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Trace Metal Levels in Sediments of Pearl Harbor (Hawaii)

T. L. Ashwood
C. R. Olsen
I. L. Larsen
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Environmental Sciences Division
Publication No. 2789

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T. L. Ashwood, C. R. Olsen, I. L. Larsen, and T. Tamura

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EXECUTIVE SUMMARY

This study was conducted to measure the distribution of lead and other trace metals in the sediments of Pearl Harbor (Hawaii) to determine whether paint chips from vessels of the U. S. Navy's Inactive Fleet have affected the environmental quality of Middle Loch.

Sediment cores (ranging from 0.5 to 3.0 m long) were collected from Middle Loch near the Naval Inactive Ships Maintenance Facility and in an area of West Loch that is relatively isolated and unaffected by naval operations. The sediment cores were dated using fallout cesium-137 (^{137}Cs) and naturally occurring lead-210 (^{210}Pb) to define three time periods: "recent" containing both ^{137}Cs and excess ^{210}Pb (i.e., deposited since 1950); "older" sediments were those containing excess ^{210}Pb but no detectable ^{137}Cs (i.e., deposited between 1930 and 1950); and "historical" sediments were those containing no detectable levels of ^{210}Pb (i.e., deposited prior to 1930).

Concentrations of copper, lead, and zinc averaged 180 µg/g, 49 µg/g, and 272 µg/g, respectively, in recent Middle Loch sediments. These concentrations are significantly higher than those in either historical Middle Loch sediments or recent West Loch sediments. However, except for lead, the concentrations in recent Middle Loch sediments are similar to those of older Middle Loch sediments, which indicates that the increase in trace metal contamination began before the onset of Inactive Fleet operations (about 1946).

Increased trace metal levels in recent Middle Loch sediments might be expected to result from two potential sources: (1) sewage discharges and (2) paint from inactive vessels. Since paint contains elevated levels of lead and zinc but little copper, the elevated copper levels in Middle Loch sediments tend to implicate sewage as the source of trace metal contamination. Moreover, the lead:zinc ratio of recent Middle Loch sediments (0.18:1) is a factor of 10 lower than that measured in paint (2.1:1), and the Middle Loch lead:zinc ratio is not significantly greater than that measured in recent West Loch sediments (0.21:1). Hence, we suggest that sewage rather than paint is the major source of trace metal contamination in Middle Loch. This is consistent with the findings of a previous study by U. S. Navy personnel. Further investigations of the composition of marine paints, and the trace metal levels and history of sewage discharge into Pearl Harbor could be conducted to verify this conclusion.

Finally, the lead concentrations in Middle Loch are no greater than those in other estuaries near urban and industrial areas of the United States, based on a brief survey of the literature.

1. INTRODUCTION

Several vessels of the U. S. Navy's Inactive Fleet are moored and maintained in Middle Loch of Pearl Harbor, Hawaii. Through natural weathering and some preservation activities, paint chips from these vessels are introduced directly into the waters of the harbor. Since marine paints are highly insoluble, most of these paint chips are probably deposited in the sediments in the general vicinity of the vessels.

The purpose of this study was to measure the concentrations of trace metals, especially lead, in the sediments and to determine, if possible, whether paint chips had contributed measurably to metal contamination of Middle Loch.

1.1 BACKGROUND

Pearl Harbor is a subtropical (lat. 21°N), coastal plain estuary composed of three major lochs (which are the drowned valleys of three streams) and an entrance channel (Fan 1976). Together these lochs drain an area of ~330 km^2 (Turner 1975). Most of this watershed is agricultural land (pineapple and sugarcane); however, in the immediate vicinity of Pearl Harbor, there is considerable residential and industrial activity, primarily associated with the Navy shipyard, Hickam Air Force Base, and Honolulu International Airport (see Fig. 1). At mean flow rates, eight major streams carry ~10.4 Mg (11.5 tons) of sediment per day into Pearl Harbor (from Fig. 3 in Fan 1976).

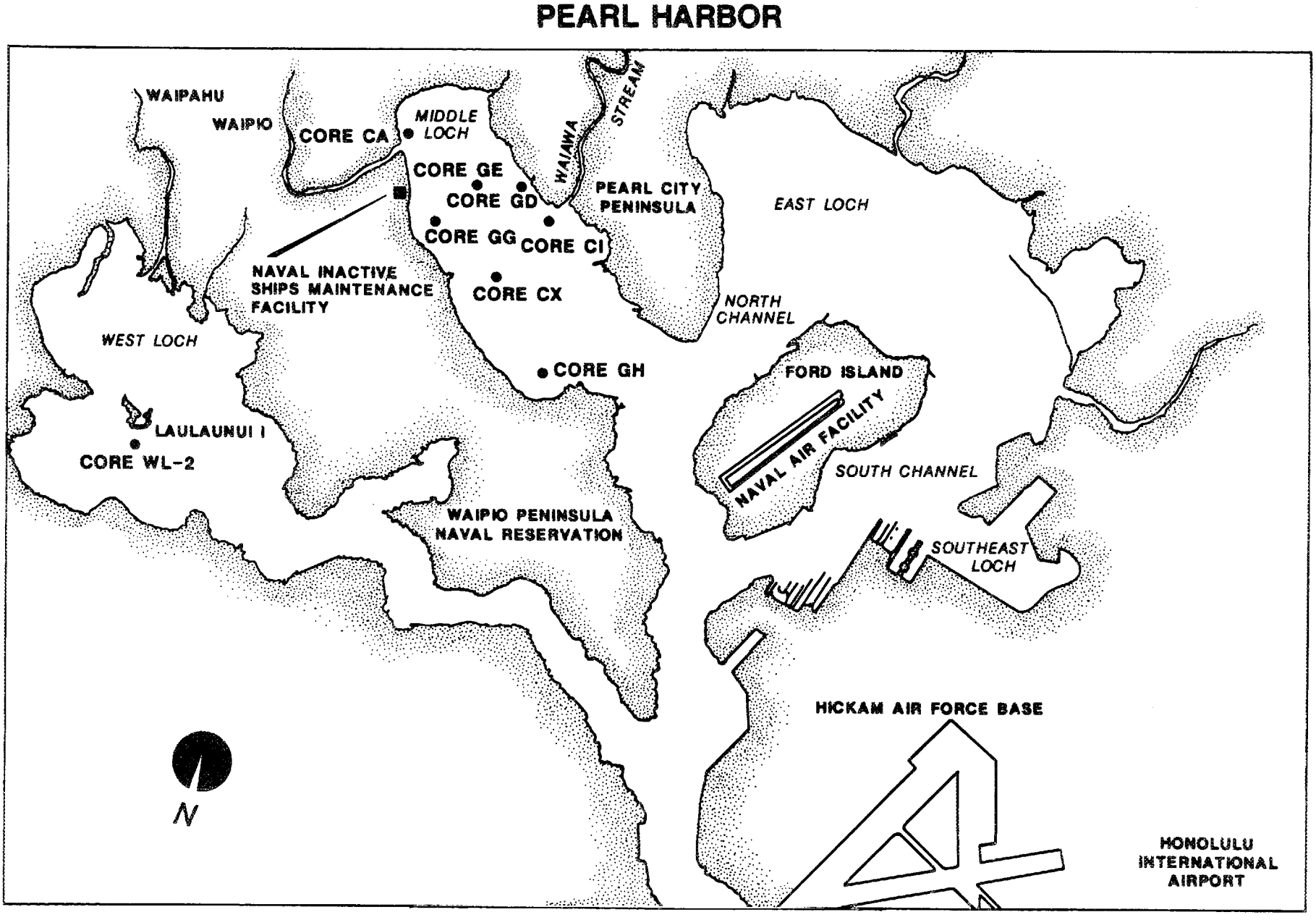

Fig. 1. Locations of sediment cores.

