEM/EDS). Heavy mineral fragments and slag particles were separated from selected core sediments in which slag particles were not readily observable with a binocular microscope. The sediments were suspended in sodium-polytungstate solution (density of 2.9 g/cm³) and then the heavy fraction was separated by centrifugation (Commeau and others, 1992). Slag particles from the heavy fractions were selected for examination by petrographic microscope and semi-micro elemental analysis using the SEM/EDS.

Accumulated Sediments in Lake Roosevelt

Description of Cores and Accumulated Sediments

Sediment cores ranging in length from 38 to 164 cm were collected from six sites in Lake Roosevelt (fig. 1 and table 2). The sediments recovered in the cores generally were grayish to dark olive gray in color throughout the core length. Near the surface (0 to 2 cm depth), sediments were often reddish-brown with a 0.2-0.4 cm layer of black material, and mottling was common in the upper 20 cm of cores. Gas vesicles from 0.1 to 0.3 cm were common as was a sulfurous odor. A sand-size particle of slag was noted in the soil-sediment interface of core CCR-705. Organic material such as root-hairs was observed in some intervals.

The pre-reservoir sediments that were encountered were easily distinguished by differences in sediment color and texture. Pre-reservoir sediments were encountered in only one of the six cores analyzed, site CCR-705, which also was the only site located away from the pre-reservoir channel. The base of CCR-705 below 39 cm contained black sediments with organic fragments, such as root hairs. While subsampling CCR-705, a large slag-like particle was observed near the interface of the soil and lacustrine sediments. Pre-reservoir sediments also were encountered at a site near RM 685. The gravity cores recovered at this site contained insufficient (less than 20 cm) lacustrine sediments needed for developing a detailed trace-element profile. About 50 cm of sandy material containing a significant fraction of slag-like particles was beneath the lacustrine sediments. The sandy material was interpreted to be a fluvial deposit of the pre-reservoir Columbia River. Although the interval of lacustrine sediments was insufficient to meet sampling requirements for subsectioning, a sample of the sandy material was retained for analysis of slag (RSS-685). During sampling, the coring equipment encountered hardrock material substantially denting the hardened stainless steel nose-piece of the core barrel at mid reservoir sites CCR-643 and CCR-692 and at the Spokane Arm site CSA-8. The hardrock material was believed to be the pre-reservoir bedrock surface indicating that in the locations sampled, the total thickness of accumulated sediments within the reservoir was less than the 3 m length of the coring equipment. Lake sediments greater than the 3 m length of the coring equipment were not observed while collecting cores from Lake Roosevelt.

Cesium-137 Concentrations and Rates of Sediment Accumulation

Assignment of Time Stratigraphic Horizons

Time horizons were assigned to each core based on the stratigraphic position of significant changes in the concentration profile of Cs-137. Additional time-stratigraphic markers used in assignment of time horizons within the sediment core included (1) the upper sediment surface, assigned the date of sample collection and (2) the lower surface of the accumulated lake bed sediments assigned a time coincident with the initial filling of the reservoir.

Cs-137 is a radioactive isotope of cesium whose presence in the hydrologic environment is directly related to above-ground testing of thermonuclear weapons conducted in the 1950s and early 1960s. Because Cs-137 is rapidly removed from the atmosphere by precipitation and fallout and has a strong affinity for fine-grained sediment particles that accumulate in lake bed sediments, the concentrations profile of Cs-137 in lake sediments can be used to identify sediments deposited at the beginning and end of the period of atmospheric testing of thermonuclear weapons. The period of major atmospheric testing of thermonuclear weapons began in November 1952 followed by increasing numbers of tests in the following years (U.S. Department of Energy, 2000). Substantial concentrations of Cs-137 greater than background concentrations were widely detected in lacustrine sediments beginning in 1954. Undisturbed sediments deposited prior to 1954 do not contain significant measurable concentrations of Cs-137. Atmospheric testing of thermonuclear weapons increased over the years until autumn 1963 when the Limited Test Ban Treaty was signed and atmospheric testing of thermonuclear weapons was halted by most Nations that were testing thermonuclear weapons at that time. A substantial peak in Cs-137 concentrations occurs in sediment deposited during 1963-64 as the result of nearly 100 atmospheric tests that were conducted in the year prior to signing the Limited Test Ban Treaty (U.S. Department of Energy, 2000).

The resulting characteristic or ideal profile of Cs-137 in lake sediments is that of relatively small concentrations in sediment at the sediment-water interface with concentrations gradually increasing with depth to a maximum value (which varies based on geographic location); below this point, the concentration of Cs-137 gradually decreases to a point where its concentrations are either undetectable or decrease sharply to concentrations much less than 0.1 pCi/g or background concentrations (Charles and Hites, 1987). Two points in this

profile are useful in assigning time stratigraphic horizons. The location of maximum concentration is indicative of the period of maximum deposition around 1964. The point in the profile below the maximum concentration at which Cs-137 ceases to be detectable or where concentrations decrease well below 0.1 pCi/g is attributed to the beginning of Cs-137 deposition in 1954. Non-ideal Cs-137 profiles that result from physical or biological mixing of sediments as well as variations in sediment source material and wave-induced remobilization of fine-grained sediments from the shallow zones to deeper zones may still provide useful stratigraphic markers for the dates of the onset and peak Cs-137 deposition (Charles and Hites, 1987). Cs-137 profiles in bed sediments have been widely used to determine sediment-accumulation rates (Ritchie and McHenry, 1990; Crusius and Anderson, 1995; and Van Metre and others, 1997).

The concentration of Cs-137 measured in core sediments from Lake Roosevelt ranged from <0.01 to 1.8 pCi/g. The concentration profiles of Cs-137 within cores CCR-643, CCR-668, and CCR-692 (fig. 3) were non-ideal but showed the basic characteristics of ideal Cs-137 profiles in lake sediments. Peak Cs-137 concentrations associated with the suspension of atmospheric weapons testing in 1964 could be identified in all six cores, but often contained short intervals in which the concentration of Cs-137 decreased substantially followed by a return to equal or larger concentrations. The pronounced decreases in Cs-137 concentrations were attributed to the influx of sediments from landslides. This effect was most readily observed in the Cs-137 profile of CCR-705, but also was present in the other cores.

Concentrations of Cs-137 in the lowest sections of the core CCR-705 range from <0.01 to 0.02 pCi/g; this interval (40-46 cm) included pre-reservoir soils and can be used to identify the range of background Cs-137 concentrations in the Lake Roosevelt area. In the overlying sections (34-38 cm), the concentrations of Cs-137 were 0.16 and 0.18 pCi/g, indicative of the influx of Cs-137 from atmospheric weapons testing. However, the concentrations of Cs-137 in the next three overlying intervals (22-32) decreased by 80 to 95 percent to concentrations of <0.01 to 0.04 pCi/g, which were immediately overlain by a section (18-20 cm) containing the maximum measured Cs-137 concentration in that core of 1.2 pCi/g. The intervals in which the concentrations of Cs-137 decrease markedly are indicative of disruption of the normal sedimentation processes and

are believed to be the result of the episodic influx of bank sediments. Landslide sediments would be devoid of Cs-137 produced from atmospheric testing of thermonuclear weapons and thus dilute the concentration of Cs-137 in the more steady influx of fluvial sediments to the reservoir from upstream drainage basins. The influx of the bank sediments likely is due to the many landslides that have occurred along the margins of the reservoir (Jones and others, 1961).

The characteristic features of typical Cs-137 profiles in sediments from Lake Roosevelt were present in sufficient detail to assign time horizons to intervals associated with the end of atmospheric testing of thermonuclear weapons, and the beginning of the testing period also was observable in some cores. Maximum Cs-137 concentrations attributable to the 1964 depositional period were identifiable in all cores (see fig. 3); however, the influx of landslide sediments substantially affected the Cs-137 profiles in core CCR-668 and interpolation between intervals containing Cs-137 concentrations of 0.76 and 0.78 were used to estimate the depth of sediments deposited around 1964 (see fig. 3 and table 3). The 1954 time horizon was assigned to the first appearance of Cs-137 greater than 0.04 pCi/g (two times the highest concentration in pre-reservoir soil sediments) and was identified in two cores (CCR-668 and CCR-705). Additional time horizons used in the evaluation of the patterns of historical deposition of sediment and trace elements in Lake Roosevelt include the sediment surface at the time of sampling (2002) and the contact between lacustrine and pre-reservoir sediments (1941).

The sediment recovered in all six cores included at least 60 percent of the reservoir sedimentary record, as peak Cs-137 concentrations exceeding 0.7 pCi/g were present in all cores. The sedimentary record in three cores (CCR-624, CCR-668, and CCR-705) extended through the 1954 time horizon to include 80 percent or more of the sediment record. Core CCR-705 was the only core where the sedimentary record included the contact between lacustrine and pre-reservoir sediments (soil), thereby extending from the time of sampling to the time of initial filling of the reservoir. Although core CCR-624 did not encounter pre-reservoir sediments, the sediment accumulation data indicates that the sediments in the lowest sections of that core were deposited in the early 1940s, thereby providing a nearly complete sedimentary record of Lake Roosevelt. The sedimentary record for core CCR-668 extended to the early 1950s, although the earliest sediments recovered in cores CCR-643, CCR-692, and CSA-8 were deposited at times between 1953 and 1964.

12 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

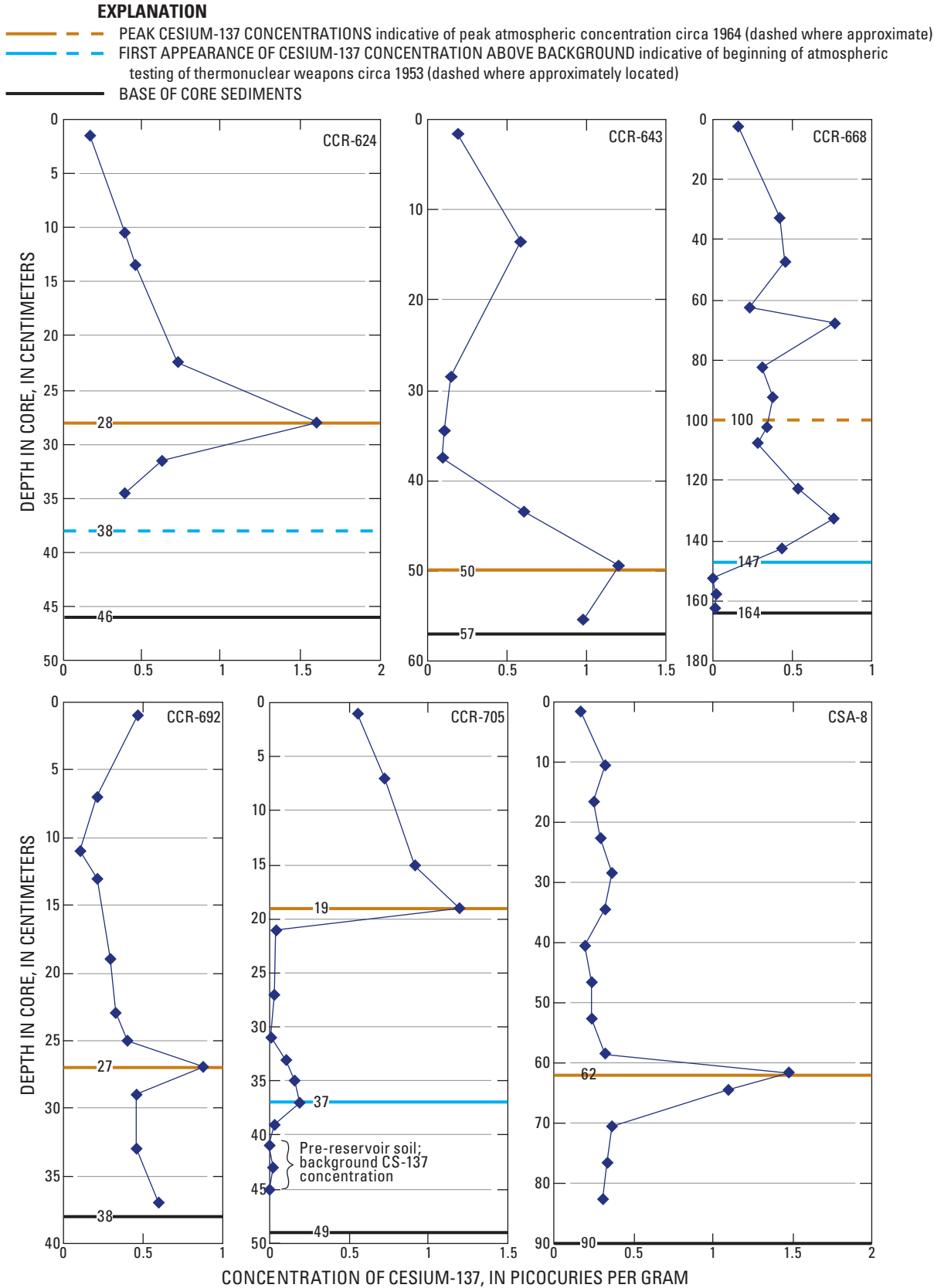


Figure 3. Vertical distribution of cesium-137 concentrations in sediment cores from Lake Roosevelt, Washington, September 2002.

Table 3. Time horizons and sediment accumulation rates for six cores from Lake Roosevelt, Washington.[est, estimate; ft, foot; cm/yr, centimeter per year; (g/cm²)/yr, gram per square centimeter per year; >, greater than]

Marker interval	Core identification No.					
	CCR-624	CCR-643	CCR-668	CCR-692	CCR-705	CSA-8
Depth to date horizons identified in cores (ft)						
Total core length including some sediment lost in retrieving core	48	74	173	38	49	90
Markers identified						
Undisturbed sediment surface 2002	0	0	0	0	0	0
Depth to Cs-137 peak (1964)	28	50	100	27	19	62
Depth to first appearance of elevated Cs-137 (1954)	38	–	147	–	37	–
Depth to pre-reservoir surface (1941)	48est	–	–	–	44	–
Linear estimate of sediment accumulation rate (cm/yr)						
Estimate between marker horizon						
1941–2002	0.79	–	–	–	0.72	–
1954–2002	.79	–	3.1	–	.77	–
1964–2002	.74	1.3	2.6	0.71	.50	1.7
1941–1964	.87	–	–	–	1.1	–
1954–1964	1.00	–	4.7	–	1.8	–
1941–1954	.77	–	–	–	.54	–
Whole core minimum value	.79	1.5	2.8	.79	.80	1.9
Mass estimate of sediment accumulation rate [(g/cm ²)/yr]						
1941–2002	0.42	–	–	–	0.53	–
1954–2002	.44	–	1.6	–	.45	–
1964–2002	.44	0.82	1.2	0.61	.24	0.00
1941–1964	>.38	–	–	–	1.1	–
1954–1964	.44	–	3.1	–	1.9	–
1941–1954	.33	–	–	–	.38	–
Whole core minimum value	.42	>.76	>1.4	>.63	.53	.00

Sedimentation Rates

The rates of sediment accumulation, measured as both the length and mass of accumulated sediments between two time horizons within the sediment core are shown in [table 3](#). Sedimentation rates based on length of accumulated sediments are reported as centimeters per year (cm/yr) and are subject to sampling artifacts, particularly core shortening, moisture content, and natural compaction of buried sediments. Compaction of the core within the coring tool barrel caused by friction along the core wall during sampling may reduce the total length of the core as much as 30 to 40 percent (Peter VanMetre, U.S. Geological Survey, unpublished data, 2002). Mass accumulation rates are reported as grams per square centimeter per year [(g/cm²)/yr]. Mass accumulation rates are based on the dry mass of sediments per unit area between time horizons and are not prone to the effects of core shortening and compaction.

Linear estimates of sediment accumulation rate in the sediment cores, based on the observed date horizons, ranged from 0.50 to 4.7 cm/yr, and typically were between 0.77 to 1.8 cm/yr ([table 3](#)). Mass estimates of sediment accumulation rates ranged from 0.24 to 3.1 (g/cm²)/yr and typically were between 0.42 and 1.00 (g/cm²)/yr. Within individual cores, the rate of sediment accumulation varied and typically was largest in the lower core sections for sediment deposited prior to 1964. Current rates (2003) of sediment accumulation likely are substantially smaller because the completion of additional dams upstream of Lake Roosevelt on the Columbia [Hugh Keenleyside Dam (1968)], Kootenay [Brilliant Dam (1940s)], and Pend Oreille Rivers [(Waneta Dam (1950s))] have further reduced the sediment input to the reservoir and the stabilization of the reservoir shoreline has reduced the frequency and magnitude of landslides.

Concentrations of Trace Elements in Accumulated Sediments

Concentrations of arsenic, cadmium, copper, lead, mercury, and zinc were high throughout the six sediment cores collected from Lake Roosevelt. Maximum concentrations in the core samples were as high as 2,200 mg/kg for zinc, 920 mg/kg for lead, and 250 mg/kg for copper, with median concentrations of 970, 260, and 53 mg/kg, respectively (table 4). Concentrations of arsenic, cadmium, and mercury were lower; with maximum concentrations as high as 34 mg/kg for arsenic, 23 mg/kg for cadmium, and 2.8 mg/kg for mercury, with median concentrations of 13, 7.5, and 0.58 mg/kg, respectively. Concentration data for 54 elements determined for bulk-sediment samples from the six cores are shown in table 5 (at back of report). The analytical results of the associated quality-control samples, presented in table 6 (at back of report), indicate acceptable levels of bias and variability in the sample analytical data.

Bias and variability of the laboratory data were within acceptable limits. Quality-assurance samples were submitted as double blind samples; the laboratory was not informed which samples were quality-assurance samples nor the specific standard reference material that was used. Bias in the samples

were assessed as a percentage of recovery by comparison of the reported concentrations of the standard reference material to the concentrations determined by the laboratory. Variability was assessed by comparison of the relative percentage of difference of replicate environmental samples. Data for the quality-control samples submitted from the field are shown in table 6. The median recovery for all trace elements for which certified or reference concentrations were reported was 99 percent; however, 5 percent of the laboratory analyses were outside the target recovery range of 80-120 percent. The median recoveries for six analyses of standard reference materials for arsenic, cadmium, copper, lead, mercury, and zinc were 94, 96, 105, 96, 100, and 96 percent, respectively. Variability generally was small, the median difference of the replicated environmental samples was 2.4 percent with 3.8 percent of the replicated analyses outside the target range of less than 20 percent difference between the replicate samples. Of the six trace elements of concern, the analysis of lead showed variability ranging from 87 to 124 percent while variability in copper concentration of one of the environmental replicate pairs was different by 46 percent. Review of the laboratory process sheets confirmed the variability in the copper analysis. The deviations observed in the copper and lead data for these samples were not observed among the other quality-assurance samples and thus considered outliers that did not significantly affect the overall acceptability of the data.

Table 4. Summary of concentrations of arsenic, cadmium, copper, lead, mercury, and zinc in all sample core subsections from Lake Roosevelt, Washington.

[Average concentrations in crustal rocks: Data from Rose and others, 1979. Range of reference: Data from Bortleson and others, 1994, and Majewski and others, 2002. Clean-up guideline: Guidelines from CCT. Clean-up guidelines adopted by Confederated Tribes of the Colville Reservation (2003)]

Constituent	Number of samples	Concentrations, in milligrams per kilogram (mg/kg)					
		Average	Minimum	Maximum	Median	10th percentile	90th percentile
Arsenic	84	14	2.1	34	13	7.1	20
Cadmium	84	8.6	1.4	23	7.5	2.4	16
Copper	84	68	18	250	53	32	130
Lead	84	310	61	920	260	83	610
Mercury	82	.82	.08	2.8	.58	.1	1.9
Zinc	84	930	151	2,200	970	330	1,500

Constituent	Average concentration in crustal rocks (mg/kg)	Range of reference concentration (mg/kg)	Percentage of samples exceeding upper reference	Percentage of samples exceeding 3X upper reference	Percentage of samples exceeding 10X upper reference	Clean-up guideline (mg/kg)	Percentage of samples exceeding clean-up guideline
Arsenic	2	3.2–10	78	1	0	9.8	78
Cadmium	.1	<0.1–0.4	100	100	77	.99	100
Copper	50	9–25	99	26	0	31.6	90
Lead	10	14–47	100	66	20	35.8	100
Mercury	.02	0.01–0.07	100	70	47	.18	74
Zinc	80	50–150	100	80	8	121	100

Concentrations of trace elements in core sediments were compared to reported concentration of trace elements in reference sediments that were collected from bank material adjacent to the reservoir (Majewski and others, 2003) and river sediment collected upstream of the smelter (Bortleson and others, 1994). The largest concentrations in these reference sediments were reported as 10 mg/kg for arsenic, 0.4 mg/kg for cadmium, 25 mg/kg for copper, 47 mg/kg for lead, 0.07 mg/kg for mercury, and 150 mg/kg for zinc. These reference values are intermediate between estimates of natural background concentration, determined as the 95th percentile level, for concentrations determined in the less than 63 micron fraction and less than 4 mm fraction of stream sediments from the area surrounding Trail, British Columbia (Reyes and others, 2004).

Compared to the concentration of trace elements from reference sites, concentrations of cadmium, copper, lead, mercury, and zinc were elevated in nearly 100 percent of core samples analyzed, and concentrations of arsenic were elevated in 78 percent of the samples analyzed (table 4). Concentrations of cadmium and mercury exceeded the upper range of background reference concentrations by 10 times or more in 77 and 47 percent of the samples analyzed, respectively. Concentrations of lead and zinc exceeded reference concentrations by 10 times in less than 25 percent of the samples analyzed. The concentrations of arsenic and copper were least often elevated above concentrations in reference sediments. In most cores, maximum concentrations of arsenic and copper generally were least elevated, typically less than 3 to 4 times the upper range of concentrations in reference sediments. However, at site CCR-692, copper concentrations were substantially larger than in the other cores, with the concentration in many intervals exceeding reference concentrations by 5 to 10 times.

All samples exceeded cleanup guidelines adopted by the Confederated Tribes of the Colville Reservation (CCT) (Colville Confederated Tribes, 2003) for cadmium, lead, and zinc and more than 70 percent of samples exceeded cleanup guidelines for mercury, arsenic, and copper (table 4). The sediment-quality guidelines adopted by the CCT were developed from the consensus based threshold effects concentrations for freshwater ecosystems (MacDonald and others, 2000).

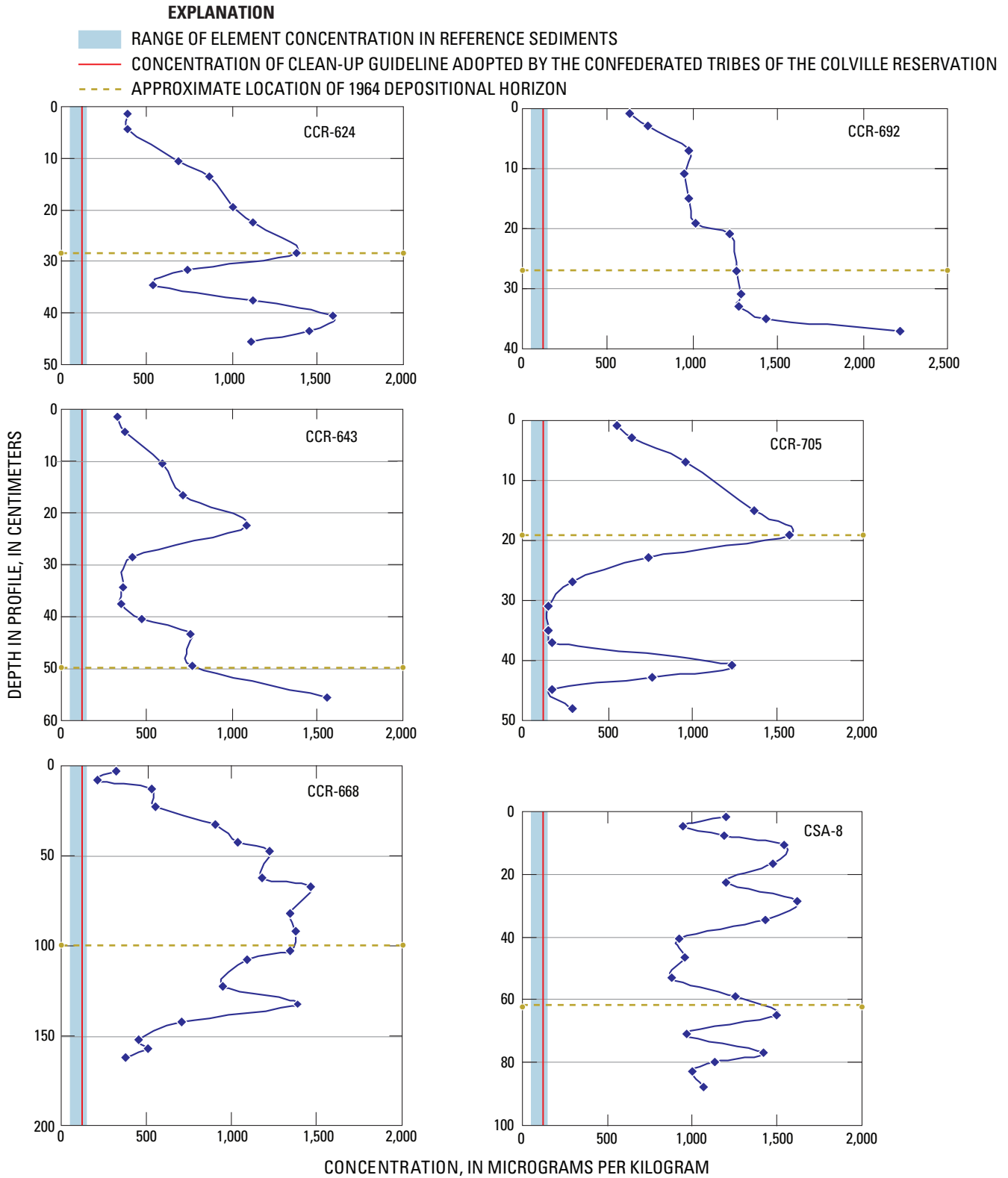
Trace-Element Profiles

The vertical distribution of trace elements was determined by generating a concentration-depth profile for each core for the six trace elements of concern. Similarities and differences can be observed in the concentration-depth profiles of arsenic, cadmium, copper, lead, mercury, and zinc of cores from different locations in Lake Roosevelt (figs. 4A-4F). These profiles show the extent that trace-element concentrations in the accumulated sediments of Lake Roosevelt exceed background reference concentrations and the concentration levels adopted as Trace-Element Clean-up Guidelines by the

Confederated Tribes of the Colville Reservation (Colville Confederated Tribes, 2003). The concentration profiles from the sediment cores support conclusions of previous investigators of the widespread occurrence of trace elements in bed sediments of Lake Roosevelt and generally decreasing concentrations in sediments toward the downstream reaches of the reservoir.

