U.S. DEPARTMENT OF INTERIOR

U.S. GEOLOGICAL SURVEY

Geochemical and lead-isotope data from stream and lake sediments, and cores from the upper Arkansas River drainage: Effects of mining at Leadville, Colorado on heavy-metal concentrations in the Arkansas River

by

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PREFACE

The following study was undertaken at the request of the U.S. Department of Justice to provide data on the origin of the heavy metals present in the Arkansas River south of California Gulch. The study concentrated on determination of the lead-isotope and trace-metal signatures in the Arkansas River sediments from the continental divide south to the Leadville area, Co. ^{210}Pb geochronology studies of a core from the Arkansas River north of California Gulch, of two cores south of California Gulch, and of a fourth core from lower Crystal Lake, a glacial moraine lake in the Arkansas River flood plain south of California Gulch, were analyzed to provide age control. Unfortunately, we were unable to determine the flux rate of ^{210}Pb indirectly, and the time-frame for this study was too short to make these determinations independently. Although excess ^{210}Pb activity exists in the cores and sedimentary age determinations could be calculated once the flux rate has been determined, no ages for the individual sedimentary layers can be calculated from the existing data. This report summarizes and interprets the data from this study.

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ABSTRACT

Geochemical studies of minus-80-mesh size fraction of stream-sediment samples collected from the upper Arkansas River drainage basin in Lake County, Co., show that the effect of mining activity, both past and present, on heavy-metal concentrations in the river can be readily documented. Application of geochemical leaching procedures often used in mineral exploration enhances the effect of acid-weathering caused by the oxidation of pyrite. Lead-isotope measurements of leaches of irregularly spaced stream-sediment samples clearly delimit the extent of elevated heavy-metal concentrations in the upper Arkansas River caused by mineralization at Climax, Leadville, and to a lessor extent, at St. Kevin Gulch. All leaches of the stream-sediment samples collected from either tributaries of Arkansas River, or from the Arkansas River itself within the boundaries of the Leadville mining district, have lead-isotopic compositions that match those of published lead-isotope data from the ores at Leadville. In contrast, leaches of all stream-sediment samples collected outside the district within the upper Arkansas River drainage basin do not match the lead-isotopic signature of ores from the Leadville mining district.

Detailed studies of the stratigraphy of four cores taken in the Arkansas River flood plain near the confluence with California Gulch in the Leadville mining district document high metal concentrations in an area immediately south of the confluence where heavy-metal-laden tailings from the Leadville mining district have been deposited. ^{210}Pb geochronological studies of these cores show that the tailings in the Arkansas River were deposited over a twenty-year period. Further work is required, however, before definite dates can be assigned to the age of deposition of these tailings. The lead-isotope data and the ^{210}Pb studies allow determination of the heavy-metal concentrations present in the Arkansas River drainage prior to mining at Leadville. Pre-mining concentration of lead in minus-80-mesh stream sediments was about 39 ppm, in sandy sediments about 29 ppm, and in soil samples collected from beneath the tailings deposit, about 38 ppm. Pre-mining concentrations of zinc were 158 ppm, 64 ppm, and about 200 ppm in these sample media. Pre-mining concentrations of copper were about 14 ppm, 10 ppm, and 17 ppm, respectively. Enrichment of various heavy metals in the stream sediments from the Leadville mining district range from 2 to 215 times normal crustal abundance with lead being the most enriched. Core samples of sediments in the Arkansas River drainage derived from tailings from the Leadville mining district have enrichments of heavy metals ranging from 63 to 944 times crustal abundance. The field and analytical methods used in this study demonstrate methods applicable to environmental geochemical perturbations caused by mining and industrial activity worldwide.

INTRODUCTION

Portions of the upper Arkansas River contain elevated levels of heavy-metals at concentrations, particularly for lead and zinc, that are many times that of the normal crustal abundance for these metals. The study area includes several mining districts. At the headwaters of the Arkansas River, the Climax porphyry molybdenum deposit has been mined for several decades. At the southern end of the study area, the Leadville mining district has had major episodes of mining activity spanning the last 130 or more years. Numerous mining prospects occur throughout the drainage area of the upper Arkansas River, including a small district at the headwaters of St. Kevin Gulch, which appears to be an extension of the Leadville mineralization.

The study area is underlain by rocks ranging in age from Precambrian crystalline granitic rocks (1,400 to 1,700 Ma) to sedimentary and igneous rocks of Tertiary age. The crystalline rocks form the basement upon which sedimentary rocks of Paleozoic, Mesozoic, and Tertiary age have been deposited. Subsequently, the area was intruded by middle Tertiary stocks in the Leadville and Climax areas that were responsible for much of the mineralization (Tweto and others, 1978; Bookstrom, 1989, 1990; DeVoto, 1990; Wallace, 1993). In addition to these magmatic hydrothermal deposits, lead-zinc mineralization is hosted in the Paleozoic carbonate rocks on Mt. Sherman on the east side of the Leadville district (Beaty and others, 1990).

SAMPLING PLAN

Stream-sediment, lake-sediment, and core samples were taken at irregular intervals along the upper Arkansas River and some of its tributaries to provide integrated samples of the detrital sedimentary material in the drainage basin. Methods of collection and sample treatment are in Appendix I. Descriptions of the cores are in Appendix II. Briefly, the stream-sediment samples were collected from the river channel and sieved to minus-10-mesh in the field, air-dried, sieved to retain the minus-80-mesh material, and ground to minus 200-mesh. The lake-sediment and core materials were ground in total to minus-200-mesh. Sample localities are shown in figure 1. From north to south, localities 93LV109, 93LV110, 93LV112, 93LV108, 93LV100, and 93LV102 are in the Arkansas River itself whereas localities 93LV111, 93LV107, 93LV104, 93LV105,

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Figure 1. Sample locality map showing the upper Arkansas River drainage. Samples 93LV100-93LV103 are core samples (see Appendix II), samples 93LV104, 93LV105, and 93LV107-93LV114 are stream-sediment samples, and 93LV106 is a sample of the slag in California Gulch (the suffix 93LV has been dropped for clarity). The topographic base map is from the 1:100,000 metric scale topographic map of the Leadville, Colorado 30'x60' quadrangle (U.S. Geological Survey, 1983). →

100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
Tennessee Pass
Tunnel
BOUNDARY
NATIONAL FOREST
SAN ISABEL NATIONAL FOREST
El Capitan Mine
Mitchell Creek
Piney
Cooper Hill
Ski Lift
Buckeye Peak
Chalk Mtn
Climax
Fremont Pass
Gravel Pit
Slide Lake
North Fork
Tennessee Creek
Gravel Pits
Sylvan Lakes
Missouri Hill
Jennie June Mine
Longs Gulch
Morton Lake
Porcupine Gulch
East Fork
Mount Zion
JEEP TRAIL
T 7 S
T 8 S
T 9 S
Temple Gulch
St Kevin Gulch
Tennessee Park
Radio Tower
English Gulch
Treasurevault Mountain
Mosquito Peak
Birdseye Gulch
COLORADO AND SOUTHERN
Prospect Mountain
Mosquito Pass
Radio Facility
Mount Arkansas
Turquoise Lake
Campgrounds
Leadville Junction
Gaging Sta
Gravel Pit
Venture Shaft
Leadville
Evergreen Cem
Little Evans Gulch
Evans Gulch
Matchless Mine
Mountain Lake
Diamond Lake
Fortune Mine
Mount Evans
Ibex Mines
Thespian Mine
Iron Hill
California Gulch
Stringtown
Colorado Mtn College
Banker Mine
Ball Mountain
West Dyer Mtn
Dyer Mountain
Malta
Evergreen Lakes
Lake Fork
County Airport
Powerlines
Moffat Mine
Helena Mine
Mount Sherman
West Sheridan
Mount Sheridan
Iowa Gulch
Thompson Gulch
Empire Reservoir
Peerless Mountain
Finnback Knob
Empire Gulch
Arkansas
Crystal Lakes
Substa
Gravel Pit
Gaging Sta
SCALE 1:100 000
1 ½ 0 1 2 3 4 5 MILES
1 .5 0 1 2 3 4 5 KILOMETERS

Figure 1.

93LV106, 93LV114, and 93LV113 are in tributaries of the Arkansas River. Sites 93LV107, 93LV106, 93LV105, 93LV100, 93LV101, 93LV102, and 93LV113 are in the Leadville mining district. Core 93LV101 is from a field adjacent to the Arkansas River south of California Gulch and core 93LV102 is from the Arkansas River flood plain. Pictures of the two core sites 93LV101 and 93LV102 are in figure 2. At site 93LV103, a lake-sediment sample was recovered from a core taken in the center of lower Crystal Lake in the Arkansas River flood plain.

METHODS

The approach followed in this study utilized multi-element, total-chemical digestions (Briggs, 1990), partial chemical-dissolution procedures (Chao, 1984; Church and others, 1987), and common lead-isotopic studies (Gulson and others, 1992) of core and stream sediments to distinguish sources and contributions of lead and other heavy metals in the sediments of the Arkansas River. Chao (1984) demonstrated the utility of partial digestions techniques in mineral exploration. Heavy metals mobilized during weathering of rocks and mineral deposits are readily adsorbed by iron- and manganese-oxide phases. Since these phases are generally precipitated on the surface of grains in the stream, fine-grained sediments are the preferred medium. Exploration geochemists have commonly used the minus-80-mesh or smaller sized fraction as the medium-of-choice in mineral exploration. Gulson and others (1992) tested the $HCl-H_2O_2$ partial digestion method on samples from the Mt. Emmons porphyry molybdenum deposit near Crested Butte, Co., and demonstrated that iron and manganese oxides scavenge lead and other heavy metals from the stream quickly. They demonstrated spatial changes in the lead-isotopic composition of these coatings in the stream on the tens-of-meters scale. Thus, the lead-isotopic signature of different sources of lead in the environment, where iron- and manganese-oxide coatings are present in the stream sediments, should reflect the local source of the heavy-metals. Descriptions of the chemical methods used for the total digestion and partial leaching procedures are in Appendix III, along with the analytical data.

Lead has four naturally occurring isotopes: ^{206}Pb accumulates from the decay of ^{238}U, ^{207}Pb accumulates from the decay of ^{235}U, and ^{208}Pb accumulates from the decay of ^{232}Th. Each of these radioactive decay schemes is shown in figure 3. Since each of the parent isotopes has a different half life, the three isotopes of lead accumulate at different rates. ^{204}Pb has no radioactive parent isotope and it does not change as a function of time. The effect of time on the change in these lead-isotope ratios is shown in figure 4. Since the age of the rocks present in the upper Arkansas River drainage basin is younger than 1,700 Ma, we expect the isotopic composition of lead in the stream-sediments to reflect compositions to the right of the 1,700 Ma line shown in figure 4. Crustal rocks contain relatively low concentrations of lead (generally 5-50 ppm), uranium (2-10 ppm), and thorium (8-40 ppm)

Figure 2. Photographs of sample localities for core 93LV101 (A) and 93LV102 (B). Two cores were taken; one core tube is four feet and the other five feet in length. Note the top of a buried fence post exposed at site 93LV101 (A). Sample locality 93LV102 is in the active flood plain of the Arkansas River.

and the lead-isotopic composition in the rocks continues to evolve with time. Generally, geochemists have sampled stream, lake, or ocean sediments to obtain representative samples of large areas (for example, Chow and Patterson, 1962; Chow 1965). Thus, the isotopic composition of lead on the earth's surface is variable. However, in mineral deposits, particularly those containing the mineral galena (PbS), lead is separated from uranium and thorium and thus the evolution of lead as a function of time is "frozen in" at the time of mineralization. The composition of lead in mineral deposits often has a very limited isotopic range. This fact, coupled with the very high concentrations of lead in many mineral deposits, allows us to "fingerprint" the heavy-metal contributions from specific mineral deposits rather effectively. Point sources of heavy-metal contamination are readily diluted by mixing of sediment derived from unmineralized rock from the surrounding country side within the drainage basin. Chemical procedures and analytical methods used in making the lead-isotope determinations are given in Appendix IV.

^{210}Pb studies were undertaken on the core samples to determine the age and depositional history of the deposits at the confluence of California Gulch with the Arkansas River. ^{210}Pb is a part of the radioactive decay scheme of ^{238}U to ^{206}Pb (see figure 3A). As ^{238}U decays, ^{222}Rn is formed; a small portion of the radon gas escapes into the atmosphere where it then decays through a series of short-lived daughters to ^{210}Pb. Estimates of this flux rate for the escape of ^{222}Rn are about 42 atoms per minute per cm^2 of land surface. ^{210}Pb is rapidly removed from the atmosphere by ice, snow, and rain over a period of ten days after it forms. ^{210}Pb is deposited on continents and in the coastal oceans. It is adsorbed by the humus and clays in the soils, and by the clays and the iron- and manganese-oxide phases in the sediments within the drainage basin. The activity of the unsupported ^{210}Pb decreases as a function of time at a rate defined by its half-life of 22.26 years. This ^{210}Pb activity can be measured and the data used to determine rate of accumulation of sediments over the last 100-150 years once a flux rate for the drainage basin is determined. Chemical procedures and analytical methods used in making the ^{210}Pb determinations, along with the analytical data from this study, are in Appendix V.

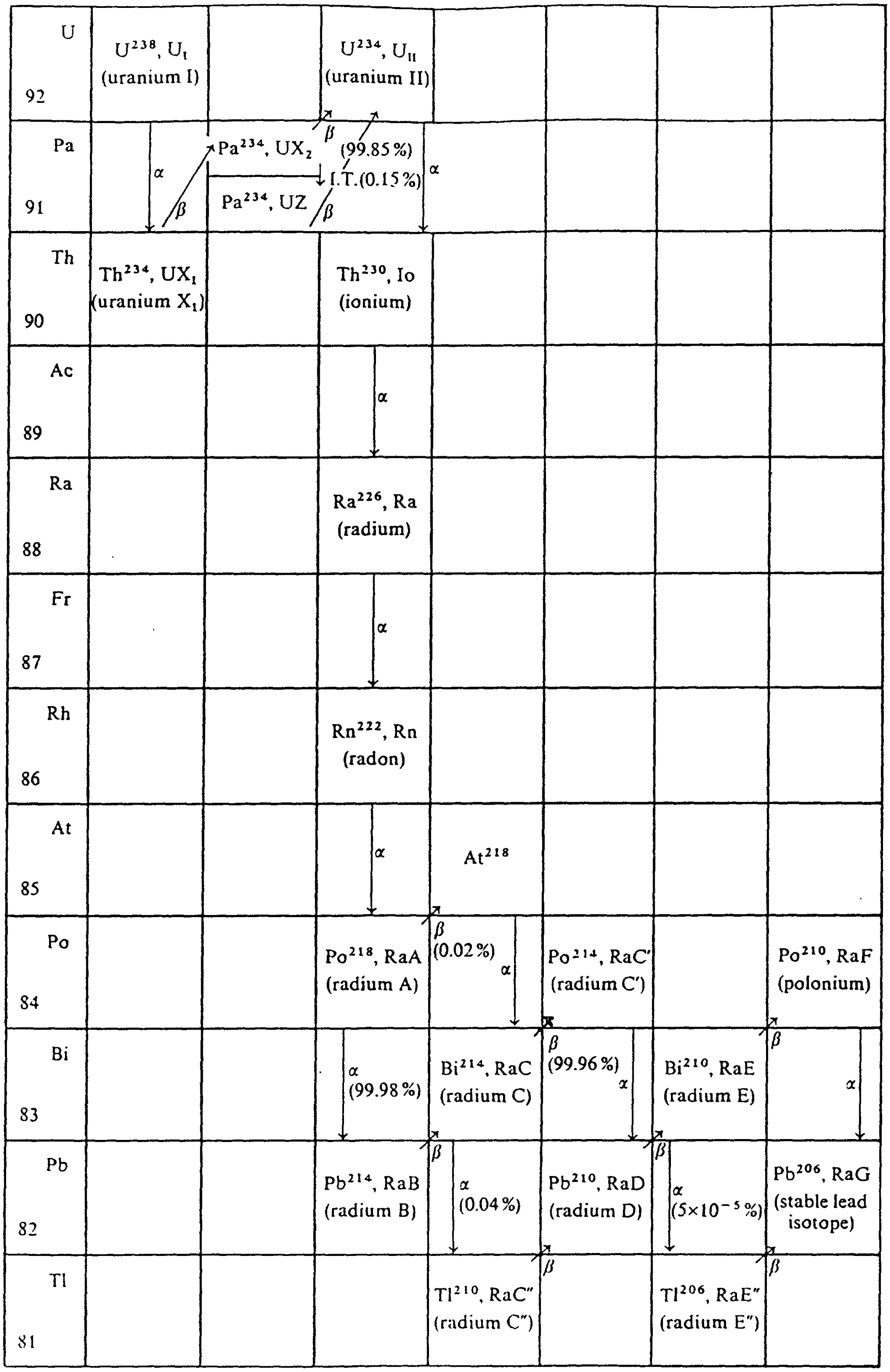


Figure 3A. Radioactive decay scheme for ^{238}U (from Doe, 1970, p. 83).

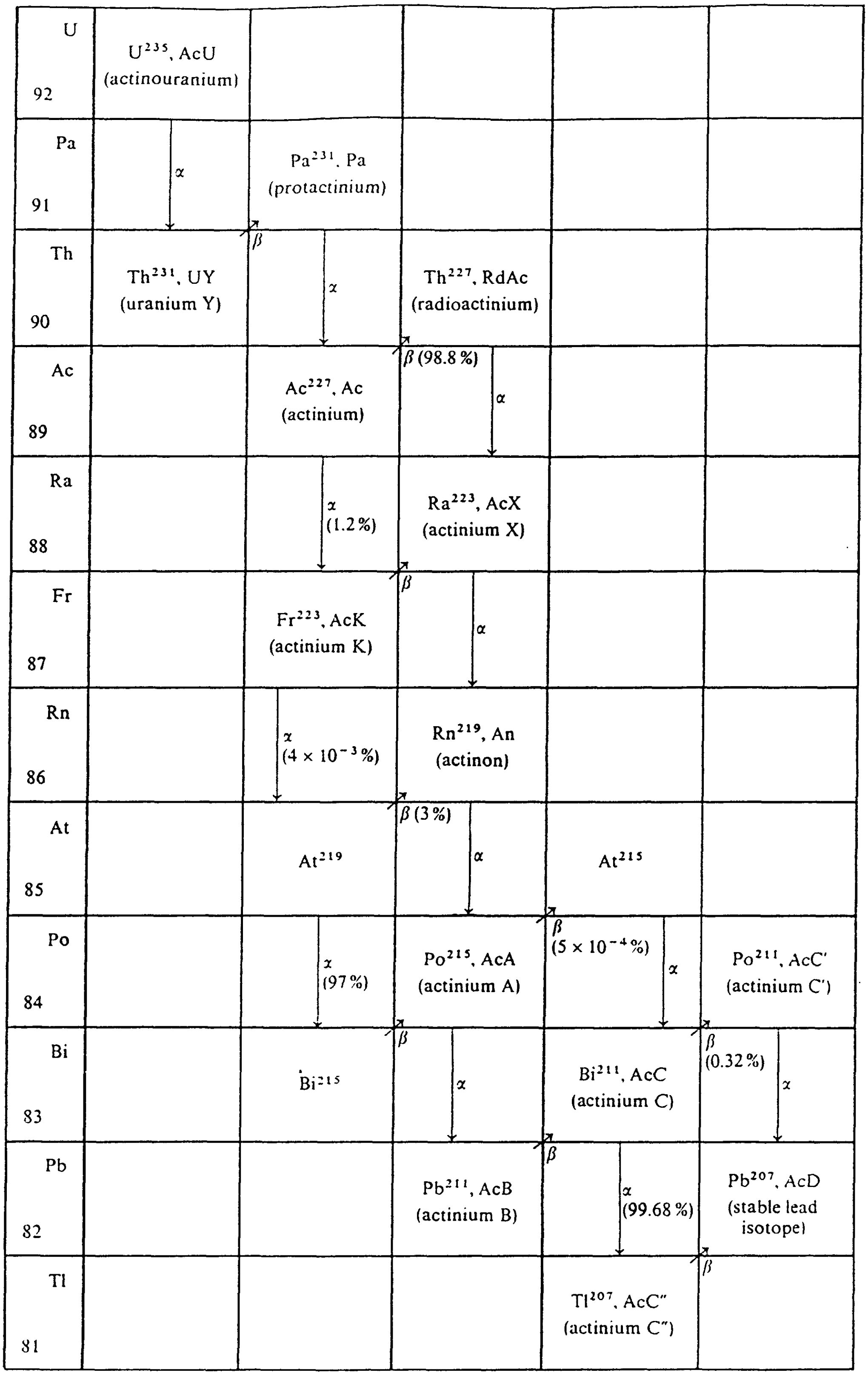


Figure 3B. Radioactive decay scheme for ^{235}U (from Doe, 1970, p. 85).