Most shipyard activity takes place in East Loch and its subsidiary Southeast Loch. As already discussed, the Naval Inactive Ship Maintenance Facility (NISMF) is located on Middle Loch, and there is some intermittent Navy activity associated with loading docks in the lower portion of West Loch. Access to Pearl Harbor is restricted by the Navy. There is some private and commercial use of the harbor by fishermen seeking bait and by a small marina located near the entrance to the harbor below Iroquois Point.

Most of the industrial activity is adjacent to East Loch and Southeast Loch. There are residential areas surrounding the harbor, primarily concentrated on the Pearl City Peninsula (which separates East Loch and Middle Loch) and the Waipahu area (around the northern portions of Middle loch and West Loch). Municipal sewage from Pearl City Peninsula has been discharged into Middle Loch (Evans 1974), and sewage from both residential and industrial sources has been discharged into streams that drain into Pearl Harbor (U. S. Navy 1973).

In the early 1970s, a series of studies (Cahill et al. 1972; U. S. Navy 1973; Turner 1975; Fan 1976) was conducted, including a large-scale biological survey (Evans 1974). Subsequent to 1976, there have been virtually no published environmental studies of the area, other than studies of groundwater quality and availability.

Cahill et al. (1972) examined cobalt-60 (^{60}Co) concentrations in the sediment of all three lochs and found that the levels were as high as 248 pCi/g dry weight, but were primarily confined to the sediments

immediately under the submarine pens in Southeast Loch. Three of the early reports (U. S. Navy 1973; Evans 1974; Turner 1975) contained the results of an extensive sediment study throughout the harbor. These results indicated that there were significant spatial variations in the levels of trace metal contamination in the surface sediments. The maximum values observed in this previous study were as follows: chromium--360 μg/g; copper--1200 μg/g; mercury--9.5 μg/g; nickel--930 μg/g; lead--1700 μg/g; zinc--1900 μg/g (from Table 3.1-2 in Evans 1974). With the exception of nickel (the level of which was highest in Middle Loch), all of these maximum values were for sediments in the area of Southeast Loch. Statistical analysis of the variations in trace metal levels between the three major lochs indicated that East Loch contamination was primarily derived from industrial (i.e., shipyard) sources, whereas that of Middle Loch and West Loch was derived from residential sources (Chap. 3.1 in Evans 1974). Since this study dealt only with surface sediments, there was no information presented on historical trends in trace metal levels. One recommendation in the biological survey (Chap. 5 in Evans 1974) was that sediment cores should be taken.

The present study grew out of a recognition by personnel of the Inactive Fleet that paint chips from their operations represented a potential source of trace metal (especially lead) contamination of the harbor sediments. The approach outlined in Sec. 1.2 of this report was developed to ascertain, if possible, the contribution of paint chips to the trace metal levels in the sediments.

1.2 APPROACH

In order to determine if paint chips from the inactive vessels were contributing measurably to the trace metal levels in Middle Loch sediments, we needed one or more control zones (where paint chips do not have any influence). Two possible control zones were: (1) sediments deposited in Middle Loch before the onset of Inactive Fleet operations, and (2) sediments from an area of adjacent West Loch where there is no naval activity now or in the past. For this study, both control zones were used.

Both long (>2 m) and short (<1 m) sediment cores were taken from several locations in Middle Loch (see Fig. 1). The sections of these cores were dated using the radioisotopes cesium-137 (^{137}Cs) and lead-210 (^{210}Pb). Cesium-137 is a fallout radionuclide that has been distributed over the surface of the earth since 1950 (see Olsen, 1979). Sediment chronologies are determined from ^{137}Cs profiles by assuming that the first appearance of ^{137}Cs represents 1950 and that peak concentrations of this radionuclide represent 1963, the date of maximum fallout. Lead-210 is a natural radionuclide that has been used extensively for dating sediment samples deposited during the last 75 years. Removal of radium-226 (^{226}Ra) decay daughters (the longest lived of which is ^{210}Pb) from the atmosphere by means of precipitation provides a measurable source of ^{210}Pb to the earth's surface. By measuring ^{210}Pb and ^{226}Ra profiles in sediment cores, chronological information can be obtained from the decline of atmospherically derived ^{210}Pb (here called excess ^{210}Pb*) in the sediment as a result of

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* Excess ^{210}Pb is the concentration of ^{210}Pb above that which can be accounted for by the uranium in the sediment.

its decay. Both ^{137}Cs and ^{210}Pb have been previously used to date sediment cores collected in rivers, lakes, and coastal areas (Robbins and Edgington 1975; Nittrouer et al. 1984; Olsen et al. 1984; Ashwood et al. 1986).

Although these radionuclide chronometers can be used to obtain average annual sediment accumulation rates (which can then be used to date individual sediment depth increments), the accuracy of these averages is dependent upon a constant sediment accumulation rate and either a lack of sediment surface mixing or at least a quantifiable amount of mixing. Since sediment accumulation rates in Pearl Harbor are probably affected by tropical storms and since ship traffic may significantly mix surface sediments (Evans 1974), we chose to use the presence or absence of ^{137}Cs and ^{210}Pb in the sediments to define three broad time periods: (1) "recent" sediments: those in which both fallout ^{137}Cs and excess ^{210}Pb are present; (2) "older" sediments: those in which only excess ^{210}Pb is present; and (3) "historical" sediments: those in which there is no detectable level of excess ^{210}Pb.

The recent sediments represent material deposited between 1985, when the cores were collected, and 1950, when ^{137}Cs was first detected (Olsen 1979). Because of the relatively low level of excess ^{210}Pb in surface sediments (~1 pCi/g) and the minimum detectable activity for this radionuclide (~0.12 pCi/g), we calculate that detectable excess

^{210}Pb should be confined to sediments deposited after about 1930 (~2.5 half-lives). Hence, the older sediments (where only excess ^{210}Pb is present) must have been deposited between 1950 and 1930. The historical sediments represent material deposited prior to 1930 and, as will be shown in Sec. 3.2, contain relatively pristine levels of copper, lead, and zinc.

The relevance of these periods for this study is that the U. S. Navy's Inactive Fleet operations did not begin until ~1946 (CDR J. E. Vroom, U. S. Navy, personal communication 1986). Thus, the impact of naval operations should not be apparent in sediments deposited prior to the recent sediments (1950-1985). Similarly, the older sediments (1930-1950) roughly approximate the period of naval buildup in Pearl Harbor associated with World War II.

Some sources of trace metal contamination in older and recent sediments are generic--that is, they may affect all lochs more or less equally. One such source is anthropogenic lead, primarily from automobile exhaust. Murozumi et al. (1969) have demonstrated that lead aerosols are distributed worldwide and that they began to increase rapidly about 1940 [see also the tree-ring data of Baes and Ragsdale (1981)]. The contributions of such generic sources can be evaluated by comparing trace metal concentrations in recent and older sediments from Middle Loch with those in similar sediments from West Loch,

2. METHODOLOGY

2.1 SAMPLE COLLECTION

Sediment cores were obtained on three separate occasions. In November 1984, short (<1 m) gravity cores were obtained from various sites around Middle Loch. These cores were obtained using a brass barrel gravity corer with plastic liners. The sediment was confined to the plastic liners and did not come in contact with the brass barrel. Each of these cores was extruded from the plastic liner, using a rubber stopper at the end of a wooden rod, and then sectioned in 5-cm increments, using a stainless steel spatula. Each increment was hermetically sealed in a plastic-lined aluminum can (~94 cm^3 vol). Sectioning and canning were accomplished on the same day that the core was taken.