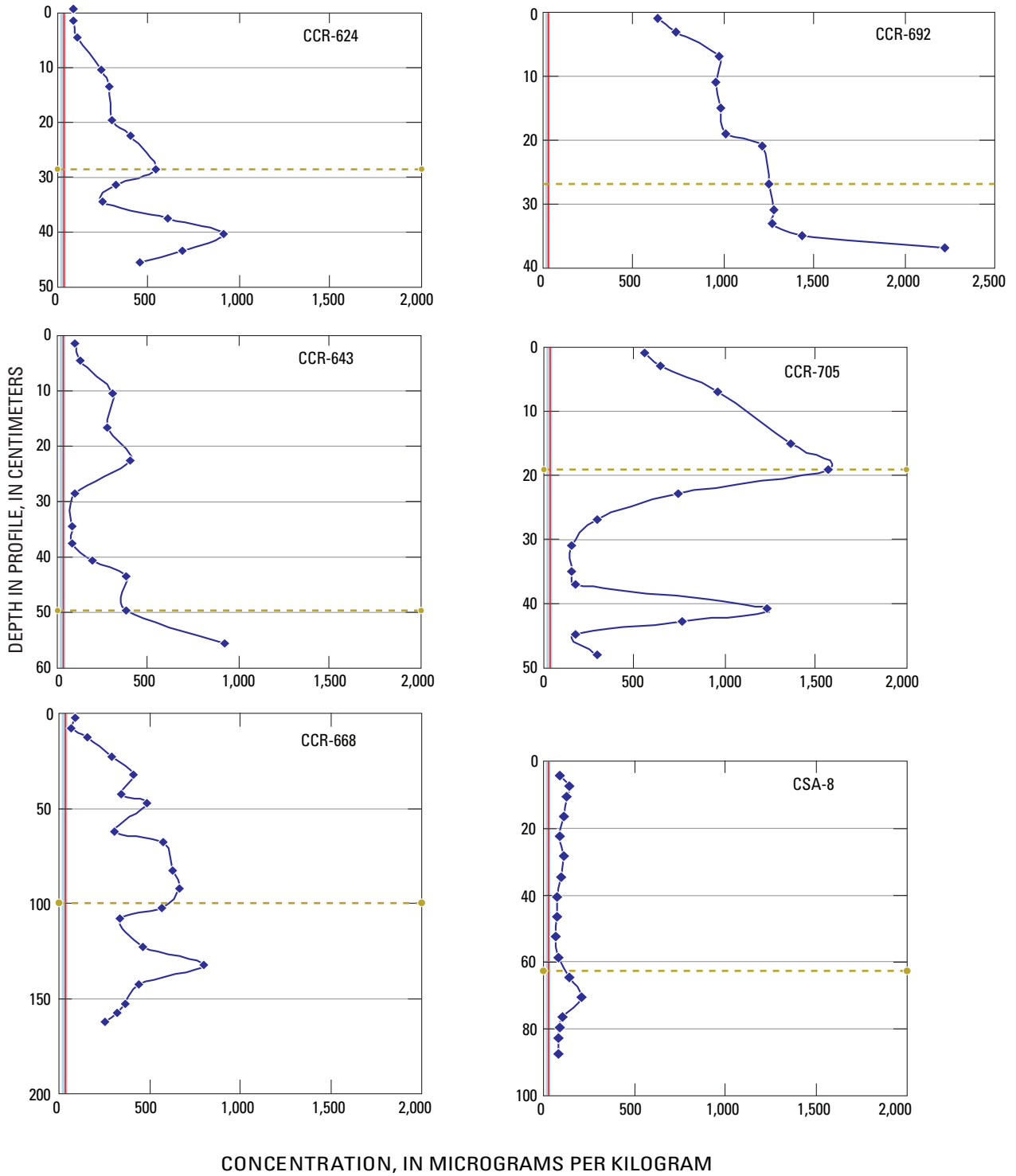
Zinc concentrations were largest and covered the widest range of the six trace elements of concern (table 5 and fig. 4A). As found in previous studies, surficial concentrations of zinc were smaller at downstream locations in the reservoir. Concentrations of zinc exceeded the range of concentrations in reference sediments and clean-up guidelines throughout the entire core at all six sites. Eighty percent of all samples exceeded the upper range of reference concentrations by a factor of three. Maximum measured concentrations typically were located in the lower or middle one-third of the cores. In all cores along the pre-reservoir channel of the Columbia River, a trend of decreasing zinc concentrations was observed between sediments deposited near the 1964 time horizon and those in recently deposited sediments. Most decreases were about 50 to 70 percent. The largest decrease was in core CCR-668 where concentrations decreased from 1,500 mg/kg at mid-core to about 300 mg/kg at the surface. Decreasing zinc concentrations near the surface were not as apparent in the core from the Spokane Arm (CSA-8) where zinc concentrations appear to fluctuate about a central value of 1,300 mg/kg throughout the entire core and do not show a clear trend of decreasing concentrations. The influx of bank material from landslides likely explains the intervals of lower concentrations in the middle of cores CCR-624, CCR-643, and CCR-705.

The concentration of lead exceeded the range of concentrations in reference sediments and cleanup guideline throughout the entire core profile at all six core sites (fig. 4B). The concentrations of lead in the cores varied considerably, particularly in cores from the lower and mid reaches of the reservoir but were much less variable in the core from the Spokane Arm. Among all cores, lead concentrations ranged from those approaching concentrations in reference sediments to concentrations greater than 1,500 mg/kg, more than 30 times larger than the upper range of reference concentrations. Concentrations were larger in cores from the upstream locations, however, the concentrations of lead at downstream sites decreased in the more recent sediment near the surface, such that lead concentrations in the uppermost intervals of these cores approached to within several fold the range of clean-up guidelines and reference sediments. The largest concentrations of lead in cores along the pre-reservoir Columbia River channel were in sediments near the 1964 horizon or deeper. Lead concentrations in cores from the lower and mid reaches of the reservoir typically decreased toward the surface by roughly 60 to 80 percent. Lead concentrations in the core from the Spokane Arm generally were lower than most samples from the lower and mid reaches of the reservoir and showed little variation or trend.



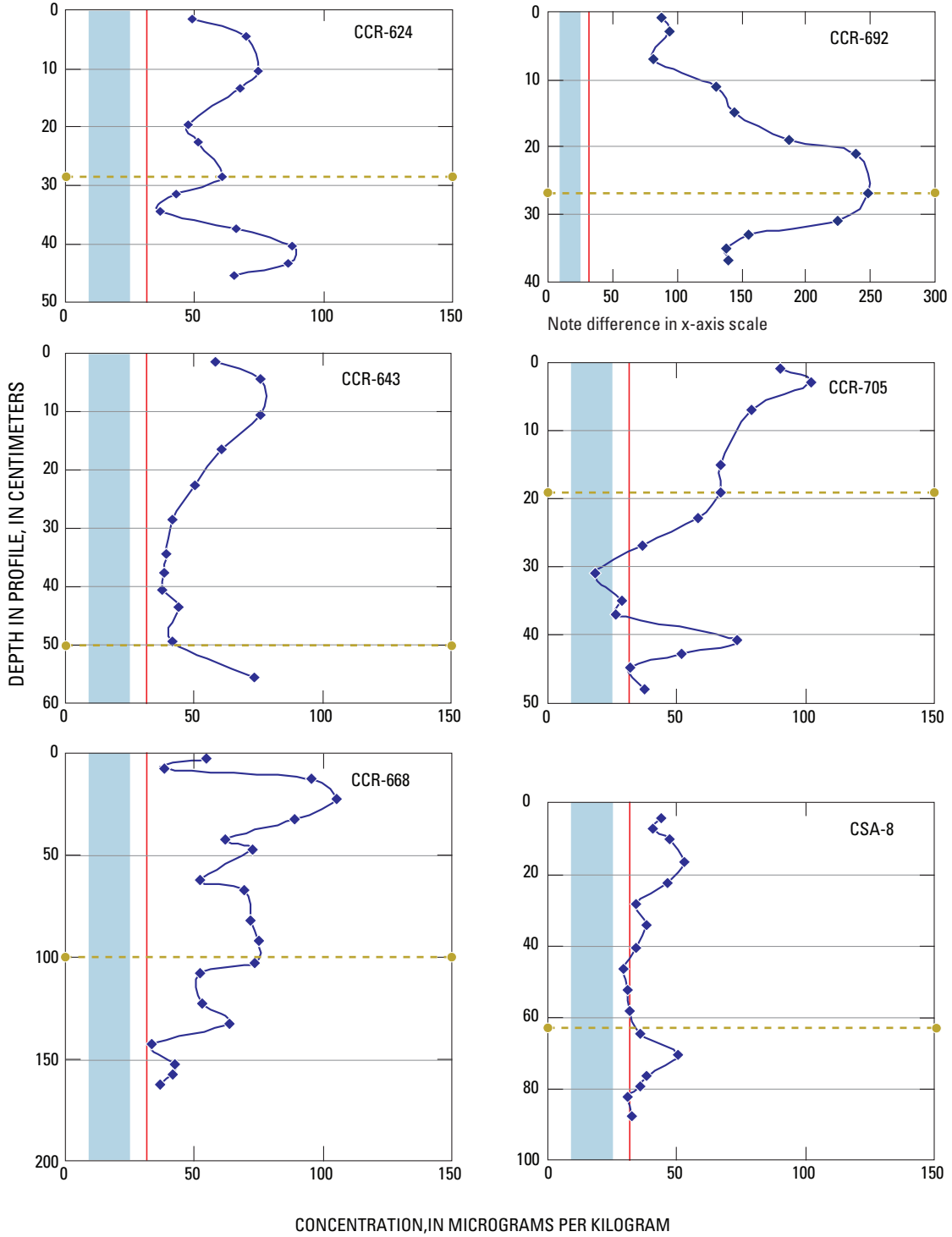
A. ZINC

Figure 4. Vertical distribution of trace-element concentrations in selected sediment cores from Lake Roosevelt, Washington, September 2002.



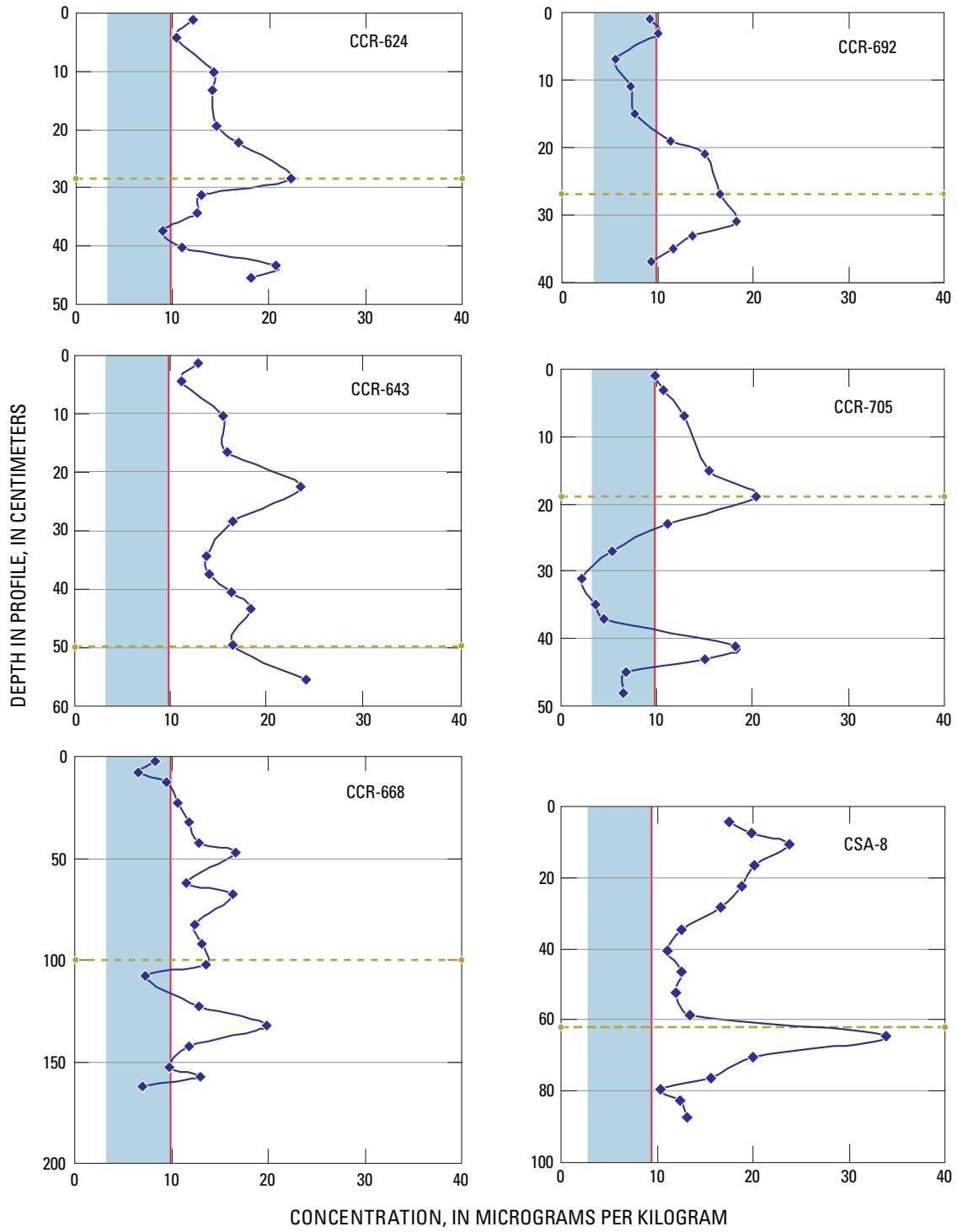
B. LEAD

Figure 4.—Continued



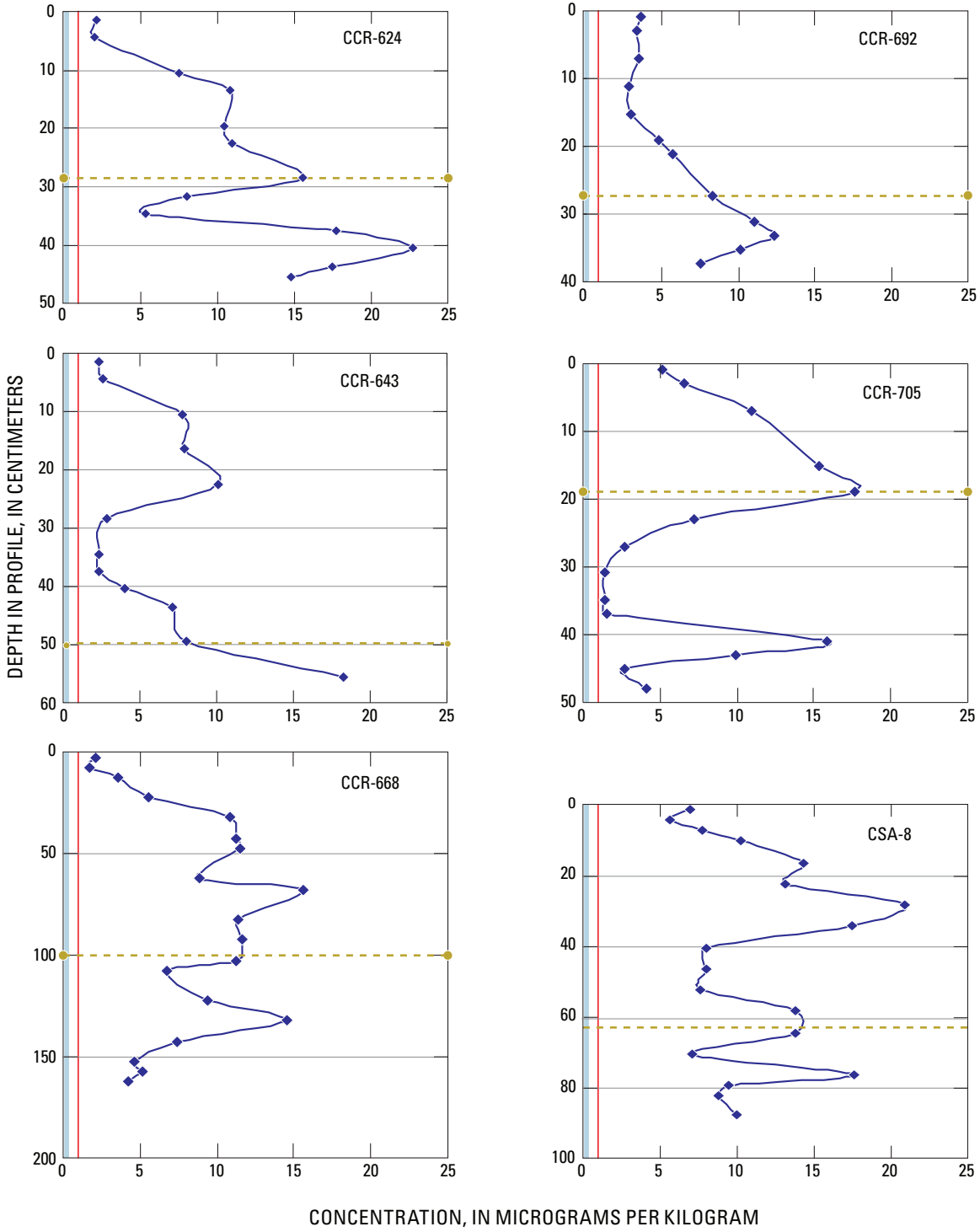
C. COPPER

Figure 4.—Continued



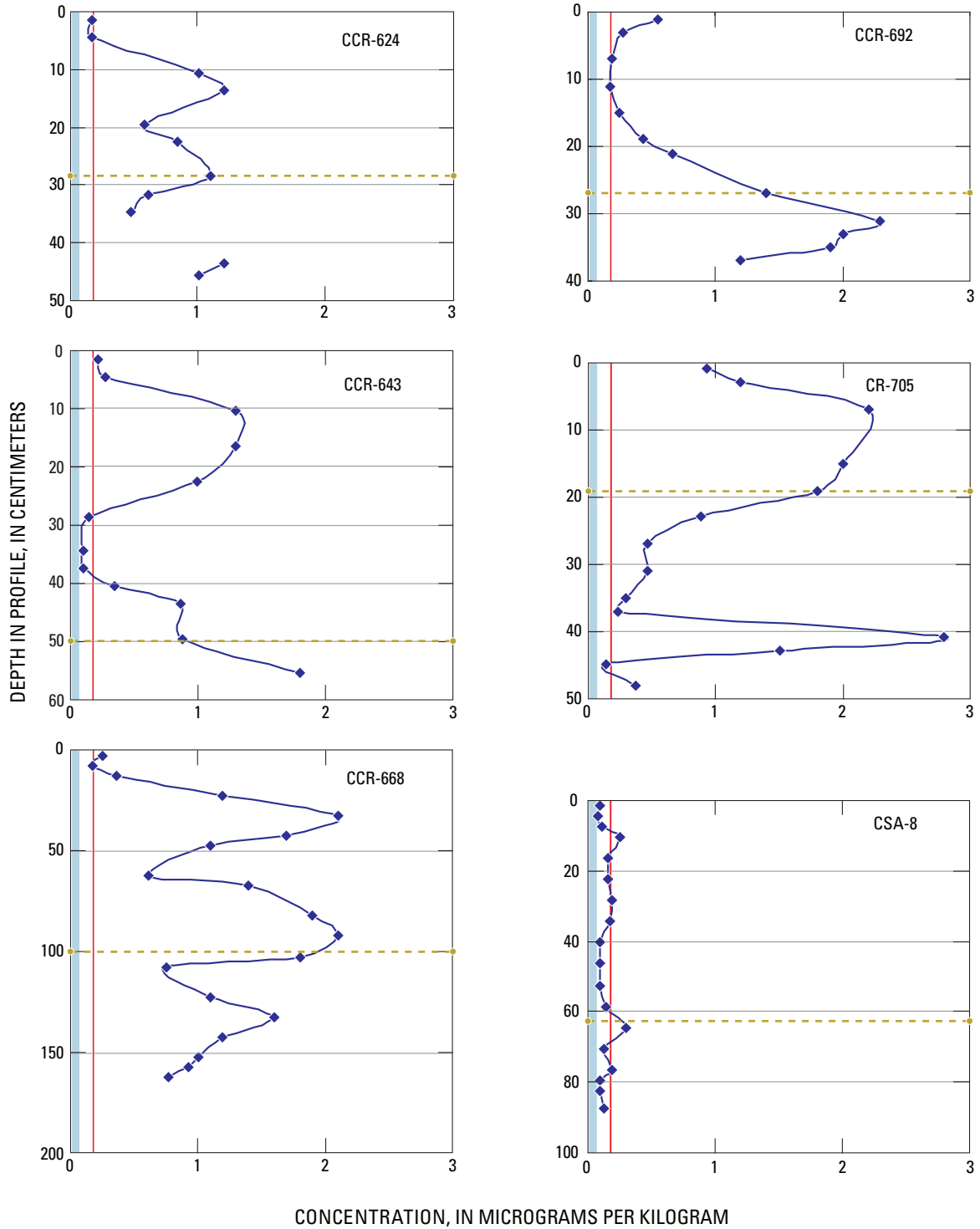
D. ARSENIC

Figure 4.—Continued



E. CADMIUM

Figure 4.—Continued



F. MERCURY

Figure 4.—Continued

The profiles of copper concentrations were unique among the six trace elements of concern in that an overall trend of increasing rather than decreasing concentrations from depth to the surface was observed in most of the core profiles (fig. 4C). Copper concentrations generally were larger than the range of reference concentrations and clean-up guidelines. Only core CCR-692 shows a definite trend of decreasing concentrations toward the surface, however, concentrations at this site were 2 to 5 times larger than at all other core sites. Copper concentrations in the Spokane Arm typically are lowest among the core profiles; however, the concentration of copper is increasing slightly in the more recently deposited sediments near the surface.

The longitudinal distribution of arsenic in bed sediments of Lake Roosevelt differed from other trace elements in that larger arsenic concentrations were more common at downstream locations, particularly in core CCR-643 (fig. 4D). This distributional pattern of comparatively larger concentrations in surficial sediments at downstream locations in Lake Roosevelt is reverse of the distributional patterns reported by Bortleson and others (1994) and Majewski and others (2003), although the longitudinal concentration gradients in all three studies were small. For cores collected along the pre-reservoir Columbia River channel, arsenic concentrations were largest near the 1964 horizon (fig. 4D) and generally decrease by roughly 40 to 50 percent toward the surficial horizon, although the decrease in core CCR-643 was only about 20 percent. Arsenic concentrations in the core collected from the Spokane Arm of the reservoir (CSA-8) show a trend of increasing concentrations in the more recent sediment horizons. Of the trace elements of concern, the concentration of arsenic in sediment of Lake Roosevelt are the most similar to concentrations in reference sediment. Although arsenic concentrations generally were larger than the range of reference concentrations and clean-up guidelines at all sites, decreasing concentrations in the upper horizons of cores collected along the upper pre-reservoir Columbia River channel (CCR-668, CCR-692, and CCR-705) were less than CCT cleanup guidelines and within the range of concentrations in reference sediments. Concentration profiles from the lower reaches of the reservoir (CCR-624 and CCR-643) were decreasing, nevertheless, the concentrations in the surficial sediments remained slightly elevated relative to the reference concentrations and CCT clean-up guidelines.

Cadmium was the only trace element for which concentrations in all samples throughout each core exceeded the upper range of reference sediments by a factor of three or more and for which all samples exceeded the CCT clean-up guideline (fig. 4E). Sediments in the core from the Spokane Arm of the reservoir generally contained larger cadmium concentrations than sediments from the rest of the reservoir. Cadmium concentrations decreased from the 1964 horizon toward the surface in all cores. Cadmium concentrations in recently deposited sediments from the top of the cores typically were about 20 to 50 percent less than those in sediments deposited near the 1964 horizon.

Concentrations of mercury were consistently larger than the range of background reference concentrations and clean-up guidelines at all sites along the pre-reservoir Columbia River channel (fig. 4F). Mercury concentrations in all core samples from the Spokane Arm exceeded the upper range of concentrations in reference sediments, however, concentrations in only two of these samples exceeded CCT clean-up guidelines. In the cores from along the pre-reservoir Columbia River, large mercury concentrations have been widespread but generally have decreased in sediments above the 1964 horizon, particularly in the most recent sediment intervals. The profile in core CCR-692 shows an increase in mercury concentration in the two most recent sections of the profile, which may be associated with the concurrent large increase in total organic carbon in those intervals (see table 5).

Overall, the depth concentration profiles typically show that concentrations of arsenic, cadmium, lead, mercury, and zinc often were highest in the lower to mid sections (closer to the bottom) and the concentrations of copper often were highest (closer to the surface) in the trace-element profiles. In several individual cores (CCR-624, CCR-643, CCR-668, and CCR-705), well-defined trends of decreasing concentrations of arsenic, lead, zinc, and to a lesser degree cadmium, were observed in the upper sections of cores corresponding to sedimentation that occurred since the 1964 horizon. The concentration profiles for arsenic, cadmium, lead, zinc, and to a lesser extent mercury also clearly show decreasing concentrations in more recently deposited sediments throughout the reservoir as reported by Majewski and others (2003). However, the concentration profiles for copper generally show trends of increasing concentrations in more recent sediments particularly in CCR-705.

Trace-element profiles for the core collected from the Spokane Arm of the reservoir showed several pronounced differences compared to the trace-element profiles in cores collected from along the mainstem of the Columbia River. The most notable differences were the comparatively larger concentrations of zinc and cadmium, and lower concentrations of mercury, lead, and copper. There also was an increasing trend toward the surface in the concentration of arsenic in the upper one-half of the profile and a decreasing trend of cadmium in the upper one-third of the profile; concentrations of copper, lead, mercury, and zinc remained relatively constant throughout the core profile. These results differ from those of Grosbois and others (2001), who reported decreasing concentrations of all six of these trace elements in the upper sections of two sediment cores obtained from the Spokane Arm of the reservoir, as well as for cores from other areas of the Spokane River basin. They attributed the trend of decreasing concentrations in the upper sections of cores to the installation of jig-tailing settling ponds at mine sites and a general improvement in environmental stewardship occurring within the Spokane River basin over the last 20 to 30 years.

The differences in the trace-element concentrations in core sediments from along the pre-reservoir channel of the Columbia River compared to sediments from the Spokane Arm are more clearly observed by the comparison of ratios of the concentration of zinc to lead versus ratios of the concentration of cadmium to mercury (fig. 5). Data for sediments from all cores obtained along the Columbia River plot in a single close grouping whereas ratios of zinc to lead and cadmium to mercury were substantially larger for data from the Spokane Arm and are more scattered and plot away from the area where data from the Columbia River plot. The ratios of zinc to lead and cadmium to mercury typically were about 2 to 4 and 3 to 20, respectively, in the sediments from the cores collected from the reservoir locations along the mainstem of the Columbia River. These same ratios in the sediments from the Spokane Arm of the reservoir were much larger, typically about 10 to 14 and 70 to 100, respectively. Other comparisons such as plots of the relation of calcium-carbonate concentrations or aluminum-titanium concentrations also show substantially different patterns for sediments from the Spokane Arm compared to sediments from the Columbia

River channel. Trace-element concentrations in the core collected downstream of the confluence of the Spokane River (CCR-624) shows predominantly the influences of trace-element input from the Columbia River with limited influence from input from the Spokane River basin. The fact that cadmium concentrations at times exceeded arsenic concentrations in deeper sediments from the 1950s time horizons may be an example of input from the Spokane River basin on trace-element concentrations in bed sediments of the lower reach of Lake Roosevelt.

The differences in the relative concentrations of trace elements in the cores collected in the Spokane Arm of the reservoir compared to cores collected along the Columbia River were most likely related to differences in the source areas contributing sediments to the Spokane and Columbia Rivers. Reservoir sediments from along the mainstem of the Columbia River primarily were affected by inputs from the Columbia River whereas sediments in the Spokane Arm of the reservoir were primarily affected by sediment sources from the Spokane River, which includes the Coeur d'Alene mining area (Horowitz and others, 1993).

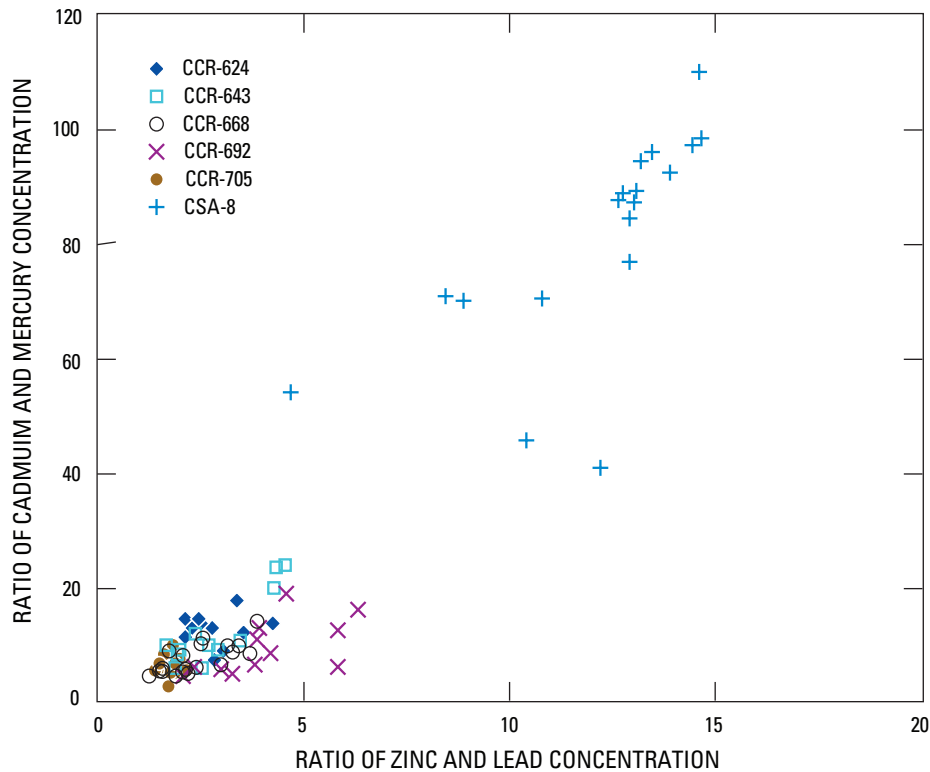


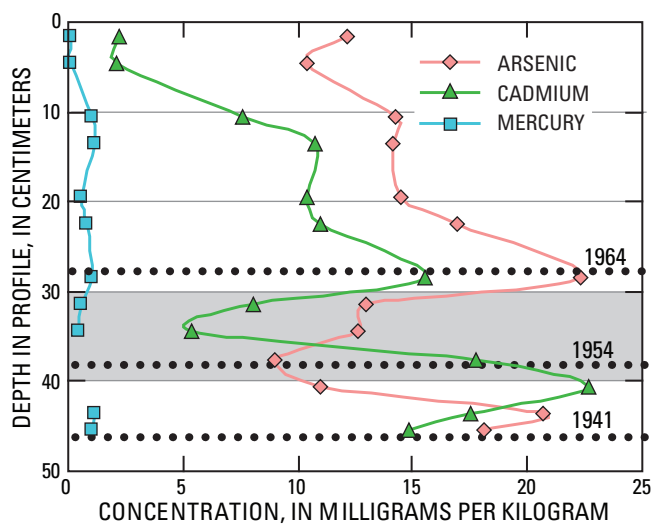
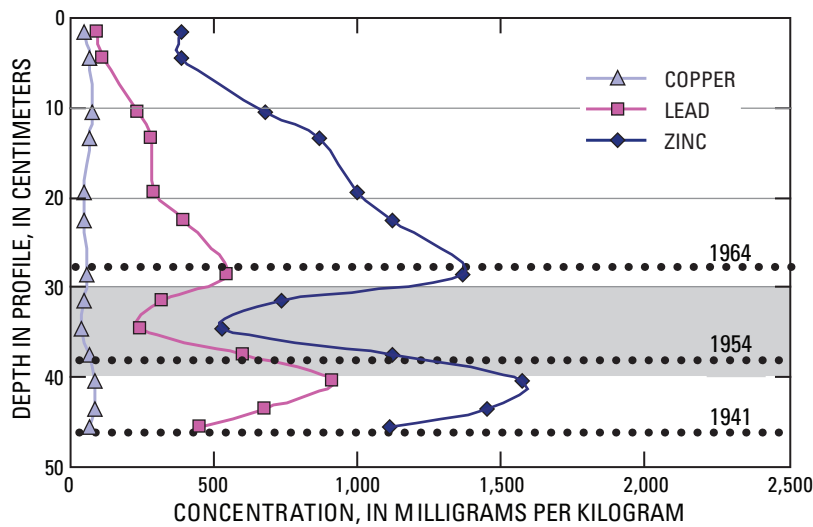
Figure 5. Ratios of cadmium to mercury and zinc to lead in samples from sediment cores from Lake Roosevelt, Washington, September 2002.