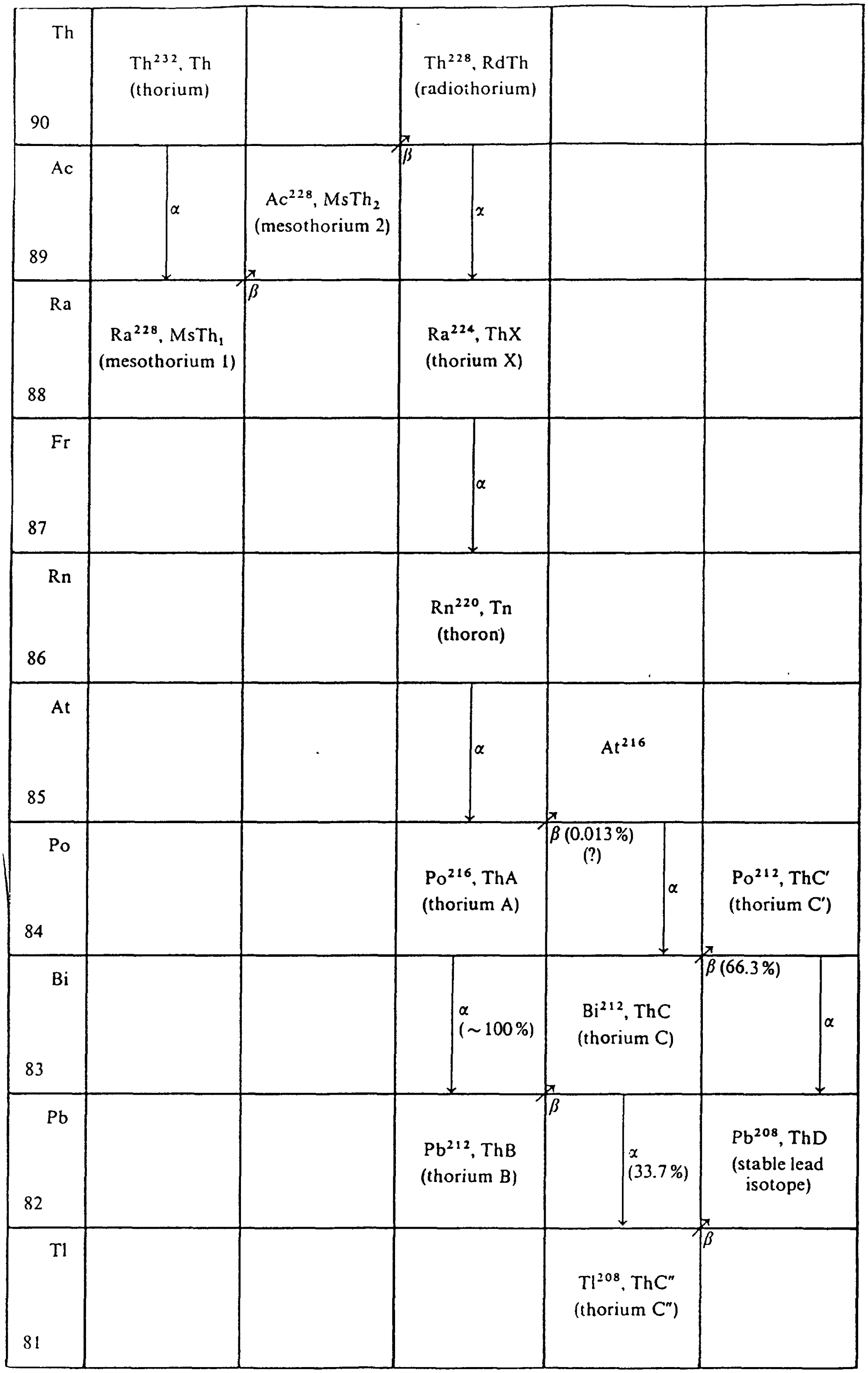


Figure 3C. Radioactive decay scheme for ^{232}Th (from Doe, 1970, p. 84).

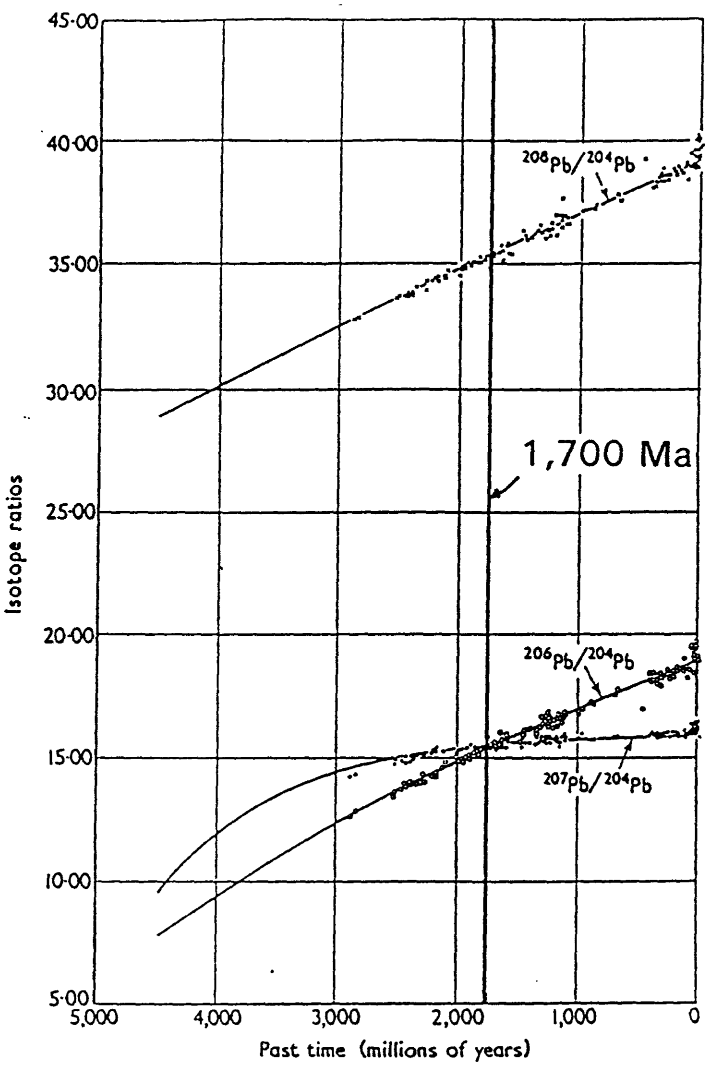


Figure 4. Diagram showing the change in the three isotopic ratios of lead relative to ^{204}Pb as a function of time (from Russell and Farquher, 1960, p. 51). Rocks in the upper Arkansas River drainage are 1,700 Ma and younger. Common lead from rocks and ores within this drainage basin all plot to the right of the 1,700 Ma line.

INTERPRETATION OF THE GEOCHEMICAL DATA

The geochemical results from the stream-sediment and core samples are compared in figures 5 through 7. For ease of presentation, plots of the stream-sediment data have been made relative to the distance from the continental divide. Data from the cores have been plotted relative to the depth interval sampled. Geochemical data plotted are from the total digestions, except where otherwise noted.

The geochemical results from the study of the stream sediments are summarized in figure 5. For the purposes of comparison, the concentrations of three transition metals, chromium, nickel, and vanadium, which are not a part of the geochemical signature pattern of any of the deposits in the upper Arkansas River drainage, have been plotted to demonstrate normal crustal variation in the stream sediments from the study area. Contrast this diagram (5A) with the diagram of the metals cobalt, copper, and molybdenum (5B), that reflect the deposits in the upper Arkansas River drainage to various degrees. For example, the Climax porphyry molybdenum deposit, which is just east of the continental divide in the Platte River drainage, is reflected at the first site at the top of the Arkansas River drainage. The molybdenum signature from the Climax deposit is rapidly diluted until sediment contributions from the Leadville mining district enter the Arkansas River drainage where the molybdenum concentrations are again elevated. Both cobalt and copper also show elevated metal levels in the drainages at or below the Leadville mining district. Likewise, in figure 5C, the contributions of lead, zinc, and cadmium from the Climax deposit are apparent, but again, these metal concentrations are rapidly diluted to normal crustal abundance levels in the Arkansas River until sediment contributions from the Leadville mining district enter the Arkansas River drainage. In figure 5D, the concentrations of silver, arsenic, and bismuth are below the limits of detection until sediments are encountered from the Leadville mining district.

Geochemical data from the cores are summarized in figure 6. Core 93LV100 was taken from a mature sand bar on the west side of the Arkansas River above the confluence with California Gulch. Geochemical data from all but the top 7-cm thick humus layer at the top of the core have background values for the metals shown. ^{210}Pb data (discussed below) indicate that the sand bar has been in place for the last 150 years or more. That is, the sand bar was formed prior to the initiation of mining activity in the Leadville mining district. In contrast, the two cores (93LV101 and 93LV102) taken from the Smith Ranch below the confluence of the Arkansas River and California Gulch indicate elevated metal concentrations from the top of the cores down to interval 17 in core 93LV101 and to the bottom of core 93LV102. In core 93LV100 and below interval 17 in 93LV101, metal concentrations are again quite low, at or near background values.

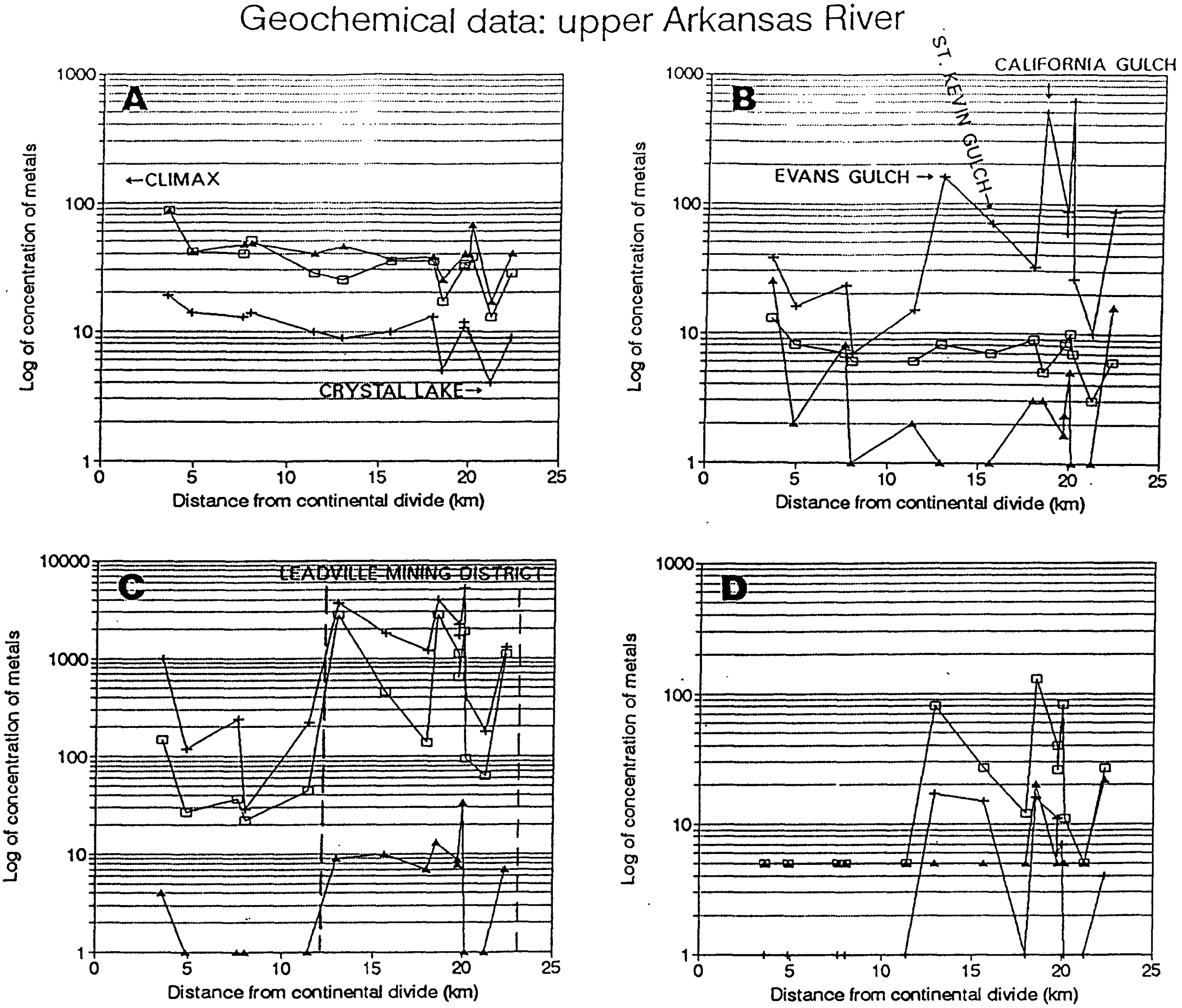


Figure 5. Geochemical data for twelve metals from sediment and selected core samples from the study area. Explanation: fig. A, chromium, □; nickel, +; vanadium, ▲; fig. B, cobalt, □; copper, +; molybdenum, ▲; fig. C, lead, □; zinc, +; cadmium, ▲; and fig. D, arsenic, □; silver, +; bismuth, ▲.

Figure 6. Concentration of metals (Table 6, Appendix III) by core interval (Appendix II) in cores 93LV100, 93LV101, and 93LV102. The figure is divided into four parts: A, metal concentrations for chromium, nickel, and vanadium; B, metal concentrations for cobalt, copper, and molybdenum; C, metal concentrations for lead, zinc, and for cores 93LV101 and 93LV102, cadmium; D, metal concentrations for silver, arsenic, and bismuth in cores 93LV101 and 93LV102. The concentrations of the metals cadmium, silver, arsenic, and bismuth were below the limit of detection in core 93LV100 (see table 5, Appendix III). →

Figure 6A

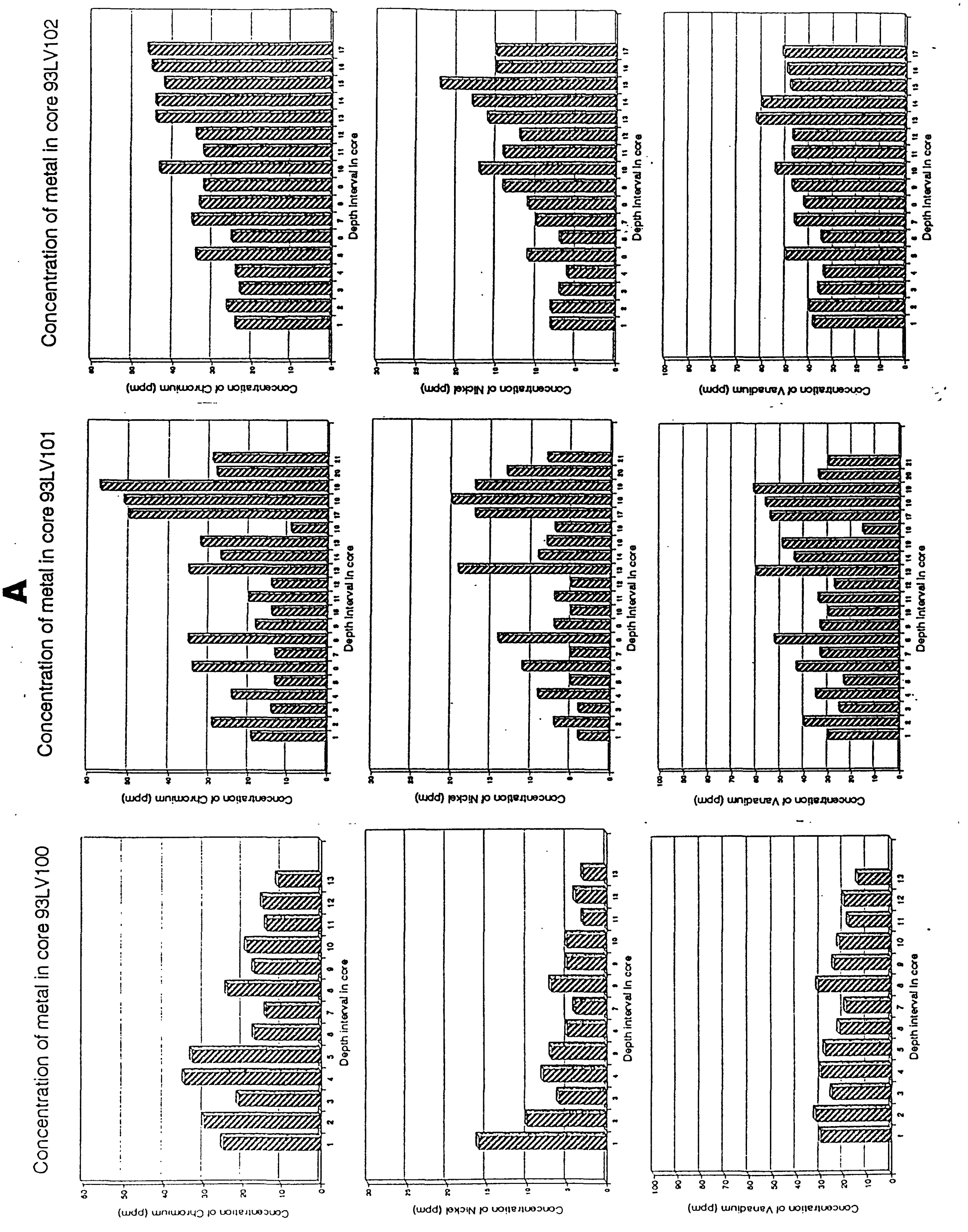

A
Concentration of metal in core 93LV100
Concentration of metal in core 93LV101
Concentration of metal in core 93LV102
Concentration of Chromium (ppm)
Concentration of Nickel (ppm)
Concentration of Vanadium (ppm)
Depth interval in core