In March 1985, three long (>2 m) vibracores were taken from Middle Loch. Vibracoring was accomplished by attaching a portable cement vibrator to one end of a long aluminum pipe (3-12 m long, 7.5 cm internal diameter), slowly lowering the free end of the pipe to the sediment surface, and then allowing the vibration to feed the pipe into the sediment [see Lanesky et al. (1979) for a detailed description of the technique]. Vibracoring effectively liquefies the sediment in the vicinity of the pipe walls and results in an undisturbed core. The vibracores were extruded from the aluminum pipe, using Teflon disks at the end of an aluminum rod. The cores were sectioned in 2- or 4-cm increments (depending upon depth), using a stainless steel spatula.

Because of the highly liquefied state of the top few centimeters of the sediment and the long extrusion length, some of the upper sediment smeared along the sides of these cores during the extrusion process. The outer layer of the core sections (containing the smeared material) was scraped off, using the spatula, and then the "clean" center sections were hermetically sealed in plastic-lined cans as before.

In December 1985, one long (>2 m) and one short (60 cm) vibracore were obtained near Laulaunui Island in West Loch (see Fig. 1). These were extruded, sectioned, and canned as described above.

During the extruding and canning of each core, records were made of the physical appearance (color, cohesiveness, and texture) of each core section. All cans were shipped by air to Oak Ridge National Laboratory (ORNL) for radionuclide and metal analyses.

2.2 RADIONUCLIDE ANALYSES

Radionuclide activities were measured in ORNL's Environmental Sciences Division by gamma-ray spectrometry, using either Ge(Li) or intrinsic germanium detectors. Calibration of the detectors has been previously described by Larsen and Cutshall (1981). The canned samples were counted for a period of typically 1000 min, using a Nuclear Data 6700 microprocessor system to acquire and store accumulated counts in 4096 channels. A modified Nuclear Data software program allows for an automated peak search routine to be performed, corrects for the presence of any background contributions (Cutshall and Larsen 1980), identifies radionuclides by their gamma-ray signature, performs activity calculations,

and corrects for decay based on the elapsed time interval between the sample collection and sample analysis dates. A hard copy printout of the data was made for each sample analyzed.

Table 1 provides decay data for the specific radionuclides of interest. Following radioactivity analysis, each sample was air-dried at $\leq 72^{o}C$ for >48 h. Radioisotope activity levels were then calculated on the basis of dry sample weight.

Table 1. Radionuclide decay properties used in analysis

Isotope	Photon energy (keV)	Photon abundance (%)	Half-life (year)
^{210}Pb	46.5	4.05	22.26
^{137}Cs	661.6	85.1	30.17

Minimum-detectable-activity (MDA) levels (Pasternak and Harley 1971) for the various radionuclides are presented in Table 2. If such quantities of radioactive material were present in the samples when counted for 1000 min, then 95% of the time a value greater than zero would be reported for these radionuclides. However, at these low activity levels, the relative analytical uncertainty may range from ± 40 to 100% of the value. The MDA depends upon the composition of the matrix (i.e., other radionuclides present and their amount), the sample size,

counting time, detector efficiency, geometry, and any background contributions. Thus, the values reported in Table 2 should not be considered absolutes; they may range up or down by several factors. Their purpose is to provide the general level of sensitivity expected from a typical 1000 min-counting interval.

Table 2. Estimated minimum-detectable-activity (MDA) levels for a 1000-min counting interval

Radionuclide	MDA (pCi)	Concentration for an 80-g dry wt sample (pCi/g)
^{210}Pb	10	0.12
^{137}Cs	1	0.01

2.3 METALS ANALYSES

After being dried and weighed as described above, selected samples were ground to a fine powder, using an agate mortar and pestle. The powder from each sample was placed in a plastic vial sealed with a plastic cap, and marked with the same information as was on the aluminum can. Care was taken to clean the mortar and pestle after each use to avoid cross-contamination.

For the Middle Loch cores, two different methods were used for total digestion. In the first method, ~250 mg of the fine powder was dissolved in a mixture of nitric acid (HNO_3) and hydrogen fluoride (HF). This solution was evaporated until it was nearly dry and then

redissolved in 8 N HNO_3 to drive off the fluorine. This new solution was again evaporated until nearly dry and then made up to ~50 cm^3 with 2% HNO_3. In the second method, a similar quantity of sample was dissolved in molten lithium metaborate ($LiBO_2$) in a pure carbon crucible. The resulting fusion was then poured into cold HNO_3. This solution was gently heated and agitated ultrasonically. Both methods yield a total digestion of the sample, but some of the silicon is lost in the HF-HNO_3 method. After digestion, the solution was injected into an inductively coupled plasma spectrometer (ICP), which determines concentrations for several metals.

For mercury determinations, U. S. Environmental Protection Agency (EPA) Method 245.1 (USEPA 1979a) was run, except that HNO_3-perchloric was used as the oxidizing agent instead of permanganate. This method utilizes cold vapor atomic absorption spectroscopy (AA) for the analysis. Also, because ICP did not have sufficient sensitivity for lead, the solutions derived from the HF-HNO_3 digestion were run through graphite furnace AA, using EPA Method 239.2 (USEPA 1979a), to obtain the lead concentrations.

For the West Loch core, the HF-HNO_3 preparation together with AA was used for copper, lead and zinc analysis. No other elemental analyses were performed on the West Loch core.

All metal analyses were conducted by the Analytical Chemistry Division of ORNL, where standard quality assurance practices, such as duplicates, blank analyses, spikes, and comparison with various standards

(from EPA, U. S. Geological Survey, and National Bureau of Standards) are routinely employed . Their quality assurance program generally meets the criteria in EPA's Handbook for Analytical Quality Control in Water and Wastewater Laboratories (USEPA 1979b). In addition, blind standards and duplicates were submitted to them for both the ICP and AA analyses. Results of the analyses of the blind standards are shown in Table 3.

3. RESULTS AND DISCUSSION

3.1 RADIOISOTOPE DATA

Results of the radioisotope analyses for ^{137}Cs, ^{210}Pb, and potassium-40 (^{40}K) are presented in Appendix A.

Potassium-40 is a naturally occurring radionuclide constituting ~0.012% of the potassium in potassium-bearing minerals such as muscovite, illite, and potassium-feldspar. Where these minerals form a large part of the sediments, the ^{40}K activity reflects the grain size and composition. However, the sediments of Pearl Harbor are quite low in potasium-bearing minerals (Turner 1975). Hence, the ^{40}K activities shown for all cores in Appendix A are relatively low.

Figures 2 to 5 present the ^{137}Cs and excess ^{210}Pb profiles for Middle Loch core CA and West Loch core WL-2. These are presented as examples of the data collected on all cores. Error bars have been omitted from the figures to make them more readable. However, by reference to the standard deviation data in Appendix A, it is apparent that the several peaks of ^{137}Cs data in the upper layers of both cores are probably not significant. Rather it appears that the ^{137}Cs

Table 3. Analytical results for National Bureau of Standards and U. S. Geological Survey Standards

Element	U. S. Geological Survey marine mud MAG-1		National Bureau of Standards[a]			
			Standard 1645		Standard 1646	
	Measured	Std.	Measured	Std.	Measured	Std.
Chromium	97[b]	104	NA	NA	NA	76
Copper	24[b]	30	108[c]	109	19[c]	18
Nickel	71[b]	55	NA	45.8	NA	32
Lead	30[d]	24	742[c]	714	28[c]	28.2
Zinc	150[b]	130	1600[c]	1720	125[c]	132

[a] NA = Not analyzed

[b] Analysis performed by inductively coupled spectrometry (ICP) at same time as analysis for Middle Loch gravity cores.

[c] Analysis performed by AA at same time as analysis for West Loch vibracore.

[d] Analysis performed by graphite furnace atomic absorption sepctroscopy (AA) at same time as analysis for Middle Loch gravity cores.