Patterns of Trace-Element Profiles Within Individual Cores

Concentration profiles of arsenic, cadmium, copper, lead, mercury, and zinc showed similar patterns of variation within all cores. The relative concentrations of trace elements remained nearly constant throughout the trace-element profiles. Zinc was present in the largest concentration followed systematically by the concentrations of lead, copper, arsenic, cadmium, and mercury, although there are a several instances in the cores from the Spokane Arm and CCR-624 where the concentrations of cadmium exceeded arsenic concentrations. Within the core sediments, the general pattern of relative concentrations remains constant; even as concentrations were

decreasing in the more recent sediments in the upper one-half of the cores. The pattern of relative concentrations observed in the core profiles generally follows relative average crustal abundances of trace elements reported by Rose and others (1979) (see table 4) with the exception that in lacustrine sediments of Lake Roosevelt, the concentration of lead generally exceeds copper by 3 to 4 times.

Because within core variations in concentrations of zinc, lead, cadmium, and mercury were consistent, concentration profiles often were near parallel (figs. 6A-6F). The influx of bank material and its diluting effect on bed-sediment concentrations accentuates variation and the near parallel concentration profiles. Variations in concentrations of arsenic commonly followed the general trends of the other four trace elements but were not nearly as extensive or consistent.



EXPLANATION

Concentrations of trace elements and cesium-137 likely affected by episodic input of sediments from landslide and bank erosion

Concentrations of trace elements in reference sediments collected upstream from the smelter discharge and from adjacent bank material as reported by Majewski and others (2003). Concentrations, in milligrams per kilogram

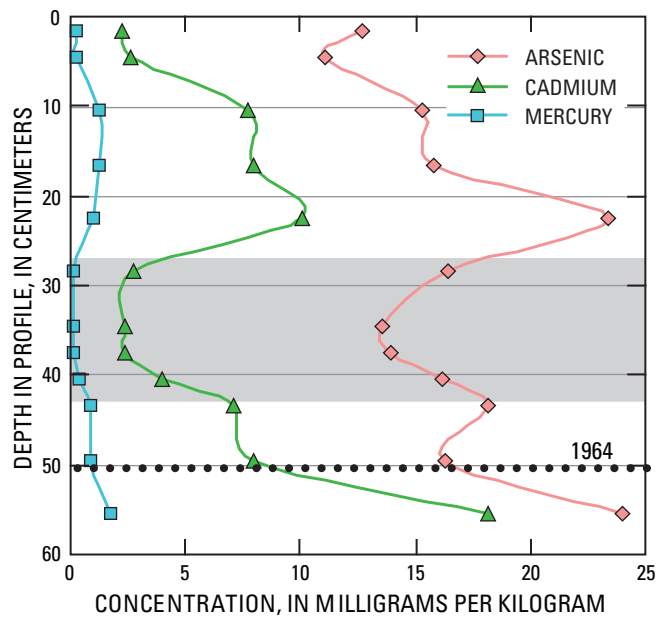
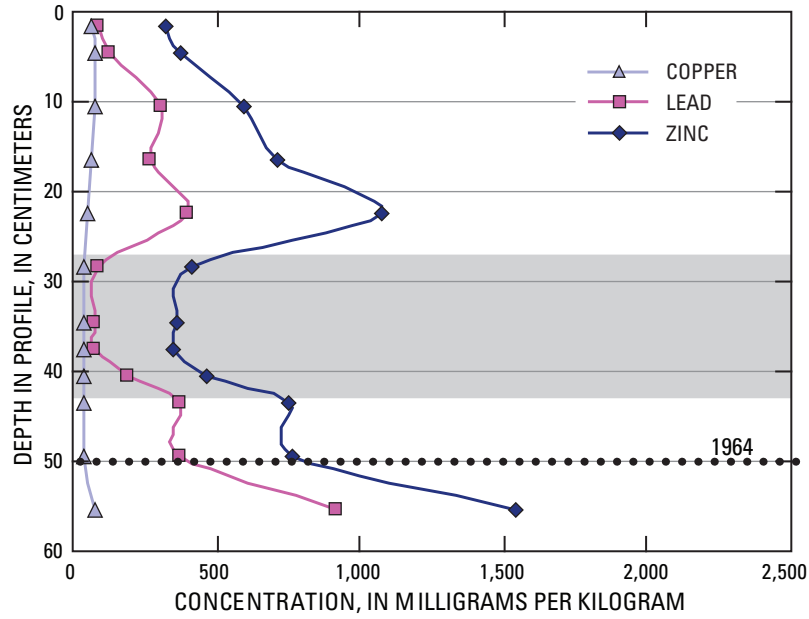
Arsenic	3.2 – 10
Cadmium	<0.1 – 0.4
Mercury	0.01 – 0.07
Copper	9 – 25
Lead	14 – 47
Zinc	53 – 130

Time Stratigraphic Horizon

CCR-624 Core designation indicates nearest Columbia River mile as shown on 7.5-minute USGS quadrangle maps

A. CCR-624

Figure 6. Vertical distribution of trace-element concentrations in six sediment cores from Lake Roosevelt, Washington, September 2002.

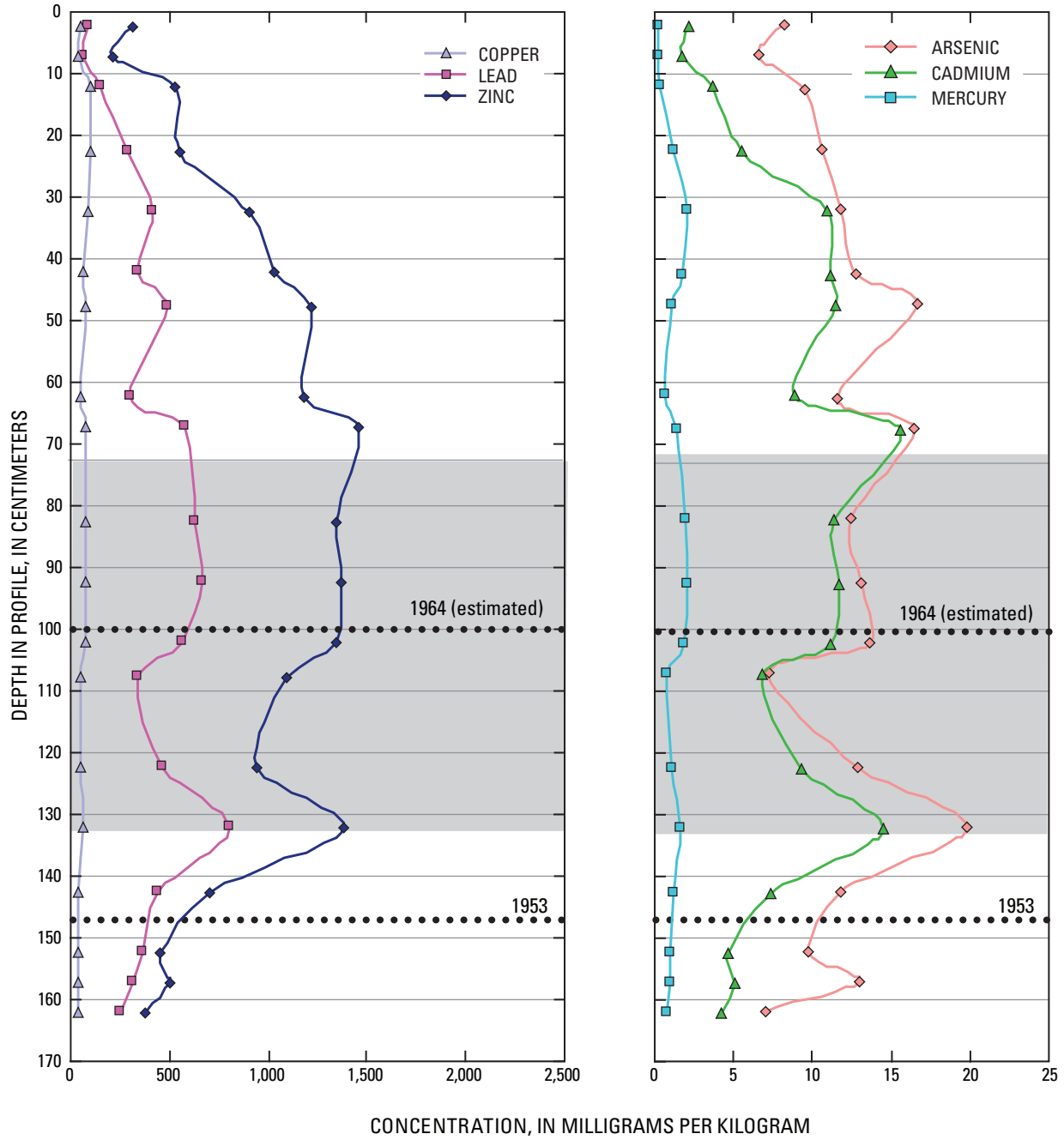


B. CCR-643

Figure 6.—Continued

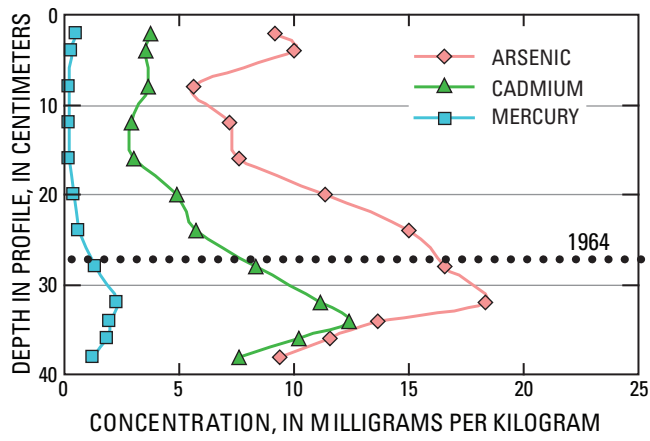
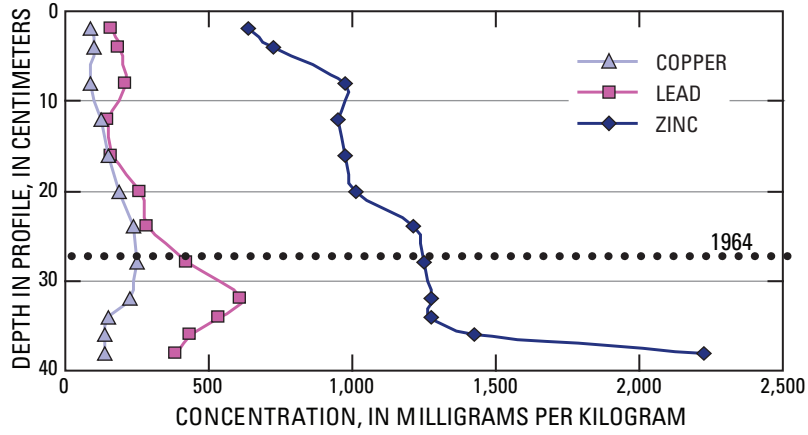
The similar pattern of variation in the concentration of zinc, lead, cadmium, and mercury observed in cores from along the mainstem of the Columbia River channel indicates that a single source, such as inflow from the Columbia River, is dominating the depositional patterns of these trace elements throughout most of the reservoir. The profiles often display features that were distinctive to an individual core indicating

that localized conditions, such as landslides, had a major influence on the concentrations of trace elements that were being deposited at a particular location. The concentration profiles for each core provide an integrated historical record that incorporates regional and localized influences of the changing depositional concentrations of trace elements at specific locations in the reservoir.



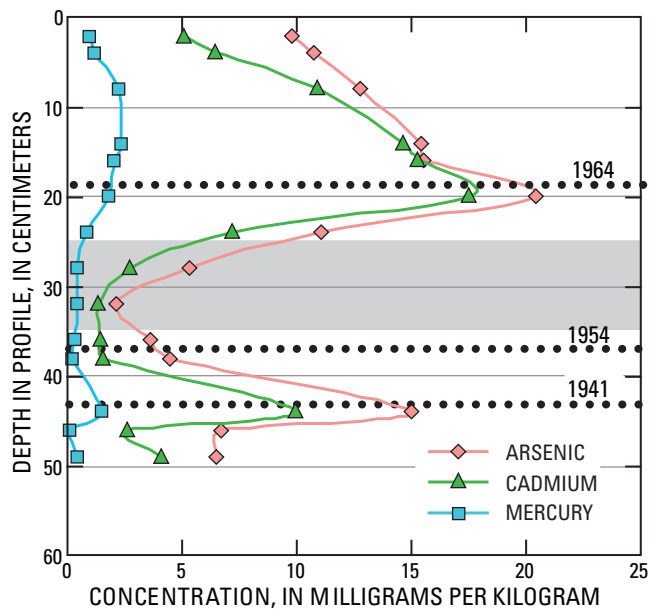
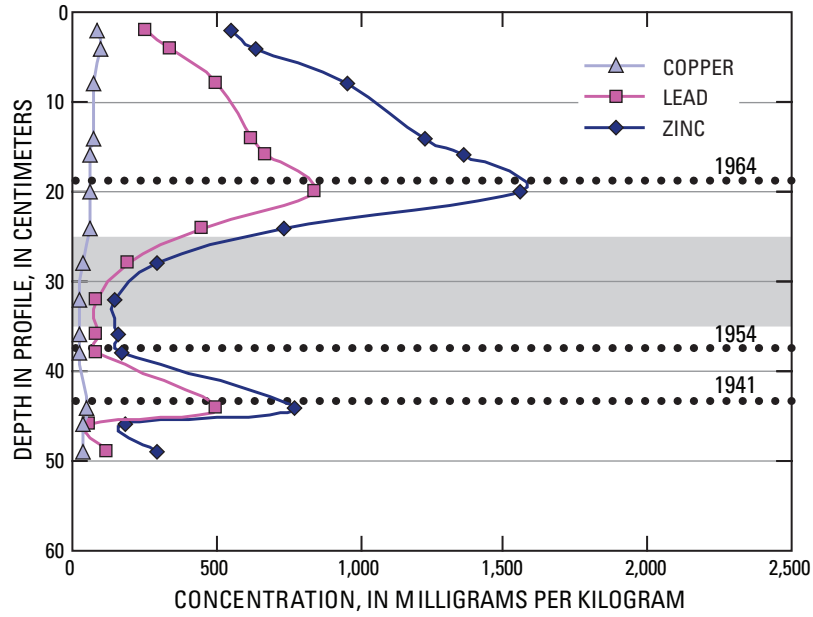
C. CCR-668

Figure 6.—Continued



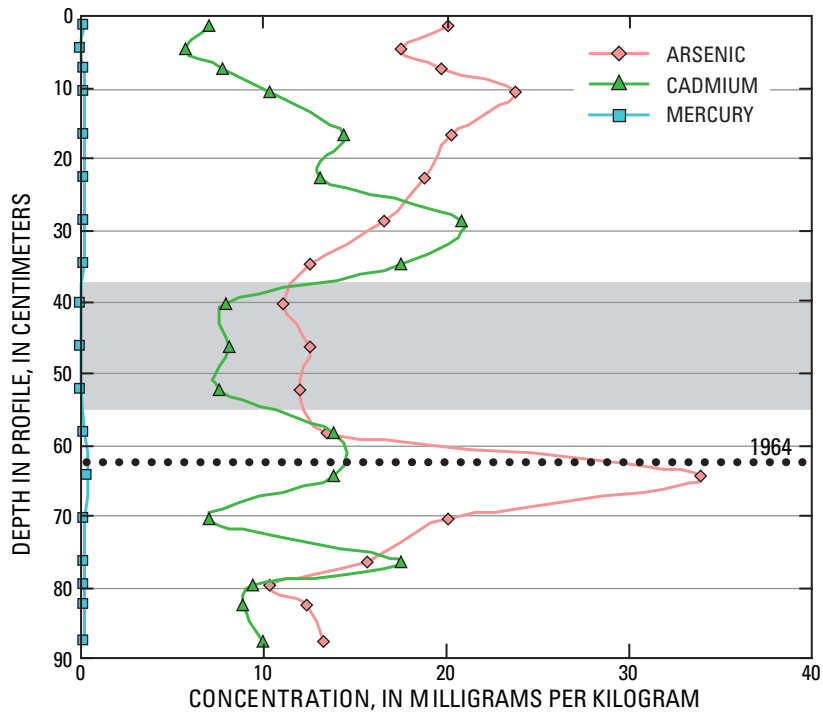
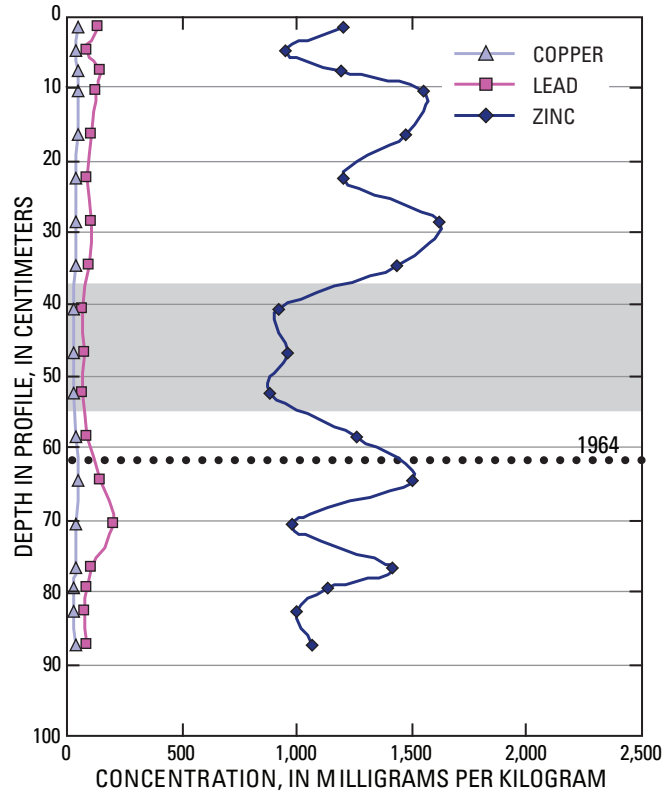
D. CCR-692

Figure 6.—Continued



E. CCR-705

Figure 6.—Continued



F. CSA-8

Figure 6.—Continued

The profiles from CCR-643 illustrate the effect of the episodic influx of sediments from landslides and bank erosion. Concentrations of zinc, lead, cadmium, and mercury decrease by roughly 50 to 80 percent in the intermediate interval between 22 to 42 cm (fig. 6B). The concentrations of arsenic and copper also decrease in this interval but to a lesser extent. Cs-137 concentrations are about 0.6 pCi/g in the sediment intervals near 20 and 42 cm within the profile but decrease to about 0.1 pCi/g in intervals between 20 and 42 cm. Ancillary trace-element concentrations data (table 5) show the concentrations of total cesium, titanium, carbonate, and to a lesser extent calcium, increased in the same interval as might be expected from the influx of landslide material composed of glacial sediments derived from carbonate bedrock. Similar patterns of a sharp decrease in trace-element concentrations attributed to episodic events also were observed in profiles of cores CCR-624, CCR-668, CCR-705, and CSA-8 (figs. 6A, 6C, 6E, 6F).

The trace-element profiles from cores collected along the pre-reservoir Columbia River channel reflect the recorded changes in the effluent discharges from the Trail smelter during the last 30 years. The relative magnitude of trace-element concentrations observed in the core sediments,

with zinc>lead>copper>arsenic>cadmium>mercury, generally matches, with the exception of arsenic, available information on trace-element loading rates in liquid effluent discharged from the Trail smelter since the mid-1970s (fig. 7). The concentration of cadmium is larger than arsenic in the effluent discharge, however, the concentration of arsenic typically is larger than the concentration of cadmium in core sediments. This difference may be due to differences in sorption properties of the two elements or additional natural sources of arsenic. Similar information on the concentration of copper in liquid effluent was not available. Since the mid-1970s, the amount of trace-element loading in liquid effluent and slag discharged to the Columbia River has been reduced through a series of improvements and modernizations. Concentrations of trace elements were often highest in sections of the trace-element profiles corresponding to the mid-1960s period. Decreasing concentrations of trace elements in the more recently deposited sediments of the upper one-half of the profiles likely reflect the substantial decreased loading of trace elements in the liquid effluent discharged from the Trail smelter. These trends also reflect the smelter’s strong influence on the trace-element composition of bed sediment throughout Lake Roosevelt.

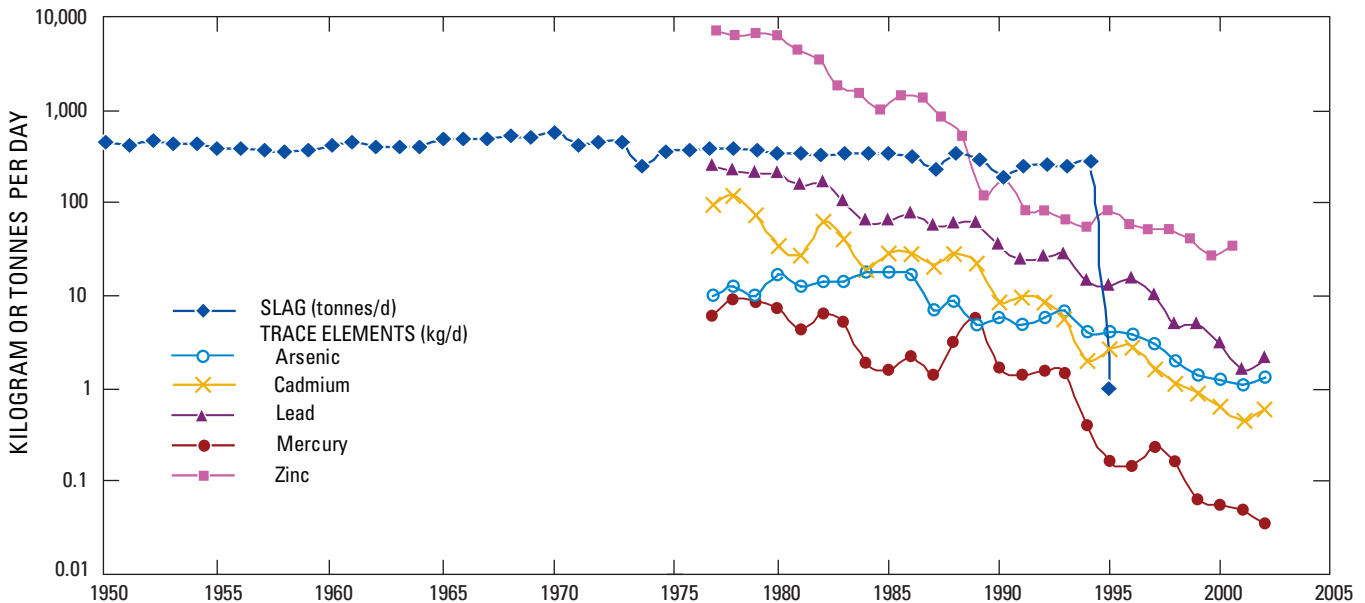


Figure 7. History of slag and trace elements in liquid effluent discharged to Columbia River by Trail smelter, British Columbia, 1940–2000. (Source of data: Cominco, 1992, 2001; U.S. Environmental Protection Agency, 2003; and William Duncan, Teck-Cominco, written commun., 2004.)

Trace Elements in Pore Water and Sediment

The concentrations of trace elements in sediment and pore-water matrixes were determined for samples collected at several depth intervals (surface to 1 cm, 1 to 2 cm, and 9 to 11 cm) in shallow cores collected at sites CCR-668, CCR-692, and CCR-705 (table 7, at back of report). Concentrations of mercury were not determined in pore water or sediment samples because the pore-water sample volume was insufficient for mercury analysis. Some uncertainty is associated with the dissolved concentration of trace elements in pore water because the concentrations of iron and zinc were quite different in replicate samples of pore water obtained from the 9 to 11 cm interval from site CCR-668. Concentrations of arsenic, cadmium, copper, lead, and zinc of the sediment matrix (table 7) also was determined for the sediments collected for pore-water analysis. Trace-element concentrations determined for pore-water sediments typically were within about 15 percent of trace-element concentrations reported for the sediments from the same or nearby horizon in the cores that were collected to determine concentration profiles within the accumulated sediments at each site (table 5).

Concentrations of dissolved arsenic, cadmium, copper, lead, and zinc in pore waters collected from these sediments (fig. 8) were often larger than ambient dissolved concentrations measured in Columbia River water at the Northport sampling station between 1992 and 2000 (Bortleson and others, 1994; Kelly and others, 2001). Thus, concentrations of these trace elements dissolved in pore water is most likely due to their close association to the elevated trace-element concentrations in the adjacent sediments through either leaching or remobilization of trace elements from the sediment phase to the pore-water phase. If present, slag may be a continuous source of zinc, and copper, which are present in slag in comparatively large concentrations. Recent studies have clearly shown that copper, lead, zinc, and other trace elements are readily leached from similar metallurgical slags (Parsons and others, 2001; Lottermoser, 2002; Piatak and others, 2004), although earlier studies by the Trail smelter report that slag was relatively inert with respect to the leaching of trace elements based on U.S. Environmental Protection Agency's Toxicity Characteristic Leaching Procedure (Cominco, 1991).

Some trace-element concentrations in pore water show a gradient of decreasing concentrations with depth that is opposite the trace-element concentration gradient in the sediment. Cadmium, copper, and to a lesser extent zinc follow this pattern. No clear pattern was noted for the pore-water concentration gradients of arsenic and lead. The precipitation of metal sulfides may explain the smaller

pore-water concentrations of some trace elements at depth. This explanation is supported by the lack of sulfate in pore water from cores CCR-668 and CCR-692 and the decreasing sulfate concentrations in the deeper intervals of core CCR-705. Under reducing conditions, which are thought to be present in sediments with pore water iron concentrations greater than 1,000 mg/L, sulfate reducing bacteria can readily convert sulfate to sulfide ions. In the presence of sulfide ions, dissolved metals such as iron, lead, mercury, and cadmium can form highly insoluble precipitates that are removed from solution.

Variability in pore-water concentrations also may occur seasonally due to the changing water levels in the reservoir. Water levels in the reservoir are lowered about 20 to 80 ft during April to June to provide storage volume for snowmelt in the upstream drainage basin. The changing lake level will affect the hydraulic head in the ground-water system discharging to the reservoir, likely increasing ground-water discharge during the drawdown period and possibly inducing the movement of surface water into the reservoir bed when the reservoir is returned to its normal operating water level. The reduction in static pressure during the drawdown period possibly increased the hydraulic gradient across the ground-water/surface-water interface increasing the potential for movement of pore water out of the bed sediments and into the overlying water. Following refilling of the reservoir to full pool elevation in June, the movement of water across the interface may have been reversed for a time when Columbia River water with relatively dilute concentration of trace elements may have seeped in the near-surface bed sediments. Pore-water samples were collected in mid-July, following return of the reservoir to full operating level after the seasonal drawdown of pool elevation to 1,265 ft the previous May. Information is not available to assess these potential effects on the pore-water concentration data.

A larger fraction of the trace-element concentrations in sediments of the mid-reach of Lake Roosevelt occur associated with the surface of sediment grains rather than associated with the interior matrix of the sediment grains. Prior to analysis of trace-element concentrations, four sediment samples were treated with hydroxylamine hydrochloride reagent to remove trace elements that are weakly sorbed to the grain surface or incorporated within iron and manganese oxide coatings. Concentrations of trace elements in the residual sediment fraction of the samples treated with hydroxylamine hydrochloride reagent were substantially lower than concentrations in untreated sediment samples (table 7). Concentration data for the total, residual, and leached fractions of arsenic, cadmium, copper, lead, and zinc (table 7) were plotted in figure 9, which shows that most of cadmium, copper, lead, and zinc concentrations are associated with the leached fraction from the surface of the sediment particle or reducible oxide coatings that have precipitated onto sediment surfaces.