Figure 6B

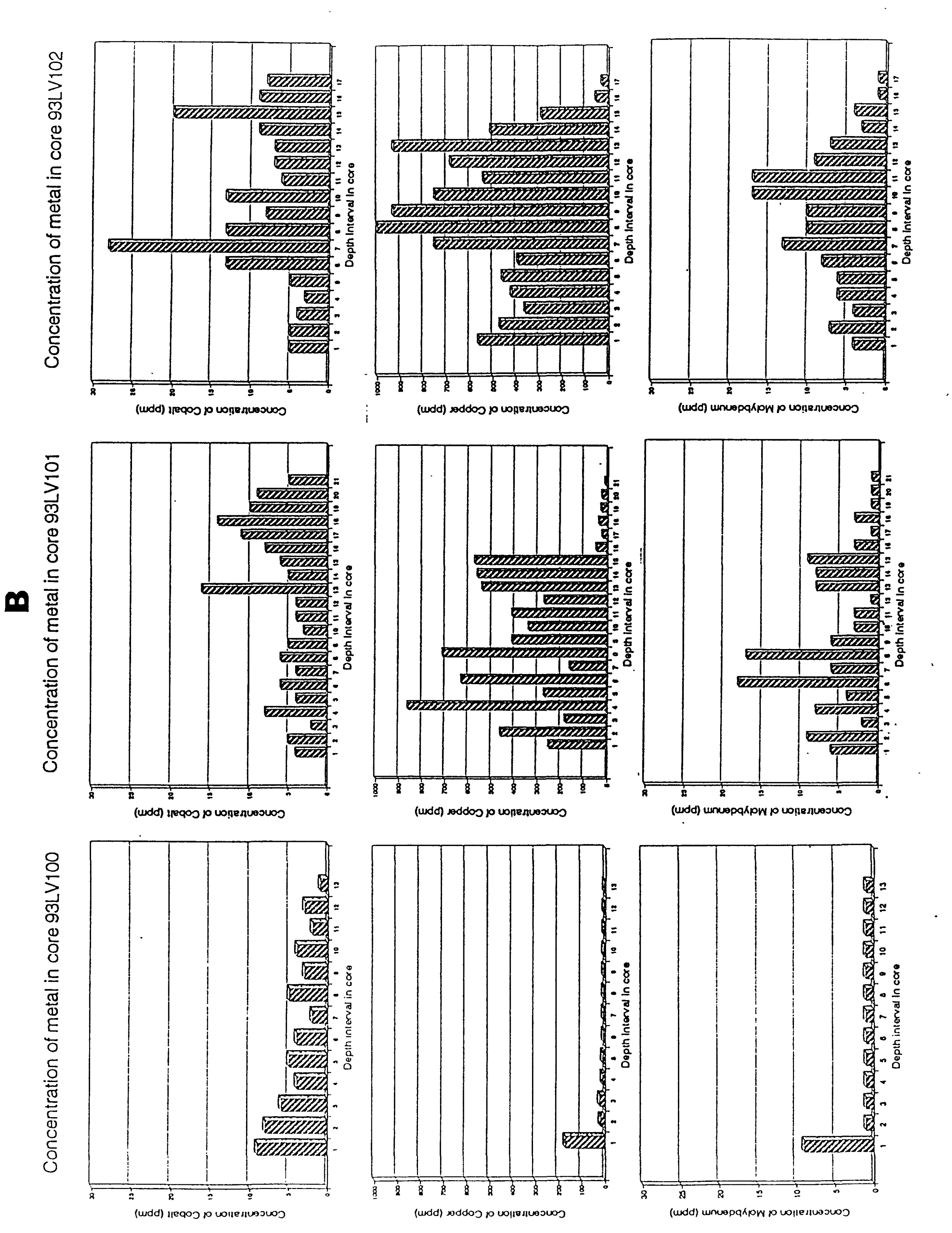
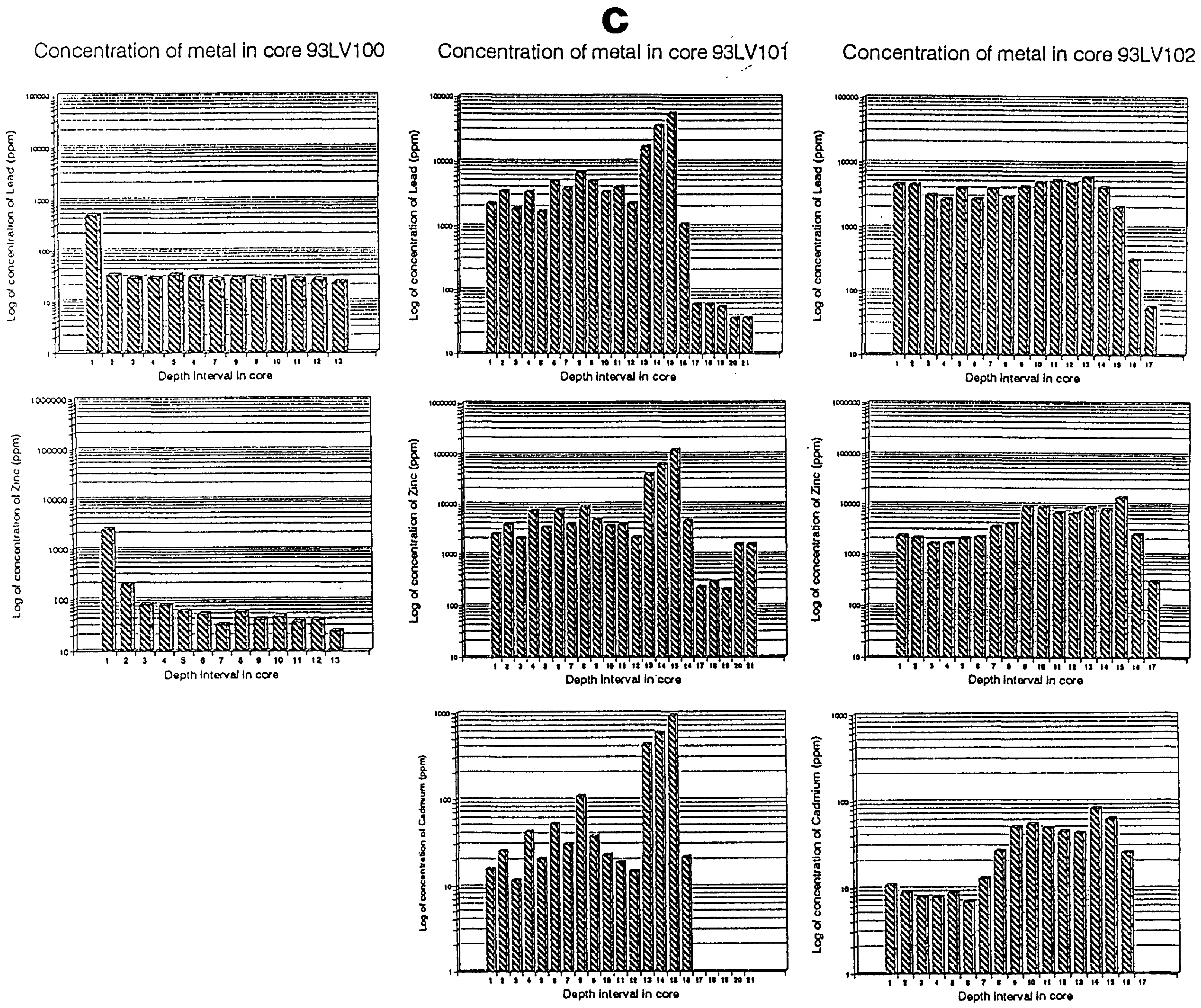

B
Concentration of metal in core 93LV100
Concentration of metal in core 93LV101
Concentration of metal in core 93LV102
Concentration of Cobalt (ppm)
Concentration of Copper (ppm)
Concentration of Molybdenum (ppm)
Depth Interval in core
0
5
10
15
20
25
30
100
200
300
400
500
600
700
800
900
1000
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

Figure 6C



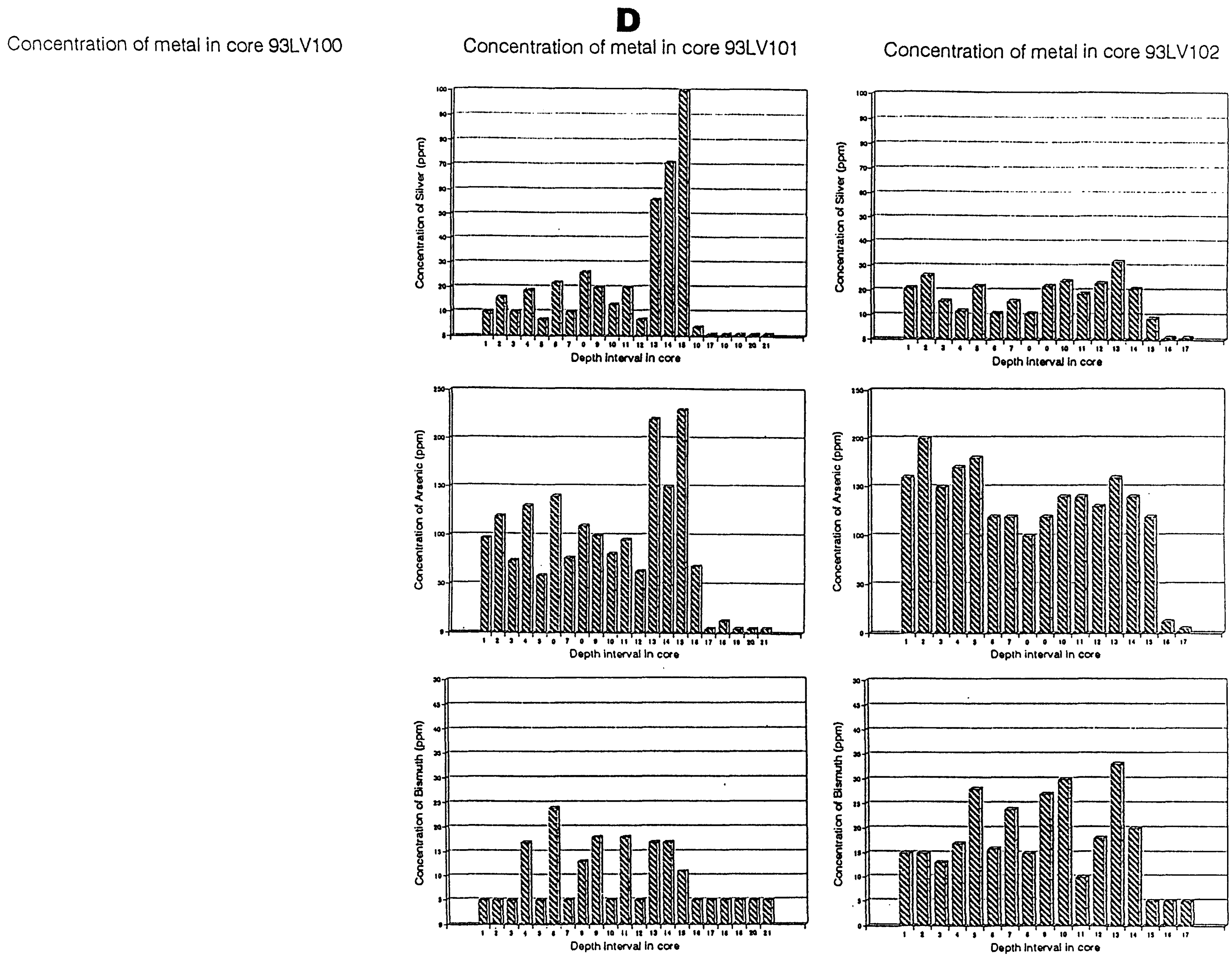
C

Concentration of metal in core 93LV100

Concentration of metal in core 93LV101

Concentration of metal in core 93LV102

Figure 6D


D
Concentration of metal in core 93LV100
Concentration of metal in core 93LV101
Concentration of metal in core 93LV102
Concentration of Silver (ppm)
0
10
20
30
40
50
60
70
80
90
100
Concentration of Arsenic (ppm)
0
50
100
150
200
250
Concentration of Bismuth (ppm)
0
5
10
15
20
25
30
35
40
45
50
Depth interval in core
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

LEAD-ISOTOPE STUDIES

Lead-isotope data have been used in mineral exploration to "fingerprint" ore deposits or ore-deposit types (for example, Gulson, 1986; Church and others, 1987). This technique has proven particularly useful in deeply weathered areas of Australia where concealed deposits buried 100 meters or more can be distinguished from the lead-isotopic signature in soils within the geochemical halo on the surface (Gulson, 1986). In the study at Mt. Emmons, Gulson and others (1992) demonstrated that the lead-isotope signature of this porphyry molybdenum deposit could be distinguished from that of surrounding lead-zinc veins having different lead-isotopic signatures utilizing a leach procedure that recovered lead from the iron- and manganese-oxide phases coating pebbles in the streams. We have adopted this leaching procedure for this study for two major reasons: First, the majority of the lead in unmineralized rocks is tightly bound in silicate mineral grains and will not be sampled by the leaching process (Church and others, 1987; unpub. data, 1989). Furthermore, the lead that is leached from unmineralized rock is largely from grain boundaries and contains radiogenic lead resulting from the decay of uranium and thorium, which was deposited on those grain boundaries since the time of formation of the rock. Second, in mineralized areas, the lead released from the weathering of sulfide minerals faithfully reflects the signature of lead in the ores (for example, Gulson, 1986). Since the concentration of lead in mineralized areas is often orders of magnitude greater than the average crustal abundance of lead, the isotopic composition of lead from the sulfide minerals quickly overwhelms the normal background-lead composition from unmineralized rock.

Using the leaching procedures also results in a greater contrast in the isotopic composition of lead. This conclusion is demonstrated by the plots in figure 7 and is based on the crystallographic structure of minerals and the site of residence of metals within those minerals (for example, see Rickwood, 1983). When the concentration of lead in the sediment sample is low, the yields for lead in the leach solutions are variable, reflecting site variability in the sediments. However, when the concentration of lead is high, generally a substantial portion (60 percent or more) of the lead is readily released by the leaching procedure. This site dependence is demonstrated in a general way by the contrast in behavior of manganese, which is mobile in the weathering environment, with that of aluminum, which is generally tightly bound in the silicate mineral structure. Manganese is generally deposited on the surface of mineral grains and is readily available, thus the majority of the samples have recoveries of 40

Figure 7. Comparison of the recoveries of lead (lead in the leach solutions divided by lead in the total sample) with manganese and aluminum. Leach data are from table 7 and total digestion data are from table 6, Appendix III. →

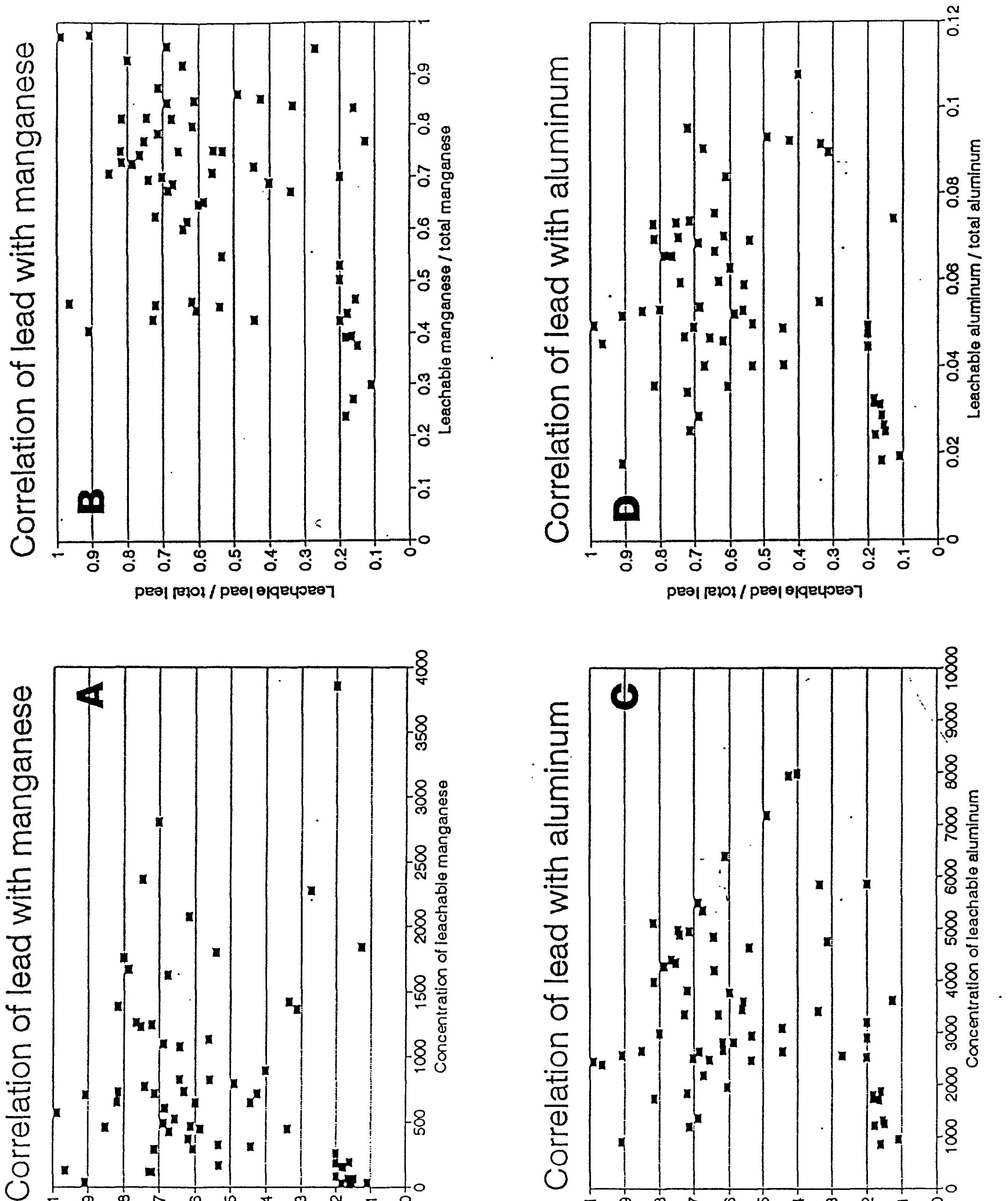
Correlation of lead with manganese
A
Leachable lead / total lead
Concentration of leachable manganese
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Correlation of lead with manganese
B
Leachable lead / total lead
Leachable manganese / total manganese
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Correlation of lead with aluminum
C
Leachable lead / total lead
Concentration of leachable aluminum
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Correlation of lead with aluminum
D
Leachable lead / total lead
Leachable aluminum / total aluminum
0
0.02
0.04
0.06
0.08
0.1
0.12

Figure 7.

percent or greater, whereas the maximum yield for leachable aluminum does not exceed 20 percent. The only major silicate minerals that contain leachable aluminum are the clay minerals. The clay minerals also may adsorb heavy metals. There is a correlation between leachable lead and leachable manganese, and between leachable lead and leachable aluminum. Those samples that contain low concentrations of all three metals are those that have background concentrations of heavy metals and give lead-isotopic signatures that reflect weathering of unmineralized rock. Conversely, those samples that contain high concentrations of leachable lead are from mineralized areas where the weathering of sulfides has resulted in substantial release of metals from the ores, some of which are adsorbed by the iron- and manganese-oxide phases (for example, Smith, 1991).

Leachable lead (fig. 8A) and zinc (fig. 8B) from the sediments and from the cores are broken down by type and location in figure 8. Leachable lead in the stream sediments, with one exception, exceeds 40 percent (fig. 8C). Low and highly variable recoveries of lead were obtained from cores 93LV100 (fig. 8D) and 93LV101 (fig. 8E), whereas recoveries from core 93LV102 (fig. 8F) generally exceed 60 percent and are independent of concentration. The low recoveries at low concentrations from core 93LV100 are from the sandy intervals in the core. The low recoveries from core 93LV101 are from intervals that contain largely background levels or from sandy intervals, or are from the layers containing the highest concentrations of metals. Some sulfide minerals, such as chalcopyrite, galena, and sphalerite, would be only partially attacked by this leach, whereas other sulfide minerals, such as arsenopyrite and pyrite, would be only slightly attacked (Church and others, unpub. data, 1989). Thus, the low yields at high concentrations could be explained by the mineralogy of the samples in the core.

The lead-isotopic data are plotted in figure 9. Both $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are plotted against distance from the continental divide. The ranges of published lead-isotope values for ores of the Leadville district (Thompson and Beaty, 1990) are: $^{206}Pb/^{204}Pb$ varies from 17.87 to 18.26 with one outlier at 17.46, and $^{208}Pb/^{204}Pb$ varies from 38.41 to 38.59 with one outlier at 38.18. In comparison with the data from the Leadville mining district, all samples except one from the Arkansas River and from tributaries draining the Leadville mining district plot within the published lead-isotopic range for the ores for both lead-isotope ratios. The $^{208}Pb/^{204}Pb$ value for site 93LV107 is within analytical error of the lead-isotopic signature for the Leadville mining district. The lead-isotopic compositions of sediments from the Arkansas River and its tributaries collected above the Leadville mining district, as well as the data from the Lake Fork drainage, have more radiogenic-lead compositions. Lead from St. Kevin Gulch (site 93LV104) does not match the lead-isotopic signature for either ratio, but is quite close in composition indicating mineralization occurred during the same geologic time interval. Lead from Lake Fork (site 93LV114), from lower Crystal Lake (site 93LV103), and from the

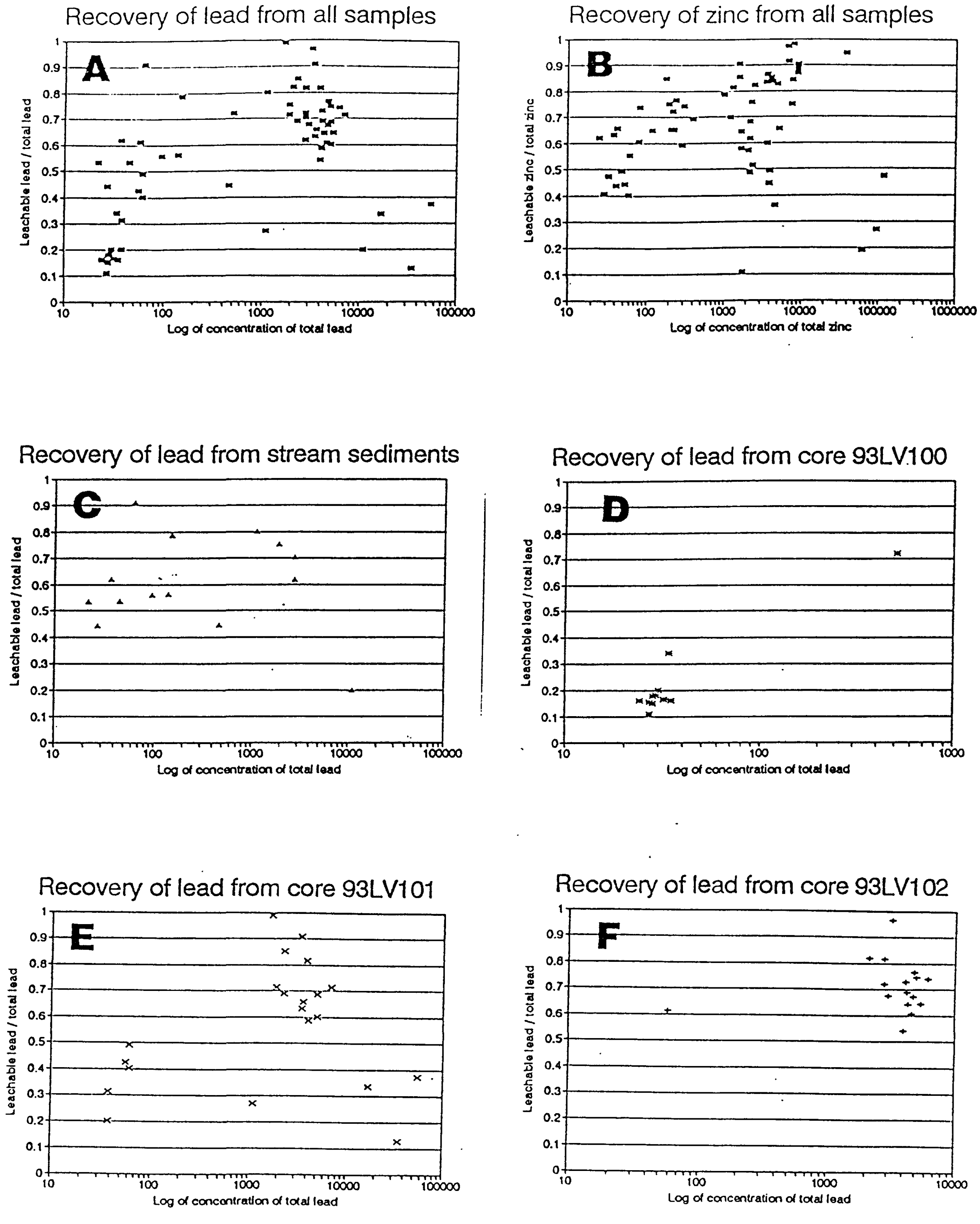


Figure 8. Recovery of lead (A) and zinc (B) from all samples collected from the upper Arkansas River drainage. Recovery of lead from stream sediments (C), from core 93LV100 (D), from core 93LV101 (E), and from core 93LV102 (F) collected in this study. Leach data are from table 7 and total digestion data are from table 6, Appendix III.