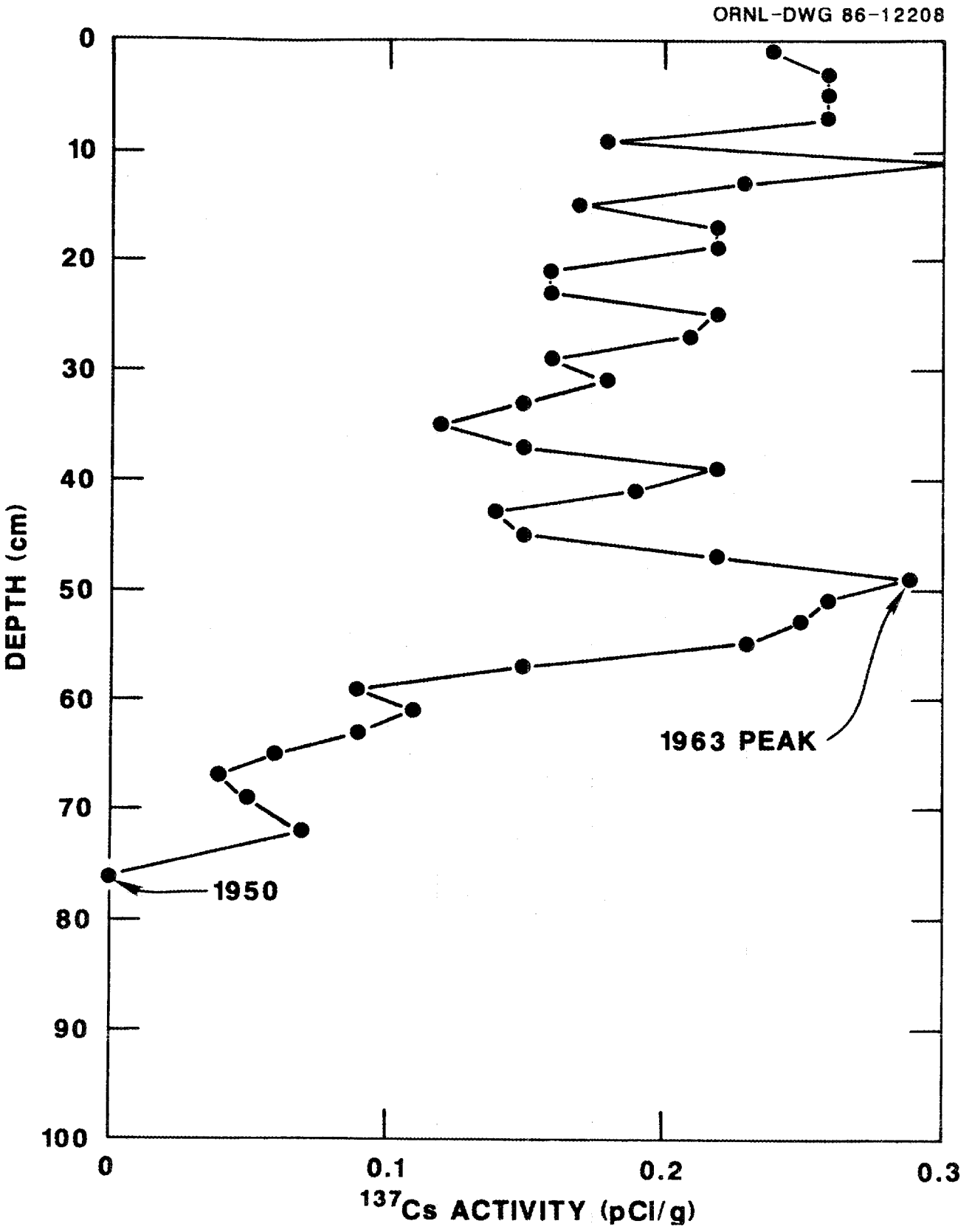

Fig. 2. Core CA ^{137}Cs profile.

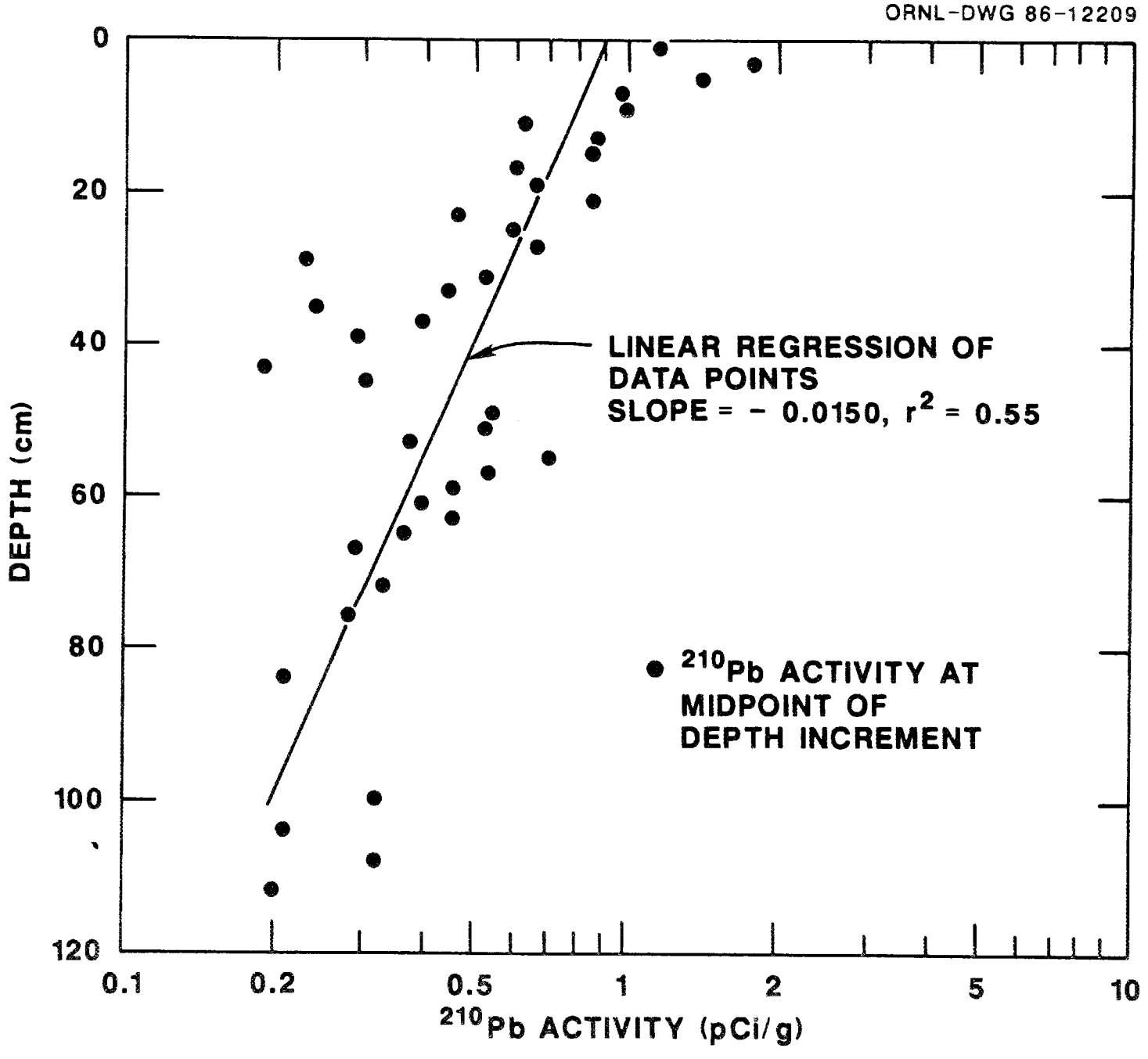

Fig. 3. Core CA ^{210}Pb profile.