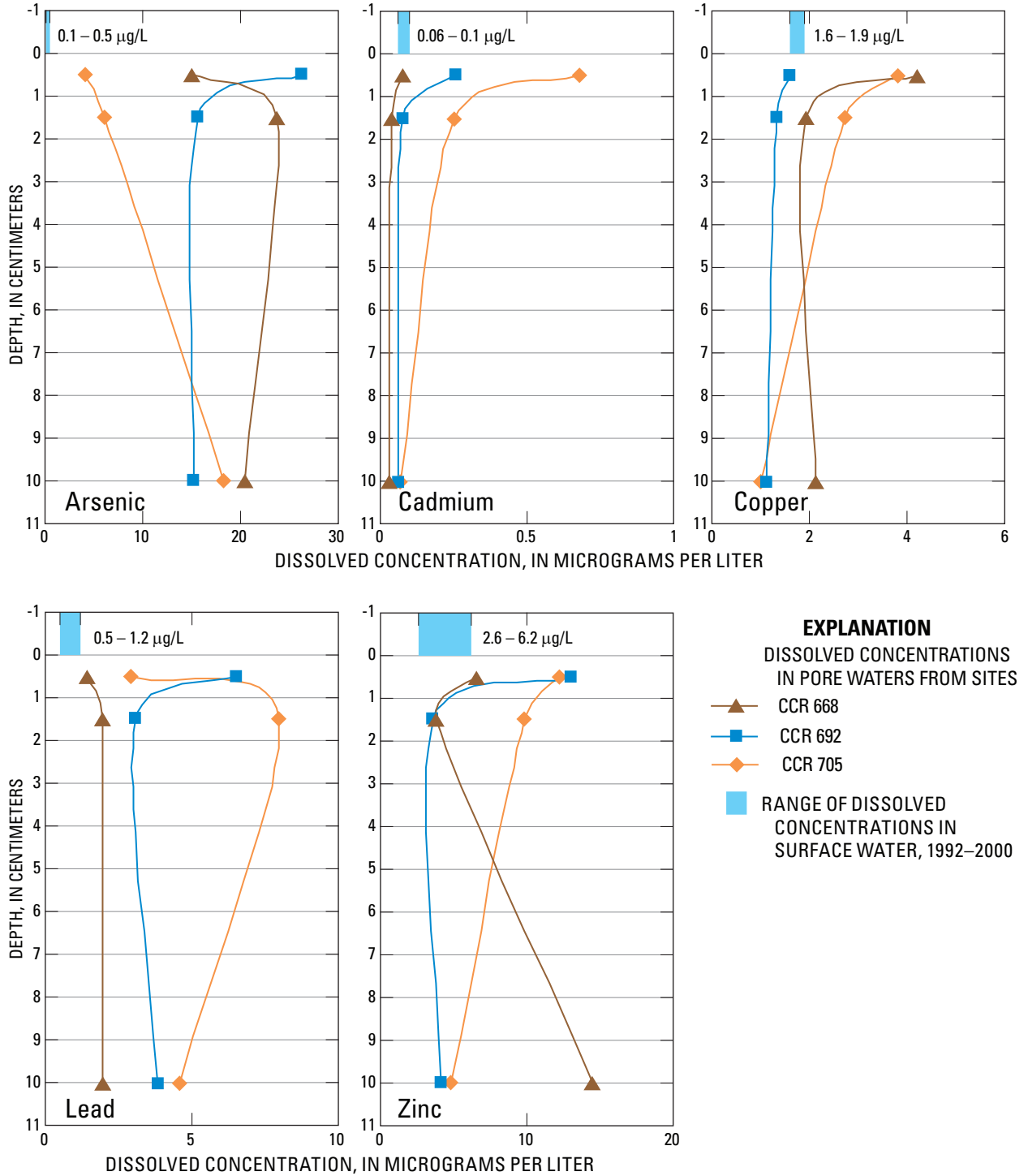


Figure 8. Vertical distribution of concentrations of dissolved arsenic, cadmium, copper, lead, and zinc in pore waters from sediment core sampling sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington.

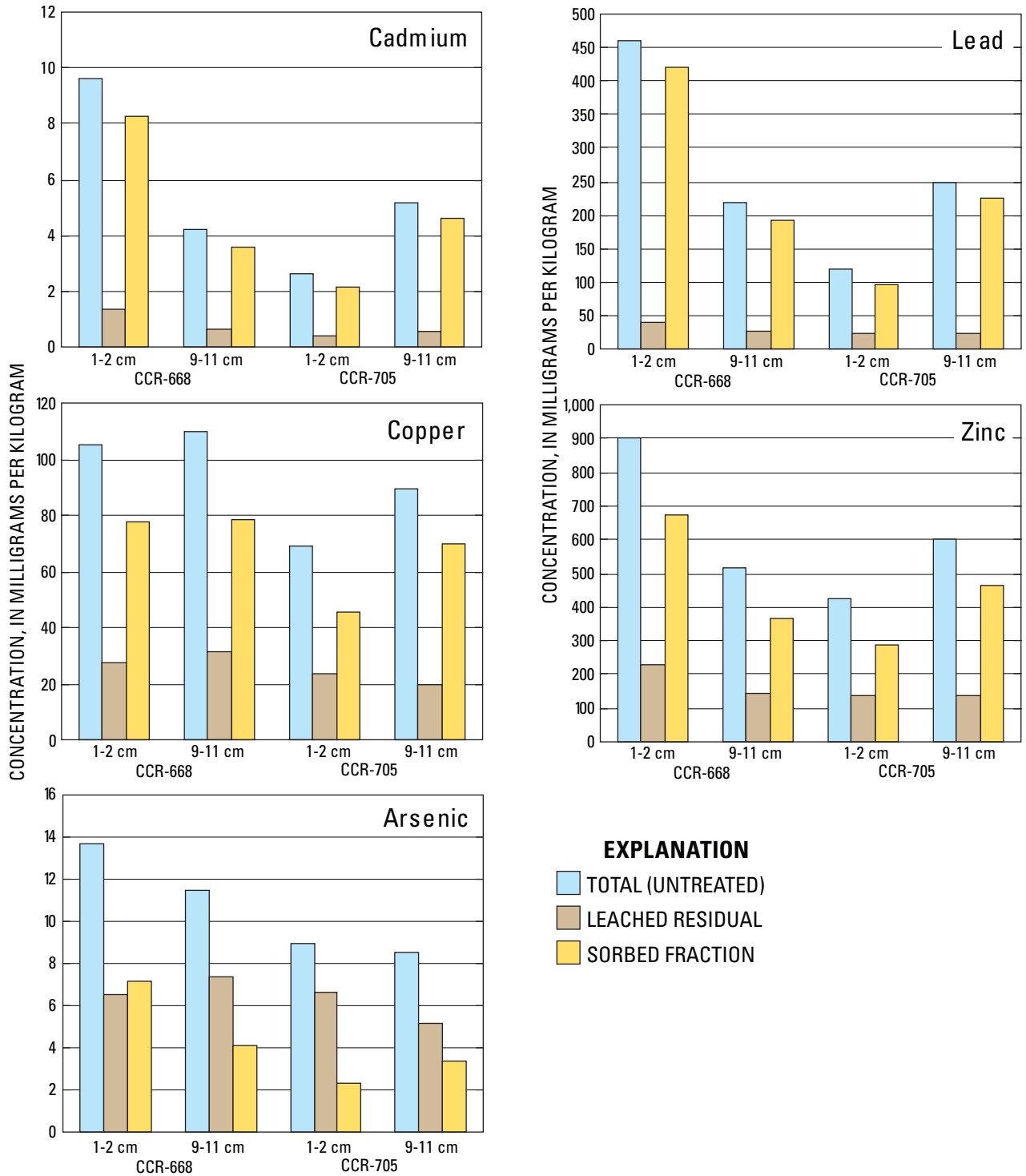


Figure 9. Concentrations of arsenic, cadmium, copper, lead, and zinc in whole sediment and leached residual (following extraction with hydroxylamine hydrochloride) from sediment core sampling sites CCR-668 and CCR-705, Lake Roosevelt, Washington, July 2003.

Thus, most of these trace elements are associated with the surface of the sediment particle where they are relatively accessible and are potentially bioavailable or susceptible to remobilization. Cadmium and lead were most influenced by sediment leaching processes as 85 to 90 percent of these trace elements generally are removed as indicated by residual sediment concentrations that were 10 to 15 percent (fig. 9) of the concentration in the untreated sediment samples. This effect is less pronounced for copper and zinc where 66 to 78 percent of copper and zinc concentrations are removed by exposure to the hydroxylamine hydrochloride reagent yielding residual sediment fractions of copper and zinc (22 to 33 percent), which are over twice those for cadmium and lead. Copper and zinc are the trace elements of concern that have the greatest concentration in the interior matrix of the slag particles, which may partially explain their higher concentration in the residual fraction. Arsenic was present mostly in the residual fraction and not as greatly associated with the surface of the sediment particles as were cadmium, copper, lead, and zinc.

Metallurgical Slag in Sediments of Lake Roosevelt

Slag particles have been widely deposited in the riverbed and along the banks of the upper and transitional reaches of Lake Roosevelt, particularly between Northport and the International Boundary. Slag particles make up from 70 to 90 percent by weight of the sand-sized particles of a black sand beach at RM 743 near the International Boundary (fig. 10). Particles of metallurgical slag have been found farther downstream in sediments of the Columbia River and Lake Roosevelt although easily identifiable slag grains diminish in number and size downstream of Northport. Slag particles can be readily distinguished from natural sediment grains of the Columbia River by a combination of distinctive morphology and physical features. The slag particles are sand size or smaller, black in color, and often have an iridescent sheen (fig. 11A). The surface texture of relatively unweathered particles is smooth, glassy, with a lustrous appearance while the surface of weathered grains has a dull-etched appearance. Slag particles have a distinctive morphology resulting from the combination of rounded and angular features often with needle-like projections, conchoidal fracture patterns, and small cavities or vugs (fig. 11B). Vugs generally are empty in unweathered particles while vugs in weathered particles are often filled with oxide precipitates, which may encrust much of weathered

particles. Slag grains in thin section often contain large voids (fig. 11C); particles are opaque to transmitted light but may transition to amber at the extreme tip of pointed projections. The matrix of slag particles is a glassy calcium-iron-silicate with varying amounts of aluminum. Internal structures within the glassy matrix include various mineral phases and rounded metallic-sulfide blebs or prills (figs. 12A, 12B, 12C) containing copper or lead; with associated metals such as antimony and arsenic (Bart Canon, Microlab Northwest, Seattle, Washington, written commun., 2001). The density of slag particles varies, generally exceeding 2.9 g/cm^3 , however, some slag particles, which may have large voids, were observed floating on the water surface near the shore.

The general trace-element composition of slag discharged to the Columbia River is reported to vary considerably with typical concentrations of weight percent of <0.1 percent for lead, (<1,000 mg/kg); 3 percent for zinc (30,000 mg/kg); <0.01 percent cadmium (<100 mg/kg); and about 1 percent copper (10,000 mg/kg) (Cominco, 1991). G.J. Gawryletz (Cominco Ltd., written commun., 1998) reported substantially larger concentrations of zinc and lead, 12 and 2 percent, respectively, from residual slag deposits along the Columbia River following demolition of the slag launder and these concentrations were about three times larger than earlier reported concentrations. These data confirm that trace-element concentrations vary in Trail smelter slag.

Readily available reported chemical analysis of slag including elements other than the six trace elements of concern include the three analyses reported by Nener (1992) in which the slag was sampled prior to release to the environment. Majewski and others (2003) provided an analyses of 'riverine slag'; a sample collected along the riverbank containing both slag and natural river sediments. A similar sample collected from the beach at RM 743 (RSS-743) was analyzed for this study; the sample was sieved and sorted using a binocular microscope in an attempt to remove as much of the non-slag material as possible. Analysis of the sorted slag sample (RSS-743) is included in table 5 (after data for CCR-705).

The slag particles collected from a beach near the Columbia River International Boundary Auxiliary Gage at RM 743 is physically and chemically similar to the description of metallurgical slag discharged from the Trail smelter (Cominco, 1991). Bulk chemical compositions were determined for the polished interior surface of individual slag particles using a scanning electron microscope equipped with an energy-dispersive X-ray spectrometer (SEM/EDS). Median element-weight percentages of the slag determined by SEM/EDS were 37 for iron, 10 for calcium, 2.8 for aluminum, 2.6 for zinc, 1.3 for sodium, 0.8 for magnesium, 0.6 for manganese, 0.5 for copper, and 0.4 for potassium.

The SEM/EDS measurements of elemental concentrations RSS-743 matched closely the reported chemical analysis of slag discharged to the Columbia River by the Trail smelter (Nener, 1992) and the chemical analysis of the slag sample RSS-743 as shown in the boxplots in [figure 13](#). The SEM/EDS analysis was determined from the measurement of 22 individual grains, whereas the elemental composition of slag from the Trail smelter was determined from an acid digest of three samples of fresh slag collected during a single day (Cominco, 1991; Nener, 1992). The comparison was limited to those elements determined by the SEM/EDS that were present in the sample at concentrations greater than 0.5 percent. The nine elements from all analyses were a close match considering differences in sample representation and methods of analysis ([fig. 13](#)). The close match between the suite of elements in the analysis of individual slag particles and bulk chemical analysis of slag also provided a method to confirm the identity of slag particles in downstream reaches of the reservoir.

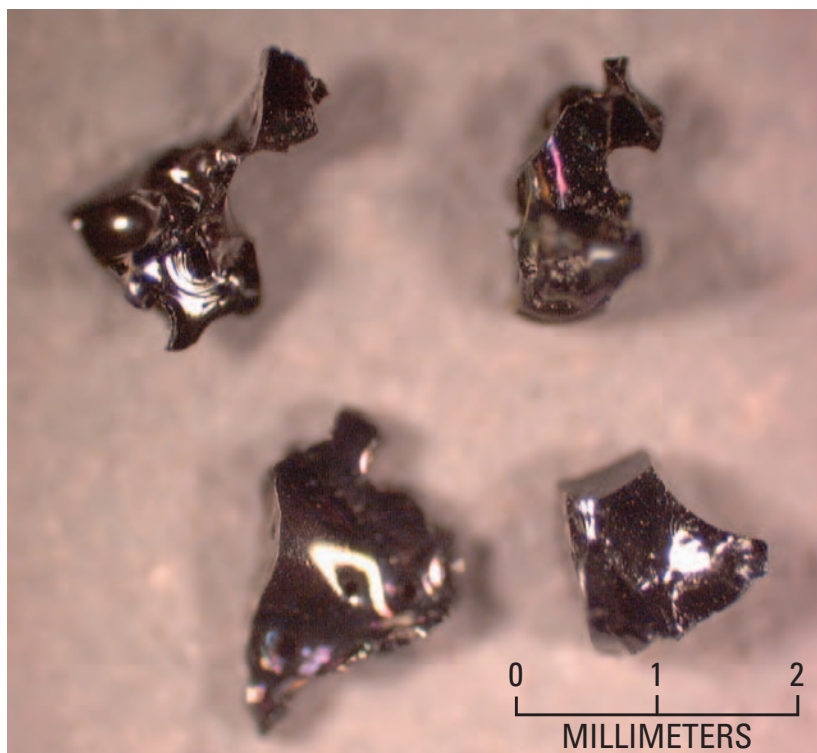
Sediment particles isolated from selected sample intervals from the three upstream cores, CCR-668 interval 95-100; CCR-692 interval 30-32 cm, and CCR-705 interval 14-16 cm were classified as slag grains based on physical characteristics, density, and chemical composition. The largest particles, on the order of 1-2 mm that were most similar to those from the Columbia River sand bar at RM 743 (RSS-743), were

from the interval 100-105 cm below the upper surface of CCR-668 (sediment-water interface). Slag particles in cores CCR-692 and CCR-705 were on the order of 0.05 to 0.1 mm, which was consistent with the predominant particle size of these sediments. The trace-element profiles for core CCR-668 indicate that the interval in which the slag particle was identified was in a section of the profile affected by landslides, thus, the slag in this interval likely was reworked material that had been transported to this area of the reservoir prior to construction of Grand Coulee Dam. Although these particles had similar color, shape, and optical properties to slag material from the gage location at RM-743, the surface appearance typically was more weathered, without the glassy-lustrous appearance, but retained some of the iridescent sheen.

The chemical composition determined by SEM/EDS of the surface of slag particles from core CCR-668 closely matched the slag particles from the recent beach deposit (sample RSS-743) except that the concentration of calcium typically was lower by as much as 70 percent in slag from core CCR-668 ([fig. 14](#)). Further SEM examination showed that the concentration of calcium on the surface of the slag particles from RSS-743 was intermediate between the relatively unweathered composition determined for the interior matrix of slag from RSS-743 and weathered surface of slag particles that had been buried with the reservoir sediments for some 20 to 40 years.



Figure 10. Black sand beach composed of 70 to 90 percent slag particles deposited near Columbia River gaging station at river mile 743, Washington.

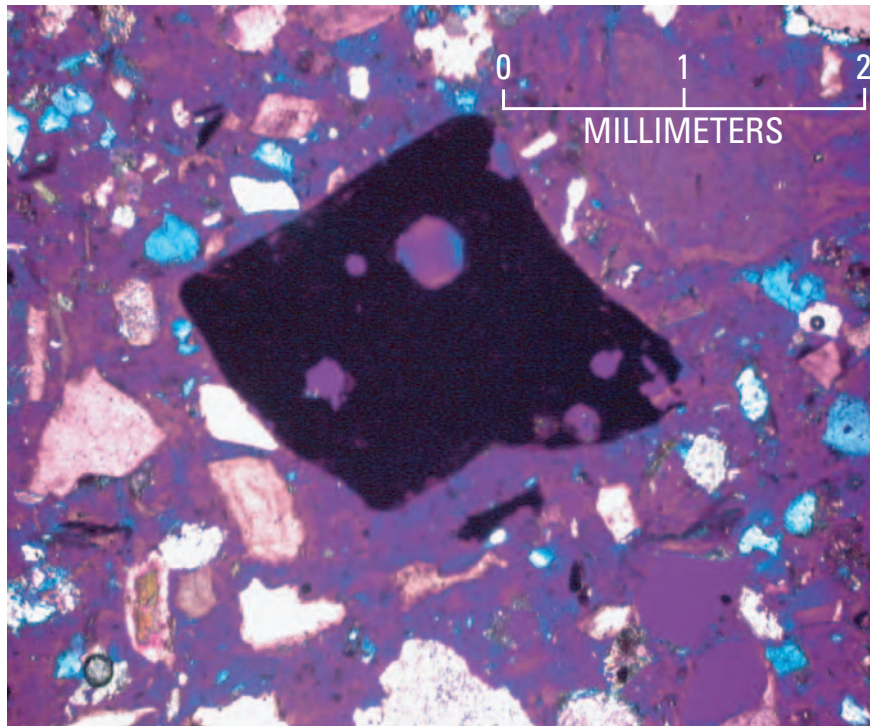


A. Recent deposited slag particles from river mile 743 (RSS-743).



B. Weathered slag particle from pre-reservoir sand deposit underlying lacustrine sediment in Lake Roosevelt near river mile 685 (RSS-685).

Figure 11. Slag particles (RS-743) identified in sediment from Lake Roosevelt and the upper Columbia River, Washington.



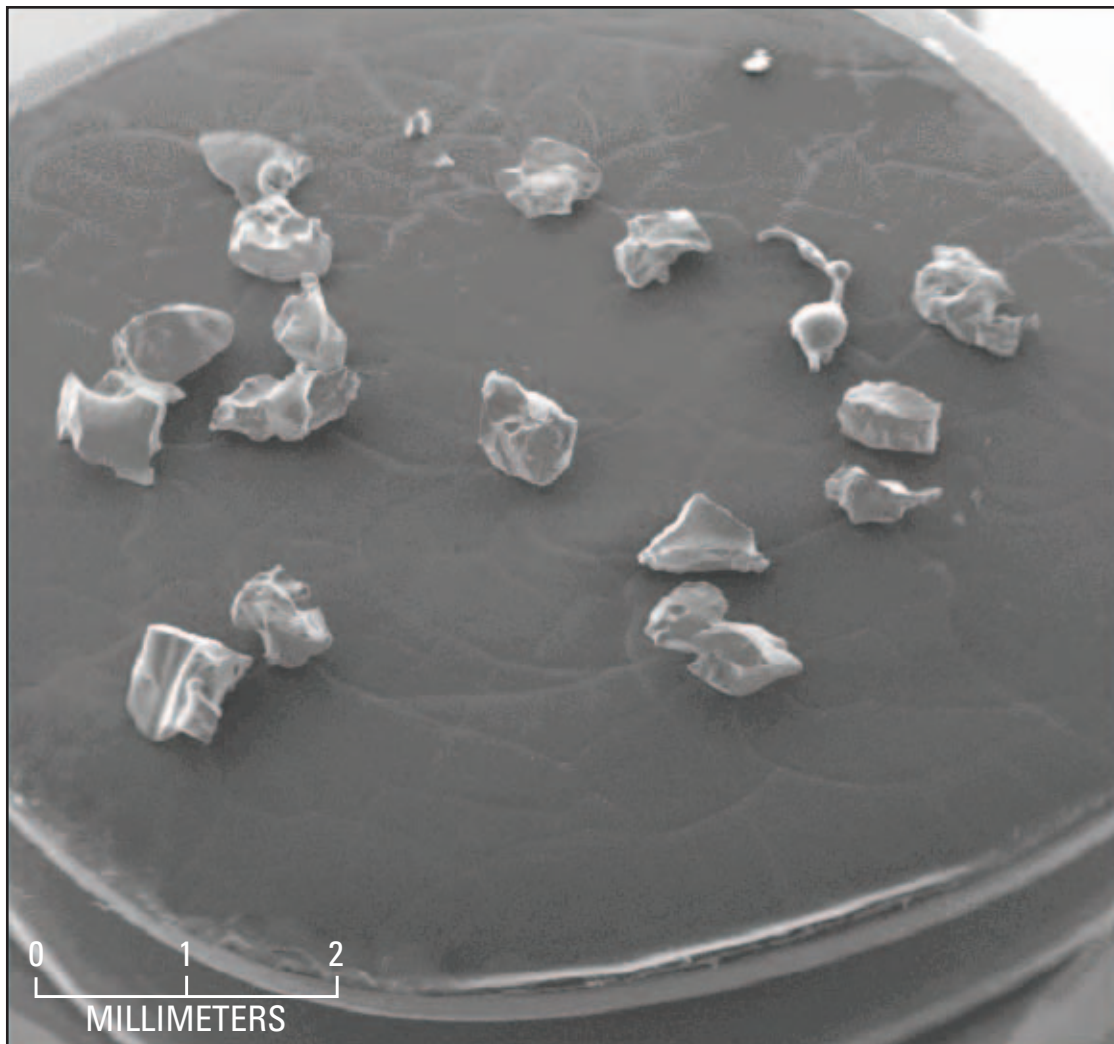
C. Thin-section of slag particle and sediment from beach deposit near river mile 724 (RSS-724).

Figure 11.—Continued

The decrease in calcium is consistent with weathering of basaltic-volcanic glass, as calcium is often the most readily leached major element from basaltic glass (Eggleton and others, 1987). Calcium was determined to be selectively mobilized from massive lead-zinc slag exposed to natural weathering in Czechoslovakia for more than 100 years (Ettler and others, 2001). The surface texture and morphology, observed by SEM, of slag-like particles from the core sediments were marked by a flaky appearance and the precipitation of iron-oxide (figs. 15A and 15B). The dimensions of the surficial flakes typically were 20 to 50 microns across and 2 to 5 microns thick and likely result from the development of exfoliation lamina on the surface of slag particles caused by the hydration of glassy slag material as described by Freidman and others (1966) and Morganstein and others (1999).

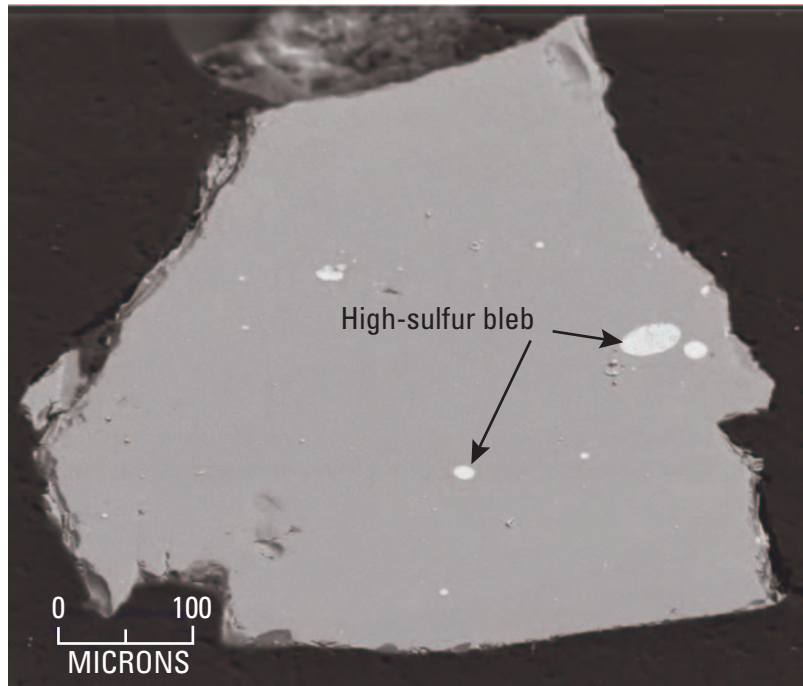
Glassy slag deposited in the sediments of Lake Roosevelt shows definite signs of undergoing hydration and chemical weathering, rather than being chemically stable as described by Cominco (1991). Fourteen of eighteen slag grains from core CCR-668 that were examined with just the SEM showed signs of surficial weathering by the development of exfoliation flakes (figs. 15A-15D). There also were differences in the

chemical compositions of the interior and exterior surfaces of the weathered slag material (fig. 16). SEM/EDS was used to measure the chemical composition of six locations on an interior surface exposed by the removal of an exfoliation flake and exterior surfaces of the slag grain shown in figure 12B. On the interior surface where the flake had been removed, the concentrations of calcium, iron, and zinc were larger compared to the outer surface. Concentrations of silicon, oxygen, potassium, aluminum, and sodium were higher on the exterior surface than on the interior surface. The distribution of these elements is consistent with weathering processes as calcium and iron are often mobile elements removed during chemical weathering while silicon, aluminum, and oxygen are more recalcitrant elements whose concentrations become larger in the residual weathered material. Further evidence of slag weathering is the development of weathering rinds, typically about 20 to 100 microns thick, as shown in slag grains below the lacustrine sediments south of French Rocks, RSS-685 (figs. 15C and 15D). Weathering rinds were not observed in the polished cross section of the unweathered slag particles collected from the beach deposit near the gage site at RM 743 (RSS-743) (fig. 12B).

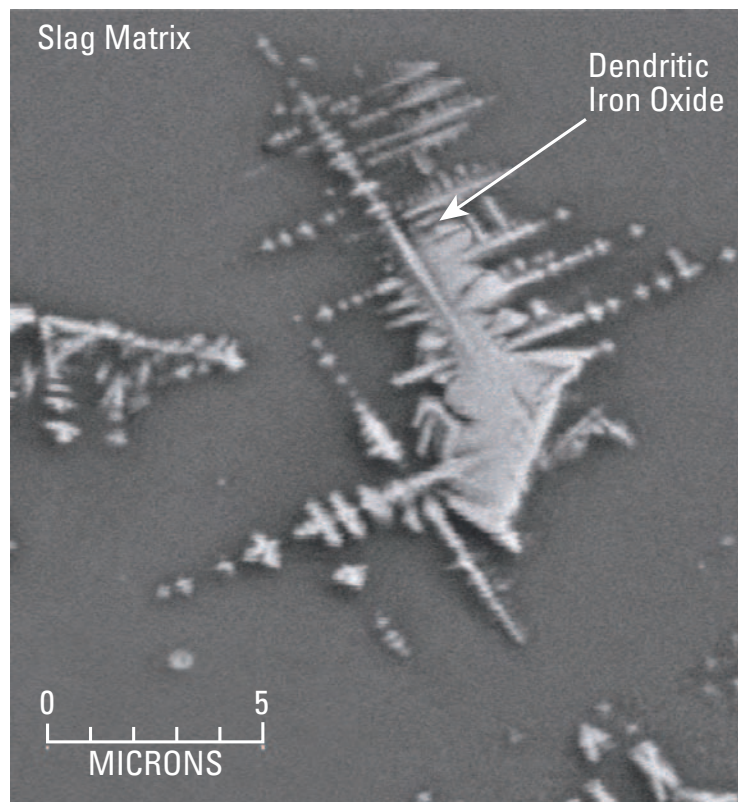


A. SEM back scatter image of recently deposited slag particle RSS-743.

Figure 12. Scanning electron microscope (backscatter images) of unweathered slag particles from Lake Roosevelt, Washington.