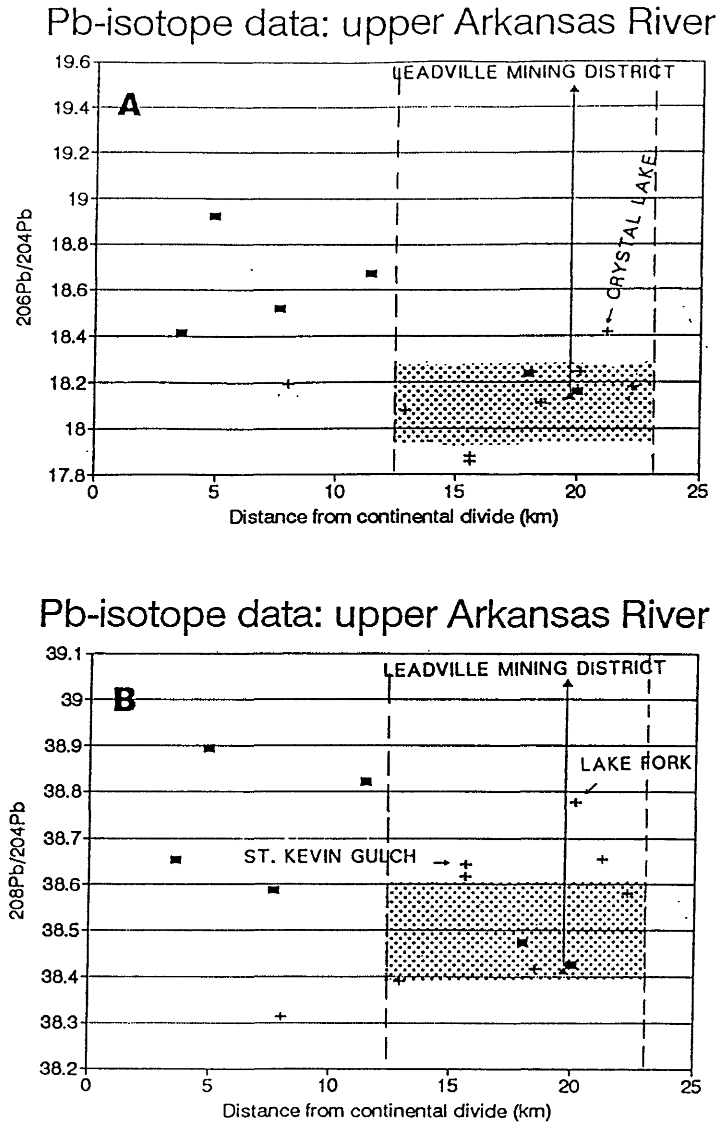


Figure 9. Lead-isotope data from the upper Arkansas River drainage plotted against distance from the continental divide. The Climax porphyry molybdenum crops out in the headwaters of the Platte River just east of the continental divide and its geochemical halo laps into the Arkansas River drainage. Samples collected from the Arkansas River are shown as ■, and samples from tributaries are shown at the point where the tributary enters the Arkansas River and are shown as +. The two samples from core 93LV101 are shown as ▲ and are joined by a tie line. The top sample from this core is from the most contaminated layers (A13-A15, see figure 6) whereas the lower sample is from the lowermost layer, 93LV101A21, and represents the pre-mining soil on which the tailings were deposited.

bottom of core 93LV101 (sample interval A21) all reflect pre-mining background-lead concentrations and lead-isotopic compositions. We conclude from these studies that the pre-mining concentration of metals in the Leadville area was relatively low.

^{210}Pb Studies

As discussed above, rates of sediment accumulation can be determined using the activity of unsupported ^{210}Pb. Goldberg (1963) determined that ^{210}Pb is rapidly removed from river waters by organic and/or inorganic adsorption on particulate matter. This observation has given rise to a useful chronometer for dating sediments. The activity of ^{210}Pb at a depth in a sedimentary column is related to the time since the initial deposition. Provided that the initial activity $^{210}\mathrm{Pb}_{T0}$ is known and the rate of sedimentation has been constant, the activity of ^{210}Pb is log-linear when plotted respective to depth. Corrections must be made for the presence of a small amount of the long-lived grandparent of ^{210}Pb, ^{226}Ra, in the sediment. This component will add "supported" ^{210}Pb to the sediment (see figure 3A). The activity of this "supported" lead must be ascertained in order to accurately determine the "age" of a sediment layer. This "supported" ^{210}Pb is most often determined by analyzing the entire sediment column and determining the depth at which the ^{210}Pb activity is constant. This level of radioactivity is considered to represent the "supported" ^{210}Pb.

The technique for determining the ^{210}Pb activity in geological material is relatively simple. The isotopic activity can be determined by assuming isotopic equilibrium between ^{210}Pb and its immediate short-lived daughter products, ^{210}Bi and ^{210}Po (see fig. 3A). One analytical method involves the determination of ^{210}Bi activity by the measurement of the γ-emission released during decay to ^{210}Po. This is the easiest method because it requires very little sample preparation. However, this method does require a relatively large sample (50 g) and heavily shielded γ-ray detectors and instrumentation. The other analytical method is the determination of ^{210}Po by the measurement of α-emission as it decays to ^{206}Pb. This method requires chemical separation, but much smaller samples (5 g) can be processed using the α-emission method. This second method was used in this study (see Appendix V for details of the procedure).

In an attempt to "date" sedimentary material in the Arkansas River Valley, four cores were taken (see figure 1) near Leadville,

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Figure 10. Photographs of core 93LV100 (A) taken from the Arkansas River above the confluence with California Gulch (collected with permission of Mrs. Edith Seppi), and the core taken from the center of lower Crystal Lake 93LV103 (B). →

Figure 11. Photographs of cores from tailings deposits sampled on Dr. Bernie Smith's Ranch (collected with permission): 93LV101 (A) and 93LV102 (B). →

Figure 10.

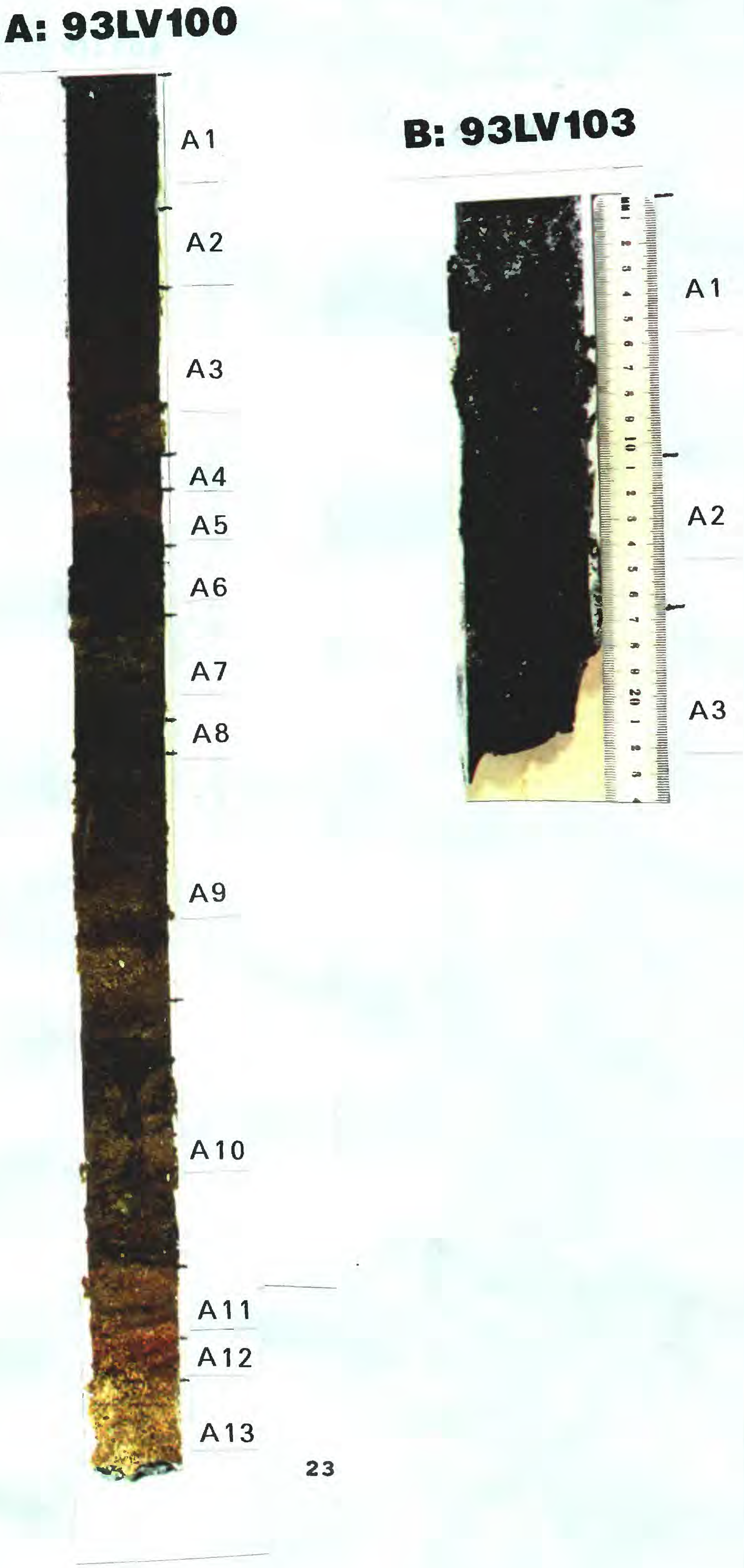

A: 93LV100
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
B: 93LV103
A1
A2
A3

Figure 11.


A: 93LV101

B: 93LV102

Colorado. All the cores exhibit excess ^{210}Pb. To establish background ("supported" ^{210}Pb), a sample was taken deep in core 93LV103 from lower Crystal Lake adjacent to the river in sediment that has been judged to be Holocene in age. Photographs of the cores are in figures 10 and 11.

Core 93LV100 was taken above the confluence of California Gulch in the Arkansas River and is composed largely of layers of coarse- to fine-grained sand (see fig. 10A and Appendix II). The upper 7 cm of the core is an organic-rich "humus soil." The remaining 69 cm of the core is composed of a sediment distribution, which suggests that it was formed by two flood events. Figure 12A shows the organic content, as determined by loss-on-ignition, and water content. The water content is used as a measure of porosity. The organic distribution in this core is typical of most sediment cores that show a decrease in organic content with depth. This suggests that the sediment in this core has been in place for a considerable period of time. The ^{210}Pb excess activity 5.4 dpm/g (disintegrations per minute per gram of sample) is limited to the upper 7-cm thick humic horizon (fig. 12B). The ^{210}Pb activity in the remaining portion of the core is close to background and can not be statistically distinguished from background. This is consistent with the interpretation based on the organic distribution.

Core 93LV101 is a 94-cm long core (see fig. 11A) taken on the edge of the flood plain of the Arkansas River immediately adjacent to a pasture (see figure 2A). Compared to core 93LV100 (fig. 12A), this core (fig. 13A) has a relatively high organic content throughout the core, with the highest concentration in the lower portion (68 cm). The core description (Appendix II) indicates that the upper portion of the core, above the organic zone, is composed of layers of fine- to very coarse-grained iron-stained sand. The entire core has excess ^{210}Pb (figure 13B). The activity above the organic zone varies from 1.5 to 2.3 dpm/g. At the organic layer, the activity jumps to 6.4 dpm/g. The remaining samples appear to decrease logarithmically as would be expected in a closed system. This activity pattern can not be explained by any known sedimentary process if the individual sedimentary layers had behaved as closed systems. One plausible explanation is that the distribution of excess ^{210}Pb is the result of percolation of ground water through the soil horizons. The elevation of site 93LV101 above the river, and the coarse-grained nature of the sediment would permit rapid transport of ground water. The ^{210}Pb leached from the overlying soil horizons would be adsorbed by the iron hydroxide coating the sand grains. Such a process would account for the low and varied nature of the ^{210}Pb activity in the upper part of the core. The organic zone in the core would present a barrier to the percolating water and an adsorption medium for mobile ^{210}Pb. The lead in the remaining portion of the core could be the result of diffusion with the pressure caused by the hydraulic head.

Core 93LV102 (fig. 11B) was taken in the active flood plain in the present course of the Arkansas River (see fig. 2B). The sedimentary record preserved in this core indicates that this is a

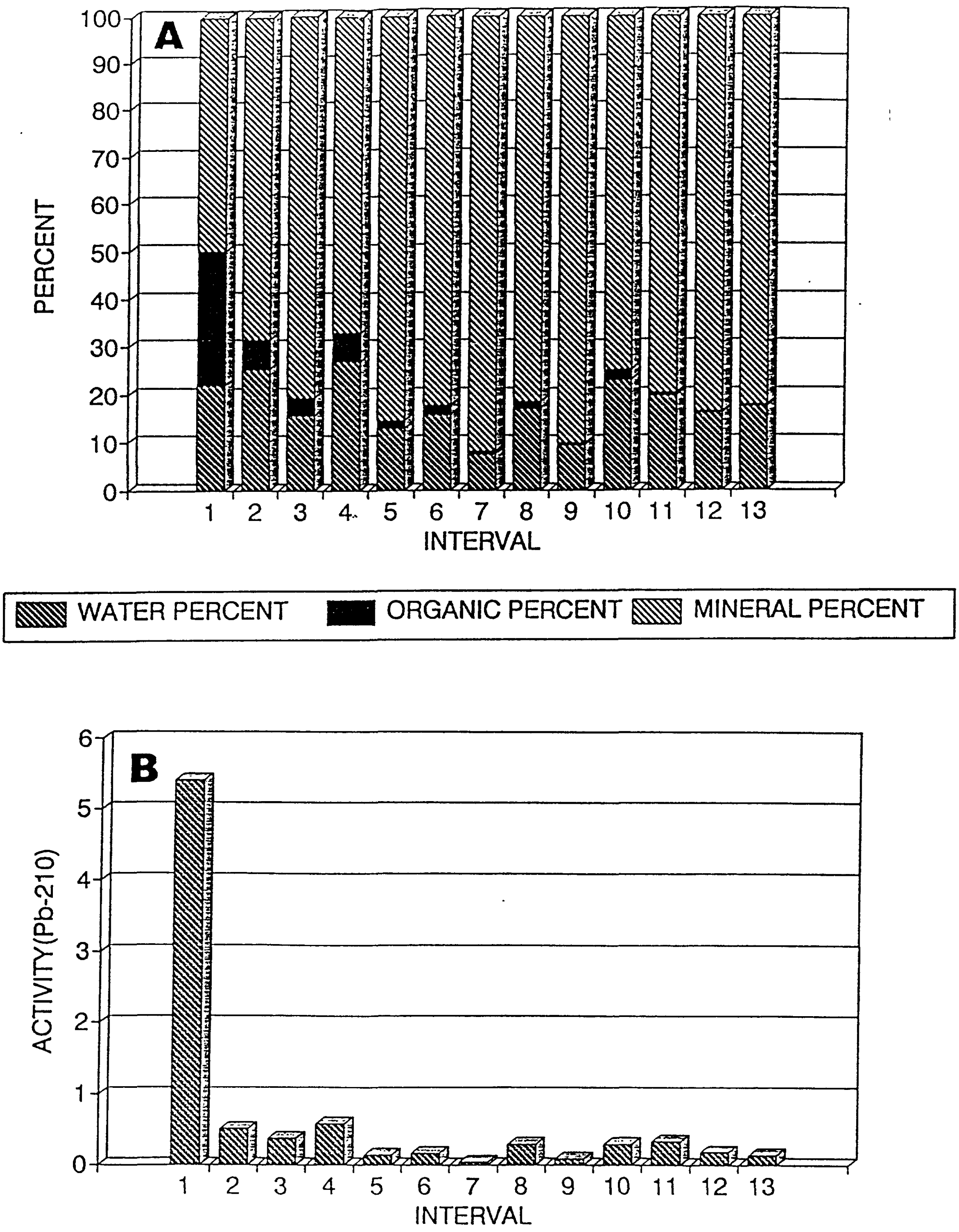
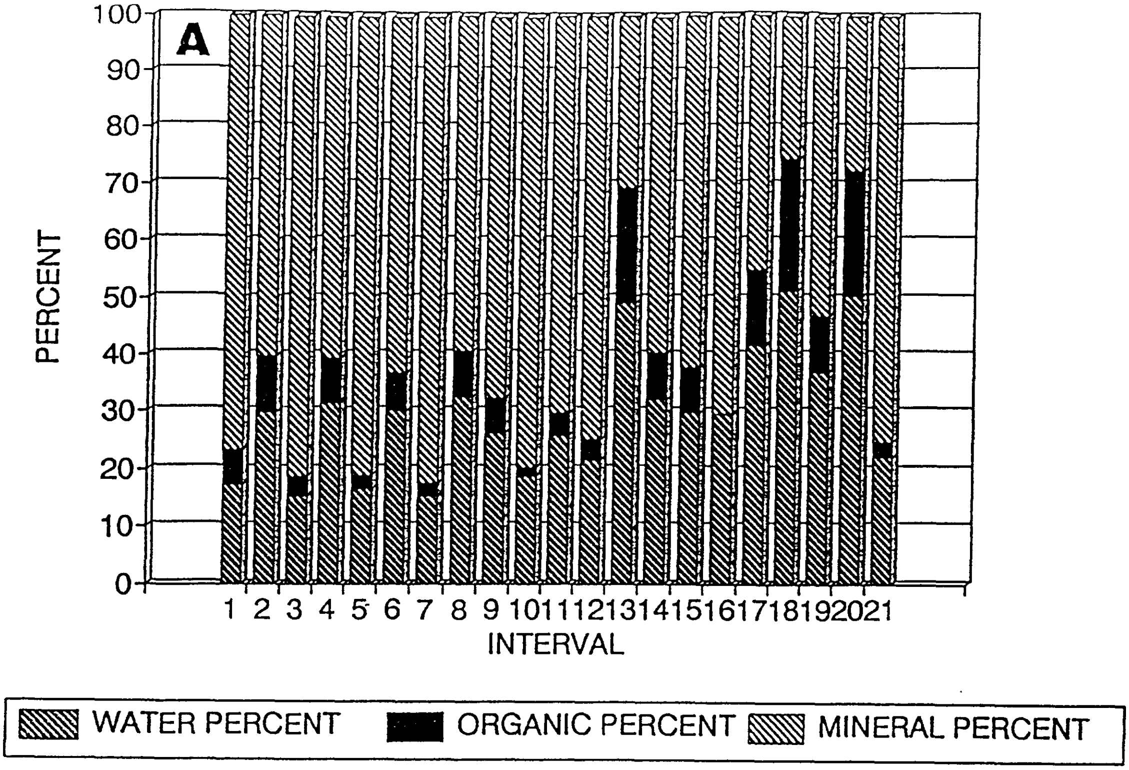


Figure 12. Water, organic, and mineral content (A) and excess ^{210}Pb activity (B) in core 93LV100.