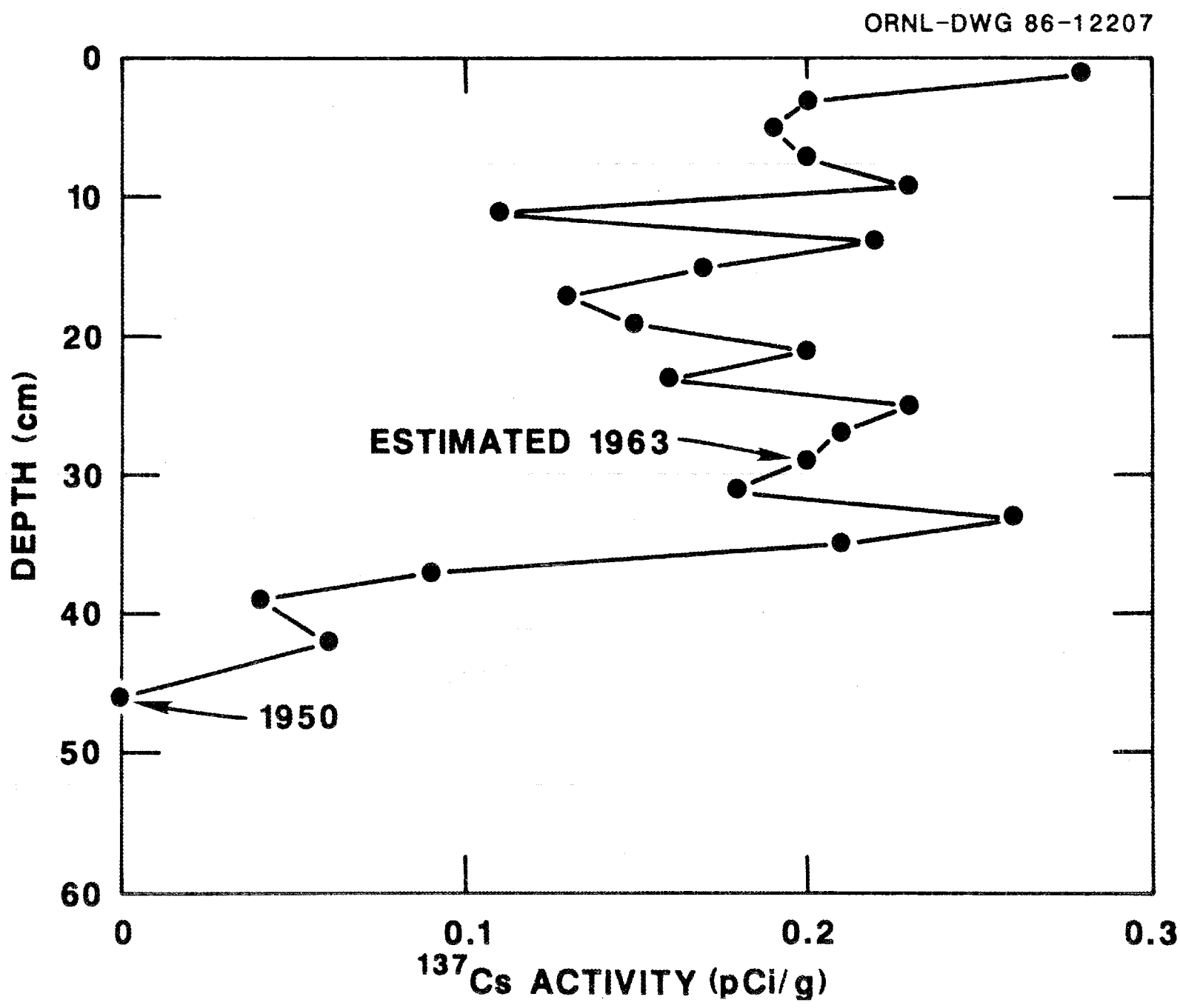

Fig. 4. Core WL-2 ^{137}Cs profile.

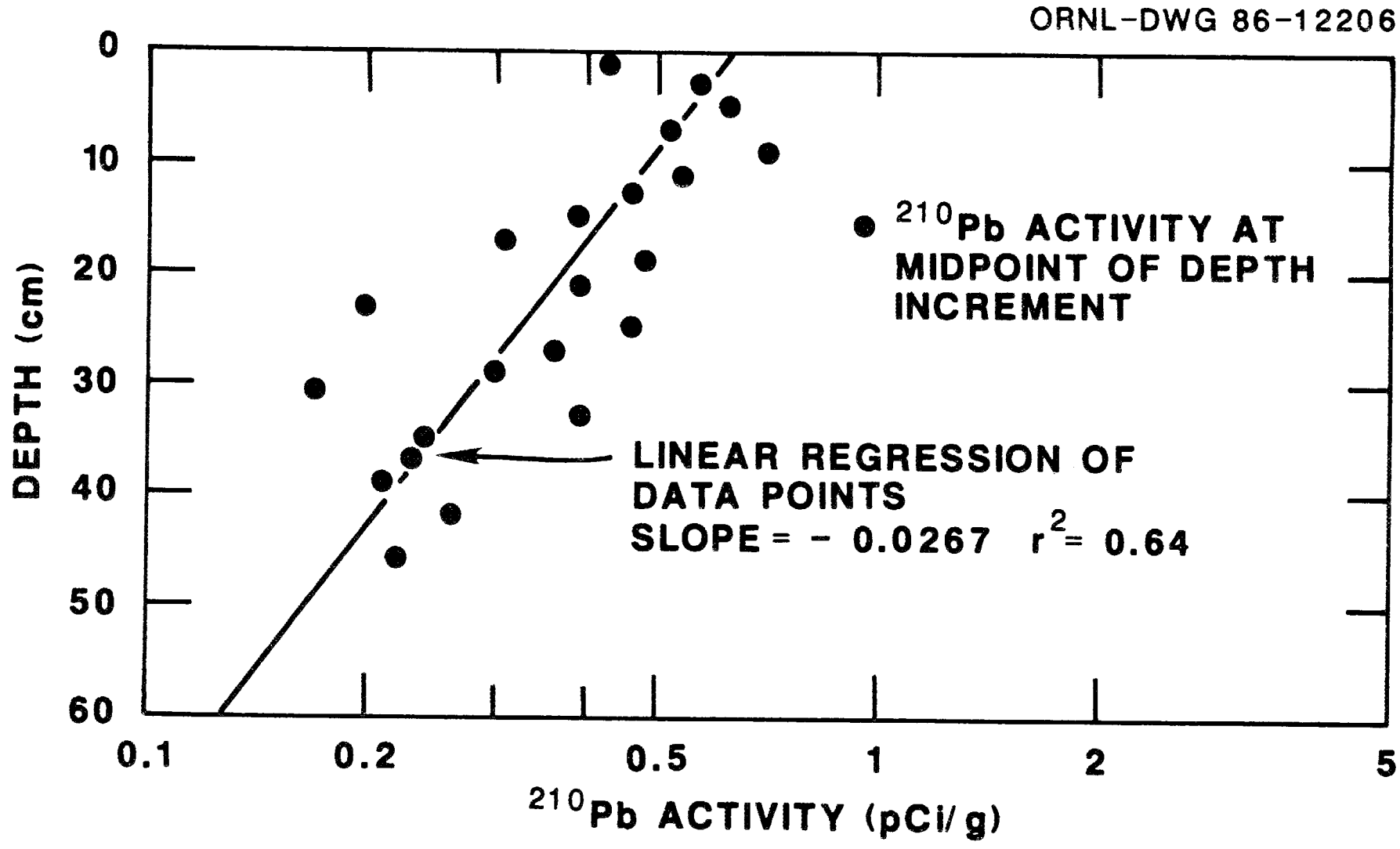

Fig. 5. Core WL-2 ^{210}Pb profile.

activity above what appears to be the 1963 peak is probably relatively constant or possibly increasing in core CA.