B. Polished grain mount of unweathered slag grain showing internal features of slag particle (RSS-743)



C. Polished grain mount of unweathered slag grain showing internal features of slag particle (RSS-743)

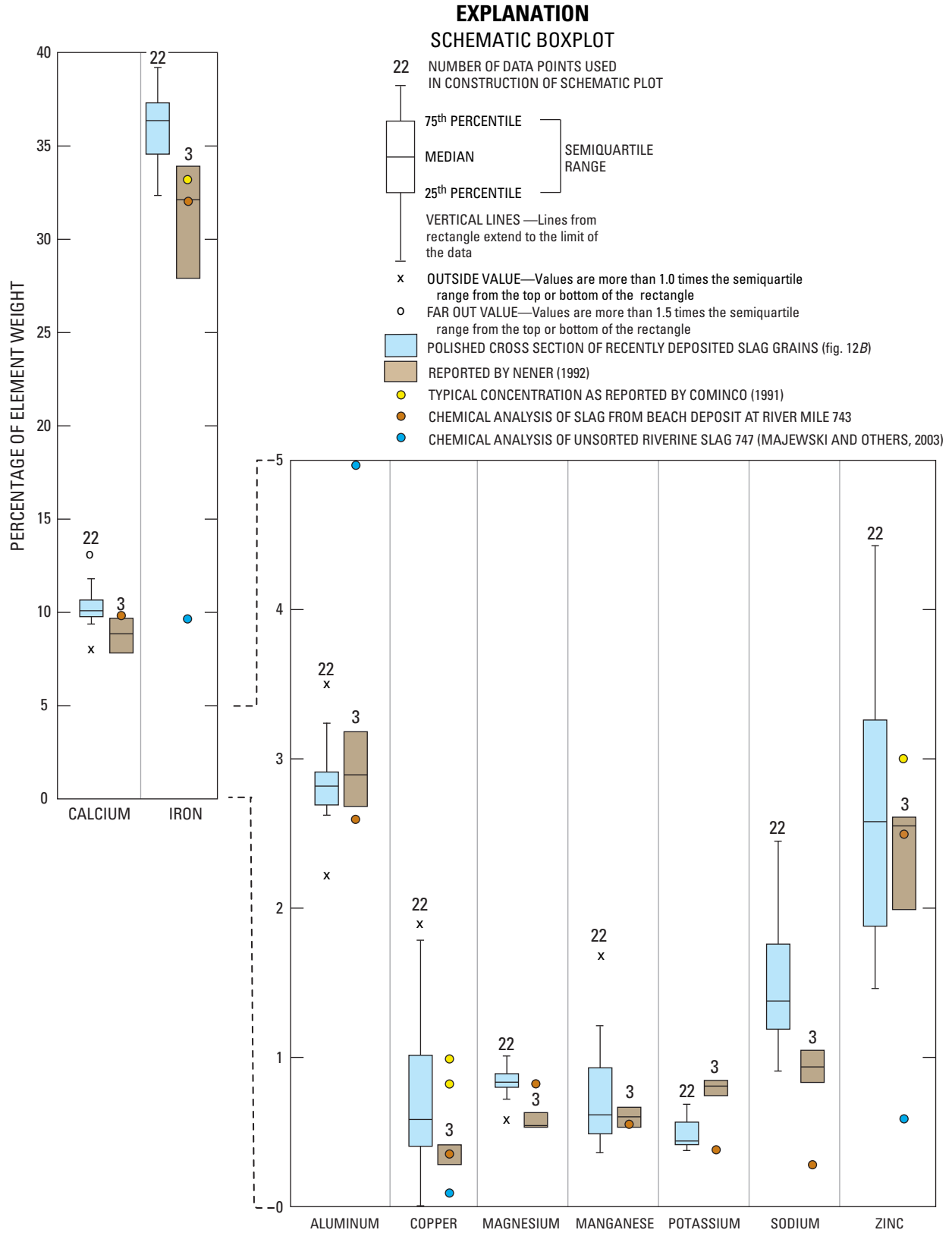


Figure 13. Trace-element concentrations determined by SEM/EDS of slag particle (sample RSS-743) and reported concentrations from previous studies determined by acid digestion and instrumental analysis, Lake Roosevelt, Washington.

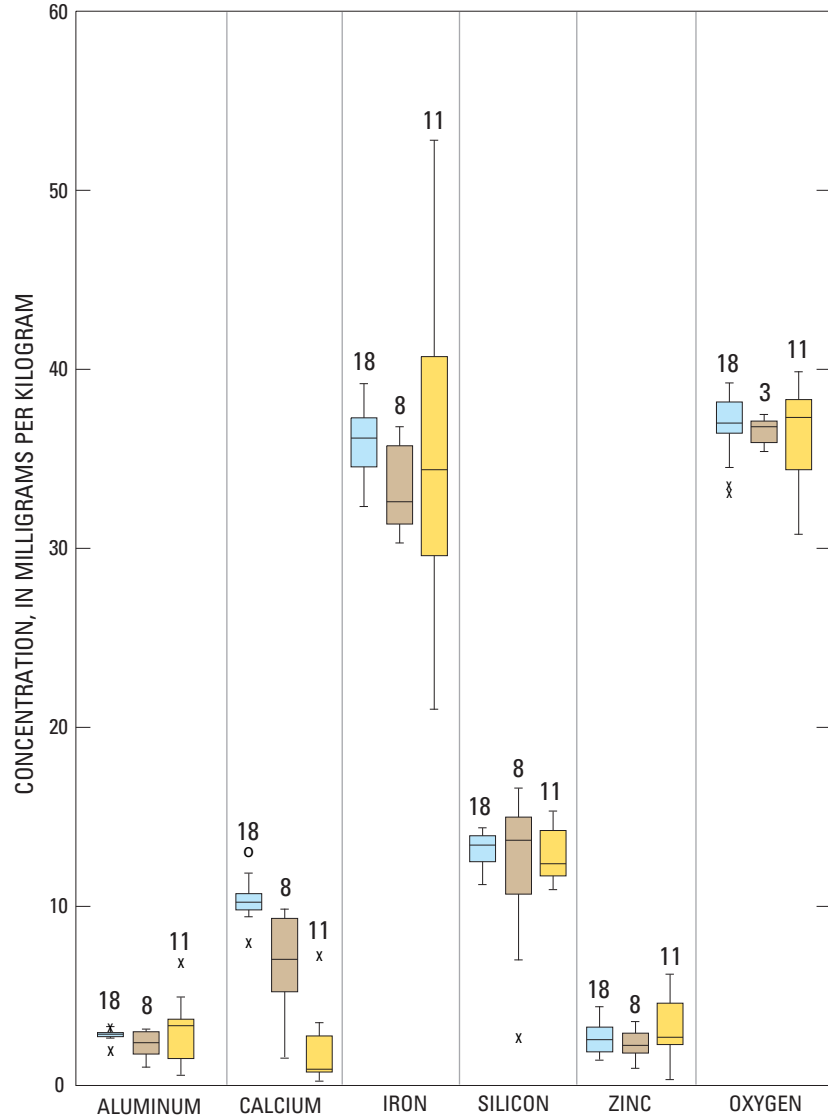
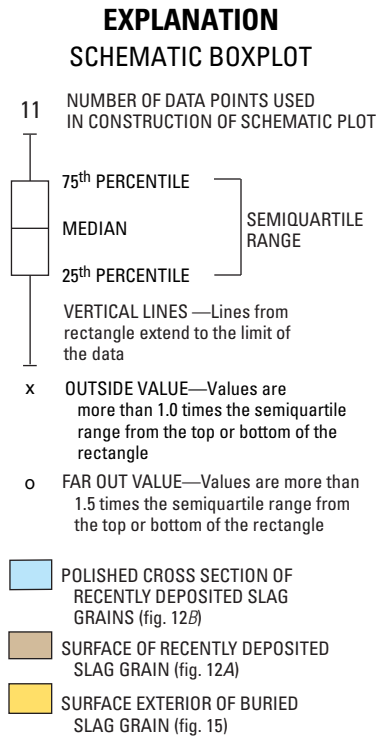
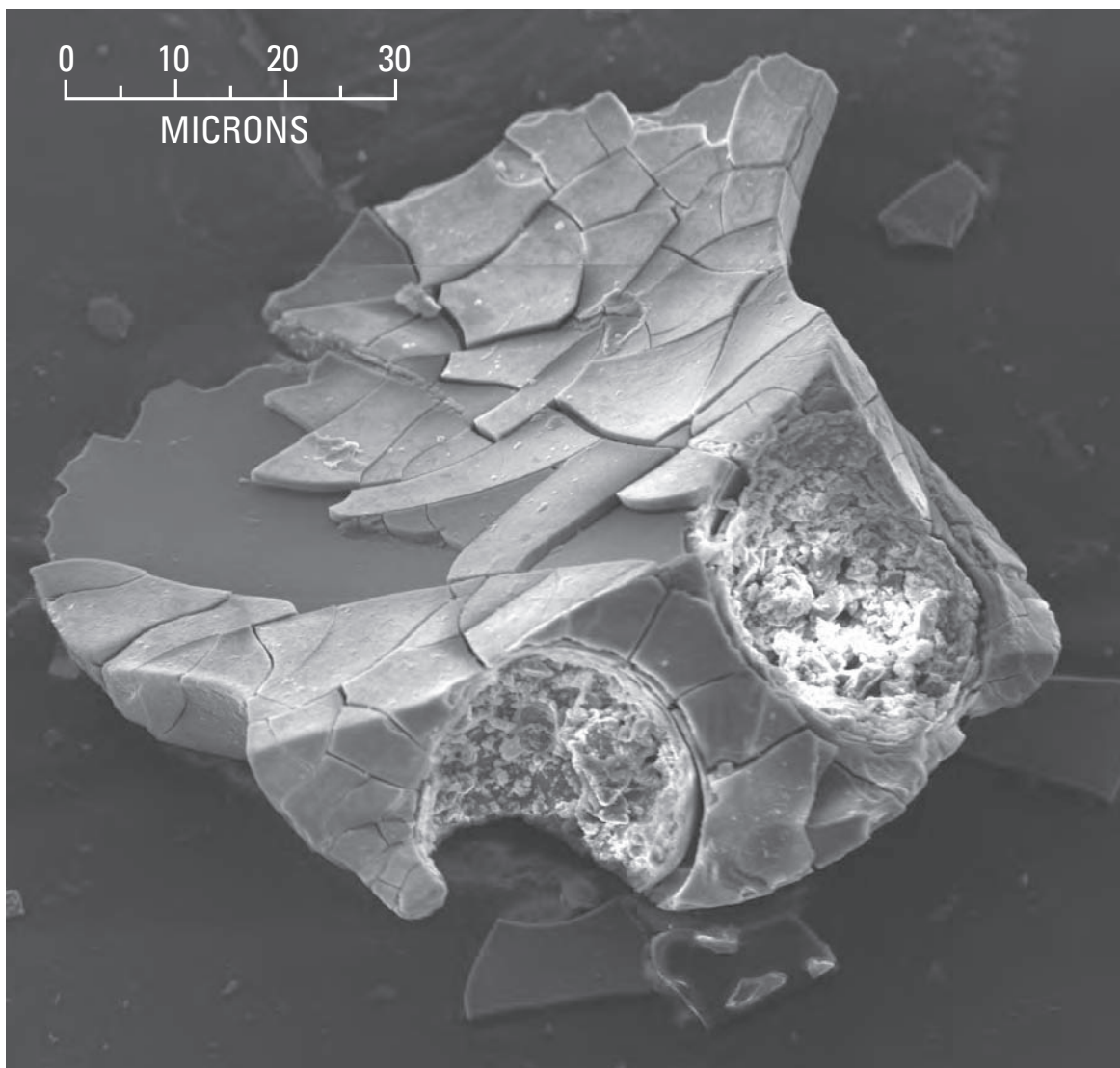
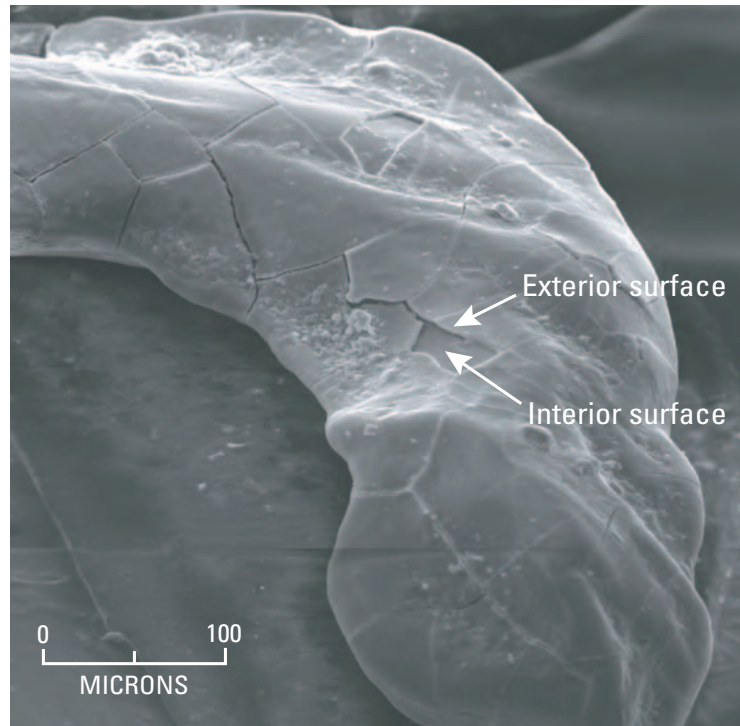


Figure 14. Trace-element concentrations determined by SEM/EDS of recently deposited slag particles and slag grains from core sediments, Lake Roosevelt, Washington.

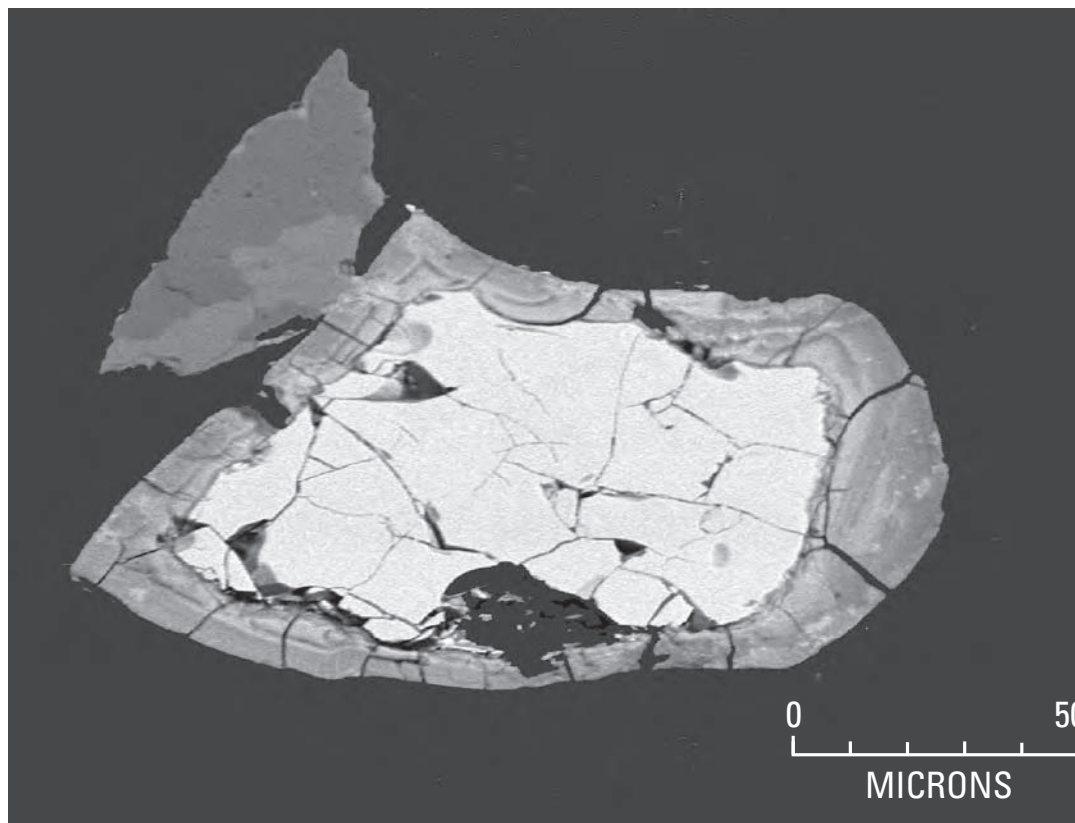


A. Weathered slag particles showing well developed flaked surface and vugs filled with iron hydroxide (CCR-668; interval 100-105 cm).

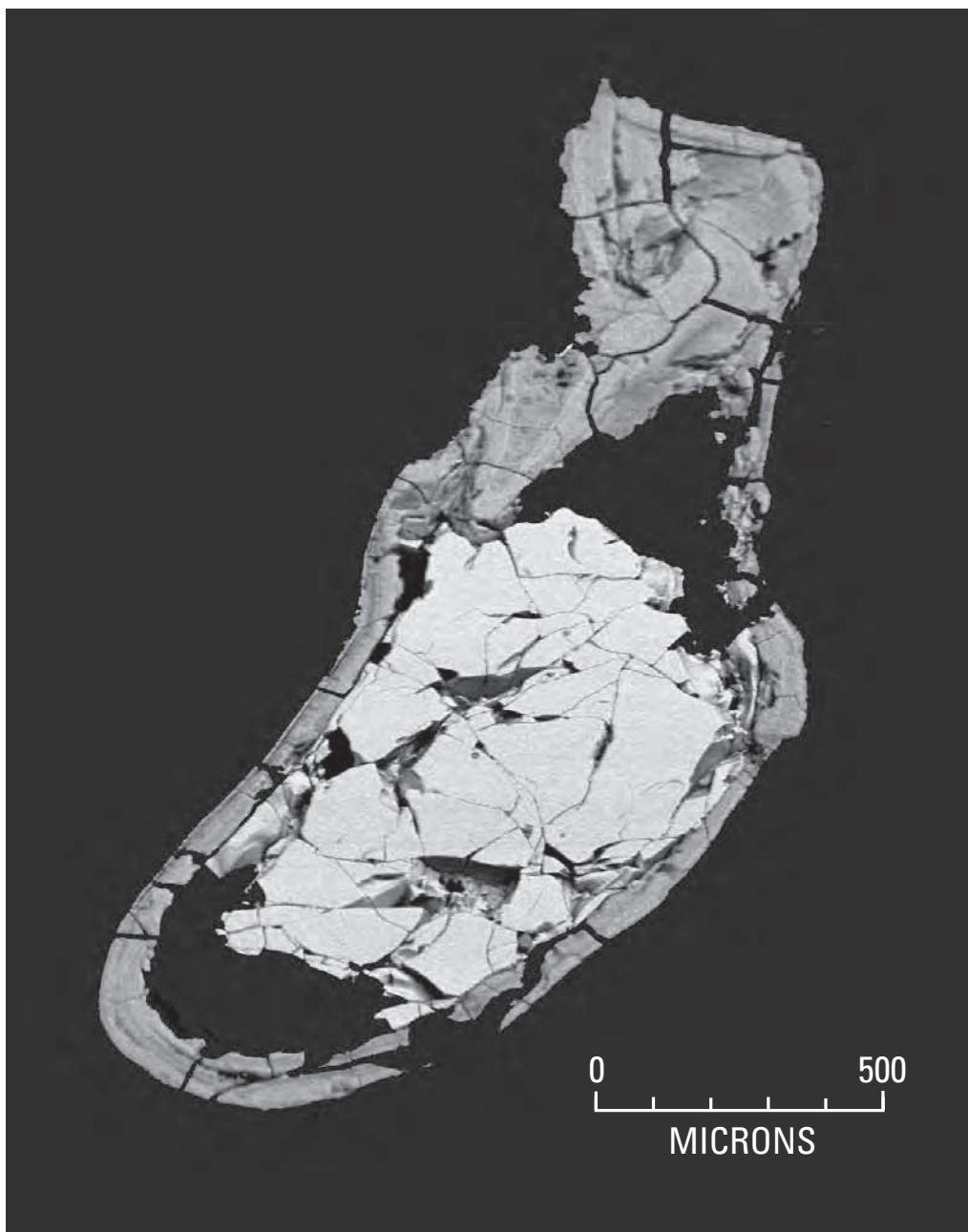
Figure 15. Scanning electron microscopic (backscatter images) of weathered slag particles from Lake Roosevelt, Washington.



B. Weathered slag particles showing well developed flaked surface and vugs filled with iron hydroxide (CCR-668; interval 100-105 cm).



C. Polished thin section of weathered slag grain showing weathering rinds; typical thickness 20 to 100 microns (RRS-685).



D. Polished thin section of weathered slag grain showing weathering rinds; typical thickness 20 to 100 microns (RRS-685).

Figure 15.—Continued

EXPLANATION
SCHEMATIC BOXPLOT

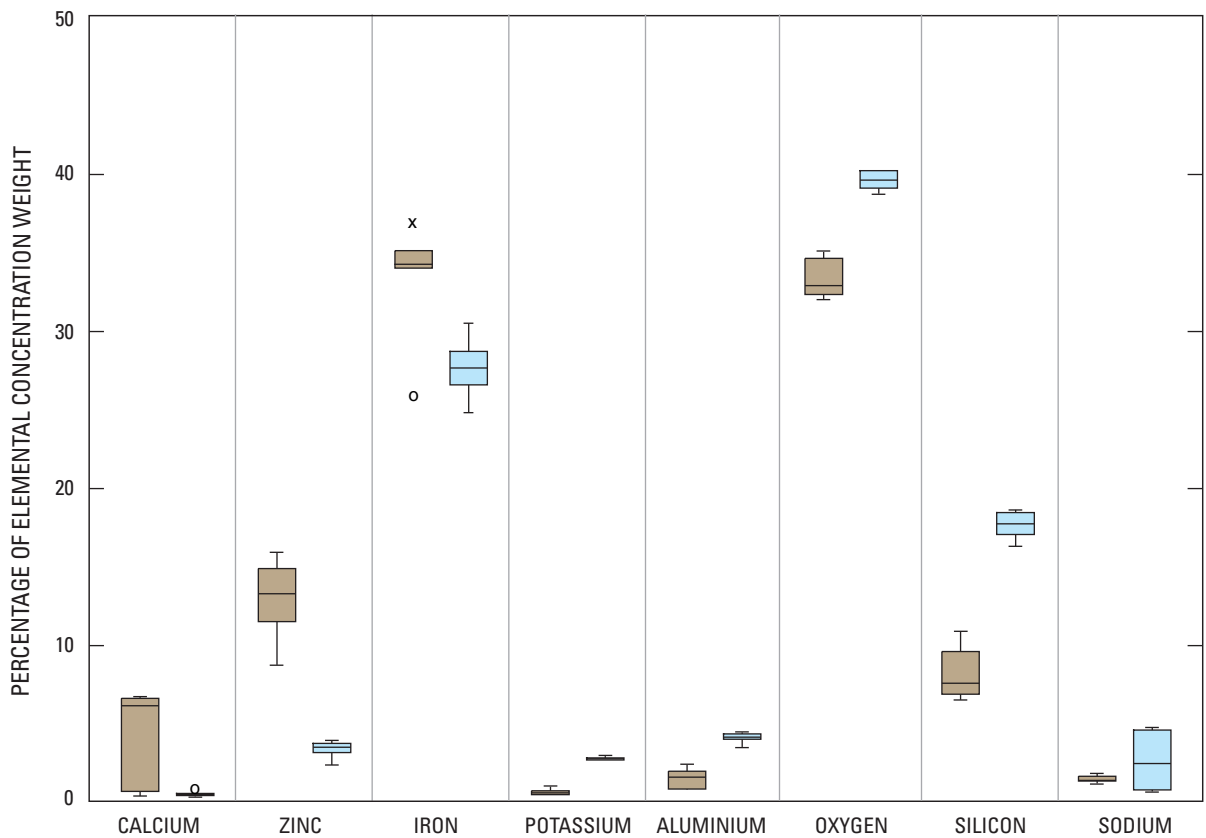
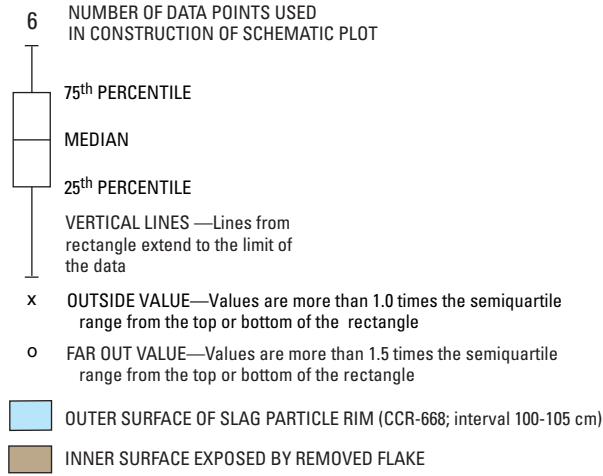


Figure 16. Trace-element concentrations determined by SEM/EDS of outer surface of slag particles and inner surface exposed by removal of exfoliation flake, Lake Roosevelt, Washington.

Relative Impacts of Slag and Liquid Effluent Discharge on Trace-Element Concentrations in Bed Sediment

Multiple lines of evidence indicate that the influence of slag on trace-element concentrations in the sediments of the middle and lower reaches of Lake Roosevelt are likely secondary to the influences of liquid effluent discharges. First, the low percentages of cadmium and lead, and to a lesser degree zinc and copper, present in the residual of the leached sediment samples indicates that these trace elements are predominantly associated with the sediment grain surface rather than the interior matrix of the sediment grains. If slag were the primary source of these trace elements, most of the mass of the element would be in the interior matrix of the slag particles and not susceptible to leaching with hydroxylamine hydrochloride reagent.

Second, the widespread and approximately concurrent decreases in trace-element concentrations observed in the trace-element profiles above the 1964 horizon in the Columbia River cores are more consistent with trace-element discharges in the liquid effluent than discharges in slag material. Trace elements sorbed to very fine-grained sediment surfaces typically originate as dissolved trace elements or trace elements bound to or associated with colloidal material such as that discharged in the liquid effluent of the Trail smelter. Dissolved and colloiddally associated trace elements are more easily transported throughout the length of the reservoir than slag that is discharged as predominantly sand-size particles and would require more time for even the smaller size fractions to be transported to the lower reaches of the reservoir. Transport of most of the slag particle-size fractions within the middle and lower reaches of the reservoir is limited to times when flow is great enough to transport larger grain sizes. As a result, the effects of slag discharge on trace-element concentrations in the accumulated bed sediments would take longer to be observed in the lower reaches of the reservoir and would likely be less pronounced.

Although slag was observed below lacustrine bed sediments at RM 680 and in core CCR-668, the presence of large slag deposits like that shown in [figure 7](#) in or below the lacustrine sediments of the reservoir is most likely an uncommon occurrence. Direct observation of slag grains in reservoir sediments generally was confined to the upper reaches of the reservoir above RM 700. Using a point-count microscopic examination, Bortleson and others (1994) estimated that slag made up about one-half of the sediment

sample from RM 745 near the International Boundary, about 28 percent of the sediment at RM 738, and only about 5 percent of the sediment at RM 730. Likewise, Bart Canon (Northwest Microprobe, written commun., 2002) estimated that while slag composed a substantial fraction of sediments from near RM 744 and RM 748, slag was a negligible fraction of sediments from near RM 723.

Third, the timing of most of the major decreases in trace-element concentrations occurring within the trace-element profiles occur throughout the period following the CS-137 peak associated with the mid-1960s. The more gradual reduction observed in the trace-element profiles from the cores also is more consistent with the trend in the reduction of trace-element loading in liquid effluent ([fig. 7](#)) than compared to trend in historical reductions of slag discharge. This is most clearly observed for mercury and cadmium and to a lesser degree lead, which are very minor components of slag (Cominco, 1991), but substantial components of the liquid effluent discharge (British Columbia Ministry of Environment, 1976). Zinc is a substantial component of both liquid effluent and slag material discharged by the Trail smelter.

The concentration of copper in bed sediments may be a useful indicator of the presence of slag in sediments from Lake Roosevelt. Copper is distinctive among the six trace elements of concern because it is discharged by the Trail smelter primarily as slag. Using estimates of slag percentage in sediments from the upper reach of the reservoir (Bortleson and others, 1994) and assuming that all copper reported in the measured concentration for the corresponding samples is due to the presence of slag, the calculated concentration of copper in slag at those locations would be expected to range from 0.7 to 1.5 percent. This is consistent with the measured and reported range of copper concentrations in slag from the Trail smelter of about 0.6 to 1 percent. If the presence of elevated copper concentration in sediments is largely the result of slag particles (a conservative assumption based on the sediment leaching data), sediment samples with less than 125 mg/kg of copper would be expected to contain less than 1 percent slag in addition to a background concentration of about 25 mg/kg of copper. Applying this reasoning to the longitudinal gradient of copper in Lake Roosevelt sediments observed by Majewski and others (2003), and Bortleson and others (1994), the major influence of slag in sediments is limited to reaches upstream of about RM 687. Thus, the trace-element concentrations of zinc, lead, cadmium, mercury and to a lesser extent arsenic in sediments in the lower and middle reaches of the reservoir are largely due to the input from liquid effluent discharged to the Columbia River, which can easily be transported the length of the reservoir as dissolved or colloidal material.