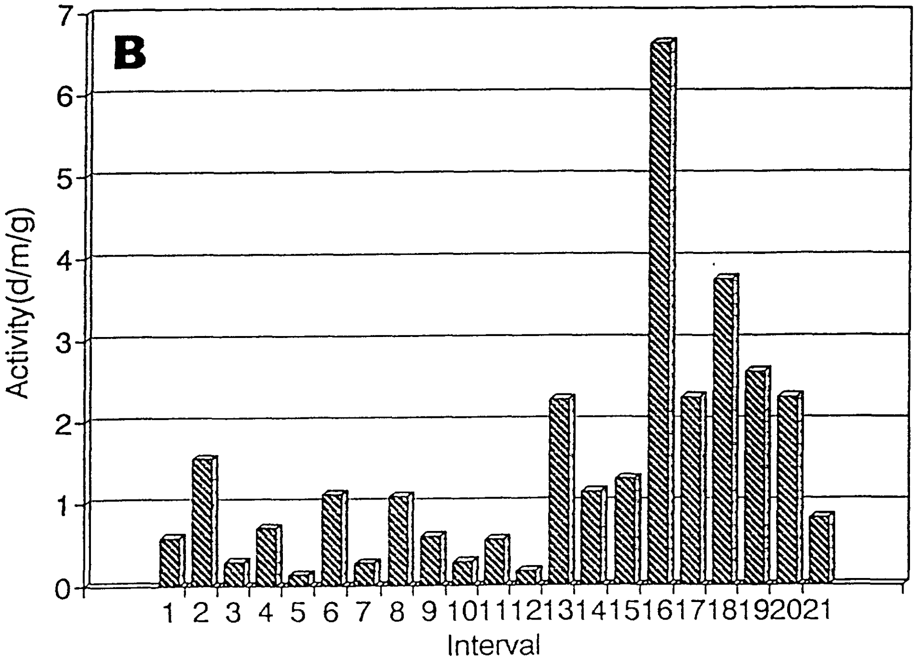


Figure 13. Water, organic, and mineral content (A) and excess ^{210}Pb activity (B) in core 93LV101.

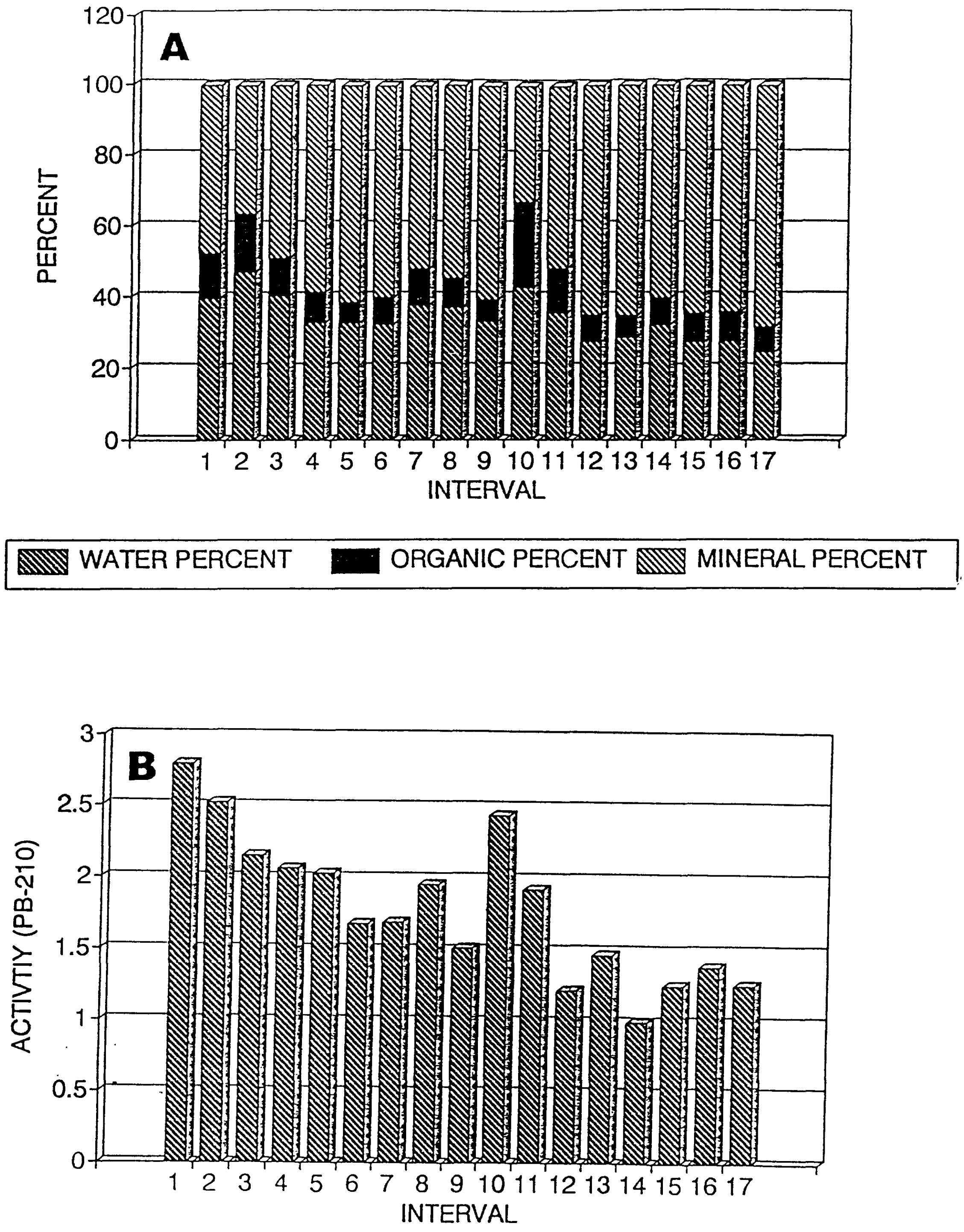


Figure 14. Water, organic, and mineral content (A) and excess ^{210}Pb activity (B) in core 93LV102.

site near the distal end of a flood deposit. The organic content is relatively high, varying from 6 to a maximum of 24 percent. Over most of the length of the core, however, the organic content is fairly constant and the ^{210}Pb activity decreases logarithmically (fig. 14B). The single sample-interval that does not fit the logarithmic decay curve is the interval that has the highest organic content (fig. 14A). Calculation of the rate of sedimentation based on the data indicated that the deposit was formed within a twenty-year period (fig. 14B).

Core 93LV103 (fig. 10B) was sampled throughout the lower interval; no discrete sedimentary layering was evident in this core (Appendix II). The ^{210}Pb activity in this sample was at background levels indicating that the sediment in this core accumulated prior to 130 years ago. Geochemical and lead-isotopic data from this core reflect pre-mining values.

The analysis of the Leadville cores indicates that unsupported ^{210}Pb exists in the sediments in the Arkansas River drainage. The large variation of sediment types, however, prevents the accurate estimate of "ages" of these deposits. There are no reliable data from these three cores to establish the flux rate, $^{210}\mathrm{Pb}_{T0}$, the parameter necessary to "date" sedimentary deposits. The fact that disequilibrium exists does indicate that an adequate chronological scale could be devised, but information on iron adsorption, organic adsorption, and the present level of ^{210}Pb in the drainage system needs to be determined. Unfortunately, the short time-frame established for this study has not permitted an independent determination of these parameters.

EVALUATION OF HEAVY-METAL ENRICHMENT IN THE ENVIRONMENT

There are numerous measures for evaluating the enrichment of heavy metals in the environment. One method used is the comparison of the raw data to the average crustal abundance of the element. By normalizing the data relative to crustal abundance, one can then evaluate the enrichment of various metals in the environment and eliminate personal bias. For this study, we use the crustal abundance data from a recent review by Fortescue (1992). The values reported by Fortescue (1992) agree reasonably well with the consensus values reported earlier by Rickwood (1983) except for the value for bismuth. For the elements discussed in this paper, the crustal abundance values used for the normalization are shown in table 1, column 4. Concentrations of the twelve metals in uncontaminated sediments and soils are shown in table 1 and normalized results are shown in table 2. In comparison with average crustal abundances, the concentration of chromium, nickel, vanadium, cobalt, and copper generally are lower than average crustal abundance levels ranging from 0.1-0.3 times crustal abundance (see table 2). Lead is enriched 2.2-3.0 times crustal abundance and zinc is enriched 0.8-2.8 times crustal abundance. In contrast, sediments from tributaries draining from the Leadville mining district and from the core samples taken from below the confluence of California Gulch with the Arkansas River (table 4) have highly elevated enrichments of copper (1.3-7.9), molybdenum (2-13), lead (85-730), zinc (17-232), cadmium (44-950), silver (50-325), arsenic (15-72), and bismuth (85-100). Enrichment of these metals in the slag sample (93LV106) from California Gulch is even greater. On-the-other-hand, concentrations of chromium, nickel, cobalt, and vanadium remain at background levels (0.1-0.3 times crustal abundance).

Table 1. Pre-mining background concentrations for selected metals from Leadville, Co.

Element	Fine-grained Sediments[1]	Sandy Sediments[2]	Soils[3]	Average Crustal Abundance[4]
Chromium	35	21	29	122
Nickel	11	6	11	99
Vanadium	39	24	32	136
Cobalt	6	4	7	29
Copper	14	10	17	68
Molybdenum	<2-3	<2	<2	1.2
Lead	39	29	38	13
Zinc	158	64	210	76
Cadmium	<2	<2	<2	0.16
Silver	<2	<2	<2	0.08
Arsenic	<10	<10	<10	1.8
Bismuth	<10	<10	<10	0.2

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[1] Average concentration calculated from samples 93LV103, 93LV108 93LV110, 93LV111, and 93LV112.

[2] Average concentration calculated from core 93LV100, sample intervals A2-A13.

[3] Average value calculated from core 93LV101, sample intervals A20 and A21; zinc concentration is from interval A19.

[4] Fortescue (1992, p. 31); bismuth crustal abundance from Rickwood (1983 p. 364-365).

Table 2. Normalized enrichments of pre-mining background concentrations of selected metals from Leadville, Co.

[Concentrations of metals for each sample type given in table 1 have been divided by the average crustal abundance, given in table 1, column 4, to arrive at the enrichment for each element]

Element	Fine-grained Sediment	Sandy Sediment	Soil
Chromium	0.3	0.2	0.2
Nickel	0.1	0.1	0.1
Vanadium	0.3	0.2	0.2
Cobalt	0.2	0.1	0.2
Copper	0.2	0.1	0.3
Molybdenum	--	--	--
Lead	3.0	2.2	2.9
Zinc	2.1	0.8	2.8
Cadmium	--	--	--
Silver	--	--	--
Arsenic	--	--	--
Bismuth	--	--	--

Table 3. Concentration of selected metals from three stream sediments, a slag, and two cores of contaminated sediment from Leadville, Co.

Element	Evans Gulch 93LV107	Iowa Gulch 93LV113	California Gulch 93LV105	Slag 93LV106	Core 93LV101 (A1-A16)	Core 93LV102 (A1-A17)
Chromium	25	28	17	110	22	34
Nickel	9	9	5	1	8	12
Vanadium	46	40	25	64	36	46
Cobalt	8	6	5	86	6	10
Copper	160	88	500	2,600	417	537
Molybdenum	<2	16	3	190	7	7
Lead	2,800	1,100	2,800	11,000	9,500	3,620
Zinc	3,700	1,300	4,000	96,000	17,600	5,040
Cadmium	9	7	13	20	151	30
Silver	17	4	16	6	26	17
Arsenic	81	27	130	730	114	127
Bismuth	<10	22	20	<10	17	20

Table 4. Normalized enrichments of selected metals from three stream sediments, a slag, and two cores of contaminated sediment from Leadville, Co.

[Concentrations of metals for each sample type given in table 3 have been divided by the average crustal abundance, given in table 1, column 4, to arrive at the enrichment for each element]

Element	Evans Gulch 93LV107	Iowa Gulch 93LV113	California Gulch 93LV105	Slag 93LV106	Core 93LV101 (A1-A16)	Core 93LV102 (A1-A17)
Chromium	0.2	0.2	0.1	0.9	0.2	0.3
Nickel	0.1	0.1	0.1	0.0	0.1	0.1
Vanadium	0.3	0.3	0.2	0.5	0.3	0.3
Cobalt	0.1	0.1	0.1	1.3	0.1	0.1
Copper	2.4	1.3	7.4	38	6.1	7.9
Molybdenum	1-2	13	2.5	158	5.8	5.8
Lead	215	85	215	846	731	278
Zinc	49	17	53	1,263	232	66
Cadmium	56	44	81	125	944	188
Silver	213	50	200	75	325	213
Arsenic	45	15	72	406	63	71
Bismuth	--	110	100	--	85	100

SUMMARY AND CONCLUSIONS

Chemical leach procedures developed for mineral exploration can be used to enhance the geochemical effects of mineralization caused by acid-weathering resulting from the oxidation of pyrite. These leach procedures also effectively enhance the lead-isotope signatures of many individual mineral deposits, which are the probable cause of much of the heavy-metal contamination in river drainages in the western U.S. Lead-isotope studies of the minus-80-mesh stream-sediment samples collected from the upper Arkansas River drainage basin show that samples collected from drainages in the Leadville district as well as from the Arkansas River below the district have lead-isotopic signatures that match published lead isotopic data from the ores. In contrast, stream-sediment samples collected from tributaries outside the district or from the Arkansas River drainage basin above the district do not match that of the Leadville ores.

Geochemical studies of the heavy-metal concentrations in minus-80-mesh stream sediments and in cores taken from the flood plain of the Arkansas River clearly show that the sediments are tailings washed into the Arkansas River from California Gulch. ^{210}Pb studies of these cores clearly show intervals beneath the tailings deposit that pre-date mining activity at Leadville, Co. Pre-mining concentrations of lead in minus-80-mesh stream sediments, sandy sediments, and soils collected from beneath the tailings deposit contain 39, 29, and 38 ppm lead, respectively. These concentration levels are 2.2 to 3.0 times the crustal abundance for lead. Likewise, zinc concentrations in these media are 158, 64, and 210 ppm, respectively, or about 0.8-2.8 times crustal abundance. Concentrations of molybdenum, silver, cadmium, arsenic, and bismuth are all below the limits of detection for these elements in that portion of the upper Arkansas River drainage basin not affected by sediments from areas of mineralization. Concentrations of vanadium, chromium, nickel, cobalt and copper are all substantially below crustal abundance levels (0.1-0.3). In contrast, the sediment samples collected from the tributaries draining the Leadville mining district are enriched in heavy metals from 2 to 215 times normal crustal abundance values with lead (85-215) showing the highest enrichment factors. Average enrichments in the two core samples from the confluence of California Gulch with the Arkansas River on Dr. Bernie Smith's Ranch range from 63 to 944 times normal crustal abundance values.

^{210}Pb studies of four cores taken near the confluence of California Gulch with the Arkansas River show that the mature sand bar sampled just above the confluence pre-dates mining activity at Leadville. Sediments recovered from this core all have low concentrations of heavy-metals. Sediments recovered from the core taken adjacent to the pasture on Dr. Bernie Smith's property contain high concentrations of heavy-metals. The ^{210}Pb activity in the sedimentary layers in this core are highly irregular and are interpreted to show open-system behavior in which the ^{210}Pb has been mobilized by ground water. High ^{210}Pb activity is correlated with high organic content in the sedimentary layers. The core from the Arkansas River flood plain just above the confluence with the Lake Fork has a regular decay pattern of ^{210}Pb activity indicating that it was deposited over a twenty-year time span. However, since we were unable to determine the annual flux rate for ^{210}Pb from these studies, we are unable to determine a sedimentary age for this deposit. Further work is planned to resolve this problem.

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Appendix I: Sample collection and preparation methods

by S.E. Church

Stream-sediment samples are composites from 5-10 sites within the stream channel at localities shown in figure 1. A clean plastic scoop was used to collect samples from the low-energy portions of the stream. The sediments were wet-sieved through a 10-mesh stainless steel screen into a plastic gold pan. Samples were then taken from the pan, placed in a zip-lock plastic bag, labeled, and placed in a chain-of-custody box in the field, sealed, and transported to the laboratory for processing.

In the laboratory, the stream-sediment samples were air dried at ambient air temperature in a locked drying oven, disaggregated in a ceramic mortar, and sieved through a stainless steel screen to collect the less-than-one-mm fraction. This sample was then further sieved through an 80-mesh (<177 microns) stainless steel sieve to collect the fine-grained sediment fraction. This minus-80-mesh fraction was then ground to minus-200-mesh (<74 microns) or finer using ceramic grinding plates to prepare the final sample. All the sieves were cleaned between samples using physical abrasion and ultrasonic cleaning and were air-dried between samples. The ceramic grinder plates were cleaned using compressed air to blow out the fine dust followed by grinding a 75-100 g sample of clean quartz sand between samples.

Cores were taken using acid-cleaned, 2" diameter, PVC tubing that was driven into the ground using an eight-pound sledge hammer. The core tube was then sealed using plastic wrap and a PVC cap was placed on the upper end. The core was then removed and the base of the core tube sealed as above. The cores were transported to the laboratory for further processing and sampling.

In the laboratory, the core tubes were split along the sides and the core was cut using a fine, braided wire. The two core halves were separated and one preserved for physical description (see Appendix II) and archive purposes. The second half was sampled using a plastic or stainless steel spatula for the chemical procedures described in Appendices III-V.

All samples were handled using chain-of-custody procedures. Samples were signed out to individual scientists for the purposes of sampling and chemical analysis. Individual solutions or derivative samples were tracked during the process of analysis and were kept under secure conditions when not in the presence of responsible parties.

Appendix II: Descriptions of cores 93LV100-93LV103

by S.E. Church

Core 93LV100:

A1	(0-7.0 cm)	Organic-rich humus layer at top of soil horizon.
A2	(7.0-11.1 cm)	Sandy, silty, and clay soil (zone A), minor amount of organic material present, some root material present; minor Fe-oxide staining on grain surfaces.
A3	(11.1-20.4 cm)	Mostly sand and silt; silty layer at bottom of interval coarsens upward to sandy (1-2mm) layer that is heavily Fe-oxide stained in central part of interval. Interval contains finer-grained sand and silt (<1mm) at top suggesting that this interval was deposited during a single flood event.
A4	(20.4-22.3 cm)	Silty clay layer with minor organic material present.
A5	(22.3-25.3 cm)	Fine-grained (<1mm) sand layer; minor Fe-oxide staining on grain surfaces.
A6	(25.3-29.5 cm)	Coarse-grained sand (1-2mm) separated from layers A5 and A7 by thin organic-rich lamellae; minor Fe-oxide staining of grains.
A7	(29.5-35.2 cm)	Coarse-grained (1-2mm) sand layer with minor Fe-oxide staining of sand grains.
A8	(35.2-36.9 cm)	Silt and clay layer with minor amount of sand (<1mm) present; minor Fe-oxide staining of sand grains.
A9	(36.9-50.4 cm)	Mostly silt at base, coarsens upward to sand (1-2mm) and becomes silty in middle of interval then coarsens again to sand (1-2mm) at top of interval; interval contains one large pebble in sandy interval. Contains only minor amount of Fe-oxide staining on grain surfaces with some organic matter present.
A10	(50.4-65.0 cm)	Silt and clay layer containing organic matter, fine-grained sandy layer (<1mm) in center interval that contains minor Fe-oxide staining on grain surfaces; 1-cm sized pebbles present at the base of sandy layer.
A11	(65.0-68.5 cm)	Sandy (1-2mm) interval separated from layers A10 and A12 by thin (5mm) silty layers containing organic material; minor Fe-oxide staining of sand grains.
A12	(68.5-71.5 cm)	Coarse-grained sandy (1-2mm) interval with only minor Fe-oxide staining of sand grains.
A13	(71.5-76.0 cm)	Coarse-grained sandy (1-2mm) interval with only minor Fe-oxide staining of sand grains.

Core bottomed against cobble-boulder mantle in stream bed.