Such constancy may reflect large-scale mixing, perhaps by ship traffic [as noted by Evans (1974)], or the continual input of drainage basin soils (containing relatively constant ^{137}Cs activities) into Pearl Harbor since the fallout peak in 1963. Note that the ^{137}Cs profiles for both Middle Loch and West Loch are similar, even though there is very little ship traffic in the Laulaunui Island area of West Loch. Olsen (1979) showed that similar ^{137}Cs profiles (i.e., exhibiting a rapid increase in activity in the sediments around 1963 and relatively constant values above this point) are typical of fine-grained coastal sediments in the Hudson River estuary and reflected the erosion of drainage basin soils and their accumulation in harbor areas.

The effects of tropical storms on sediment erosion and accumulation in Pearl Harbor are unknown but probably significant. Storms may account for some of the scatter in the ^{210}Pb data (Figs. 3 and 5).

For all the above reasons, and as discussed in Sec. 1.2, we chose to use the presence or absence of detectable levels of ^{137}Cs and ^{210}Pb to define three time periods in the history of sediment accumulation. The depth of sediment representing these time periods in each core is indicated in the data tables in Appendices A and B and is summarized in Table 4. For information purposes only, the average annual sediment accumulation rate calculated from a regression of the ^{210}Pb data is also presented in Table 4 (see Nittrouer et al. 1984 for details on the method of calculating sediment accumulation rates from ^{210}Pb data).

Table 4. Dating of sediments based on radiosiotope data for Middle Loch and West Loch cores

Middle Loch Core CA

Sediment accumulation rate predicted from excess ^{210}Pb: 2.1 cm/year (slope = -0.0150; r^2 = 0.55; N = 39)

Estimated depth of first ^{137}Cs appearance: 74 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): 70-74 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): 110-114 cm

Middle Loch Core CI

Actual depth of first ^{137}Cs appearance (i.e., ~1950): >224 cm

Sediment accumulation rate predicted from ^{137}Cs: >6.4 cm/year

Middle Loch Core CX

Sediment accumulation rate predicted from excess ^{210}Pb: 1.5 cm/year (slope = -0.0213; r^2 = 0.67; N = 29)

Estimated depth of first ^{137}Cs appearance: 52 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): 70-72 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): 84-88 cm

Middle Loch Core GD

Sediment accumulation rate predicted from excess ^{210}Pb: 0.8 cm/year (slope = -0.0394; r^2 = 0.82; N = 12)

Estimated depth of first ^{137}Cs appearance: 28 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): 40-45 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): >63 cm

Table 4. (continued)

Middle Loch Core GE

Sediment accumulation rate predicted from excess ^{210}Pb: 0.2 cm/year (slope = -0.202; r^2 = 0.92; N-5)

Estimated depth of first ^{137}Cs appearance: 7 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): 5-10 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): 15-20 cm

Middle Loch Core GG

Sediment accumulation rate predicted from excess ^{210}Pb: 1.1 cm/year (slope = -0.0278; r^2 = 0.59; N = 11)

Estimated depth of first ^{137}Cs appearance: 38 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): >60 cm

Middle Loch Core GH

Sediment accumulation rate predicted from excess ^{210}Pb: 0.4 cm/year (slope = -0.0754; r^2 = 0.76; N = 8)

Estimated depth of first ^{137}Cs appearance: 14 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1930): 15-20 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): 35-40 cm

West Loch Core WL-2

Sediment accumulation rate predicted from excess ^{210}Pb: 1.2 cm/year (slope = -0.0266; r^2 = 0.64; N = 23)

Estimated depth of first ^{137}Cs appearance: 42 cm

Actual depth of first ^{137}Cs appearance (i.e., ~1950): 40-44 cm

Actual depth of excess ^{210}Pb penetration (i.e., ~1930): >60 cm

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The degree to which mixing has affected the ^{210}Pb profile can be inferred by comparing the predicted depth of the first appearance of ^{137}Cs (based on the sediment accumulation rate calculated by ^{210}Pb data) with the actual depth of ^{137}Cs penetration (Nittrouer et al. 1984). This comparison is also presented in Table 4.

From the data in Table 4 and Appendix A, it is apparent that Middle Loch core CI was taken from an area of extremely high sediment accumulation rates. Leaves and twigs were found throughout the length of core CI, and the sediment throughout most of its length had a black, organic-rich appearance. The core was taken from the delta at the mouth of a stream. Local Navy personnel indicated that a sewage outfall pipe also discharged in the same area. Due to the apparently high organic content (which was also indicated by extremely low ^{40}K activity), coupled with the fact that the core did not penetrate to pre-1950 sediments (^{137}Cs was present even in the bottom sections), it was decided not to run elemental analyses on this core. However, the material from this core is still available at ORNL and could be analyzed, if deemed necessary.

Several other gravity cores were taken from Middle Loch in November 1984. These cores either did not penetrate the sediment deep enough to yield a picture of pre-Inactive Fleet trace metal levels, or they were taken from such sandy material that the trace metal concentrations would have been suspect. Although radioisotope data were obtained for these cores, they are not reported here.

3.2 TRACE METALS

The U. S. Navy (1973) conducted a trace metal survey of soils and stream sediments from the Pearl Harbor area and compared the results with those from a survey of Pearl Harbor sediments. They found that the following metals were present at higher levels in Pearl Harbor sediments than in local soils: silver, cadmium, chromium, copper, mercury, nickel, lead, and zinc. The ICP technique used in our study did not yield satisfactory results for silver or cadmium, because the detection limits were too high. Hence, the trace metal results given in Appendix B include only the remaining six elements.

In October 1983, ORNL personnel removed a small piece of paint that was peeling off the exterior of the U.S.S. Hornet (moored at the NISMF in Bremerton, Washington). The paint was ground to a fine powder, dissolved in HNO_3, and analyzed by ICP. The following metals were detected at significant levels: chromium--890 μg/g; lead--17,000 μg/g; titanium--140,000 μg/g; zinc--8100 μg/g. Copper was found to be <170 μg/g. Although the titanium concentration in the paint sample is quite high (as might be expected), Hawaiian basalts are also high in titanium (see Table III in Gladney 1980); therefore, finding traces of titanium from paint chips in the sediments is quite unlikely. While this does not represent a rigorous analysis of the paint on inactive Navy vessels, it does provide an indication that elevated levels of chromium, lead, and zinc, in sediments may indicate the presence of paint chips.

Table 5 summarizes the results given in Appendix B by loch and by time period. Also included in Table 5 are results of the ICP analysis for aluminum and results of the total organic carbon (TOC) analyses on nine sections of Middle Loch core CA. The total digestion method we used yields total values for each sample, including the metals bound in the mineral lattice. Hence, the aluminum concentrations in Table 5 are total aluminum. Together with the TOC values, they indicate that there was not a significant shift in the mineralogy of the sediments from one time period to another. Similar analyses were not performed for the West Loch core. For comparison purposes, Table 6 lists values from previous studies of Hawaiian basalts and local soils.

Both chromium and nickel are higher in all Middle Loch sediments than in local soils. Nickel is also higher in Middle Loch sediments than in Hawaiian basalts. However, neither chromium nor nickel are higher in recent sediments (post-1950) than in historical sediments (pre-1930). Hence, it would appear that contamination by these metals is no greater at present than it was over 50 years ago. This is important for this study because the data from the paint chip analysis indicate that paint would be expected to be a source of chromium contamination. The lack of any discernible increase in chromium levels in recent sediments (post-1950) potentially impacted by Inactive Fleet operations implies that paint is not a significant source of the trace metal contamination in Middle Loch.