Summary and Conclusions

In 2002, the U.S. Geological Survey conducted a study of Lake Roosevelt to collect information on the vertical distribution of trace elements within the accumulated bed sediments and pore water of Lake Roosevelt, the 217-km-long impoundment of the Columbia River upstream of Grand Coulee Dam, Washington. Vertical distributions of trace-element concentrations were determined from six sediment cores collected in September 2002. The analysis of cesium-137 data indicate that two sediment cores contained sedimentary records extending to the initial reservoir filling in 1941 and the remaining four cores contained at least 60 percent of the sedimentary record. Pore-water samples were collected and analyzed from the top 10 cm at the three upstream core sites.

Concentrations of the trace elements of concern, arsenic, cadmium, copper, lead, mercury, and zinc, varied greatly in the sediment core profiles, often covering a range of 5 to 10 fold. Maximum concentrations in sediment samples were as high as 2,200 milligrams per kilogram (mg/kg) for zinc, 920 mg/kg for lead, and 250 mg/kg for copper, with median concentrations of 970, 260, and 53 mg/kg, respectively. Concentrations of arsenic, cadmium, and mercury were lower. Maximum concentrations were as high as 34 mg/kg for arsenic, 23 mg/kg for cadmium, and 2.8 mg/kg for mercury, with median concentrations of 13, 7.5, and 0.58 mg/kg, respectively. Concentrations of cadmium and mercury exceeded the upper range of reference sediments by 10 times or more in 77 and 47 percent of the samples analyzed, respectively.

Concentrations of lead and zinc exceeded reference sediments by 10 times in less than 25 percent of the samples analyzed. Prominent temporary decreases in the concentrations of cesium-137 and trace elements indicate an influx of sediments from landslides. Of these trace elements of concern, concentrations of arsenic and copper were least elevated above concentrations in reference sediments. All samples exceeded cleanup guidelines adopted by the Colville Confederated Tribes for cadmium, lead, and zinc and more than 70 percent of samples exceeded cleanup guidelines for mercury, arsenic, and copper. Although 100 percent of samples exceeded sediment guidelines for cadmium, lead, and zinc, surficial concentrations of arsenic, copper, lead, and mercury in some cores were less than the sediment-quality guidelines.

Trace-element concentrations were highest beneath surficial sediments, typically in the lower one-half of each profile. With the exception of copper, the trace-element profiles of the five cores collected along the pre-reservoir

Columbia River channel typically showed trends of decreasing concentrations from the 1964 sediment horizon to the sediment-water surface. Along the longitudinal profile of the reservoir, surficial concentrations of zinc, copper, lead, cadmium, and mercury showed trends of decreasing concentration, while concentrations of arsenic tended to increase slightly downstream. Trace-element concentrations and profiles in sediments from the Spokane Arm of the reservoir showed distinct differences compared to the similarities observed among the cores from along the pre-reservoir Columbia River. These differences likely are due to the greater influence of sediment inflow from the Coeur d'Alene basin to that portion of the reservoir.

Overall, the depth concentration profiles typically show maximum concentrations of arsenic, cadmium, lead, mercury, and zinc often occurred in the lower to mid sections (closer to the bottom) of the trace-element profile and the concentrations of copper often were highest (closer to the surface) in the trace-element profiles. The concentration profiles for arsenic, cadmium, lead, zinc, and to a lesser extent mercury, also clearly show decreasing concentrations in more recently deposited sediments throughout the reservoir as reported by Majewski and others (2003). However, the concentration profiles for copper generally show trends of increasing concentrations in more recent sediments with the exception of core CCR-692. Within individual cores, the concentration profiles of arsenic, cadmium, copper, lead, mercury and zinc showed similar patterns of relative concentrations. Variation in the concentration of zinc, lead, cadmium, and mercury were consistent to the extent that concentration profiles were often near parallel. In some core intervals, the influx of sediments from bank material accentuated the near parallel concentration profiles.

Concentrations of dissolved arsenic, cadmium, copper, lead and zinc in pore waters were often higher than ambient dissolved concentrations measured in Columbia River water and thus may be a source of trace elements to the overlying surface water. The limited pore-water concentration data was inconclusive with respect to the extent of remobilization of trace metals from buried sediments to the overlying water. Additional information is needed on possible seasonal variation in pore concentrations that may be affected by the changing pool elevation in the reservoir. The leaching experiment indicated that most of the mass of trace elements associated with the contaminated sediments is associated with the surface of the sediment particle where it is more accessible to physical, chemical, and biological processes that could remobilize the trace element into the overlying water column.

Selected samples were analyzed for the presence of metallurgical slag, a trace element-rich byproduct of metals smelting processes, which was discharged into the Columbia River by a smelter in Trail, British Columbia, upstream of the reservoir prior to 1995. Particles that had physical and chemical characteristics of slag discharged to the Columbia River were present in the sediments of Lake Roosevelt. Particles of slag were isolated from three cores based on their distinctive physical characteristics, appearance (smooth, glassy-lustrous, black in color, and being both angular and rounded in shape), and chemical composition measured using a scanning electron microscope equipped with an energy dispersive spectrometer (SEM/EDS). The chemical composition of the interior matrix of slag collected from a black-sandy beach near the International Border closely approximated the reported elemental concentrations of fresh smelter slag. Slag particles isolated from the core sediments appeared more weathered due to the lack of the glassy-lustrous appearance; however, their chemical composition closely matched the composition of unweathered particles except that the concentration of calcium was roughly 20 percent smaller. SEM/EDS examination of the morphology of the surface of many of the slag particles from the core sediments showed the development of exfoliation flakes suggesting that the glassy slag material was undergoing hydration and chemical weathering.

Slag, while common in the uppermost reaches of the reservoir above river mile 720, may be present only in minor amounts in sediments of the lower and mid reaches of the reservoir. Trace elements in sediments in the lower and mid reaches of the reservoir are thus largely due to the liquid effluent discharged to the Columbia River, which can easily be transported the length of the reservoir. Relative concentrations of trace elements in the cores from those reaches of the reservoir resemble relative loading of trace elements from the liquid effluent, further supporting that conclusion.

References Cited

- Arbogast, B.F. (ed.), 1996, Analytical methods manual for the Mineral Resource Surveys Program: U.S. Geological Survey Open-File Report 96-525, 248 p.
- Bortleson, G.C., Cox, S.E., Munn, M.D., Schumaker, R.J., Block, E.K., Bucy, L.R., and Cornelius, S.B., 1994, Sediment-quality assessment of Franklin D. Roosevelt Lake and the upstream reach of the Columbia River, Washington, 1992: U.S. Geological Survey Open-File Report 94-315, 130 p.
- British Columbia Ministry of Environment, 1976, Kootenay Air and Water Quality Study Phase I: Water Quality in the Lower Columbia River Basin, Victoria, British Columbia, 234 p.
- British Columbia Ministry of Environment, 1979, Kootenay Air and Water Quality Study Phase II: Water Quality in the Lower Columbia River Basin, Victoria, British Columbia, 238 p.
- Chao, T.T., and Zhou, Liyi, 1983, Extraction techniques for selective dissolution of amorphous iron oxides from soils and sediments: *Soil Science Society of America Journal*, v. 47, no. 2, p. 225-232.
- Charles, M.J., and Hites, R.A., 1987, Sediments as archives of environmental pollution trends: In Hites, R.A. and Eisenreich, S.J., eds., *Sources and Fates of Aquatic Pollutants*, Advances in Chemistry Series Number 216: Washington, DC, American Chemical Society, p. 365-389.
- Colville Confederated Tribes, 2003, Sediment cleanup levels for the protection of human health and sediment dwelling organism: Nespelum, Washington, Colville Confederated Tribes, in Colville Tribe Hazardous Substances Control Act, Appendix C, p. 25-28.
- Commeau, J.A., Poppe, L.J., and Commeau, R.J., 1992, Separation and identification of the silt-sized heavy-mineral fraction of sediments: U.S. Geological Survey Circular 1071, 13 p.
- Cominco, 1991, Slag disposal options: environmental and engineering studies: Trail Operations-Cominco Metals, Trail, British Columbia, 24 p., with 3 appendixes.
- Cominco, 1992, Cominco Trail Operations Environment Report: Trail Operations-Cominco Metals, Trail, British Columbia, 24 p.
- Cominco, 2001, Trail operations environmental performance review of the new KIVCET lead smelter and elimination of slag discharge: Assessment of Columbia River receiving waters, Summary: Trail Operations-Cominco Metals, Trail, British Columbia, 11 p.
- Crusius, John, and Anderson, R.F., 1995, Sediment focusing in six small lakes inferred from radionuclide profiles: *Journal of Paleolimnology*, v. 13, p. 143-155.
- Derewetzyk, R.F., Funk, W.H., and Juul, S.T.J., 1994, Lake Franklin D. Roosevelt: Water Quality Retrospective Analysis: State of Washington Water Research Center-Washington State University, Report 90, Pullman, Washington, p. 152.
- Eggleton, R.A., Foudoulis, Chris, and Varkevisser, Dane, 1987, Weathering of basalt: Changes in Rock Chemistry and Mineralogy: *Clays and Clay Minerals*, v. 35, no. 3, p. 161-169.
- Ettler, Vojtech, Legendre, Olivier, Bodenan, and Touray, Jean-Claude, 2001, Primary phases and natural weathering of old lead-zinc pyrometallurgical slag from Czech Republic: *Canadian Mineralogist*, v. 39, p. 873-888.
- Friedman, Irving, Smith, R.L., and Long, W.D., 1966, Hydration of natural glass and the formation of perlite: *Geological Society of America Bulletin*, v. 77, p. 323-328.
- G3 Consulting, Ltd., 2001, Assessment of Columbia River receiving waters, Final Report: Prepared for Teck Cominco Metals, Ltd., Trail Operations, by G3 Consulting, Ltd., Burnaby, British Columbia, 183 p.

- Grosbois, C.A., Horowitz, A.J., Smith, J.J., and Elrick, K.A., 2001, The effect of mining and related activities on the sediment-trace element geochemistry of Lake Coeur d'Alene, Idaho, USA. Part III. Downstream effects: the Spokane River Basin: *Hydrological Processes*, v. 15, no. 5, p. 855-875.
- Horowitz, A.J., Elrick, K.A., and Cook, R.B., 1993, Effect of mining and related activities on the sediment-trace element geochemistry of Lake Coeur d'Alene, Idaho, USA. Part I. Surface sediments: *Hydrological Processes*, v. 7, p. 403-423.
- Johnson, A.J., Norton, Dale, Yake, W., and Twiss, S., 1988 [1989], An assessment of metals contamination in Lake Roosevelt: Washington State Department of Ecology, Olympia, Washington, 71 p.
- Johnson, A., Norton, Dale, Yake, W., and Twiss, S., 1990, Transboundary metal pollution of the Columbia River (Franklin D. Roosevelt Lake): *Bulletin of Environmental Contamination and Toxicology*, v. 45, 7 p. 703-710.
- Jones, F.O., Embody, D.R., Peterson, W.L., and Hazelwood, R.M., 1961, Landslides along the Columbia River valley, northeastern Washington, with a section on seismic surveys: U.S. Geological Survey Professional Paper 367, 98 p.
- Kelly, V.J., Hooper, R.P., Aulenbach, B.T., and Janet, Mary, 2001, Concentrations and annual fluxes for selected water-quality constituents from the USGS National Stream Quality Accounting Network (NASQAN), 1996-2000: U.S. Geological Survey Water-Resources Investigations Report 01-4255 URL: <http://water.usgs.gov/nasqan/progdocs/wri014255/results/data/sed.dat>, accessed March 2004.
- Kiver, E.P., and Stradling, D.R., 1995, Geology of the Franklin D. Roosevelt Reservoir Shoreline: Glacial geology, terraces, landslides, and lineaments: Grand Coulee, Washington, U.S. Bureau of Reclamation, Pacific Northwest Region, 147 p.
- Levinson, A.A., 1974, Introduction to exploration geochemistry: Calgary, Canada, Applied Publishing, Ltd., 612 p.
- Lowe, T.P., May, T.W., Brumbaugh, W.G., and Kane, D.A., 1985, National contaminant biomonitoring program—Concentrations of seven elements in freshwater fish, 1978-1981: *Archives of Environmental Contamination and Toxicology*, v. 14, p. 363-388.
- Lottermoser, B.G., 2002, Mobilization of heavy metals from historical smelting slag dumps, north Queensland, Australia: *Mineralogical Magazine*, v. 66, p. 475-490.
- Lydon, J.W., 2000, A synopsis of the current understanding of the geological environment of the Sullivan Deposit, in J.W. Lydon, Hoy, T., Slack, J.F., and Knapp, M.E. [eds.], *Geological Environment of the Sullivan Deposit*, British Columbia, Chapter 3: Geological Association of Canada Mineral Deposits Division Special Publication No. 1, p. 12-31.
- MacDonald, D.D., Ingersoll, C.G., and Berger, T.A., 2000, Development and evaluation of consensus-based sediment-quality guidelines for freshwater ecosystems: *Archive of Environmental Contamination and Toxicology*, v. 39, p. 20-31.
- Majewski, M.S., Kahle, S.C., Ebbert, J.C., and Josberger, E.G., 2003, Concentrations and distribution of slag-related trace elements and mercury in fine-grained beach and bed sediments of Lake Roosevelt, Washington, April-May, 2001: U.S. Geological Survey Water-Resources Investigations Report 03-4170, 29 p.
- Mills, J.W., 1977, Zinc and lead ore deposits in carbonate rocks, Stevens County, Washington: Washington State Department of Natural Resources-Division of Geology and Earth Resources, Olympia, WA Bulletin 70, 171 p.
- Morganstein, M.E., Wicket, C.L., and Barkatt, Aaron, 1999, Considerations of hydration-rind dating of glass artifacts: Alteration morphologies and experimental evidence of hydrogeochemical soil-zone pore water control: *Journal of Archaeological Science*, v. 26, p. 1193-1210.
- Munn, M.D., 2000, Contaminant trends in sport fish from Lake Roosevelt and the upper Columbia River, Washington, 1994-1998: U.S. Geological Survey Water-Resources Investigations Report 00-4024, 12 p.
- Munn, M.D., Cox, S.E., and Dean, C.J., 1995, Concentrations of mercury and other trace elements in walleye, smallmouth bass, and rainbow trout in Franklin D. Roosevelt Lake and the upper Columbia River, Washington, 1994: U.S. Geological Survey Open-File Report 95-195, 35 p.
- Nener, Jennifer, 1992, Survival and water-quality results of bioassays on five species of aquatic organisms exposed to slag from Cominco's Trail operation: Fisheries and Oceans Canada, Vancouver, British Columbia, Canada, 20 p. plus tables and appendixes.
- NORECOL Environmental Consultants Ltd., 1989, Statistical analysis of metal levels in fish of the Columbia River near the International Boundary, 1980 to 1988: NORECOL Environmental Consultants Ltd., Vancouver, British Columbia, p. 30.
- Orlob, G.T., and Saxton, W.W., 1950, Mining and mill waste pollution in the Upper Columbia River Basin and Lake Roosevelt: Washington Pollution Control Commission, Olympia, 12 p.
- Parsons, M.B., Bird, D.K., Einaudi, M.T., Alpers, C.N., 2001, Geochemical and mineralogical controls of trace element release from the Penn Milebase-metal slag dump, California: *Applied Geochemistry*, v. 16, p. 1567-1593.
- Piatak, N.M., Seal, R.R., and Hammarstorm, J.M., 2004, Mineralogical and geochemical controls on the release of trace elements from slag produced by base- and precious-metal smelting at abandon mine sites: *Applied Geochemistry*, v. 19, p. 1039-1064.

- Reyes, Julito, Goodarzi, Fari, Sanei, Hamed, Hilts, Steven, and Duncan, W.F., 2004, Concentrations of elements in the stream sediments of Trail, B.C. and surrounding area and the Natural Background Concentrations: Geological Survey of Canada, Environmental Study Group, Calgary Alberta, 58 p.
- Ritchie, J.C., and McHenry, J.R., 1990, Application of radioactive cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review: *Journal of Environmental Quality*, v. 19, p. 215-233.
- Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, *Geochemistry in mineral exploration*: London, Academic Press Ltd., 2nd edition, 657 p.
- Shacklette, H.T., and Boerngen, J.G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p.
- Sheehan, S. W., and Lamb, M., 1987, *Water Chemistry of the Columbia and Pend d'Oreille Rivers near the International Border*: Environment Canada, Inland Waters and Lands, Pacific and Yukon Region, Vancouver, British Columbia, 312 p.
- Sigma Engineering Ltd., 1987, *Statistical analysis of water chemistry data from the Columbia and Pend D'Oreille Rivers*: Vancouver, British Columbia, Environment Canada, Inland Water Directorate, Water Quality Branch, Report E5496, 30 p. with 5 appendixes
- Smith, A.L., 1987, Levels of metals and metallothionein in fish of the Columbia River near the international boundary: Environment Canada & British Columbia Ministry of Environment, Victoria, British Columbia 133 p.
- Teck-Cominco, 2002, Annual Information Form: March 1, 2002: Vancouver, British Columbia, Teck Cominco Limited, 19 p. <http://www.teckcominco.com/investors/reports/aif-circ/tc-aif-01.pdf>, accessed December 2003.
- U.S. Bureau of Reclamation, 2001, Franklin D. Roosevelt Lake—2001 Landslide Inspection Report, Grand Coulee Power Office: Grand Coulee, Washington, 40 p.
- U.S. Department of Energy-Nevada Operations Office, December 2000, United States Nuclear Test July 1945 through September 1992: DOS/NV—209-REV115, 189 p.
- U.S. Environmental Protection Agency, 2000, Upper Columbia River/Lake Roosevelt river mile 597 to 745—Preliminary assessment report, Washington: TDD: 99-10-0002, U.S. Environmental Protection Agency Superfund Technical Assessment and Response Team, variously paginated.
- U.S. Environmental Protection Agency, 2003, Upper Columbia River Expanded Site Investigation Report, northeast Washington: TDD: 01-02-0028, U.S. Environmental Protection Agency Superfund Technical Assessment and Response Team, variously paginated.
- Van Metre, P.C., Callender, E., and Fuller, C.C., 1997, Historical trends in organochlorine compounds in river basins identified using sediment cores from reservoirs: *Environmental Science and Technology*, v. 31, no. 8, p. 2339-2344.
- Washington State Department of Natural Resources, Division of Geology and Earth Resources: The geology of Washington-Okanogan Highland, <http://www.dnr.wa.gov/geology/okanogan.htm>, accessed November 2003.

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; -, no data]

CCR-624											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-3	0.15	74,000	2.4	12	840	2.2	0.53	2.2	13,000	0.02	1.4
3-6	-	73,000	3.1	10	820	2.3	.54	2.1	13,000	.03	1.4
9-12	.38	76,000	5.2	14	940	2.5	.67	7.6	11,000	.03	1.6
12-15	.46	75,000	3.3	14	950	2.4	.70	12	11,000	.04	1.6
18-21	-	74,000	4.5	14	960	2.3	.69	10	15,000	.26	1.2
21-24	.73	73,000	4.9	17	1,100	2.3	.74	11	17,000	.36	1.2
27-30	1.6	78,000	5.2	22	1,000	2.1	.82	16	18,000	.39	1.6
30-33	.62	70,000	4.4	13	760	1.9	.56	8.0	16,000	.12	1.6
33-35	.38	69,000	3.3	13	740	1.8	.49	5.4	16,000	.1	1.6
36-39	-	77,000	9.8	9.0	880	2.3	1.5	18	17,000	-	-
39-42	-	80,000	6.9	11	990	2.5	1.9	23	16,000	-	-
42-45	-	94,000	5.6	21	920	2.6	1.4	18	14,000	.13	1.8
45-48	-	81,000	2.9	18	840	2.5	1.1	15	12,000	.06	1.8

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-3	100	6.4	64	16	49	18	46,000	58	90	38	12,000
3-6	110	6.4	62	16	70	19	42,000	65	110	39	12,000
9-12	110	7.1	91	17	74	19	45,000	110	240	42	13,000
12-15	100	7.2	94	16	67	19	43,000	100	280	42	13,000
18-21	100	6.9	74	15	47	18	40,000	76	300	41	15,000
21-24	120	6.7	74	15	51	18	39,000	91	400	40	16,000
27-30	110	6.5	75	18	60	18	44,000	100	540	40	13,000
30-33	84	5.0	50	14	43	17	40,000	57	320	34	11,000
33-35	86	4.6	46	15	37	17	40,000	53	250	30	10,000
36-39	-	6.0	64	17	66	20	48,000	49	600	37	12,000
39-42	-	7.0	80	18	88	20	46,000	58	920	42	14,000
42-45	80	7.6	93	21	86	22	55,000	55	680	45	14,000
45-48	76	7.0	67	19	66	19	48,000	50	450	39	15,000

52 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-624—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-3	1,100	0.16	0.88	36	18	1,200	19,000	110	15	0.34	<3
3-6	910	.17	.69	33	16	960	19,000	110	15	.38	<3
9-12	1,100	1.0	1.1	41	20	1,200	20,000	120	16	.77	<3
12-15	1,100	1.2	1.2	42	18	1,200	21,000	120	15	1.1	<3
18-21	940	.58	1.7	36	18	1,100	21,000	120	14	.63	<3
21-24	970	.84	2.5	37	18	1,300	21,000	120	13	.62	<3
27-30	1,300	1.1	4.5	40	18	1,600	20,000	110	15	.62	<3
30-33	980	.61	2.2	26	15	1,000	16,000	91	15	.35	<3
33-35	960	.47	2.1	25	17	940	16,000	86	14	.24	<3
36-39	1,400	—	4.8	32	20	1,400	19,000	100	16	—	<3
39-42	1,500	—	4.6	39	22	1,400	22,000	120	16	—	<3
42-45	1,500	1.2	2.8	40	22	1,400	25,000	120	19	.75	<3
45-48	1,200	1.0	1.5	33	24	1,100	22,000	110	16	.69	<3

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-3	13,000	270	1.2	1.0	13	4,400	3.4	120	3.2	42	380
3-6	13,000	260	1.2	1.3	13	4,400	3.1	110	3.2	38	390
9-12	11,000	250	1.7	1.9	13	4,300	3.7	120	4.3	80	680
12-15	11,000	250	1.4	1.7	13	4,200	3.8	110	4.0	78	860
18-21	12,000	260	1.7	1.1	13	4,300	3.4	100	3.2	47	1,000
21-24	12,000	280	1.8	1.1	14	4,200	3.8	100	3.3	54	1,100
27-30	9,500	240	2.1	1.6	13	4,300	5.2	120	4.6	90	1,400
30-33	13,000	260	.65	1.2	11	4,500	3.2	110	3.6	50	730
33-35	14,000	280	1.2	1.0	10	4,600	3.0	120	3.2	44	530
36-39	11,000	230	—	1.2	13	4,800	4.3	130	—	56	1,100
39-42	10,000	230	—	1.7	14	4,500	4.6	120	—	75	1,600
42-45	9,400	210	1.2	1.5	14	4,800	4.1	130	4.0	60	1,400
45-48	11,000	200	1.8	1.1	13	4,900	3.0	110	3.7	48	1,100

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-643											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-3	0.19	74,000	3.2	13	1,100	2.3	0.59	2.3	11,000	0.05	1.2
3-6	—	72,000	4.0	11	1,100	2.2	.62	2.6	11,000	.07	1.2
9-12	—	69,000	4.6	15	1,000	2.3	.66	7.7	11,000	.06	1.3
15-18	.58	71,000	3.3	16	1,100	2.2	.68	7.9	12,000	.10	1.1
21-24	—	71,000	4.5	23	1,100	2.1	.86	10	20,000	.54	.98
27-30	.15	83,000	2.8	16	940	2.5	.85	2.8	20,000	.48	.64
33-36	.11	78,000	2.5	14	870	2.6	.82	2.4	19,000	.47	.61
36-39	.10	74,000	2.4	14	870	2.3	.80	2.4	20,000	.50	.56
39-42	—	67,000	2.7	16	870	2.1	.72	4.0	20,000	.49	.67
42-45	.61	70,000	3.7	18	1,000	2.1	.87	7.1	18,000	.38	.75
48-51	1.2	65,000	3.1	16	1,200	2.2	.57	8.0	18,000	.36	1.9
54-57	.98	78,000	7.4	24	1,200	2.1	.97	18	22,000	.68	1.1

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-3	120	6.5	83	16	58	17	41,000	74	94	40	14,000
3-6	110	6.6	80	15	76	17	39,000	74	130	39	14,000
9-12	120	6.3	110	15	76	17	39,000	120	310	37	14,000
15-18	130	6.3	100	15	60	17	38,000	120	280	39	14,000
21-24	120	5.9	85	14	50	17	36,000	96	400	36	16,000
27-30	120	9.3	86	16	41	20	43,000	67	96	46	15,000
33-36	120	9.2	75	16	39	19	41,000	64	78	46	15,000
36-39	130	8.8	72	15	38	18	39,000	73	79	43	15,000
39-42	130	7.1	67	13	37	17	35,000	83	190	37	14,000
42-45	120	5.5	74	13	44	16	34,000	89	380	33	13,000
48-51	100	4.9	68	12	42	15	31,000	88	380	30	13,000
54-57	110	6.6	93	15	73	18	41,000	122	920	41	17,000

54 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-643—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-3	1,500	0.21	1.4	48	20	1,200	22,000	120	14	0.58	<3
3-6	1,000	.28	1.4	44	19	1,100	22,000	120	13	.54	<3
9-12	1,200	1.3	1.6	47	20	1,400	22,000	110	13	1.0	<3
15-18	990	1.3	1.8	45	19	1,400	22,000	120	13	.84	<3
21-24	790	1.0	3.6	40	20	1,200	22,000	110	12	.70	<3
27-30	850	.14	1.6	41	18	990	26,000	140	16	.35	<3
33-36	840	.10	1.2	40	18	930	25,000	140	14	.31	<3
36-39	840	.10	1.2	38	21	960	24,000	140	14	.38	<3
39-42	740	.34	2.0	35	17	970	21,000	120	12	.40	<3
42-45	760	.86	3.3	37	18	1,200	22,000	110	12	.49	<3
48-51	780	.88	3.9	33	20	1,100	22,000	100	10	.58	<3
54-57	1,100	1.8	9.6	44	19	1,600	23,000	120	14	.76	<3

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-3	12,000	290	1.3	1.1	14	4,200	3.4	110	2.7	32	330
3-6	12,000	280	1.4	1.5	13	4,200	3.3	100	2.8	35	370
9-12	12,000	280	1.4	1.7	14	4,200	3.7	100	3.9	75	590
15-18	12,000	290	1.4	1.3	14	4,200	3.5	100	3.4	60	710
21-24	12,000	300	1.6	1.0	13	4,200	3.7	98	3.1	52	1,100
27-30	8,900	210	1.4	.88	14	4,300	3.3	110	3.0	38	410
33-36	9,200	210	1.3	.83	14	4,200	3.1	100	3.1	40	360
36-39	9,800	220	2.2	.79	14	4,200	3.2	100	2.9	32	340
39-42	12,000	260	1.7	.85	14	4,200	3.4	90	3.0	38	470
42-45	13,000	330	1.5	1.1	12	4,200	3.7	95	3.0	49	760
48-51	15,000	380	1.1	1.1	12	4,200	4.3	88	3.1	60	770
54-57	9,800	270	1.6	1.6	13	4,200	6.8	120	4.1	92	1,500

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-668											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-5	0.16	74,000	2.9	8.3	1,100	2.5	0.44	2.2	20,000	0.23	1.1
5-10	—	73,000	1.9	6.6	1,100	2.3	.30	1.7	22,000	.25	.86
10-15	—	73,000	4.4	8.8	1,100	2.6	.47	3.3	18,000	.25	1.8
20-25	—	73,000	6.4	11	1,200	2.5	.67	5.6	17,000	.12	1.4
30-35	.42	75,000	5.3	12	1,200	2.8	.82	11	17,000	.16	1.5
40-45	—	74,000	4.3	13	1,200	2.8	.75	11	23,000	.47	1.1
45-50	.46	68,000	5.7	17	1,400	2.5	.79	12	34,000	1.1	1.6
60-65	.23	59,000	4.1	12	1,600	2.0	.38	8.8	44,000	1.5	.72
65-70	.77	69,000	6.2	16	1,500	2.7	.81	16	33,000	1.1	1.3
80-85	.31	55,000	6.6	12	1,800	2.0	.89	11	57,000	2.1	1.2
90-95	.38	55,000	7.1	13	1,700	2.0	.88	12	54,000	2.0	1.2
100-105	.34	55,000	6.0	14	1,700	2.1	.92	11	54,000	2.0	1.3
105-110	.28	53,000	3.3	7.3	1,500	1.9	.70	6.8	52,000	1.9	.79
120-125	.54	71,000	4.8	13	1,500	2.5	.56	9.3	33,000	.89	.61
130-135	.76	70,000	9.4	20	1,500	2.4	.74	14	33,000	.96	.65
140-145	.43	44,000	9.9	12	820	1.6	.36	7.4	19,000	.67	.59
150-155	<.01	72,000	2.4	9.7	1,100	2.5	.51	4.6	25,000	.42	.38
155-160	.02	72,000	2.2	13	1,100	2.5	.47	5.1	25,000	.37	.38
160-164	.01	64,000	1.6	7.1	990	2.2	.43	4.2	24,000	.44	.32