Core 93LV101:

A1	(0-4.5 cm)	Heavily Fe-oxide stained clay layer, no organic material present; integrity of layering in this interval disturbed by coring process.
A2	(4.5-10.5 cm)	Heavily Fe-oxide stained clay layer with grass and roots present in soil.
A3	(10.5-21.3 cm)	Heavily Fe-oxide stained, poorly sorted sand layer that fines upward, grain size at base is 1-5mm; upper part fines to sandy silt at top of layer; organic material present but not in place at top of layer. Layer probably represents a flood-stage deposit.
A4	(21.3-23.2 cm)	Thin clay layer, organic-rich, heavily stained with Fe-oxides.
A5	(23.2-27.0 cm)	Clay and silt layer with some sand grains up to 3 mm in size with heavy Fe-oxide staining of sand grains.
A6	(27.0-32.0 cm)	Silt and clay layer containing organic material; grass mat appears to be in place; heavily Fe-oxide stained.
A7	(32.0-39.7 cm)	Heavily Fe-oxide stained, poorly sorted sand (1-5mm) layer.
A8	(39.7-41.7 cm)	Heavily Fe-oxide stained clay layer with grassy organic material present.
A9	(41.7-46.5 cm)	Heavily Fe-oxide stained silt and clay layer with grassy organic material present.
A10	(46.5-49.5 cm)	Heavily Fe-oxide stained fine-grained (<1mm) sand layer.
A11	(49.5-51.0 cm)	Heavily Fe-oxide stained clay layer; very minor organic material present.
A12	(51.0-55.5 cm)	Heavily Fe-oxide stained silt and fine sand (<1mm) layer.
A13	(55.5-58.8 cm)	Dark gray clay layer, minor organic debris present with minor Fe-oxide staining.
A14	(58.8-63.6 cm)	Dark gray clay layer, grass roots present; minor Fe-oxide staining.
A15	(63.6-68.7 cm)	Gray-brown clay layer, some organic debris present with minor Fe-oxide staining.
A16	(68.7-75.2 cm)	Black humus-rich layer, largely organic debris.
A17	(75.2-77.3 cm)	Gray-brown clay layer, organic debris present.
A18	(77.3-78.4 cm)	Black, organic-rich clay layer.
A19	(78.4-82.8 cm)	Gray-brown clay layer, organic debris present.
A20	(82.8-87.8 cm)	Black organic-rich layer of humus at top overlying silt and clay.
A21	(87.8-93.0 cm)	Gray fine-grained sand (.5-1mm) that grades upward into silt; base of core contains pebbles (<5cm).

Core 93LV102:

A0	(0-5.8 cm)	Silty clay layer disturbed by coring process, heavily Fe-oxide stained; interval not analyzed.
A1	(5.8-12.5 cm)	Heavily Fe-oxide stained silt layer containing organic debris.
A2	(12.5-18.3 cm)	Heavily Fe-oxide stained silt layer with black organic lamellae (1mm); organic debris present.
A3	(18.3-20.0 cm)	Heavily Fe-oxide stained clay layer.
A4	(20.0-24.1 cm)	Organic-rich, heavily Fe-oxide stained silt layer.
A5	(24.1-27.2 cm)	Fe-oxide stained, gray-brown clay layer.
A6	(27.2-28.6 cm)	Heavily Fe-oxide stained fine-grained (<1mm) sand layer.
A7	(28.6-31.8 cm)	Heavily Fe-oxide stained silt and clay layer.
A8	(31.8-38.4 cm)	Silt layer containing abundant twigs and grass.
A9	(38.4-41.6 cm)	Minor Fe-oxide stained gray-brown silt layer.
A10	(41.6-46.0 cm)	Fe-oxide stained silt and clay layer.
A11	(46.0-51.0 cm)	Gray-brown silt layer with minor Fe-oxide staining.
A12	(51.0-54.5 cm)	Fe-oxide stained fine-grained (<1mm) sand layer.
A13	(54.4-58.5 cm)	Heavily Fe-oxide stained clay layer.
A14	(58.5-60.4 cm)	Gray clay layer containing Fe-stained twigs.
A15	(60.4-62.5 cm)	Gray clay layer.
A16	(62.5-76.0 cm)	Dark clay and soil horizon containing Fe-stained twigs.
A17	(76.0-87.5 cm)	Dark clay and soil horizon containing Fe-stained twigs.

Core bottomed against cobble and boulder mantle in stream bed.

Core 93LV103:

A total of 23 cm of core was recovered from the center of the lake from a depth of about 3 m.

0-10.5 cm	Light gray silt and clay containing a few (<1 percent) freshwater ostracods.
10.5-16.5 cm	Light gray silt and clay containing a few (<1 percent) freshwater ostracods; lower 3 cm of sediment deposited between pebbles (1-2 cm).
16.5-23.0 cm	Black silt and clay containing a few (<1 percent) freshwater ostracods, sediment deposited between larger cobbles (2-10 cm).

Core bottomed against cobble and boulder mantle(?) in lake bottom.

Appendix III: Chemical procedures and data

by P.E. Briggs and S.E. Church

Thirty-seven major and trace elements were determined in geological materials by inductively coupled plasma-atomic emission spectrometry (ICP-AES). A 0.200 g sample, to which 50 μg lutetium had been added as an internal standard was digested to dryness with 3 mL hydrochloric acid, 2 mL nitric acid, 1 mL perchloric acid, and 2 mL hydrofluoric acid at 110°C. An additional 1 mL perchloric acid and deionized water were added to the residue and taken to dryness at 160°C. One mL aqua regia (3 parts hydrochloric acid to 1 part nitric acid) was added to the residue and the sample was diluted to 10.00 g with 1-percent nitric acid (Briggs, 1990).

The digested sample was aspirated into the plasma discharge where the element emission signal was measured simultaneously for the thirty-seven elements. Calibration was performed using digested rock reference standards and a series of multi-element solution standards (Lichte and others, 1987). The elements and limits of determination for which this method is useful are shown in table 5.

Elemental analysis of partial extraction solutions of geological material was performed by ICP-AES. The chemical methods used to prepare the samples are very similar to that described by Gulson and others (1992). Two and a half to five grams of dried and ground minus-80-mesh stream-sediment material, or one to five grams of unground core material, were placed in an acid-washed 50-mL disposable centrifuge tube. Fifteen to 25 mL of ultraclean 2M HCl and 0.2 mL of reagent-grade, 30-percent H_2O_2 were added and the centrifuge tube was capped. The samples were placed in a water bath at 55-60°C and shaken for 2 hours. The samples were removed, centrifuged, and the solution pipetted into clean test tubes for chemical or isotopic analysis. Volumes used for the calculated concentrations of metals in the leach solutions were those of the 2M HCl added to the sample rather than the volume of the solution recovered from the centrifuge tube. Twenty-seven major and trace elements were determined in partial extraction solutions by ICP-AES. The analysis is similar to the 37-element procedure previously described. The elements, their chemical symbols, and the limits of determination for the two chemical procedures are listed in table 5. Element symbols are used in the column headings and concentrations are given in either weight percent (pct.) or parts per million (ppm). Concentrations less than these limits of determination are indicated by less than symbol, <, in tables 6 and 7. That is, the concentration of europium (Eu) in the samples, as shown in table 6, is often less than the limit of determination, which is 2 ppm, and is shown as <2.

Table 5. ICP-AES elements and limits of determination

[Values given for the total digestion procedure are limits in the sample. Values given for the $HCl-H_2O_2$ leach procedure are limits in the solution analyzed. The values for the leach procedure have been multiplied by the dilution factor of the sample to arrive at the limits of determination used in table 7.]

Element	Chemical Symbol	Total Digestion Procedure	$HCl-H_2O_2$ Leach Procedure
aluminum	Al	.005 pct.	1 ppm
calcium	Ca	.005 pct.	1 ppm
iron	Fe	.005 pct.	1 ppm
potassium	K	.01 pct.	1 ppm
magnesium	Mg	.005 pct.	1 ppm
sodium	Na	.005 pct.	1 ppm
phosphorous	P	.005 pct.	1 ppm
silicon	Si	--	1 ppm
titanium	Ti	.005 pct.	1 ppm
silver	Ag	2 ppm	0.04 ppm
arsenic	As	10 ppm	.2 ppm
gold	Au	8 ppm	--
barium	Ba	1 ppm	.02 ppm
beryllium	Be	1 ppm	.02 ppm
bismuth	Bi	10 ppm	.2 ppm
cadmium	Cd	2 ppm	.04 ppm
cerium	Ce	4 ppm	--
cobalt	Co	1 ppm	.02 ppm
chromium	Cr	1 ppm	.02 ppm
copper	Cu	1 ppm	.02 ppm
europium	Eu	2 ppm	--
gallium	Ga	4 ppm	--
lanthanum	La	2 ppm	--
lithium	Li	2 ppm	.04 ppm
manganese	Mn	4 ppm	.04 ppm
molybdenum	Mo	2 ppm	.04 ppm
niobium	Nb	4 ppm	--
neodymium	Nd	4 ppm	--
nickel	Ni	2 ppm	.04 ppm
lead	Pb	4 ppm	.08 ppm
scandium	Sc	2 ppm	--
tin	Sn	5 ppm	.1 ppm
strontium	Sr	2 ppm	.04 ppm
thorium	Th	4 ppm	--
vanadium	V	2 ppm	.04 ppm
yttrium	Y	2 ppm	--
ytterbium	Yb	1 ppm	--
zinc	Zn	2 ppm	.02 ppm

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.

Sample	Latitude	Longitude	Al-pct.	Ca-pct.	Fe-pct.	K-pct.	Mg-pct.	Na-pct.	P-pct.	Ti-pct.	Mn-ppm	Ag-ppm
93LV100C	39°13'38"	106°21'27"	6.5	0.7	2.2	2.8	0.55	0.97	0.11	0.17	1600	<2
93LV102C	39°12'07"	106°21'09"	5.9	0.7	5.1	2.3	0.50	0.84	0.10	0.17	1600	7
93LV103	39°11'42"	106°20'16"	5.0	2.7	1.1	2.5	0.49	0.75	0.05	0.09	110	<2
93LV104	39°17'29"	106°22'05"	6.3	0.4	7.5	2.9	0.38	0.91	0.16	0.20	900	15
93LV105	39°13'38"	106°20'01"	3.8	0.7	7.8	1.4	0.52	0.37	0.07	0.07	2600	16
93LV106	39°13'54"	106°19'19"	2.5	13.0	25.0	0.7	0.82	0.58	0.11	0.16	9100	6
93LV107	39°16'18"	106°17'55"	5.1	1.5	5.3	2.0	0.62	0.73	0.13	0.18	4000	17
93LV108	39°17'09"	106°16'45"	6.1	0.7	2.1	2.9	0.54	0.95	0.12	0.20	590	<2
93LV109	39°21'36"	106°11'50"	6.5	1.0	5.3	2.7	0.64	1.30	0.13	0.27	2300	<2
93LV110	39°20'58"	106°13'10"	6.5	1.5	2.5	3.1	1.10	0.83	0.07	0.23	730	<2
93LV111	39°18'20"	106°13'33"	5.9	0.3	2.2	2.9	0.49	0.21	0.06	0.25	220	<2
93LV112	39°18'54"	106°13'23"	6.1	1.1	2.7	2.9	0.76	0.94	0.11	0.24	810	<2
93LV113	39°13'18"	106°16'17"	5.6	1.1	3.0	2.3	0.71	0.82	0.16	0.19	1900	4
93LV114	39°13'22"	106°22'42"	6.1	0.8	3.6	2.9	0.32	1.60	0.17	0.49	1100	<2
93LV100-A1	39°13'38"	106°21'27"	4.0	2.1	1.9	1.4	0.56	0.40	0.10	0.13	2000	3
93LV100-A2	39°13'38"	106°21'27"	6.2	0.6	1.9	2.9	0.48	0.97	0.08	0.15	670	<2
93LV100-A3	39°13'38"	106°21'27"	5.7	0.4	1.7	3.0	0.34	0.95	0.06	0.14	360	<2
93LV100-A4	39°13'38"	106°21'27"	6.1	0.6	1.6	3.0	0.45	0.98	0.07	0.15	160	<2
93LV100-A5	39°13'38"	106°21'27"	6.5	0.5	1.5	3.5	0.37	1.20	0.08	0.14	230	<2
93LV100-A6	39°13'38"	106°21'27"	5.5	0.4	1.4	3.0	0.29	1.00	0.06	0.11	180	<2
93LV100-A7	39°13'38"	106°21'27"	5.0	0.4	1.1	2.9	0.22	0.98	0.06	0.09	180	<2
93LV100-A8	39°13'38"	106°21'27"	5.5	0.5	1.6	2.8	0.36	0.95	0.08	0.15	410	<2
93LV100-A9	39°13'38"	106°21'27"	5.0	0.4	1.3	2.7	0.23	0.94	0.08	0.11	340	<2
93LV100-A10	39°13'38"	106°21'27"	5.5	0.5	1.1	2.9	0.30	1.00	0.08	0.10	150	<2
93LV100-A11	39°13'38"	106°21'27"	5.0	0.3	1.1	2.8	0.21	0.97	0.04	0.08	90	<2
93LV100-A12	39°13'38"	106°21'27"	5.0	0.3	1.3	2.8	0.23	0.98	0.05	0.08	120	<2
93LV100-A13	39°13'38"	106°21'27"	4.7	0.3	0.7	2.8	0.17	0.97	0.04	0.07	86	<2
93LV101-A1	39°12'23"	106°21'04"	4.7	0.8	5.4	2.2	0.31	0.79	0.09	0.12	510	10
93LV101-A2	39°12'23"	106°21'04"	5.3	0.8	7.1	2.0	0.48	0.68	0.11	0.16	700	16
93LV101-A3	39°12'23"	106°21'04"	4.7	0.4	3.4	2.2	0.26	0.68	0.06	0.09	330	10
93LV101-A4	39°12'23"	106°21'04"	5.6	0.8	4.7	2.3	0.54	0.66	0.09	0.13	1200	19
93LV101-A6	39°12'23"	106°21'04"	6.0	0.9	5.2	2.1	0.70	0.61	0.10	0.15	1000	22
93LV101-A5	39°12'23"	106°21'04"	4.9	0.6	3.1	2.3	0.39	0.72	0.05	0.08	590	7
93LV101-A7	39°12'23"	106°21'04"	4.8	0.4	3.4	2.3	0.36	0.65	0.06	0.08	1000	10
93LV101-A8	39°12'23"	106°21'04"	6.7	0.8	4.6	2.2	0.79	0.68	0.10	0.18	910	26
93LV101-A9	39°12'23"	106°21'04"	4.9	0.6	4.4	1.9	0.51	0.55	0.08	0.12	900	20
93LV101-A10	39°12'23"	106°21'04"	4.9	0.4	3.8	2.1	0.39	0.61	0.07	0.10	730	13
93LV101-A11	39°12'23"	106°21'04"	5.4	0.3	5.2	2.1	0.37	0.52	0.07	0.11	690	20
93LV101-A12	39°12'23"	106°21'04"	5.0	0.3	3.0	2.2	0.28	0.63	0.06	0.09	650	7
93LV101-A13	39°12'23"	106°21'04"	6.4	0.7	4.9	1.9	0.73	0.43	0.14	0.17	1700	56
93LV101-A14	39°12'23"	106°21'04"	4.9	1.5	5.2	1.7	1.10	0.47	0.13	0.13	2400	71
93LV101-A15	39°12'23"	106°21'04"	4.8	2.6	5.6	1.5	1.70	0.29	0.10	0.13	3700	100

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Latitude	Longitude	Al-pct.	Ca-pct.	Fe-pct.	K-pct.	Mg-pct.	Na-pct.	P-pct.	Ti-pct.	Mn-ppm	Ag-ppm
93LV101-A16	39°12'23"	106°21'04"	1.7	1.3	4.8	0.5	0.36	0.10	0.07	0.04	2400	4
93LV101-A17	39°12'23"	106°21'04"	7.7	0.7	2.9	2.5	0.84	0.71	0.11	0.23	920	<2
93LV101-A18	39°12'23"	106°21'04"	7.4	0.8	3.3	2.2	0.85	0.52	0.12	0.21	1300	<2
93LV101-A19	39°12'23"	106°21'04"	8.6	0.6	2.7	2.7	0.93	0.66	0.10	0.25	840	<2
93LV101-A20	39°12'23"	106°21'04"	5.3	0.7	1.7	2.1	0.47	0.72	0.12	0.12	1300	<2
93LV101-A21	39°12'23"	106°21'04"	6.5	0.5	1.2	2.9	0.44	1.10	0.07	0.15	370	<2
93LV102-A1	39°12'07"	106°21'09"	5.4	0.8	5.8	2.0	0.39	0.73	0.08	0.14	620	21
93LV102-A2	39°12'07"	106°21'09"	5.5	0.3	5.6	2.1	0.42	0.68	0.09	0.16	660	26
93LV102-A3	39°12'07"	106°21'09"	5.2	0.2	5.1	2.1	0.37	0.72	0.08	0.16	280	16
93LV102-A4	39°12'07"	106°21'09"	5.3	0.3	5.1	2.2	0.35	0.75	0.08	0.15	260	12
93LV102-A5	39°12'07"	106°21'09"	7.1	0.3	5.1	2.3	0.52	0.88	0.10	0.23	280	22
93LV102-A6	39°12'07"	106°21'09"	5.7	0.2	4.8	2.3	0.38	0.58	0.08	0.13	1700	11
93LV102-A7	39°12'07"	106°21'09"	6.7	0.3	6.1	2.2	0.52	0.53	0.11	0.18	4000	16
93LV102-A8	39°12'07"	106°21'09"	5.9	0.3	4.8	1.9	0.49	0.48	0.10	0.18	2000	11
93LV102-A9	39°12'07"	106°21'09"	6.3	1.1	5.3	2.2	1.00	0.57	0.11	0.17	1800	22
93LV102-A10	39°12'07"	106°21'09"	7.1	0.6	5.1	2.3	0.74	0.61	0.12	0.21	2900	24
93LV102-A11	39°12'07"	106°21'09"	6.4	0.5	5.7	2.1	0.62	0.68	0.11	0.18	900	19
93LV102-A12	39°12'07"	106°21'09"	6.7	0.6	5.0	2.3	0.70	0.50	0.10	0.16	1700	23
93LV102-A13	39°12'07"	106°21'09"	8.2	0.6	6.3	2.5	0.88	0.39	0.12	0.21	1100	32
93LV102-A14	39°12'07"	106°21'09"	8.0	0.5	7.0	2.5	0.75	0.51	0.11	0.23	1300	21
93LV102-A15	39°12'07"	106°21'09"	7.0	0.6	3.1	2.5	0.68	0.61	0.10	0.20	870	9
93LV102-A16	39°12'07"	106°21'09"	7.2	0.8	2.3	2.4	0.74	0.68	0.10	0.22	870	<2
93LV102-A17	39°12'07"	106°21'09"	7.6	0.7	1.8	2.6	0.75	0.72	0.09	0.21	550	<2
SRM2704			6.4	2.7	4.2	2.0	1.30	0.64	0.10	0.32	600	<2
SRM2704			6.3	2.7	4.3	2.0	1.30	0.61	0.11	0.34	590	<2
SRM2710			6.3	1.3	3.5	2.0	0.87	1.10	0.11	0.27	9900	32
SRM2711			6.7	3.0	2.9	2.5	1.10	1.20	0.09	0.29	650	4