Table 5. Elemental concentrations in sediments of Pearl Harbor, Hawaii

	Metal and organics concentrations, mean ± std. dev. (µg/g)				
	Middle Loch			West Loch	
Element	Recent[a]	Older[b]	Historical[c]	Recent[d,e]	Older[e,f]
Aluminum, mg/g	83 ± 9 (n = 52)	85 ± 13 (n = 16)	93 ± 9 (n = 19)	NA	NA
Chromium	233 ± 30 (n = 52)	256 ± 35 (n = 16)	288 ± 37 (n = 19)	NA	NA
Copper	180 ± 41 (n = 52)	172 ± 68 (n = 16)	121 ± 22 (n = 19)	107 ± 8 (n = 17)	96 ± 11 (n = 6)
Mercury[g]	0.40 ± 0.24 (n = 40)	0.47 ± 0.68 (n = 14)	0.17 ± 0.10 (n = 12)	NA	NA
Nickel	168 ± 31 (n = 52)	200 ± 110 (n = 16)	177 ± 30 (n = 19)	NA	NA
Lead[h]	49 ± 19 (n = 50)[h]	34 ± 22 (n = 16)	5 ± 3 (n = 19)	35 ± 3 (n = 17)	21 ± 3 (n = 6)
Zinc	272 ± 68 (n = 52)	247 ± 96 (n = 16)	122 ± 40 (n = 19)	167 ± 5 (n = 17)	164 ± 14 (n = 6)
Total Organic Carbon,[i] %	0.9 ± 0.2 (n = 5)	1.5 ± 0.1 (n = 2)	0.4 ± 0.1 (n = 2)	NA	NA

[a] Based on sections from cores CA, CX, GD, GE, GG, and GH containing both ^{137}Cs and excess ^{210}Pb (i.e., sediment deposited between 1985 and 1950), except for anomalous values of core CX, section 0-4 cm.
[b] Based on sections from cores CA, CX, GD, GE, and GH containing only excess ^{210}Pb (i.e., sediment deposited between 1950 and 1930), except for anomalous values of core CA, section 102-106 cm.
[c] Based on sections of cores CA, CX, GE, and GH containing no detectable levels of excess ^{210}Pb (i.e., sediment deposited prior to 1930).
[d] Based on sections of core WL-2 containing both ^{137}Cs and excess ^{210}Pb (i.e., sediment deposited between 1985 and 1950).
[e] NA = not analyzed.
[f] Based on sections of core WL-2 containing only excess ^{210}Pb (i.e., sediment deposited between 1950 and 1930).
[g] Mercury values were not obtained for any sections of core CX.
[h] Anomalously high lead levels in core CX sections 38-40 cm and 52-54 cm were not included.
[i] Based on sections of core CA analyzed for total organic carbon.

Table 6. Trace metal concentrations in Hawaiian basalts and local soils

	Trace metal concentration (μg/g)		
		Local soils[b]	
Element	Hawaiian basalt[a]	Cultivated	Uncultivated
Chromium	290 ± 30	58	66
Copper	130 ± 13	99	34
Mercury	NA[c]	0.65	0.78
Nickel	120 ± 16	280	80
Lead	3.3 to 6.2	13	11
Zinc	102 ± 8	159	44

[a] From BHVO data in Table III of Gladney (1980).

[b] From Tables 1 and 2 in U. S. Navy (1973).

[c] NA = Not Analyzed.

Mercury does not appear to be a significant contaminant in Middle Loch sediments in any time period. Although the mercury concentrations have apparently risen in post-1930 sediments, the level is still lower than that in local soils.

Recent Middle Loch sediments contain higher levels of copper, lead and zinc than do local soils. Recent Middle Loch sediments also contain higher levels of these three metals than do historical sediments, and recent Middle Loch sediments are more contaminated with these metals than

are recent West Loch sediments. For all three of these metals, the levels began to increase in the older sediments (i.e., 1930-1950). Hence, the contamination appears to have begun before the onset of Inactive Fleet operations, although in the case of lead there is also a significant increase in concentration in recent sediments over that in older sediments.

There are four potential sources of copper, lead, and zinc: (1) atmospheric deposition from automobile and/or industrial sources (e.g., the power plants in the area); (2) sewage (the U. S. Navy's 1973 study lists several industrial sources of metals that are found in storm and sanitary sewage); (3) inter-loch transport of contaminants from the main shipyard activities in East Loch and Southeast Loch by currents and ship traffic; and (4) paint chips removed from inactive vessels moored in Middle Loch.

Anthropogenic lead aerosols have spread across the world, as demonstrated by the work of Murozumi et al. (1969). While the sharp increase in atmospheric lead levels since 1940 is undoubtedly reflected in the difference between recent and historical sediments, it seems unlikely that atmospheric deposition of lead would be greater in Middle Loch than in adjacent West Loch. Moreover, the recent work of Baes and Ragsdale (1981) and Berish and Ragsdale (1985) demonstrates that atmospheric lead levels are declining. Yet, there is no evidence that sediment the lead levels in the sediments in either Middle Loch or West Loch are declining. Hence, the differences in trace metal levels between these two lochs are unlikely to result from atmospheric deposition.

Results of a study of water circulation in Pearl Harbor (Chap. 3.3 in Evans 1974) appear to indicate little potential for contaminant transport into Middle Loch. This is borne out by the results of the ^{60}Co study conducted in the late 1960s (Cahill et al. 1972), as discussed in Sec. 1.1. Thus, the evidence of previous studies indicates that cross-contamination from East Loch and Southeast Loch is unlikely to have contributed significantly to the trace metal levels in recent Middle Loch sediments.

Sewage has been discharged directly into Middle Loch from the residential area on the Pearl City peninsula as late as 1983 (M. W. F. Won, U. S. Navy, personal communication, 1986). Sewage is known to contain elevated levels of copper, lead, and zinc (U. S. Navy 1973; Table 19 in Olsen et al. 1984), and could account for the elevated levels of these metals in the recent sediments of Middle Loch, furthermore, if the sewage input to Middle Loch were greater than the input to West Loch, sewage could also account for the differences in metal levels between lochs. Further study of the history of sewage input to both lochs as well as the composition of the sewage is required to confirm this hypothesis.

As previously discussed, we have analyzed a single sample of paint from an inactive ship. The results indicated that such paint chips are a potential source of lead and zinc contamination. However, the copper content of the paint is deficient compared to the levels found in recent Middle Loch sediments. Moreover, if paint chips were contributing

significantly to increased zinc levels in recent Middle Loch sediments, we would expect that the lead levels in these sediments would be much higher than in West Loch, since the paint has a lead:zinc ratio of 2:1, whereas the lead:zinc ratio in recent Middle Loch sediments (0.18:1) is not significantly different from that in recent West Loch sediments (0.21:1). While firm conclusions cannot be drawn on the basis of one paint sample, it seems that paint chips can not account for the suite of trace metal contamination present in the harbor.

In compiling the data in Table 6, we omitted four anomalous sections of Middle Loch cores, as indicated in the footnotes. We believe that the three sections in core CX that were omitted (0-4 cm for all metals; 38-40 cm and 52-54 cm for lead) probably represent material that was deposited in some significant, localized mixing event--perhaps during the movement of an anchor chain or rearrangement of mooring sites. Such events can produce resuspension of sediments from a contaminated area and subsequent deposition in an adjacent area. The anomalies in core CA, section 102-106, appear to be of too great a magnitude to be explained by simple resuspension and deposition. On the other hand, the placement of this section in the 1930-1950 time period offers the tantalizing possibility that the anomalies represent a signature of the bombing of Pearl Harbor in 1941. With the high sediment accumulation rate (~2 cm/year) indicated for this core, it is possible that the resolution of a 4-cm section is sufficient to record such a signature, whereas the lower

apparent accumulation rates of other cores may cause the signature to be lost through homogenization with sediment having much lower trace metal levels.