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-5	92	4.2	69	14	54	17	38,000	53	86	30	16,000
5-10	92	3.4	76	12	38	16	34,000	52	67	26	15,000
10-15	84	4.5	76	13	92	17	39,000	50	150	31	16,000
20-25	93	4.6	100	15	100	17	41,000	71	290	32	16,000
30-35	98	5.0	110	15	89	18	42,000	75	410	34	17,000
40-45	94	4.8	96	13	62	18	40,000	67	340	33	20,000
45-50	81	4.4	84	13	72	16	42,000	57	480	32	27,000
60-65	76	2.5	57	8.9	52	13	35,000	49	310	20	26,000
65-70	88	4.7	80	13	70	16	42,000	64	580	33	27,000
80-85	69	2.8	67	9.5	72	13	36,000	51	620	23	32,000
90-95	68	2.9	66	9.7	75	13	37,000	50	660	23	30,000
100-105	69	2.8	65	9.8	73	13	38,000	49	560	23	32,000
105-110	61	2.3	56	8.6	52	13	31,000	40	330	20	26,000
120-125	90	4.0	87	13	53	17	38,000	63	460	30	23,000
130-135	92	4.3	72	14	63	16	38,000	64	800	31	24,000
140-145	54	2.4	39	7.6	33	10	22,000	36	440	18	13,000
150-155	98	3.6	78	12	43	16	34,000	60	360	27	17,000
155-160	97	3.7	77	14	42	17	36,000	60	320	28	16,000
160-164	89	3.2	71	13	37	15	33,000	51	250	24	15,000

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-668—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-5	790	0.25	1.0	35	27	—	25,000	96	12	0.86	<3
5-10	630	.17	1.0	32	31	1,200	25,000	91	11	.62	<3
10-15	740	.47	1.5	33	30	1,200	24,000	96	12	.86	<3
20-25	740	1.2	1.6	37	35	1,600	25,000	98	13	1.3	5
30-35	660	2.1	1.8	38	30	1,600	25,000	100	13	1.8	<3
40-45	610	1.7	2.0	36	28	1,600	25,000	100	13	1.4	3
45-50	620	1.1	4.4	35	29	1,400	23,000	92	12	1.4	<3
60-65	570	.61	4.1	25	23	1,300	21,000	75	8.6	.74	<3
65-70	680	1.4	4.3	34	31	1,600	23,000	94	12	1.4	4
80-85	600	1.9	8.1	28	23	1,400	20,000	72	8.7	1.2	3
90-95	620	2.1	8.2	29	26	1,400	19,000	73	8.8	1.2	3
100-105	610	1.8	8.4	30	24	1,400	19,000	72	8.7	.94	4
105-110	550	.75	6.3	24	23	1,200	19,000	73	7.4	.62	<3
120-125	700	1.1	4.6	36	29	1,600	25,000	95	12	.97	<3
130-135	740	1.6	8.5	36	29	1,600	24,000	94	12	1.1	3
140-145	430	1.2	4.0	20	17	910	16,000	59	6.9	.52	<3
150-155	650	1.0	2.4	32	29	1,300	26,000	93	11	.69	<3
155-160	670	.92	3.6	34	28	1,400	25,000	94	12	.70	<3
160-164	650	.77	1.9	31	26	1,200	23,000	83	11	.53	3

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-5	21,000	420	1.5	0.94	14	4,300	3.1	100	2.4	25	320
5-10	22,000	430	1.7	.84	12	4,100	2.3	96	2.2	23	210
10-15	20,000	380	1.6	1.1	12	4,200	3.5	100	2.7	29	530
20-25	19,000	390	2.0	1.8	13	3,800	3.7	110	3.8	50	550
30-35	20,000	400	1.7	1.4	14	4,500	3.9	110	3.5	51	900
40-45	19,000	390	1.6	1.0	14	4,400	3.5	100	3.2	42	1,000
45-50	19,000	380	1.6	1.1	12	4,000	4.0	100	3.1	36	1,200
60-65	21,000	440	1.3	.89	11	3,200	3.8	78	2.2	27	1,200
65-70	18,000	370	1.6	1.2	13	4,000	4.1	100	3.3	42	1,500
80-85	18,000	400	1.3	1.0	9.8	3,100	5.0	88	3.0	34	1,300
90-95	17,000	390	1.3	1.1	9.8	3,100	4.9	88	2.6	35	1,400
100-105	18,000	420	1.4	1.0	9.7	3,000	4.9	88	2.3	32	1,300
105-110	17,000	450	1.2	1.1	8.7	2,800	4.5	77	1.9	23	1,100
120-125	20,000	420	1.6	1.0	13	4,100	4.3	110	2.9	44	940
130-135	19,000	390	1.6	1.4	14	4,100	5.8	110	3.1	45	1,400
140-145	13,000	270	1.0	.66	7.8	2,400	2.9	64	1.8	22	700
150-155	22,000	440	1.6	.87	13	4,000	2.9	98	2.8	33	450
155-160	22,000	430	1.6	.85	13	4,400	2.8	100	3.3	35	500
160-164	20,000	400	1.4	.74	12	3,800	2.4	92	2.1	25	380

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-692											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-2	0.46	63,000	5.7	9.2	1,200	2.3	0.80	3.7	21,000	0.42	2.8
2-4	—	61,000	5.5	10	1,200	2.1	.57	3.5	28,000	.80	2.4
6-8	.21	49,000	6.1	5.6	1,400	1.8	.19	3.6	51,000	2.0	0.6
10-12	.11	59,000	10	7.2	1,400	1.9	.24	2.9	34,000	.91	0.6
14-16	.22	60,000	9.9	7.6	1,300	2.0	.27	3.0	30,000	.74	0.8
18-20	.30	62,000	12	11	1,200	2.4	.64	4.8	24,000	.44	2.6
22-24	.32	61,000	18	15	1,200	2.4	.60	5.8	22,000	.29	4.0
26-28	.88	64,000	15	17	1,200	2.2	.70	8.4	20,000	.22	2.8
30-32	—	63,000	17	18	1,200	2.4	.86	11	18,000	.20	2.8
32-34	.46	64,000	10	14	1,200	2.3	.73	12	18,000	.21	2.6
34-36	—	63,000	8.0	12	1,200	2.2	.61	10	22,000	.38	2.1
36-38	.60	60,000	6.8	9.4	1,200	2.1	.43	7.6	25,000	.42	1.6

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-2	100	5.0	66	12	87	15	37,000	75	170	32	16,000
2-4	100	4.2	64	12	94	15	35,000	70	190	30	18,000
6-8	84	1.8	44	7.2	82	12	25,000	53	210	17	26,000
10-12	100	1.9	56	8.8	130	14	29,000	68	150	18	16,000
14-16	88	2.8	58	9.9	140	14	30,000	66	170	21	15,000
18-20	120	4.4	74	14	190	15	39,000	94	260	31	16,000
22-24	110	4.5	79	15	240	15	40,000	95	290	32	14,000
26-28	110	4.7	92	13	250	16	39,000	130	420	34	13,000
30-32	110	5.4	110	12	220	16	40,000	160	610	36	14,000
32-34	130	4.9	99	12	160	16	39,000	150	540	33	14,000
34-36	110	4.2	81	11	140	15	38,000	110	440	30	15,000
36-38	100	3.3	66	9.9	140	14	42,000	92	380	24	14,000

Table 5. Vertical distribution of major and trace-element concentrations in sediment cores subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CR-692—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-2	770	0.55	2.2	35	21	1,400	19,000	97	11	0.86	<3
2-4	700	.27	3.8	32	19	1,300	19,000	91	9.9	.93	<3
6-8	530	.19	7.6	20	16	1,200	17,000	72	6.3	.54	<3
10-12	580	.18	3.6	21	18	1,400	20,000	81	7.5	.54	<3
14-16	600	.24	3.3	23	17	1,200	20,000	86	7.8	.69	<3
18-20	770	.43	3.0	35	23	1,400	19,000	94	10	1.3	4
22-24	820	.66	2.7	34	22	1,500	18,000	92	11	1.4	5
26-28	720	1.4	3.0	36	22	1,500	20,000	94	11	1.6	4
30-32	730	2.3	2.6	38	21	1,700	19,000	100	11	2.1	8
32-34	700	2.0	2.4	38	21	1,600	20,000	98	11	2.2	<3
34-36	670	1.9	3.4	34	20	1,500	20,000	95	9.9	1.8	<3
36-38	780	1.2	4.3	26	18	1,400	20,000	88	8.5	1.3	<3

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-2	17,000	440	1.4	0.89	12	4,100	4.7	87	2.8	33	630
2-4	17,000	470	1.2	.92	12	4,100	5.0	83	2.4	30	730
6-8	18,000	520	1.5	.75	9.8	4,000	4.6	58	1.7	20	970
10-12	20,000	600	1.2	.95	9.9	4,000	3.5	65	2.1	27	960
14-16	20,000	590	1.0	1.1	10	4,000	3.8	63	2.0	32	980
18-20	17,000	480	1.5	1.5	13	4,100	4.9	87	2.9	41	1,000
22-24	16,000	460	1.3	1.8	12	4,100	5.9	88	3.0	48	1,200
26-28	15,000	440	1.5	1.8	12	4,200	5.2	93	4.0	78	1,200
30-32	15,000	420	1.4	1.5	13	4,100	5.5	100	4.4	100	1,300
32-34	16,000	450	1.3	1.5	13	4,100	5.1	89	3.8	78	1,300
34-36	18,000	500	1.3	1.2	13	4,100	4.9	84	3.0	56	1,400
36-38	19,000	520	1.2	.86	27	4,100	6.8	80	2.6	43	2,200

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-705											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-2	—	81,000	5.6	9.8	1,200	2.6	0.72	5.2	18,000	0.13	1.7
2-4	0.55	81,000	6.7	11	1,200	2.4	.70	6.5	18,000	.14	1.5
6-8	.72	81,000	6.1	13	1,400	2.5	.73	11	23,000	.37	1.2
14-16	.92	77,000	9.6	16	1,700	2.6	.80	15	33,000	.96	1.1
18-20	1.2	72,000	11	20	1,800	2.3	.82	18	40,000	1.4	.91
22-24	.04	84,000	5.2	11	1,400	2.6	.54	7.3	36,000	.87	.72
26-28	.03	75,000	1.9	5.4	1,100	2.2	.30	2.8	31,000	.70	.68
30-32	<.01	40,000	.98	2.1	580	1.3	.19	1.4	16,000	.68	.63
34-36	.16	59,000	1.1	3.6	870	1.9	.19	1.5	23,000	.54	.69
36-38	.19	77,000	1.7	4.4	1,100	2.3	.26	1.6	26,000	.40	.72
40-42	<.01	76,000	6.1	18	1,100	2.6	1.3	16	23,000	.47	2.3
42-44	.02	54,000	3.5	15	760	1.8	.88	10	14,000	.20	4.9
44-46	<.01	55,000	1.5	6.7	750	1.7	.30	2.7	13,000	.02	6.8
46-49	—	57,000	1.7	6.5	780	1.7	.41	4.2	15,000	.08	6.3
RSS-743	—	27,000	160	28	2,800	1.1	<0.005	0.004	99,000	—	—

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-2	93	5.1	94.1	14	91	18	44,000	60	260	32	16,000
2-4	96	4.9	106	14	100	18	44,000	68	350	33	16,000
6-8	93	4.6	108	14	79	18	43,000	69	500	31	18,000
14-16	90	4.6	100	13	68	17	43,000	67	680	32	25,000
18-20	86	4.2	92.6	12	67	16	42,000	64	850	30	27,000
22-24	93	4.4	91.5	14	59	19	43,000	57	450	35	21,000
26-28	90	3.8	79.6	13	37	18	37,000	51	200	31	17,000
30-32	48	2.0	41.3	6.3	18	9.2	19,000	29	85	17	9,200
34-36	72	2.5	54.7	8.2	29	13	25,000	42	86	21	12,000
36-38	77	3.2	65.3	11	26	16	30,000	45	90	25	13,000
40-42	86	4.8	89.7	12	74	18	34,000	65	850	34	19,800
42-44	75	4.5	56.2	9.8	52	12	22,000	61	500	28	11,000
44-46	47	3.6	49.1	6.5	32	12	20,000	30	61	22	7,500
46-49	56	3.7	53.9	6.7	37	13	22,000	35	130	22	8,700
RSS-743	47	0.78	250	88	3,600	35	320,000	25	400	18	8,300

60 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CCR-705—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-2	1,000	0.93	1.6	37	36.1	1,600	27,000	110	13	1.1	5
2-4	860	1.2	1.6	37	35.9	1,700	27,000	100	13	1.2	4
6-8	700	2.2	2.8	37	34.9	1,800	28,000	100	13	1.5	<3
14-16	720	2.0	7.3	36	33.2	2,100	26,000	100	13	1.4	7
18-20	750	1.8	9.1	36	31.4	2,100	25,000	95	12	1.4	3
22-24	750	.88	4.0	39	36.7	1,400	29,000	110	14	.54	<3
26-28	690	.47	1.7	34	33.7	1,200	27,000	99	12	.55	<3
30-32	380	.46	.71	18	16.0	650	14,000	50	6.3	.38	<3
34-36	540	.29	.86	22	24.8	970	21,000	72	8.8	.34	<3
36-38	570	.23	1.3	28	29.0	1,100	28,000	90	11	.41	<3
40-42	530	2.8	7.0	35	32.7	1,600	26,000	110	13	1.4	<3
42-44	380	1.5	5.9	28	19.81	1,200	17,000	91	9.0	1.9	<3
44-46	310	.14	2.2	19	19.2	1,100	18,000	79	8.6	2.4	<3
46-49	350	.38	2.4	21	21.1	1,200	18,000	82	9.1	2.2	<3
RSS-743	5,400	—	54	26	5.0	570	4,800	20	6.2	—	9

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-2	18,000	430	1.9	1.3	14	4,200	3.6	110	2.9	35	560
2-4	19,000	440	1.8	1.4	14	4,100	3.7	110	3.2	46	640
6-8	19,000	450	2.6	1.4	13	4,200	3.8	110	3.1	47	960
14-16	18,000	420	2.0	1.4	13	4,100	5.5	120	3.2	48	1,400
18-20	16,000	400	2.0	1.5	12	3,800	6.5	110	3.2	48	1,600
22-24	20,000	500	2.1	1.0	14	4,400	3.4	120	2.6	32	740
26-28	19,000	480	1.9	.71	13	4,100	2.5	98	2.2	24	300
30-32	11,000	260	1.0	.38	7.4	2,100	1.4	51	1.2	13	150
34-36	18,000	420	1.3	.50	10	3,100	1.9	69	1.7	18	160
36-38	22,000	530	1.5	.74	11	3,800	2.3	90	2.2	22	170
40-42	17,000	400	1.8	1.3	13	4,000	6.0	110	3.2	49	1,200
42-44	12,000	310	1.3	.81	11	4,000	9.5	72	2.6	36	770
44-46	12,000	310	1.1	.62	8.6	2,500	13	62	1.9	19	180
46-49	12,000	310	1.2	.69	9.4	2,700	14	67	2.3	21	300
RSS-743	2,900	430	—	0.02	7.3	3,600	6.2	50	—	23	25,000

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CSA-8											
Depth interval (cm)	Cesium-137 (pCi/g)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium	Carbonate (percent)	Organic carbon (percent)
0-3	0.17	84,000	2.6	20	770	2.8	1.1	7.0	9,800	0.06	2.4
3-6	—	78,000	1.9	18	730	2.6	1.1	5.7	12,000	.11	1.9
6-9	—	85,000	2.6	20	760	2.7	1.1	7.8	9,200	.04	2.4
9-12	.32	76,000	8.0	24	790	2.4	.81	10	8,900	.04	2.4
15-18	.25	81,000	2.4	20	710	2.7	1.2	14	11,000	.05	1.9
21-24	.29	74,000	2.3	19	700	2.6	.94	13	13,000	.07	1.6
27-30	.36	74,000	2.8	17	700	2.5	.95	21	12,000	.05	1.8
33-36	.33	74,000	3.0	13	700	2.5	1.2	18	13,000	.05	1.7
39-42	.2	70,000	2.0	11	660	2.2	.96	8.0	15,000	.09	1.3
45-48	.24	70,000	2.1	13	660	2.2	1.9	8.0	15,000	.09	1.4
51-54	.24	71,000	2.1	12	680	2.2	1.2	7.6	15,000	.09	1.5
57-60	.33	72,000	2.4	13	690	2.5	1.5	14	13,000	.06	1.7
63-66	1.1	83,000	5.7	34	740	2.7	1.3	14	10,200	.03	2.2
69-72	.36	73,000	3.2	20	740	2.4	2.0	7.0	11,000	.03	1.2
75-78	.34	72,000	2.7	16	710	2.3	2.2	18	12,000	.06	1.6
78-81	—	74,000	2.2	10	650	2.1	.84	9.5	15,000	.07	1.5
81-84	.31	72,000	2.2	12	690	2.6	1.8	8.8	15,000	.07	1.5
86-90	—	78,000	2.8	13	700	2.3	1.4	10	14,000	.06	1.7

Depth interval (cm)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanum	Lead	Lithium	Magnesium
0-3	82	9.2	64	17	44	20	50,000	41	140	45	13,000
3-6	77	7.8	55	15	40	19	43,000	40	88	39	13,000
6-9	77	8.8	63	16	48	21	50,000	41	140	45	12,000
9-12	69	8.0	64	16	53	20	45,000	36	130	42	12,000
15-18	76	7.5	58	16	46	20	42,000	40	110	40	12,000
21-24	76	6.6	49	13	34	18	37,000	40	92	34	12,000
27-30	75	6.7	51	14	38	18	39,000	40	110	35	12,000
33-36	80	6.7	51	14	34	18	38,000	42	100	34	12,000
39-42	76	5.8	42	12	29	16	34,000	40	72	30	11,000
45-48	82	6.0	46	12	31	16	35,000	43	74	30	11,000
51-54	82	6.2	35	12	31	16	35,000	43	69	32	11,000
57-60	74	6.4	48	13	36	17	36,000	39	86	34	11,000
63-66	80	7.7	60	18	51	20	46,000	43	140	41	11,000
69-72	80	7.0	50	13	38	17	37,000	43	210	34	11,000
75-78	81	6.5	51	14	36	18	38,000	43	100	34	12,000
78-81	75	6.1	54	13	31	17	36,000	38	87	32	9,700
81-84	78	6.4	48	12	32	17	36,000	41	79	33	12,000
86-90	73	6.6	49	13	36	18	38,000	38	83	33	12,000

62 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 5. Vertical distribution of major and trace-element concentrations in sediment core subsections from Lake Roosevelt, Washington, September 2002.—Continued

[Concentrations of trace elements are given in micrograms per kilogram unless otherwise noted. **Abbreviations:** cm, centimeter; pCi/g, picoCuries per gram; <, less than; —, no data]

CSA-8—Continued											
Depth interval (cm)	Manganese	Mercury	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver
0-3	1,600	0.10	0.75	28	23	1,300	22,000	120	17	0.65	<3
3-6	930	.08	.65	25	18	1,000	22,000	110	16	.39	<3
6-9	1,200	.11	.80	30	23	1,400	22,000	120	18	.82	<3
9-12	940	.25	1.2	29	22	1,300	20,000	110	16	.69	<3
15-18	860	.15	.86	26	21	1,100	21,000	110	15	.74	<3
21-24	750	.15	.65	21	20	990	21,000	100	14	.46	<3
27-30	840	.19	.66	23	19	1,200	21,000	100	14	.68	<3
33-36	790	.18	.56	22	20	1,200	21,000	100	14	.38	<3
39-42	670	.09	.55	18	19	980	21,000	94	13	.40	<3
45-48	680	.09	.61	19	18	1,000	21,000	94	13	.40	<3
51-54	640	.09	.71	19	19	970	21,000	96	13	.64	<3
57-60	720	.14	.55	21	16	1,000	20,000	99	13	.49	<3
63-66	980	.30	.86	28	20	1,300	21,000	120	17	.52	<3
69-72	680	.13	.65	20	20	890	24,000	120	13	.42	<3
75-78	820	.19	.64	22	18	1,200	22,000	100	14	.42	<3
78-81	730	.10	.79	21	15	1,100	22,000	100	14	.46	<3
81-84	690	.10	.65	20	15	1,000	21,000	99	13	.32	<3
86-90	730	.13	.82	22	22	1,000	22,000	120	17	.65	<3

Depth interval (cm)	Sodium	Strontium	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Ytterbium	Yttrium	Zinc
0-3	8,700	140	1.7	0.88	14	5,400	6.4	100	3.8	32	1,200
3-6	11,000	170	1.1	.76	13	5,300	5.7	98	3.4	29	950
6-9	8,600	140	1.8	.89	13	5,400	6.0	110	3.6	32	1,200
9-12	8,300	130	1.8	.81	12	4,900	6.4	97	3.1	28	1,600
15-18	12,000	170	1.5	1.0	12	5,200	5.6	95	3.4	31	1,500
21-24	15,000	210	1.3	.84	11	5,100	4.4	86	3.6	28	1,200
27-30	14,000	200	.96	.92	11	5,100	4.1	89	3.1	28	1,600
33-36	15,000	210	1.3	.83	12	5,300	4.0	88	3.2	28	1,400
39-42	16,000	240	1.5	.67	11	5,300	3.6	85	3.1	26	930
45-48	16,000	230	1.2	.64	12	5,200	3.5	86	3.0	26	960
51-54	15,000	230	1.4	.66	12	5,200	3.4	84	3.0	26	890
57-60	14,000	210	1.0	.73	11	5,100	3.6	85	3.1	26	1,300
63-66	9,700	160	1.6	1.0	13	5,500	4.8	98	3.7	34	1,500
69-72	12,000	210	1.4	.76	12	4,600	3.3	85	2.9	26	980
75-78	14,000	200	1.0	.86	12	5,000	4.1	88	3.2	27	1,400
78-81	12,000	220	.61	.66	11	4,300	3.2	89	2.6	25	1,100
81-84	16,000	230	1.0	.73	12	5,200	3.6	86	3.2	27	1,000
86-90	15,000	220	1.5	.73	11	5,200	3.3	88	3.0	27	1,100

Table 6. Analytical results for standard reference material and environmental duplicate samples for quality assurance.

[Concentrations are in micrograms per kilogram unless otherwise noted. **Sample designation:** PACS-2: Standard reference material (SRM) from the National Research Council of Canada. SRMs are reported. BR-2704: SRM from the U.S. National Institute of Standards and Testing, Special Publication 260 (1990–91). <, less than; –, no data]

Sample designation	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium
Standard Reference Material (SRM)— <i>Italicized</i> number is percentage recovery of SRM								
PACS-2	66,200	11.3	26.2	–	1.0	–	2.11	¹ 19,600
Sample 1	71,000 <i>107</i>	12.4 <i>110</i>	25 95	1,000 –	1.1 <i>110</i>	0.37 –	2.3 <i>109</i>	20,000 <i>102</i>
Sample 2	71,000 <i>107</i>	12.4 <i>110</i>	28 <i>107</i>	1,000 –	1.1 <i>110</i>	.26 –	2.4 <i>114</i>	22,000 <i>112</i>
Sample 3	60,000 <i>91</i>	11.1 98	25 95	890 –	.92 92	.38 –	2.2 <i>104</i>	18,000 92
BR-2704	61,100	3.79	23.4	414	–	–	3.45	26,000
Sample 4	64,000 <i>105</i>	3.9 <i>103</i>	22 99	420 <i>101</i>	1.9 –	.50 –	3.7 <i>107</i>	27,000 <i>104</i>
Sample 5	56,000 92	3.6 95	21 90	390 <i>94</i>	1.6 –	.64 –	3.3 96	23,000 88
Sample 6	66,000 <i>108</i>	4.6 <i>121</i>	20 85	450 <i>109</i>	2.0 –	.63 –	3.5 <i>101</i>	26,000 <i>100</i>
Environmental Duplicate Samples (EDS)— <i>Italicized</i> number is relative percentage difference of EDS								
CCR624:3-6	77,000 <i>0.0</i>	3.1 9.8	10 9.5	820 <i>0.0</i>	2.3 9.1	0.54 <i>7.1</i>	2.1 4.9	12,800 <i>1.6</i>
CCR624:3-6DUP	77,000	2.9	11	820	2.1	.58	2.0	13,000
CCR-643:3-6	72,000 <i>1.4</i>	4.0 2.5	11 8.1	1,100 <i>.0</i>	2.2 <i>.0</i>	.62 <i>6.7</i>	2.6 <i>.0</i>	11,000 <i>.0</i>
CCR-643:3-6DUP	73,000	3.9	12	1,100	2.2	.58	2.6	11,000
CCR668:10-15	73,000 <i>2.7</i>	4.4 <i>.0</i>	8.8 7.6	1,100 8.7	2.6 <i>7.4</i>	.47 <i>19.2</i>	3.3 8.7	18,000 <i>5.4</i>
CCR668:10-15DUP	75,000	4.4	9.5	1,200	2.8	.57	3.6	19,000
CCR692:2-4	61,000 <i>1.6</i>	5.5 5.6	10 2.0	1,200 <i>.0</i>	2.1 21	.57 <i>11.1</i>	3.5 2.9	28,000 <i>7.4</i>
CCR692:2-4DUP	62,000	5.2	9.8	1,200	2.6	.51	3.4	26,000
CCR705:14-16	77,000 <i>.0</i>	9.6 24.6	16 <i>.0</i>	1,700 <i>.0</i>	2.6 <i>.0</i>	.80 <i>4.9</i>	15 <i>.0</i>	33,000 <i>3.1</i>
CCR705:14-16DUP	77,000	7.5	16	1,700	2.6	.84	15	32,000
CSA:3-6	80,000 <i>2.5</i>	2.1 <i>10</i>	17 5.7	750 <i>2.7</i>	2.7 3.8	.94 <i>15.7</i>	5.7 <i>.0</i>	12,000 <i>.0</i>
CSA:3-6DUP	78,000	1.9	18	730	2.6	1.1	5.7	12,000
Sample designation	Organic carbon (percent)	Total carbon (percent)	Cerium	Cesium	Chromium	Cobalt	Copper	Gallium
Standard Reference Material (SRM)— <i>Italicized</i> number is percentage recovery of SRM								
PACS-2	–	¹ 3.3	–	–	90.7	11.5	310	–
Sample 1	3.1 –	3.2 97	34 –	2.2 –	90 99	11.7 <i>102</i>	300 97	14 –
Sample 2	3.1 –	3.2 97	31 –	2.2 –	110 <i>121</i>	12.6 <i>110</i>	330 <i>106</i>	14 –
Sample 3	3.0 –	3.1 94	23 –	2.6 –	82 90	10.8 94	280 90	13 –
BR-2704	–	3.35	¹ 72	¹ 6	135	14.0	98.6	¹ 15
Sample 4	2.5 –	3.4 <i>101</i>	57 79	5.4 90	160 <i>119</i>	14.2 <i>101</i>	98 99	15 <i>100</i>
Sample 5	2.4 –	3.3 99	76 <i>106</i>	5.9 98	120 89	12.6 90	89 90	14 93
Sample 6	2.5 –	3.4 <i>101</i>	61 85	5.4 90	140 <i>104</i>	13.2 94	94 95	14 93
Environmental Duplicate Samples (EDS)— <i>Italicized</i> number is relative percentage difference of EDS								
CCR624:3-6	1.4 <i>0.0</i>	1.4 <i>0.0</i>	110 <i>0.0</i>	6.4 <i>1.6</i>	62 1.6	15.8 <i>0.6</i>	70 19	19 <i>5.4</i>
CCR624:3-6DUP	1.4	1.4	110	6.3	61	15.7	58	18
CCR-643:3-6	1.2 <i>.0</i>	1.2 8.0	110 <i>16.7</i>	6.6 <i>.0</i>	80 2.5	14.7 <i>.7</i>	76 <i>1.3</i>	17 <i>5.7</i>
CCR-643:3-6DUP	1.2	1.3	130	6.6	82	14.8	75	18
CCR668:10-15	1.8 <i>11.8</i>	2.0 5.1	84 2.4	4.5 6.4	76 <i>.0</i>	13.4 <i>4.4</i>	92 4.3	17 <i>5.7</i>
CCR668:10-15DUP	1.6	1.9	86	4.8	76	14.0	96	18
CCR692:2-4	2.4 <i>.0</i>	3.2 3.2	100 9.5	4.2 2.4	64 <i>.0</i>	11.6 <i>1.7</i>	94 5.5	15 <i>.0</i>
CCR692:2-4DUP	2.4	3.1	110	4.1	64	11.4	90	15
CCR705:14-16	1.1 <i>.0</i>	2.0 <i>.0</i>	90 2.2	4.6 <i>.0</i>	100 <i>.0</i>	12.6 <i>.8</i>	68 <i>1.5</i>	17 <i>.0</i>
CCR705:14-16DUP	1.1	2.0	92	4.6	100	12.7	67	17
CSA8:3-6	1.9 <i>.0</i>	2.0 <i>.0</i>	79 2.6	8.1 3.8	56 1.8	15.4 2.0	64 46	19 <i>.0</i>
CSA8:3-6DUP	1.9	2.0	77	7.8	55	15.1	40	19