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	As-ppm	Ba-ppm	Be-ppm	Bi-ppm	Cd-ppm	Ce-ppm	Co-ppm	Cr-ppm	Cu-ppm	Eu-ppm	Ga-ppm	La-ppm	Li-ppm
93LV100C	12	690	4.0	<10	7	100	9	35	32	<2	19	56	33
93LV102C	83	800	3.0	<10	33	94	10	32	610	<2	17	51	25
93LV103	<10	710	2.0	<10	<2	77	3	13	10	<2	12	42	13
93LV104	27	540	2.0	<10	10	190	7	35	69	<2	17	94	19
93LV105	130	550	1.0	20	13	37	5	17	500	<2	12	20	14
93LV106	730	430	2.0	<10	20	46	86	110	2600	<2	<4	28	29
93LV107	81	1200	2.0	<10	9	100	8	25	160	<2	19	52	18
93LV108	<10	650	4.0	<10	<2	140	6	28	15	<2	18	75	39
93LV109	<10	790	4.0	<10	4	250	13	87	38	<2	20	140	29
93LV110	<10	750	6.0	<10	<2	85	8	41	16	<2	19	41	64
93LV111	<10	480	3.0	<10	<2	81	6	51	7	<2	14	43	17
93LV112	<10	810	6.0	<10	<2	120	7	40	23	<2	18	67	49
93LV113	27	1100	2.0	22	7	230	6	28	88	<2	17	120	18
93LV114	11	580	2.0	<10	<2	660	7	38	26	3	17	330	21
93LV100-A1	31	570	4.0	<10	23	47	9	25	170	<2	15	27	21
93LV100-A2	<10	640	3.0	<10	<2	79	8	30	20	<2	16	42	29
93LV100-A3	<10	600	3.0	<10	<2	64	6	21	24	<2	15	36	27
93LV100-A4	<10	620	4.0	<10	<2	76	4	35	13	<2	16	41	31
93LV100-A5	<10	690	3.0	<10	<2	72	5	33	10	<2	15	40	30
93LV100-A6	<10	580	3.0	<10	<2	53	4	17	8	<2	13	30	29
93LV100-A7	<10	570	3.0	<10	<2	57	2	14	8	<2	11	31	21
93LV100-A8	<10	570	3.0	<10	<2	120	5	24	9	<2	15	66	25
93LV100-A9	<10	530	2.0	<10	<2	110	3	17	7	<2	12	56	20
93LV100-A10	<10	590	2.0	<10	<2	68	4	19	7	<2	12	38	23
93LV100-A11	<10	560	2.0	<10	<2	62	2	14	7	<2	12	36	20
93LV100-A12	<10	560	3.0	<10	<2	58	3	15	7	<2	12	33	24
93LV100-A13	<10	490	2.0	<10	<2	43	<2	11	4	<2	11	24	21
93LV101-A1	97	770	1.0	<10	16	59	4	19	250	<2	12	33	16
93LV101-A2	120	730	2.0	<10	26	56	5	29	460	<2	14	32	23
93LV101-A3	74	710	1.0	<10	12	40	2	14	180	<2	11	23	16
93LV101-A4	130	740	3.0	17	43	66	8	24	860	<2	15	35	22
93LV101-A6	140	780	2.0	24	53	65	6	34	630	<2	<4	35	23
93LV101-A5	59	710	2.0	<10	21	37	4	13	270	<2	13	21	16
93LV101-A7	77	780	2.0	<10	31	51	4	13	160	<2	13	29	15
93LV101-A8	110	870	3.0	13	110	67	6	35	710	<2	<4	36	30
93LV101-A9	100	750	2.0	18	38	54	5	18	410	<2	<4	30	19
93LV101-A10	81	770	2.0	<10	23	47	3	14	340	<2	14	25	15
93LV101-A11	96	690	3.0	18	19	54	4	20	410	<2	13	29	17
93LV101-A12	64	720	2.0	<10	15	44	4	14	270	<2	13	22	16
93LV101-A13	220	690	3.0	17	440	66	16	35	540	<2	<4	38	25
93LV101-A14	150	260	2.0	17	600	51	5	27	560	<2	<4	30	18
93LV101-A15	230	100	2.0	11	940	45	6	32	570	<2	<4	25	17

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	As-ppm	Ba-ppm	Be-ppm	Bi-ppm	Cd-ppm	Ce-ppm	Co-ppm	Cr-ppm	Cu-ppm	Eu-ppm	Ga-ppm	La-ppm	Li-ppm
93LV101-A16	69	330	<1.0	<10	22	19	8	9	47	<2	7	11	7
93LV101-A17	<10	780	5.0	<10	<2	89	11	50	22	<2	21	52	42
93LV101-A18	13	820	6.0	<10	<2	89	14	51	35	<2	20	55	41
93LV101-A19	<10	800	6.0	<10	<2	97	10	57	26	<2	23	58	49
93LV101-A20	<10	670	3.0	<10	<2	53	9	28	23	<2	15	31	25
93LV101-A21	<10	690	3.0	<10	<2	83	5	29	10	<2	17	45	30
93LV102-A1	160	750	2.0	15	11	52	5	24	560	<2	14	29	21
93LV102-A2	200	770	2.0	15	9	52	5	26	470	<2	15	30	21
93LV102-A3	150	770	2.0	13	8	53	4	23	360	<2	13	31	21
93LV102-A4	170	800	2.0	17	8	52	3	24	420	<2	12	29	20
93LV102-A5	180	950	2.0	28	9	52	5	34	460	<2	18	31	28
93LV102-A6	120	670	2.0	16	7	50	13	25	390	<2	16	27	22
93LV102-A7	120	720	4.0	24	13	67	28	35	750	<2	23	33	27
93LV102-A8	100	680	4.0	15	27	83	13	33	1000	<2	18	42	26
93LV102-A9	120	750	3.0	27	51	63	8	32	930	<2	20	35	25
93LV102-A10	140	830	3.0	30	55	72	13	43	750	<2	<4	39	30
93LV102-A11	140	900	3.0	10	50	62	6	32	540	<2	<4	34	27
93LV102-A12	130	790	3.0	18	45	61	7	34	680	<2	21	34	26
93LV102-A13	160	790	3.0	33	44	77	7	44	930	<2	<4	42	32
93LV102-A14	140	980	3.0	20	83	78	9	44	510	<2	22	43	33
93LV102-A15	120	290	4.0	<10	63	83	20	42	290	<2	22	46	32
93LV102-A16	12	730	5.0	<10	26	91	9	45	54	<2	20	54	38
93LV102-A17	<10	770	4.0	<10	<2	92	8	46	27	<2	21	54	40
SRM2704	19	420	2.0	<10	3	62	16	150	98	<2	15	33	50
SRM2704	19	430	2.0	<10	3	64	17	150	100	<2	15	34	50
SRM2710	570	690	2.0	18	19	55	11	32	2900	<2	<4	33	41
SRM2711	93	730	2.0	<10	38	77	11	53	120	<2	17	42	29

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Mo-ppm	Nb-ppm	Nd-ppm	Ni-ppm	Pb-ppm	Sc-ppm	Sn-ppm	Sr-ppm	Th-ppm	V-ppm	Y-ppm	Yb-ppm	Zn-ppm
93LV100C	3	11	48	13	140	7	<5	160	23	38	19	2	1200
93LV102C	5	11	44	10	1900	6	26	150	20	39	26	2	5200
93LV103	<2	7	32	4	63	3	7	140	15	17	11	1	180
93LV104	<2	10	92	10	460	7	<5	110	74	36	19	1	1800
93LV105	3	4	16	5	2800	4	6	100	6	25	8	<1	4000
93LV106	190	<4	17	<2	11000	6	930	470	6	64	14	1	96000
93LV107	<2	7	46	9	2800	5	12	150	17	46	17	1	3700
93LV108	2	16	59	10	45	6	<5	150	26	40	19	2	220
93LV109	25	16	110	19	150	7	<5	250	46	86	27	2	1000
93LV110	2	18	34	14	27	8	<5	120	29	41	21	2	120
93LV111	<2	10	36	14	22	8	<5	64	20	48	17	2	29
93LV112	8	20	54	13	37	7	<5	140	33	47	22	2	240
93LV113	16	11	100	9	1100	5	<5	130	53	40	32	2	1300
93LV114	<2	12	320	9	95	7	<5	160	200	67	53	2	400
93LV100-A1	9	7	23	16	510	5	21	150	12	30	16	2	2500
93LV100-A2	<2	11	38	10	34	6	<5	150	16	32	14	2	200
93LV100-A3	<2	12	30	6	30	5	<5	140	16	25	10	<1	82
93LV100-A4	<2	10	36	8	30	6	<5	150	17	30	13	1	80
93LV100-A5	<2	10	32	7	35	5	47	170	14	28	11	1	61
93LV100-A6	<2	10	25	5	32	4	<5	150	13	22	8	<1	53
93LV100-A7	<2	8	27	4	28	3	26	130	12	19	9	1	33
93LV100-A8	<2	10	59	7	29	5	10	140	31	31	19	2	59
93LV100-A9	<2	8	49	5	28	4	9	130	25	24	15	1	42
93LV100-A10	<2	8	33	5	29	4	5	150	16	22	12	1	48
93LV100-A11	<2	6	28	3	27	3	<5	130	12	18	7	<1	38
93LV100-A12	<2	8	30	4	27	3	6	140	14	20	8	<1	41
93LV100-A13	<2	6	19	3	24	2	<5	120	10	14	6	<1	25
93LV101-A1	6	7	27	4	2300	4	56	160	12	30	8	<1	2600
93LV101-A2	9	9	25	7	3600	6	17	140	14	40	9	<1	4100
93LV101-A3	2	6	19	4	1900	3	100	140	8	25	7	<1	2200
93LV101-A4	8	8	31	9	3500	5	210	130	10	35	19	2	7500
93LV101-A6	18	9	29	11	5100	6	6	130	11	43	18	2	7700
93LV101-A5	4	6	18	5	1700	3	54	130	9	23	9	<1	3500
93LV101-A7	6	5	24	5	3900	3	<5	140	8	33	9	<1	4100
93LV101-A8	17	10	33	14	7000	7	9	140	11	52	23	2	8900
93LV101-A9	6	6	23	7	5100	4	10	140	8	33	15	1	4900
93LV101-A10	3	6	24	5	3400	4	16	130	9	30	13	1	3700
93LV101-A11	3	7	27	7	4100	5	23	110	10	34	13	2	3900
93LV101-A12	<2	6	21	5	2300	4	9	140	7	27	11	1	2200
93LV101-A13	8	9	33	19	17000	7	67	130	5	60	21	2	38000
93LV101-A14	8	7	25	9	35000	5	15	180	<4	44	14	1	63000
93LV101-A15	9	8	21	8	55000	6	16	170	<4	49	13	1	120000

Table 6. Analytical data from total digestions of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Mo-ppm	Nb-ppm	Nd-ppm	Ni-ppm	Pb-ppm	Sc-ppm	Sn-ppm	Sr-ppm	Th-ppm	V-ppm	Y-ppm	Yb-ppm	Zn-ppm
93LV101-A16	3	<4	9	7	1100	2	<5	61	<4	15	5	<1	4700
93LV101-A17	<2	13	45	17	61	10	<5	130	24	54	24	2	230
93LV101-A18	3	14	48	20	61	10	6	110	21	56	27	2	290
93LV101-A19	<2	14	50	17	56	12	5	130	25	61	28	3	210
93LV101-A20	<2	7	28	13	38	6	<5	110	14	34	14	1	1600
93LV101-A21	<2	10	38	8	38	6	<5	150	20	30	15	1	1600
93LV102-A1	4	9	23	8	4700	5	11	130	8	38	9	<1	2400
93LV102-A2	7	9	24	8	4600	6	<5	140	11	40	12	1	2200
93LV102-A3	4	9	25	7	3200	5	91	150	12	36	11	<1	1700
93LV102-A4	6	9	23	6	2800	5	14	150	12	34	11	1	1700
93LV102-A5	6	13	23	11	4100	7	7	170	10	50	14	1	2100
93LV102-A6	8	9	22	7	2800	6	5	130	10	35	13	1	2300
93LV102-A7	13	10	31	10	4000	7	20	130	11	46	21	2	3600
93LV102-A8	10	10	39	11	3000	7	30	130	13	42	32	2	4300
93LV102-A9	10	10	31	14	4300	7	<5	120	11	47	22	2	9100
93LV102-A10	17	12	35	17	5000	8	11	130	13	54	23	2	8900
93LV102-A11	17	10	31	14	5400	7	8	140	10	47	23	2	6900
93LV102-A12	9	10	28	12	4800	7	7	110	11	47	19	1	6800
93LV102-A13	7	12	37	16	6100	10	6	100	12	62	20	2	8800
93LV102-A14	3	13	36	18	4200	10	16	120	12	60	21	2	8000
93LV102-A15	4	12	42	22	2100	9	<5	130	17	48	22	2	14000
93LV102-A16	<2	14	48	15	320	10	11	130	22	49	24	2	2600
93LV102-A17	<2	14	48	15	58	10	30	140	22	51	24	2	310
SRM2704	<2	7	29	44	160	12	6	140	10	93	20	2	440
SRM2704	<2	7	31	44	170	12	5	140	9	92	21	3	440
SRM2710	15	9	25	12	5100	9	<5	330	11	70	20	2	6600
SRM2711	<2	11	34	20	1200	10	<5	250	14	81	25	3	350

Table 7. Analytical data from HCl-H_2O_2 leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.

Sample	Latitude	Longitude	Al-ppm	Ca-ppm	Fe-ppm	Mg-ppm	K-ppm	Mn-ppm	Na-ppm	Ag-ppm
93LV100C	39°13'38"	106°21'27"	3451	3254	9318	1725	542	1134	44	0.5
93LV102C	39°12'07"	106°21'09"	4338	3599	23368	1873	444	1233	79	4.9
93LV103	39°11'42"	106°20'16"	892	30508	1911	3248	229	45	45	0.3
93LV104	39°17'29"	106°22'05"	3089	797	48724	847	847	648	45	10.0
93LV105	39°13'38"	106°20'01"	2673	5148	37175	3119	450	2079	64	9.9
93LV106	39°13'54"	106°19'19"	5864	56200	91876	3225	2590	3861	2248	4.9
93LV107	39°16'18"	106°17'55"	2511	9405	22158	2462	492	2807	74	14.8
93LV108	39°17'09"	106°16'45"	2463	4250	6857	2318	579	324	53	0.2
93LV109	39°21'36"	106°11'50"	4275	3882	8452	2064	885	1671	69	0.2
93LV110	39°20'58"	106°13'10"	2636	11681	9165	6170	563	312	48	<0.2
93LV111	39°18'20"	106°13'33"	2942	2354	6120	1353	824	165	24	<0.2
93LV112	39°18'54"	106°13'23"	2811	8031	8547	4474	631	373	52	<0.2
93LV113	39°13'18"	106°16'17"	2996	9812	9166	3995	570	1763	47	3.5
93LV114	39°13'22"	106°22'42"	3595	2888	8900	1415	1120	825	94	1.2
93LV100-A1	39°13'38"	106°21'27"	3820	21009	8374	3085	837	1249	44	2.9
93LV100-A2	39°13'38"	106°21'27"	3410	3353	9595	1908	526	451	17	<0.2
93LV100-A3	39°13'38"	106°21'27"	2536	2476	10870	1449	380	181	24	<0.2
93LV100-A4	39°13'38"	106°21'27"	2907	2725	8841	1696	382	85	24	<0.2
93LV100-A5	39°13'38"	106°21'27"	1861	1748	6259	1071	344	192	17	<0.2
93LV100-A6	39°13'38"	106°21'27"	1713	2008	5610	1004	295	71	24	<0.2
93LV100-A7	39°13'38"	106°21'27"	1250	1458	4167	729	250	68	16	<0.2
93LV100-A8	39°13'38"	106°21'27"	1726	1786	5536	1012	310	161	18	<0.2
93LV100-A9	39°13'38"	106°21'27"	1213	1654	3969	662	226	149	17	<0.2
93LV100-A10	39°13'38"	106°21'27"	1782	2079	3861	950	279	36	18	<0.2
93LV100-A11	39°13'38"	106°21'27"	1318	1318	5513	719	240	42	18	<0.2
93LV100-A12	39°13'38"	106°21'27"	958	898	6048	521	210	36	18	<0.2
93LV100-A13	39°13'38"	106°21'27"	854	1009	2949	473	210	23	16	0.2
93LV101-A1	39°12'23"	106°21'04"	1350	6928	36341	1115	881	487	235	5.9
93LV101-A2	39°12'23"	106°21'04"	2484	4563	45283	1617	566	526	110	11.6
93LV101-A3	39°12'23"	106°21'04"	1188	2659	24557	679	368	289	51	5.7
93LV101-A4	39°12'23"	106°21'04"	3350	4556	23783	2144	268	737	20	13.4
93LV101-A6	39°12'23"	106°21'04"	3772	7662	18802	3418	342	648	24	17.7
93LV101-A5	39°12'23"	106°21'04"	2435	4291	17974	2029	238	574	17	5.8
93LV101-A7	39°12'23"	106°21'04"	1722	3758	16284	2244	193	731	21	10.4
93LV101-A8	39°12'23"	106°21'04"	4944	5481	19301	3634	477	715	30	17.9
93LV101-A9	39°12'23"	106°21'04"	2639	4112	15344	2516	252	608	25	12.3
93LV101-A10	39°12'23"	106°21'04"	2552	3205	17511	1721	285	712	24	11.9
93LV101-A11	39°12'23"	106°21'04"	2820	1140	18000	720	216	450	12	12.0
93LV101-A12	39°12'23"	106°21'04"	2650	1037	15668	634	207	461	17	5.8
93LV101-A13	39°12'23"	106°21'04"	5850	5550	13575	3075	533	1425	38	37.5
93LV101-A14	39°12'23"	106°21'04"	3628	12322	17102	6564	351	1843	40	34.5
93LV101-A15	39°12'23"	106°21'04"	14706	116043	86096	50802	1337	13102	267	107.0

Table 7. Analytical data from HCl-H_2O_2 leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Latitude	Longitude	Al-ppm	Ca-ppm	Fe-ppm	Mg-ppm	K-ppm	Mn-ppm	Na-ppm	Ag-ppm
93LV101-A16	39°12'23"	106°21'04"	2562	12381	40275	2704	185	2277	43	1.4
93LV101-A17	39°12'23"	106°21'04"	7178	4337	19143	3589	583	793	30	0.3
93LV101-A18	39°12'23"	106°21'04"	7979	4664	19640	3928	651	896	49	0.2
93LV101-A19	39°12'23"	106°21'04"	7926	3576	14482	3576	596	715	36	<0.2
93LV101-A20	39°12'23"	106°21'04"	4751	5760	11105	2257	261	1366	36	<0.2
93LV101-A21	39°12'23"	106°21'04"	3201	1601	4726	1601	381	259	23	0.2
93LV102-A1	39°12'07"	106°21'09"	2178	2525	27478	644	371	426	114	14.9
93LV102-A2	39°12'07"	106°21'09"	1956	782	26156	636	303	293	29	14.7
93LV102-A3	39°12'07"	106°21'09"	2380	772	28365	836	360	129	32	12.9
93LV102-A4	39°12'07"	106°21'09"	1821	837	28542	640	290	118	25	9.8
93LV102-A5	39°12'07"	106°21'09"	3349	778	30443	957	484	120	24	17.9
93LV102-A6	39°12'07"	106°21'09"	3968	962	31924	1022	337	1383	24	12.0
93LV102-A7	39°12'07"	106°21'09"	4629	1142	30962	1082	337	1804	24	12.0
93LV102-A8	39°12'07"	106°21'09"	5347	1453	27431	1395	360	1627	29	11.6
93LV102-A9	39°12'07"	106°21'09"	4203	11229	21377	6485	402	1081	36	18.0
93LV102-A10	39°12'07"	106°21'09"	4966	3666	22763	2483	503	2365	30	17.7
93LV102-A11	39°12'07"	106°21'09"	4843	3484	24803	2421	484	827	35	17.7
93LV102-A12	39°12'07"	106°21'09"	4392	3971	24368	2647	487	1264	30	24.1
93LV102-A13	39°12'07"	106°21'09"	4882	4059	32765	2824	582	765	29	29.4
93LV102-A14	39°12'07"	106°21'09"	5491	3179	27457	2312	694	1098	35	17.3
93LV102-A15	39°12'07"	106°21'09"	5105	3502	15611	2374	546	653	30	5.9
93LV102-A16	39°12'07"	106°21'09"	6615	4708	12932	2861	656	775	36	2.4
93LV102-A17	39°12'07"	106°21'09"	6391	5030	8639	2722	651	467	36	0.3
SRM2704			7246	26087	21739	7729	386	459	97	0.5
SRM2704			6763	24397	20532	7488	362	459	121	1.0
SRM2710			6699	3495	14709	2767	2621	6845	437	29.1
SRM2711			6843	21017	8553	5132	2273	464	196	2.4

Table 7. Analytical data from HCl-H_2O_2 leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	As-ppm	Ba-ppm	Be-ppm	Bi-ppm	Cd-ppm	Co-ppm	Cr-ppm	Cu-ppm	Li-ppm
93LV100C	4	148	1.0	<1.0	4.9	5	5	20	5
93LV102C	39	163	1.5	3.9	24.7	5	5	542	4
93LV103	3	108	0.1	1.3	1.3	2	3	6	1
93LV104	20	40	0.2	3.0	1.5	4	10	45	3
93LV105	40	20	0.4	5.0	5.0	3	3	277	1
93LV106	147	440	2.0	19.5	4.9	29	15	391	10
93LV107	30	355	0.3	1.0	4.9	4	3	94	2
93LV108	3	92	1.0	1.0	1.0	3	4	10	3
93LV109	3	123	1.5	1.0	3.9	5	10	25	5
93LV110	2	144	1.8	<1.0	0.3	4	5	6	4
93LV111	2	112	1.2	<1.0	0.1	2	4	4	2
93LV112	2	161	1.1	<1.0	0.6	3	5	17	4
93LV113	12	229	0.5	11.8	5.9	5	4	76	3
93LV114	4	71	0.4	<1.0	1.8	4	6	18	12
93LV100-A1	15	309	1.5	1.5	14.7	4	4	147	3
93LV100-A2	3	121	1.2	<1.0	0.6	5	6	6	5
93LV100-A3	4	79	0.6	<1.0	0.1	4	4	4	4
93LV100-A4	2	91	1.2	<1.0	0.2	3	5	6	5
93LV100-A5	2	56	0.6	<1.0	0.1	5	3	3	3
93LV100-A6	2	47	0.5	<1.0	0.1	2	3	3	2
93LV100-A7	2	36	0.4	<1.0	0.1	1	3	2	2
93LV100-A8	2	54	0.5	<1.0	0.1	2	3	3	2
93LV100-A9	2	33	0.4	<1.0	0.1	2	2	2	2
93LV100-A10	<1	53	0.6	<1.0	0.1	1	3	4	3
93LV100-A11	2	36	0.5	<1.0	0.1	2	2	2	2
93LV100-A12	3	30	0.4	<1.0	0.1	1	2	1	1
93LV100-A13	<1	23	0.3	<1.0	0.2	1	2	1	2
93LV101-A1	76	18	0.2	2.9	17.6	2	4	217	2
93LV101-A2	87	23	0.3	5.2	23.1	3	6	375	3
93LV101-A3	57	34	0.2	4.0	11.3	2	2	158	1
93LV101-A4	67	60	1.3	6.7	26.8	3	4	610	2
93LV101-A6	47	59	0.6	17.7	41.3	3	6	477	2
93LV101-A5	46	70	0.6	4.6	23.2	3	6	307	2
93LV101-A7	57	110	0.4	2.6	26.1	2	2	130	1
93LV101-A8	42	131	1.2	11.9	178.7	3	5	554	3
93LV101-A9	43	129	0.6	6.1	30.7	2	3	325	1
93LV101-A10	42	137	1.2	5.9	17.8	2	3	380	1
93LV101-A11	42	96	0.6	6.0	12.0	2	2	240	1
93LV101-A12	46	86	0.6	4.6	11.5	2	2	207	1
93LV101-A13	60	75	1.5	7.5	615.0	15	5	473	4
93LV101-A14	40	92	0.6	17.3	213.1	2	4	322	2
93LV101-A15	241	455	2.7	53.5	855.6	11	16	749	8

Table 7. Analytical data from HCl-H_2O_2 leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	As-ppm	Ba-ppm	Be-ppm	Bi-ppm	Cd-ppm	Co-ppm	Cr-ppm	Cu-ppm	Li-ppm
93LV101-A16	43	228	0.7	1.4	8.5	6	1	28	1
93LV101-A17	10	329	3.0	1.5	0.9	9	12	15	9
93LV101-A18	9	356	3.7	1.2	0.9	12	12	25	10
93LV101-A19	3	232	3.0	<1.0	0.6	6	12	18	12
93LV101-A20	5	160	1.8	<1.0	1.2	6	5	18	4
93LV101-A21	<1	114	0.8	<1.0	0.2	3	6	8	5
93LV102-A1	89	30	0.3	9.9	5.0	2	3	381	1
93LV102-A2	68	68	0.3	9.8	4.9	2	3	303	1
93LV102-A3	129	103	0.3	12.9	6.4	1	4	315	1
93LV102-A4	118	74	0.2	9.8	4.9	1	3	344	1
93LV102-A5	150	108	0.4	23.9	6.0	2	5	371	2
93LV102-A6	72	96	0.6	12.0	6.0	12	6	397	2
93LV102-A7	54	96	1.2	12.0	12.0	12	6	523	3
93LV102-A8	64	110	1.7	11.6	17.4	12	6	814	3
93LV102-A9	48	162	1.2	18.0	42.0	4	6	721	3
93LV102-A10	59	195	1.2	17.7	53.2	12	12	591	4
93LV102-A11	65	189	1.2	11.8	41.3	3	5	449	3
93LV102-A12	66	211	1.2	18.1	42.1	4	5	602	3
93LV102-A13	76	194	1.2	29.4	41.2	3	6	824	3
93LV102-A14	64	197	1.2	17.3	57.8	5	6	399	4
93LV102-A15	71	107	1.2	5.9	59.4	12	6	237	5
93LV102-A16	6	203	1.8	1.2	29.8	6	12	72	6
93LV102-A17	6	237	1.8	<1.0	1.8	6	12	24	6
SRM2704	17	72	0.5	2.4	2.4	10	97	97	17
SRM2704	14	72	<0.5	5	2	12	72	97	14
SRM2710	568	248	0.9	14.6	14.6	6	9	2621	10
SRM2711	73	171	<0.5	5	49	7	7	98	7

Table 7. Analytical data from $HCl-H_2O_2$ leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Mo-ppm	Ni-ppm	P-ppm	Pb-ppm	Sr-ppm	Ti-ppm	V-ppm	Zn-ppm	Si-ppm
93LV100C	1	5	592	79	10	74	5	838	1035
93LV102C	2	5	641	1430	15	69	10	3402	3007
93LV103	<0.5	3	369	57	38	32	4	153	892
93LV104	<0.5	2	897	204	2	115	5	194	1146
93LV105	1	2	421	1733	10	10	5	1980	941
93LV106	24	5	195	2199	195	293	10	25901	31765
93LV107	<0.5	3	739	1970	25	30	10	2216	6450
93LV108	1	5	966	24	10	68	5	159	1014
93LV109	10	10	934	118	20	93	10	786	1130
93LV110	1	6	557	12	18	36	5	78	1318
93LV111	<0.5	5	341	12	6	71	4	12	1236
93LV112	3	6	918	23	17	52	5	184	1262
93LV113	12	5	1293	881	12	29	12	1058	1410
93LV114	<0.5	5	1120	53	12	224	6	277	1532
93LV100-A1	1	10	500	367	88	88	6	2057	2351
93LV100-A2	<0.5	5	468	12	12	98	6	150	1503
93LV100-A3	1	4	574	6	12	127	6	60	1510
93LV100-A4	<0.5	4	466	6	12	157	6	48	1453
93LV100-A5	<0.5	3	485	6	6	107	5	34	1184
93LV100-A6	<0.5	2	549	5	6	118	4	24	1063
93LV100-A7	1	2	448	4	4	94	4	16	938
93LV100-A8	1	2	542	5	5	113	5	24	1131
93LV100-A9	1	2	606	5	4	77	3	28	882
93LV100-A10	<0.5	2	493	5	6	125	4	24	1129
93LV100-A11	1	2	390	4	5	96	4	24	1019
93LV100-A12	1	1	281	3	4	66	4	18	778
93LV100-A13	<0.5	1	326	4	3	62	2	16	761
93LV101-A1	5	1	505	1585	12	59	6	2877	881
93LV101-A2	4	2	635	2368	12	52	12	4216	982
93LV101-A3	2	1	441	1358	6	28	6	1358	849
93LV101-A4	3	4	482	2211	6	33	7	5628	1273
93LV101-A6	2	5	554	3065	6	24	12	6483	1120
93LV101-A5	3	3	400	1681	5	35	6	4117	1102
93LV101-A7	3	2	407	3184	10	26	10	3497	1044
93LV101-A8	3	6	566	5004	12	24	18	7744	1251
93LV101-A9	2	2	522	3498	12	25	12	4051	1105
93LV101-A10	2	2	653	3087	12	24	12	3205	1247
93LV101-A11	1	2	432	2400	6	24	6	1740	1260
93LV101-A12	1	2	409	1959	6	23	6	1498	1152
93LV101-A13	2	15	825	5700	15	15	23	36000	1275
93LV101-A14	1	3	806	4491	17	23	17	12035	1152
93LV101-A15	3	13	2674	20588	80	53	80	56684	5882

Table 7. Analytical data from $HCl-H_2O_2$ leaches of stream, core, and lake sediments from the upper Arkansas River basin, Lake County, Co.--continued

Sample	Mo-ppm	Ni-ppm	P-ppm	Pb-ppm	Sr-ppm	Ti-ppm	V-ppm	Zn-ppm	Si-ppm
93LV101-A16	<0.5	6	256	299	43	28	6	1708	1565
93LV101-A17	1	10	613	30	15	105	15	150	2692
93LV101-A18	1	12	565	25	12	74	25	172	2455
93LV101-A19	<0.5	12	483	24	12	42	18	137	1490
93LV101-A20	<0.5	12	433	12	18	24	18	1366	1306
93LV101-A21	<0.5	5	457	8	6	114	8	1448	1677
93LV102-A1	1	1	460	3169	5	30	10	1238	891
93LV102-A2	1	1	401	2787	15	29	10	1076	880
93LV102-A3	3	2	450	3087	19	39	6	1093	1158
93LV102-A4	2	1	438	2018	10	34	5	984	837
93LV102-A5	2	2	550	2990	18	30	12	1196	1256
93LV102-A6	4	3	583	2285	12	30	12	1743	1202
93LV102-A7	4	4	583	2164	6	30	12	3006	1202
93LV102-A8	3	5	570	2034	6	35	12	3603	1220
93LV102-A9	1	6	600	2762	12	30	12	8227	1321
93LV102-A10	2	6	650	3725	12	24	12	7864	1360
93LV102-A11	2	6	591	3484	12	30	12	6319	1358
93LV102-A12	2	6	662	3670	12	18	12	6619	1264
93LV102-A13	1	6	765	4529	12	18	12	9176	1235
93LV102-A14	1	6	636	2890	12	23	12	7861	1503
93LV102-A15	1	12	772	1721	12	53	12	14187	1543
93LV102-A16	<0.5	6	572	441	18	60	12	3576	1490
93LV102-A17	<0.5	6	544	36	18	71	18	231	1479
SRM2704	1	24	918	145	48	72	12	386	4589
SRM2704	1	24	870	145	24	72	12	362	4348
SRM2710	10	6	801	4078	73	379	29	4223	2913
SRM2711	1	12	684	1026	49	293	17	244	4154

Appendix IV: Lead-isotopic Methods

by R.B. Vaughn and S.E. Church

One to 5 mL aliquants of the 2M HCl-H_2O_2 solutions prepared by leaching the core and stream-sediment samples were used for the lead-isotopic determinations. The solutions were transferred to FEP teflon beakers and taken to dryness in laminar-flow clean hoods. The samples were dissolved in ultraclean 2M HBr, centrifuged, and the lead separated on Dowex 1x8 anion exchange resin in the HBr medium. A 5 μg aliquant of lead from each sample was then cleaned on a second Dowex 1x8 anion exchange column in the HCl medium. Column blanks were 10 to 25 ng, total solution blanks were as high as 100 ng. Blanks for the samples analyzed ranged between 20-60 ng. This would account for a maximum of less than 0.5 percent of the total lead in the sample with the lowest lead recovery (93LV102-A21). Since this sample has the most radiogenic lead of all the samples, it is clear that the effect of the blank lead, whose $^{206}Pb/^{204}Pb$ composition is about 18.8, is negligible. The samples were randomized, assigned laboratory numbers, and submitted for isotopic analysis as blind samples.

The isotopic composition of Pb was determined on a 12-inch, 68° sector, solid-source, thermal-emission mass spectrometer of NBS design. About 1-2 μg of lead were loaded on a single Re-filament and analyzed at 1250°C using the silica-gel emitter technique (Cameron and others, 1969). At least three sets of ten ratio pairs were measured for the isotopic ratios $^{204}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{206}Pb$ of each sample. The data have been corrected for thermal fractionation using a running-average correction based on data from regular runs of the NIST common-lead standard SRM-981. Precision of all ratios reported is 0.08 percent (1 sigma) or better within a single run. Replicate analyses of samples are usually within these error limits. Isotopic analyses of the NIST soil standards SRM-2704 and SRM-2711 are reported as an independent measure of analytical precision and accuracy.

Table 8. Lead-isotope data from leaches of stream-sediment and core samples, upper Arkansas River, Co.

Sample No.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$
93LV100A	18.236	15.567	38.475
93LV101A13-15	18.138	15.563	38.412
93LV101A21	19.478	15.656	39.036
93LV102	18.159	15.565	38.426
93LV103	18.417	15.588	38.655
93LV104A	17.881	15.534	38.644
93LV104B	17.856	15.529	38.615
93LV105	18.110	15.554	38.417
93LV107	18.075	15.569	38.391
93LV108	18.673	15.609	38.821
93LV109	18.412	15.574	38.653
93LV110	18.919	15.606	38.896
93LV111	18.194	15.550	38.314
93LV112	18.521	15.592	38.589
93LV113	18.181	15.567	38.583
93LV114	18.244	15.540	38.766
SRM-2704	18.769	15.641	38.393
SRM-2711	17.103	15.436	36.937
SRM-2711	17.104	15.440	36.960

Appendix V: ^{210}Pb methods and data

by C.W. Holmes, James Cathcart, and Margaret Marot

The procedure used to determine the ^{210}Pb activity was modified from that of Martin and Rice (1981a,b). Wet samples were placed in precleaned and weighed porcelain evaporating dishes, weighed, and dried at 40°C. After drying, the sample was reweighed to determine water content; these data were later used to normalize depths in the core. The dried samples were ground to minus 75 to 100 mesh, and a 5-g sample was placed in a porcelain crucible and heated to 450°C for 6 hours. The samples were cooled and weighed to determine loss-on-ignition. The sample was then transferred to a 100 mL teflon beaker using 5-10 mL of reagent-grade 16M HNO_3 and spiked with a known amount of ^{209}Po. The sample was mixed and allowed to stand overnight. The solution was evaporated to dryness under heat lamps at 109°C and the sides of the beaker washed with reagent-grade 8M HCl. The solution was again mixed and taken to dryness under the heat lamps. Reagent-grade 30-percent H_2O_2 was added in 1 mL aliquots until the sample was entirely wetted. Following completion of the reaction of the H_2O_2 with the sample, the sample was evaporated to dryness under the heat lamps. This procedure was repeated two more times. The sample was washed twice with reagent-grade 8M HCl and evaporated to dryness under the heat lamps to remove all traces of HNO_3. Five mL of 8M HCl were added to the sample and it was transferred to a pyrex beaker and diluted to about 50 mL with deionized water. Two mL of 25-percent sodium citrate and 5 mL of hydroxylamine hydrochloride are added to minimize interference of Fe^{+3} and Cr^{+6} in the autoplating, and 1 mL of bismuth nitrate was added to prevent deposition of ^{212}Bi. The pH of the solution was adjusted to 1.85-1.95 using reagent-grade ammonium hydroxide to inhibit interference in the autoplating process by tellurium and selenium. A teflon-coated stirring bar was added to the solution and the solution heated at a temperature of 85-90°C for 5 minutes to reduce oxidants that may be present in the solution. Silver foil held in a teflon holder, which allows autoplating on only one side of the foil, was placed in the beaker and the beaker stirred at 85-90°C for a minimum of 90 minutes while the ^{210}Pb was autoplated onto the silver foil. The silver foil was removed, washed with deionized water, and dried for α-counting.

The data collection procedure used standard, multi-channel α-counting methods. The sample was positioned beneath the detector in the counting chamber and placed under vacuum. Samples were counted for 24 to 48 hours, depending upon the α-activity from ^{210}Po (see figure 3A; Flynn, 1968). Data were accumulated using a multi-channel, pulse-height analyzer and collected on floppy disk by computer for up to 16 samples at a time. A typical energy spectrum is shown in figure 15.

From the raw analytical data, the ^{210}Po activity was determined for each sample of each core. Background activity (^{226}Ra-supported ^{210}Pb) was ascertained for each core where possible. The background activity level was estimated (using nearest data) for cores that are of insufficient length to reach a background point. The background activity was subtracted from each sample to resolve the excess ^{210}Pb activity. Excess ^{210}Pb activities (activity minus background) are plotted against normalized depths for each core and sedimentation rates are calculated over intervals of straight line decay.

The ^{210}Pb activity was determined, following evaluation of the quality of the raw data using statistical measures of precision, from the α-activity of ^{210}Po. Calibration of the activity of the ^{209}Po spike must be made and the data normalized to determine chemical yield. The ^{210}Pb activity (A) is determined from equation (1) where:

z = activity of ^{210}Po (expressed in disintegrations per minute, or dpm)
y = activity of ^{209}Po (in dpm)
g = weight of sample (in grams, g)
mL = milliliter(s) of ^{209}Po spike added
d = disintegrations per minute (dpm) of spike (^{209}Po)
x = d * mL

$$A = ((x * z)/y)g \tag{1}$$

Table 9. Data for water, organic, and mineral content and excess ^{210}Pb activity from cores 93LV100 and 93LV101, Leadville, Co.

Sample No.	Percent Water	Percent Organic Material	Percent Mineral Content	Median Depth (cm)	Excess ^{210}Pb
93LV100-A1	22.00	28.00	50.00	3.50	5.412020
93LV100-A2	25.37	6.35	68.28	9.05	0.504989
93LV100-A3	15.61	3.75	80.64	15.75	0.371236
93LV100-A4	27.06	6.15	66.79	21.35	0.572456
93LV100-A5	12.96	1.79	85.24	23.80	0.131549
93LV100-A6	15.73	1.97	82.29	27.40	0.163579
93LV100-A7	7.50	0.80	91.70	32.50	0.037928
93LV100-A8	17.12	1.59	81.29	36.05	0.289220
93LV100-A9	9.42	0.59	89.99	43.65	0.076104
93LV100-A10	23.13	2.17	74.70	57.70	0.282606
93LV100-A11	19.74	0.79	79.47	66.70	0.333647
93LV100-A12	16.32	0.40	83.29	70.00	0.169454
93LV100-A13	17.38	0.60	82.02	73.50	0.137930
93LV101-A1	17.22	6.18	76.60	2.250	0.585158
93LV101-A2	29.81	10.06	60.13	7.500	1.554751
93LV101-A3	15.27	3.57	81.16	15.900	0.286108
93LV101-A4	31.44	8.07	60.48	22.500	0.701830
93LV101-A5	16.49	2.56	80.94	25.100	0.129507
93LV101-A6	30.08	6.86	63.06	29.500	1.113075
93LV101-A7	15.36	2.36	82.29	35.850	0.276224
93LV101-A8	32.42	8.10	59.48	40.700	1.089715
93LV101-A9	26.26	6.18	67.56	44.100	0.604508
93LV101-A10	18.70	1.77	79.52	48.000	0.293719
93LV101-A11	25.79	3.95	70.26	50.250	0.553893
93LV101-A12	21.49	3.78	74.73	53.250	0.175342
93LV101-A13	49.05	20.37	30.58	57.150	2.271034
93LV101-A14	32.03	8.50	59.48	61.200	1.141473
93LV101-A15	29.79	7.97	62.25	66.150	1.296374
93LV101-A16	19.63	9.30	71.07	71.070	6.626025
93LV101-A17	41.57	13.39	45.04	76.250	2.299486
93LV101-A18	51.12	23.41	25.47	77.850	3.746363
93LV101-A19	36.85	10.12	53.03	80.600	2.620993
93LV101-A20	50.22	22.11	27.67	85.300	2.301821
93LV101-A21	22.12	2.76	75.13	90.400	0.817100

Table 10. Data for water, organic, and mineral content and excess ^{210}Pb activity from cores 93LV102 and 93LV103, Leadville, Co.

Sample No.	Percent Water	Percent Organic Material	Percent Mineral Content	Median Depth (cm)	Excess ^{210}Pb
93LV102-A1	39.43	12.94	47.67	9.10	2.79583
93LV102-A2	47.01	16.73	36.29	15.40	2.52653
93LV102-A3	40.34	10.62	48.97	19.10	2.15356
93LV102-A4	32.67	8.78	58.55	22.50	2.06398
93LV102-A5	32.47	6.11	61.42	25.60	2.03058
93LV102-A6	32.19	7.72	60.09	27.90	1.67542
93LV102-A7	37.44	10.53	52.00	30.20	1.69002
93LV102-A8	36.82	8.51	54.67	35.15	1.94938
93LV102-A9	33.11	6.35	60.54	40.00	1.51006
93LV102-A10	42.59	24.43	33.01	43.80	2.44272
93LV102-A11	35.35	12.64	52.03	48.50	1.91564
93LV102-A12	27.06	7.57	65.37	52.75	1.21127
93LV102-A13	28.48	6.16	65.36	56.45	1.46522
93LV102-A14	32.18	7.55	60.27	59.45	0.98875
93LV102-A15	27.23	8.33	64.44	61.45	1.25059
93LV102-A16	27.40	8.53	64.07	69.25	1.37981
93LV102-A17	24.46	7.39	68.15	81.75	1.25523
93LV103	28.60	3.59	67.82	19.75	0.28022