64 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 6. Analytical results for standard reference material and environmental duplicate samples for quality assurance.—Continued

[Concentrations are in micrograms per kilogram unless otherwise noted. **Sample designation:** PACS-2: Standard reference material (SRM) from the National Research Council of Canada. SRMs are reported. BR-2704: SRM from the U.S. National Institute of Standards and Testing, Special Publication 260 (1990–91). <, less than; –, no data]

Sample designation	Iron	Lanthanum	Lead	Lithium	Magnesium	Manganese	Mercury
Standard Reference Material (SRM)— <i>Italicized</i> number is percentage recovery of SRM							
PACS-2	40,900	–	183	32.2	14,700	440	3.04
Sample 1	44,000 <i>108</i>	18 –	160 <i>87</i>	30 <i>93</i>	16,000 <i>109</i>	440 <i>100</i>	2.8 <i>92</i>
Sample 2	45,000 <i>110</i>	16 –	180 <i>98</i>	32 <i>99</i>	14,000 <i>95</i>	470 <i>107</i>	2.9 <i>95</i>
Sample 3	38,000 <i>93</i>	2.9 –	180 <i>98</i>	32 <i>99</i>	14,000 <i>95</i>	440 <i>100</i>	2.8 <i>92</i>
BR-2704	41,100	¹29	161	¹50	12,000	555	1.44
Sample 4	43,000 <i>105</i>	30 <i>103</i>	150 <i>93</i>	45 <i>90</i>	12,000 <i>100</i>	600 <i>108</i>	1.4 <i>97</i>
Sample 5	37,000 <i>90</i>	33 <i>114</i>	160 <i>99</i>	44 <i>88</i>	11,000 <i>92</i>	580 <i>104</i>	1.5 <i>104</i>
Sample 6	43,000 <i>105</i>	31 <i>107</i>	200 <i>124</i>	42 <i>84</i>	13,000 <i>108</i>	580 <i>104</i>	1.4 <i>97</i>
Environmental Duplicate Samples (EDS)— <i>Italicized</i> number is relative percentage difference of EDS							
CCR624:3-6	42,000 <i>0.0</i>	65 <i>1.5</i>	110 <i>9.5</i>	39 <i>2.6</i>	12,000 <i>8.7</i>	910 <i>1.1</i>	0.17 <i>6.1</i>
CCR624:3-6DUP	42,000	66	100	38	11,000	900	.16
CCR-643:3-6	39,000 <i>.0</i>	74 <i>13.8</i>	130 <i>7.4</i>	39 <i>2.5</i>	14,000 <i>.0</i>	1,000 <i>.0</i>	.28 <i>6.9</i>
CCR-643:3-6DUP	39,000	85	140	40	14,000	1,000	.30
CCR668:10-15	39,000 <i>2.5</i>	50 <i>7.7</i>	150 <i>6.4</i>	31 <i>9.2</i>	16,000 <i>.1</i>	740 <i>2.7</i>	.47 <i>26</i>
CCR668:10-15DUP	40,000	54	160	34	17,000	760	.36
CCR692:2-4	35,000 <i>.0</i>	70 <i>5.6</i>	190 <i>11</i>	30 <i>3.4</i>	18,000 <i>12</i>	700 <i>1.4</i>	.27 <i>3.8</i>
CCR692:2-4DUP	35,000	74	170	29	16,000	690	.26
CCR705:14-16	43,000 <i>.0</i>	67 <i>2.9</i>	680 <i>.0</i>	32 <i>.0</i>	25,000 <i>.0</i>	720 <i>.0</i>	2.0 <i>.0</i>
CCR705:14-16DUP	43,000	69	680	32	25,000	720	2.0
CSA:3-6	44,000 <i>2.3</i>	41 <i>2.5</i>	88 <i>.0</i>	40 <i>.2.5</i>	14,000 <i>7.4</i>	960 <i>3.2</i>	.08 <i>.0</i>
CSA:3-6DUP	43,000	40	88	39	13,000	930	.08
Sample designation	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium
Standard Reference Material (SRM)— <i>Italicized</i> number is percentage recovery of SRM							
PACS-2	5.43	39.5	–	960	12,400	–	–
Sample 1	6.1 <i>112</i>	37 <i>94</i>	13 –	1,000 <i>104</i>	14,000 <i>113</i>	42 –	15 –
Sample 2	5.9 <i>109</i>	42 <i>106</i>	11 –	1,200 <i>125</i>	14,000 <i>113</i>	43 –	16 –
Sample 3	6.4 <i>118</i>	40 <i>101</i>	8.5 –	920 <i>96</i>	11,000 <i>89</i>	44 –	13 –
BR-2704	–	44.1	–	998	20,000	¹100	¹12
Sample 4	4.6 –	43 <i>98</i>	15 –	1,100 <i>110</i>	21,000 <i>105</i>	98 <i>98</i>	13 <i>108</i>
Sample 5	4.7 –	45 <i>102</i>	9.3 –	920 <i>92</i>	18,000 <i>90</i>	100 <i>100</i>	11 <i>92</i>
Sample 6	4.6 –	41 <i>93</i>	15 –	1,000 <i>102</i>	22,000 <i>110</i>	96 <i>96</i>	12 <i>100</i>
Environmental Duplicate Samples (EDS)— <i>Italicized</i> number is relative percentage difference of EDS							
CCR624:3-6	0.69 <i>35</i>	33 <i>0.0</i>	16 <i>6.1</i>	960 <i>4.3</i>	19,000 <i>0.0</i>	108 <i>0.9</i>	15 <i>0.0</i>
CCR624:3-6DUP	1.0	33	17	920	19,000	107	15
CCR-643:3-6	1.4 <i>.0</i>	44 <i>.0</i>	19 <i>.0</i>	1,100 <i>.0</i>	22,000 <i>.0</i>	117 <i>.9</i>	13 <i>.0</i>
CCR-643:3-6DUP	1.4	44	19	1,100	22,000	118	13
CCR668:10-15	1.5 <i>12</i>	33 <i>3.0</i>	30 <i>18</i>	1,200 <i>8.0</i>	24,000 <i>4.1</i>	96.0 <i>4.1</i>	12 <i>8</i>
CCR668:10-15DUP	1.7	34	25	1,300	25,000	100	13
CCR692:2-4	3.8 <i>2.7</i>	32 <i>.0</i>	19 <i>5.1</i>	1,300 <i>.0</i>	19,000 <i>.3</i>	91.2 <i>.2</i>	9.9 <i>2.0</i>
CCR692:2-4DUP	3.7	32	20	1,200	19,000	91.0	9.7
CCR705:14-16	7.3 <i>15</i>	36 <i>.0</i>	33 <i>3.0</i>	2,100 <i>.0</i>	26,000 <i>.0</i>	101 <i>.0</i>	13 <i>.0</i>
CCR705:14-16DUP	6.3	36	34	2,100	26,000	101	13
CSA:3-6	.86 <i>28</i>	25 <i>.0</i>	23 <i>24</i>	1,000 <i>.0</i>	23,000 <i>4.4</i>	113 <i>1.8</i>	16 <i>.0</i>
CSA:3-6DUP	.65	25	18	1,000	22,000	111	16

Table 6. Analytical results for standard reference material and environmental duplicate samples for quality assurance.—Continued

[Concentrations are in micrograms per kilogram unless otherwise noted. **Sample designation:** **PACS-2:** Standard reference material (SRM) from the National Research Council of Canada. SRMs are reported. **BR-2704:** SRM from the U.S. National Institute of Standards and Testing, Special Publication 260 (1990–91). <, less than; –, no data]

Sample designation	Selenium		Silver		Sodium		Strontium		Tantalum		Thallium		Thorium	
Standard Reference Material (SRM)— <i>Italicized number is percentage recovery of SRM</i>														
PACS-2	0.92		1.22		34,500		276		–	–	¹ 0.6		–	
Sample 1	1.0	<i>109</i>	<3	–	38,000	<i>110</i>	290	<i>105</i>	0.92	–	.70	<i>117</i>	4.1	–
Sample 2	1.2	<i>130</i>	<3	–	33,000	<i>96</i>	290	<i>105</i>	.39	–	.65	<i>108</i>	4.0	–
Sample 3	.81	<i>88</i>	<3	–	31,000	<i>90</i>	290	<i>105</i>	.25	–	.60	<i>100</i>	6.1	–
BR-2704	¹ 1.1		–		5,470		¹ 130		–	–	1.2		9.2	
Sample 4	1.2	<i>109</i>	<3	–	5,500	<i>101</i>	130	<i>100</i>	.74	–	1.1	<i>92</i>	8.6	<i>93</i>
Sample 5	1.1	<i>100</i>	<3	–	5,400	<i>99</i>	130	<i>100</i>	<.20	–	1.1	<i>92</i>	9.6	<i>104</i>
Sample 6	1.1	<i>100</i>	<3	–	6,400	<i>117</i>	140	<i>108</i>	1.1	–	1.2	<i>100</i>	8.6	<i>93</i>
Environmental Duplicate Samples (EDS)— <i>Italicized number is relative percentage difference of EDS</i>														
CCR624:3-6	0.38	<i>14</i>	<3	<i>0.0</i>	13,000	<i>8.0</i>	260	<i>0.0</i>	1.2	<i>15</i>	1.3	<i>8.0</i>	13	<i>0.0</i>
CCR624:3-6DUP	.33		<3		12,000		260		1.4		1.2		13	
CCR-643:3-6	.54	<i>18</i>	<3	<i>.0</i>	12,000	<i>.0</i>	280	<i>3.5</i>	1.4	<i>.0</i>	1.5	<i>.0</i>	13	<i>7.4</i>
CCR-643:3-6DUP	.65		<3		12,000		290		1.4		1.5		14	
CCR668:10-15	.86	<i>3.6</i>	<3	<i>.0</i>	20,000	<i>.0</i>	380	<i>2.6</i>	1.6	<i>6.4</i>	1.1	<i>.0</i>	12	<i>8</i>
CCR668:10-15DUP	.83		<3		20,000		390		1.5		1.1		13	
CCR692:2-4	.93	<i>18</i>	<3	<i>.0</i>	17,000	<i>6.1</i>	470	<i>.0</i>	1.2	<i>8</i>	.92	<i>6.7</i>	12	<i>.0</i>
CCR692:2-4DUP	.78		<3		16,000		470		1.3		.86		12	
CCR705:14-16	1.4	<i>15</i>	7	<i>55</i>	18,000	<i>.0</i>	420	<i>.0</i>	2.0	<i>18</i>	1.4	<i>6.9</i>	13	<i>.0</i>
CCR705:14-16DUP	1.2		4		18,000		420		2.4		1.5		13	
CSA:3-6	.55	<i>34</i>	<3	<i>.0</i>	12,000	<i>8.0</i>	170	<i>.0</i>	1.6	<i>37</i>	.80	<i>5.1</i>	12	<i>8</i>
CSA:3-6DUP	.39		<3		11,000		170		1.1		.76		13	
Standard Reference Material (SRM)— <i>Italicized number is percentage recovery of SRM</i>														
PACS-2	4,430		¹ 3		133		–		–		364			
Sample 1	5,100	<i>115</i>	2.2	<i>73</i>	140	<i>105</i>	2.0	–	18	–	352	<i>97</i>		
Sample 2	4,400	<i>99</i>	2.2	<i>73</i>	150	<i>113</i>	1.9	–	18	–	411	<i>113</i>		
Sample 3	4,300	<i>97</i>	2.2	<i>73</i>	120	<i>90</i>	1.9	–	20	–	343	<i>94</i>		
BR-2704	4,570		3.13		95		–		–		438			
Sample 4	3,600	<i>79</i>	2.8	<i>89</i>	100	<i>105</i>	2.8	–	24	–	465	<i>106</i>		
Sample 5	4,100	<i>90</i>	2.8	<i>89</i>	86	<i>91</i>	3.1	–	31	–	404	<i>92</i>		
Sample 6	3,800	<i>83</i>	2.7	<i>86</i>	93	<i>98</i>	3.2	–	26	–	405	<i>92</i>		
Environmental Duplicate Samples (EDS)— <i>Italicized number is relative percentage difference of EDS</i>														
CCR624:3-6	4,400	<i>0.0</i>	3.1	<i>0.0</i>	110	<i>0.0</i>	3.2	<i>3.2</i>	38	<i>0.0</i>	390	<i>8</i>		
CCR624:3-6DUP	4,400		3.1		110		3.1		38		360			
CCR-643:3-6	4,200	<i>.0</i>	3.3	<i>5.9</i>	100	<i>.0</i>	2.8	<i>13</i>	35	<i>.0</i>	370	<i>2.7</i>		
CCR-643:3-6DUP	4,200		3.5		100		3.2		35		380			
CCR668:10-15	3,800	<i>10</i>	3.2	<i>9.0</i>	97	<i>3.0</i>	2.5	<i>7.7</i>	28	<i>3.5</i>	480	<i>9.9</i>		
CCR668:10-15DUP	4,200		3.5		100		2.7		29		530			
CCR692:2-4	4,100	<i>.0</i>	5.0	<i>6.2</i>	83	<i>1.2</i>	2.4	<i>4.1</i>	30	<i>15</i>	730	<i>4.2</i>		
CCR692:2-4DUP	4,100		4.7		82		2.5		35		700			
CCR705:14-16	4,100	<i>2.5</i>	5.5	<i>.0</i>	120	<i>8.7</i>	3.2	<i>.0</i>	48	<i>.0</i>	1,400	<i>.0</i>		
CCR705:14-16DUP	4,000		5.5		110		3.2		48		1,400			
CSA:3-6	5,200	<i>1.9</i>	5.6	<i>1.8</i>	98	<i>.0</i>	3.6	<i>5.7</i>	31	<i>5.7</i>	920	<i>3.2</i>		
CSA:3-6DUP	5,300		5.7		98		3.4		29		950			

¹Value is uncertified and is included for reference only.

66 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 7. Vertical distribution of concentrations of selected trace elements and major ions in pore water, bulk sediment, and residual sediment from shallow cores from sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington, July 2003.

[**Bulk and Residual Sediment Analysis:** Replicate analysis of bulk sediment. **Residual Sediment:** Concentrations of residual sediment following 30 minute leach with 0.25 Molar hydroxylamine hydrochloride. **Residual Percent:** Residual as percentage of unleached bulk-sediment concentration. **Abbreviations:** cm, centimeter; mg/L, milligram per liter; <, less than; -, no data]

Sediment core sampling site	Depth interval (cm)	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Cadmium	Calcium (mg/L)	Cerium	Cesium	
Pore Water Analysis (microgram per liter unless otherwise noted)												
CCR-668	0-1	70	0.85	15	96	<0.05	<0.2	0.08	22	0.23	0.13	
	1-2	63	.67	24	91	<.05	<.2	.04	22	.24	.15	
	9-11	50	1.0	20	140	<.05	<.2	.03	31	.19	.23	
	9-11	28	.68	24	140	<.05	<.2	.03	30	.15	.20	
CCR-692	18-20	18	.50	11	190	<.05	<.2	<.02	44	.08	.22	
	0-1	150	.61	26	87	<.05	<.2	.26	31	.59	.15	
	1-2	60	1.1	16	110	<.05	<.2	.08	33	.21	.16	
CCR-705	9-11	45	2.0	15	180	<.05	<.2	.06	38	.20	.15	
	0-1	58	1.2	4.1	64	<.05	<.2	.68	19	.23	.06	
	1-2	100	1.0	6.0	68	<.05	<.2	.25	19	.44	.06	
	9-11	43	1.4	18	80	<.05	<.2	.07	20	.17	.04	
Bulk Sediment Analysis (milligram per kilogram)												
CCR-668	1-2	76,000	3.9	7.2	1,100	2.6	0.53	2.5	15,000	87	5.2	
	9-11	75,000	6.2	9.2	1,100	2.3	.54	4.1	16,000	87	4.8	
CCR-692	1-2	70,000	4.2	5.2	1,200	2.5	.46	3.0	21,000	83	4.1	
	9-11	66,000	7.2	7.7	1,500	2.2	.46	4.6	36,000	72	4.1	
CCR-705	1-2	76,000	5.3	7	1,200	2.5	.61	5.0	17,000	88	4.9	
	9-11	74,000	7.2	10	1,300	2.6	.64	9.2	20,000	92	4.5	
Bulk and Residual Sediment Analysis (milligram per kilogram)												
CCR-668	Bulk sediment	1-2	74,000	3.8	9.0	1,100	2.6	0.30	2.6	15,000	96	5.1
	Residual sediment		67,000	3.6	6.7	902	1.80	.16	.44	10,000	52	4.6
	Residual (percent)		91	94	74	83	69	55	17	67	54	90
CCR-692	Bulk sediment	9-11	72,000	6.1	12	1,100	2.5	.32	4.2	16,000	97	4.7
	Residual sediment		68,000	5.5	7.4	950	2.0	.15	.64	10,000	52	4.2
	Residual (percent)		94	90	64	83	80	47	15	66	53	89
CCR-705	Bulk sediment	1-2	73,000	5.1	8.5	1,200	2.4	.41	5.2	17,000	96	4.8
	Residual sediment		64,000	4.4	5.2	940	1.8	.13	.52	9,700	52	4.2
	Residual (percent)		89	86	61	80	76	31	10	57	54	87
CCR-705	Bulk sediment	9-11	73,000	7.2	14	1,300	2.7	.44	9.6	20,000	100	4.6
	Residual sediment		70,000	6.3	6.5	1,100	2.1	170	1.4	11,000	57	4.1
	Residual (percent)		96	88	48	87	78	39	14	58	57	90

Table 7. Vertical distribution of concentrations of selected trace elements and major ions in pore water, bulk sediment, and residual sediment from shallow cores from sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington, July 2003.—Continued

[**Bulk and Residual Sediment Analysis:** Replicate analysis of bulk sediment. **Residual Sediment:** Concentrations of residual sediment following 30 minute leach with 0.25 Molar hydroxylamine hydrochloride. **Residual Percent:** Residual as percentage of unleached bulk-sediment concentration. **Abbreviations:** cm, centimeter; mg/L, milligram per liter; <, less than; –, no data]

Sediment core sampling site	Depth interval (cm)	Chromium	Cobalt	Copper	Gallium	Iron	Lanthanun	Lead	Lithium	Magne-sium	Manganese	
Pore Water Analysis (microgram per liter unless otherwise noted)												
CCR-668	0-1	<1	1.1	1.6	0.20	180	0.15	1.4	1.6	5.0	6,000	
	1-2	<1	.82	1.3	.20	1,300	.16	2.0	1.6	4.8	4,100	
	9-11	<1	.70	1.1	.10	1,400	.22	2.0	1.5	6.0	4,300	
	9-11	<1	.61	1.0	.10	5,600	.16	1.4	1.8	6.3	4,200	
CCR-692	18-20	<1	.52	1.8	.08	3,400	.08	1.3	1.8	8.6	4,100	
	0-1	<1	1.0	4.2	.07	3,000	.42	6.5	1.4	9.0	2,100	
	1-2	<1	.45	1.9	<.05	160	.16	3.0	1.5	11	750	
CCR-705	9-11	<1	.21	2.1	<.05	990	.17	3.8	1.2	15	260	
	0-1	<1	.62	3.8	<.05	120	.20	2.9	1.6	5.1	1,200	
CCR-705	1-2	<1	.54	2.7	<.05	250	.44	8.0	1.8	5.2	890	
	9-11	<1	.39	1.0	<.05	410	.25	4.6	1.8	5.9	690	
Bulk Sediment Analysis (milligram per kilogram)												
CCR-668	1-2	83	15	69	18	41,000	51	110	33	14,000	1,100	
	9-11	91	15	110	17	40,000	60	210	32	14,000	1,000	
CCR-692	1-2	68	20	75	16	37,000	50	130	28	15,000	620	
	9-11	73	12	130	15	38,000	47	250	28	21,000	550	
CCR-705	1-2	92	14	91	17	42,000	57	230	33	14,000	860	
	9-11	110	13	100	17	39,000	74	430	32	16,000	700	
Bulk and Residual Sediment Analysis (milligram per kilogram)												
CCR-668	Sediment	1-2	81.1	15	69	18	41,000	56	120	34	16,000	1,200
		Residual sediment	70.2	8.8	24	16	29,000	30	22	29	12,000	440
	Residual (percent)	86.56	59	34	90	71	53	19	86	75	39	
	Sediment	9-11	88.0	15	110	17	40,000	66	220	33	15,000	1,000
		Residual sediment	77.9	8.2	32	16	28,000	31	27	28	12,000	410
	Residual (percent)	88.52	56	29	91	71	47	12	85	76	39	
CCR-705	Bulk sediment	1-2	88	14	90	17	42,000	63	250	33	16,000	850
		Residual sediment	75	7	20	15	26,000	30	22	28	11,000	360
	Residual (percent)	85	53	22	86	64	48	9.0	84	68	42	
	Bulk sediment	9-11	110	13	100	17	40,000	81	460	32	17,000	710
		Residual sediment	99	8.0	28	16	28,000	35	41	28	12,000	396
	Residual (percent)	92	60	26	94	71	43	8.8	88	69	56	

68 Vertical Distribution of Trace Elements and Metallurgical Slag in Sediments, Lake Roosevelt, Washington, 2002

Table 7. Vertical distribution of concentrations of selected trace elements and major ions in pore water, bulk sediment, and residual sediment from shallow cores from sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington, July 2003.—Continued

[**Bulk and Residual Sediment Analysis:** Replicate analysis of bulk sediment. **Residual Sediment:** Concentrations of residual sediment following 30 minute leach with 0.25 Molar hydroxylamine hydrochloride. **Residual Percent:** Residual as percentage of unleached bulk-sediment concentration. **Abbreviations:** cm, centimeter; mg/L, milligram per liter; <, less than; –, no data]

Sediment core sampling site	Depth interval (cm)	Molybdenum	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Sodium	Silver	
Pore Water Analysis (micrograms per liter unless otherwise noted)											
CCR-668	0-1	3.5	2.5	<0.2	0.1	1.6	5.0	5.9	3.4	<3	
	1-2	2.6	2.0	<.2	.1	1.7	5.0	6.6	2.4	<3	
	9-11	1.9	2.1	<.2	.02	2.3	6.7	7.5	3.3	<3	
	9-11	2.3	2.0	<.2	.04	2.1	6.1	9.4	3.4	<3	
	18-20	2.0	2.4	<.2	.01	2.9	7.7	9.0	4.6	<3	
CCR-692	0-1	<2.0	3.0	<.2	.2	1.9	4.7	6.8	3.3	<3	
	1-2	<2.0	1.8	<.2	.04	2.3	4.8	7.4	3.2	<3	
	9-11	<2.0	2.0	<.2	.2	3.2	3.8	8.0	3.5	<3	
CCR-705	0-1	<2.0	1.9	<.2	.05	1.1	3.7	4.6	2.2	<3	
	1-2	<2.0	1.6	<.2	.07	1.2	3.6	5.1	2.2	<3	
	9-11	2.8	1.3	<.2	.09	1.3	2.3	5.7	2.7	<3	
Bulk Sediment Analysis (milligram per kilogram)											
CCR-668	1-2	1.4	39	30	1,400	23,000	100	13	16,000	1.5	
	9-11	2.0	38	30	1,500	23,000	98	13	16,000	2.7	
CCR-692	1-2	1.4	30	29	1,600	22,000	88	11	18,000	1.1	
	9-11	4.4	30	26	1,500	21,000	85	11	16,000	2.6	
CCR-705	1-2	1.4	37	34	1,700	24,000	100	13	16,000	2.0	
	9-11	3.8	37	33	1,700	24,000	99	13	17,000	.16	
Bulk and Residual Sediment Analysis (milligram per kilogram)											
CCR-668	Bulk sediment	1-2	1.7	42	29	1,400	24,000	99	13	17,000	–
	Residual sediment		1.3	27	17	400	21,000	94	12	15,000	–
	Residual (percent)		78	65	58	28	88	95	94	85	–
CCR-692	Bulk sediment	9-11	2.2	40	29	1,600	24,000	97	12	18,000	–
	Residual sediment		1.5	26	16	340	22,000	93	12	16,000	–
	Residual (percent)		68	65	57	22	92	96	97	90	–
CCR-705	Bulk sediment	1-2	1.9	39	32	1,700	24,000	100	12	18,000	–
	Residual sediment		1.5	24	17	310	20,000	90	11	15,000	–
	Residual (percent)		79	61	52	18	84	90	91	83	–
CCR-705	Bulk sediment	9-11	4.5	39	32	1,800	24,000	99	12	19,000	–
	Residual sediment		2.4	25	19	310	23,000	98	12	17,000	–
	Residual (percent)		53	64	58	17	94	98	98	90	–

Table 7. Vertical distribution of concentrations of selected trace elements and major ions in pore water, bulk sediment, and residual sediment from shallow cores from sites CCR-668, CCR-692, and CCR-705, Lake Roosevelt, Washington, July 2003.—Continued

[**Bulk and Residual Sediment Analysis:** Replicate analysis of bulk sediment. **Residual Sediment:** Concentrations of residual sediment following 30 minute leach with 0.25 Molar hydroxylamine hydrochloride. **Residual Percent:** Residual as percentage of unleached bulk-sediment concentration. **Abbreviations:** cm, centimeter; mg/L, milligram per liter; <, less than; –, no data]

Sediment core sampling site	Depth interval (cm)	Sulfate	Tantalum	Thallium	Thorium	Titanium	Uranium	Vanadium	Yttrium	Zinc	
Pore Water Analysis (microgram per liter unless otherwise noted)											
CCR-668	0-1	3	<0.02	<0.1	<0.2	1.2	0.33	1.3	0.19	6.6	
	1-2	<2	<.02	<.1	<.2	1.0	.26	1.9	.22	3.8	
	9-11	<2	<.02	.2	<.2	.50	.35	1.1	.44	26	
	9-11	<2	.05	.1	<.2	.90	.30	1.4	.39	3.4	
CCR-692	18-20	<2	.05	<.1	<.2	.80	.33	.60	.26	40	
	0-1	<2	<.02	<.1	<.2	3.7	.59	1.2	.41	13	
	1-2	<2	<.02	<.1	<.2	1.3	.50	1.1	.20	3.7	
CCR 705	9-11	<2	<.02	<.1	<.2	1.4	.54	1.6	.35	4.2	
	0-1	7	<.02	.1	<.2	1.2	.16	.7	.20	12	
	1-2	<2	<.02	.1	<.2	1.7	.17	1.0	.42	10	
9-11	<2	<.02	<.1	<.2	<.50	.22	1.0	.30	4.9		
Bulk Sediment Analysis (milligram per kilogram)											
CCR-668	1-2	–	1.6	0.97	14	3,600	3.8	100	26	430	
	9-11	–	1.7	1.7	14	3,600	4.0	100	39	540	
CCR-692	1-2	–	1.5	.91	12	3,300	3.9	90	25	540	
	9-11	–	1.4	1.2	11	3,000	5.3	91	27	960	
CCR-705	1-2	–	1.8	1.0	14	3,500	3.9	110	33	650	
	9-11	–	1.9	1.4	14	3,500	4.4	110	50	980	
Bulk and Residual Sediment Analysis (milligram per kilogram)											
CCR-668	Bulk sediment	1-2	–	–	1.0	16	3,900	4.0	100	29	420
	Residual sediment	–	–	–	.72	14	3,700	2.1	88	16	140
	Residual (percent)	–	–	–	70	88	96	53	84	55	32
CCR-692	Bulk sediment	9-11	–	–	1.8	15	3,800	4.3	110	43	520
	Residual sediment	–	–	–	.87	13	3,700	2.2	91	13	150
	Residual (percent)	–	–	–	50	87	96	51	86	31	28
CCR-705	Bulk sediment	1-2	–	–	1.1	15	3,700	4.1	110	37	600
	Residual sediment	–	–	–	.76	14	3,400	2.3	85	11	140
	Residual (percent)	–	–	–	70	89	92	56	81	30	23
CCR-705	Bulk sediment	9-11	–	–	1.5	15	3,900	4.4	110	58	900
	Residual sediment	–	–	–	.84	14	3,800	2.6	96	15	230
	Residual (percent)	–	–	–	57	95	97	57	88	25	26

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Cox and others

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