Finally, our results must be compared with those of previous investigators. Table 7 presents the surface sediment results of Evans (1974) for Middle and West Lochs. With the exception of nickel, our results for recent sediments are higher than those in Table 7. This may be due, in part, to the difference in the preparations used. Although it was not specifically described, Evans (1974) apparently used an acid leach preparation. The total dissolution procedure we used might be expected to yield somewhat higher values, since any trace metals bound in mineral lattices would also be included in our results. Another possible reason for the difference in concentrations between the two studies may be the small number of samples in Evans' (1974) study. The standard deviations in Table 7 are frequently quite high, indicating a wide variation among samples. This is especially true for the nickel results and may be the major reason for the apparent difference in nickel results between the two studies. Evans (1974, pg 5.0-25) attributes the high level of nickel in Middle Loch to sewage from the Pearl City Sewage Treatment Plant, which is consistent with our conclusion that sewage is probably the major source of metal contamination in Middle Loch. In general, the trend noted in our study is also reflected in Evans' study--that is, the levels of copper, lead, and zinc are higher in Middle Loch than in West Loch.

Table 7. Results of previous surface sediment study[a]

	Trace metal concentrations (μg/g)			
	Middle Loch		West Loch	
Element	Upper[b]	Middle[c]	Lower[d]	Upper[e]
Chromium	170 ± 29	150 ± 84	140 ± 36	120 ± 39
Copper	120 ± 75	120 ± 38	87 ± 15	72 ± 25
Mercury	0.92 ± 0.9	0.41 ± 0.2	0.36 ± 0.2	0.31 ± 0.1
Nickel	220 ± 110	470 ± 410	190 ± 210	200 ± 120
Lead	42 ± 39	26 ± 13	20 ± 8	20 ± 7
Zinc	210 ± 110	190 ± 45	160 ± 34	160 ± 43
No. of samples	6	5	6	10

[a] Data from Table 3.1-3 in Evans (1974).

[b] "Upper" refers to the area of Middle Loch generally above the Naval Inactive Ships Maintenance Facility (NISMF) docks.

[c] "Middle" refers to the area around the NISMF docks, which is labeled "STP" in Table 3.1-3 in Evans (1974).

[d] "Lower" refers to the area from the NISMF docks to the mouth of Middle Loch.

[e] "Upper" refers to area of West Loch that includes Laulaunui Island.

4. SUMMARY AND CONCLUSIONS

The following conclusions can be drawn from this study:

1. Recent Middle Loch sediments contain higher levels of copper, lead, and zinc than do historical sediments of Middle Loch or recent West Loch sediments. The contamination by copper, lead, and zinc began in the older (1930-1950) sediments prior to the onset of Inactive Fleet operations.

2. Neither atmospheric inputs nor inputs from other lochs are likely to explain the differences in trace metal levels between Middle Loch and West Loch.

3. Both sewage and paint chips have the potential to cause the elevated levels of lead and zinc found in Middle Loch. However, paint chips do not appear to be a potential source of the copper contamination.

4. The trace metal signature in both older and recent Middle Loch sediments (i.e., high level of copper and low lead:zinc ratio) is similar to that in older and recent West Loch sediments. This strongly suggests that the same source of contamination is affecting both lochs.

5. The sediment input from Waiawa Stream (the major freshwater source for Middle Loch) is approximately 3 tons/day (fig. 3 in Fan 1976). This is equivalent to 10^9 g/y. The lead level in Waiawa Stream is 22 µg/g (fig. 3.1-10 in Evans 1974). Since the mean level of

lead in recent Middle Loch sediments is 49 µg/g (Table 5), some source is increasing the lead level of Waiawa Stream sediments by 27 µg/g. This is equal to an annual input of 2.7×10^4 g, or 60 lbs, of lead. If paint with a lead content of 17000 µg/g (sec. 3.2) were the source of this lead, then 1.6×10^6 g (or 1.7 tons) of paint would have to be input to Middle Loch each year. Weathering and preservation activities on inactive vessels are unlikely to generate anything approaching this mass of paint chips (CDR J. E. Vroom, U. S. Navy, personal communication, 1986). On the other hand, some sewage contains approximately 375 µg/g of lead (Olsen et al. 1984). Hence, approximately 7.2×10^7 g (or 79 tons) of sewage input to Middle Loch each year would account for the lead increase. This amounts to only about 430 lbs/day (dry weight), which seems quite possible.

Further study could be conducted to verify these conclusions. Specifically, additional samples of paint from the exterior of inactive vessels could be analyzed for copper lead and zinc composition. Also, the trace metal content and discharge history of sewage inputs to both Middle Loch and West Loch could be determined. It may be possible, if these additional studies are not conclusive, to analyze selected samples for grain size to determine if the lead is associated with paint chips or with sediment particles.

Table 8 compares the lead levels in Middle Loch with those in other estuarine areas around the United States. The level of lead in recent Middle Loch sediments is lower than that in some of the contaminated estuaries.

Table 8. Comparison of lead levels in various estuarine sediments

Location	Lead level (μg/g)
Recent Middle Loch sediments	49 ± 19
West Loch sediments	35 ± 3
Buzzards Bay, Mass. (surface sediments)[a]	110
Buzzards Bay, Mass. (deep sediments)[a]	18 ± 6
Hudson Estuary, New York Harbor [b]	390
Hudson Estuary (background sediments)[b]	25
Long Island Sound, Conn. (surface sediments)[c]	59
Long Island Sound, Conn. (deep sediments)[c]	≤10
Puget Sound, Elliot Bay, Wash.[d]	82 ± 16
Puget Sound, Duwamish River, Wash.[d]	316
Savannah River, Ga.[e]	38 - 60

[a] From Table 10 in Summerhayes et al. 1977.

[b] From Table 7 in Olsen et al. 1984.

[c] From top 12 cm of Table 2 in Thompson et al. 1975.

[d] From Table 5.4 in Curl 1982.

[e] From data for Savannah River and Wilmington River in Table IV in Goldberg et al. 1979.

No attempt was made in this study to assess the environmental fate and effects of the elevated levels of copper, lead and zinc found in Pearl Harbor sediments. Due to the access control provided by Navy ownership and the natural isolation between lochs, Pearl Harbor would be an ideal location to test for the biological effects of different levels of sediment-bound trace metals.

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APPENDIX A
RADIOISOTOPE LEVELS IN PEARL HARBOR SEDIMENTS

Table A-1. Radioisotope concentrations in Middle Loch vibracore CA

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Recent (1950 - 1985)		
0-2	0.24 ± 0.03	1.15 ± 0.25	5.3 ± 0.40
2-4	0.26 ± 0.05	1.77 ± 0.22	5.0 ± 0.60
4-6	0.26 ± 0.03	1.41 ± 0.19	6.3 ± 0.50
6-8	0.26 ± 0.04	0.97 ± 0.21	5.6 ± 0.70
8-10	0.18 ± 0.03	0.99 ± 0.17	5.0 ± 0.40
10-12	0.31 ± 0.04	0.62 ± 0.15	5.0 ± 0.50
12-14	0.23 ± 0.04	0.87 ± 0.16	5.5 ± 0.50
14-16	0.17 ± 0.04	0.85 ± 0.17	5.9 ± 0.50
16-18	0.22 ± 0.04	0.60 ± 0.15	5.1 ± 0.50
18-20	0.22 ± 0.03	0.66 ± 0.11	4.5 ± 0.50
20-22	0.16 ± 0.02	0.85 ± 0.14	4.9 ± 0.30
22-24	0.16 ± 0.03	0.46 ± 0.16	3.7 ± 0.40
24-26	0.22 ± 0.04	0.59 ± 0.10	4.3 ± 0.40
26-28	0.21 ± 0.03	0.66 ± 0.10	3.5 ± 0.40
28-30	0.16 ± 0.02	0.23 ± 0.10	4.8 ± 0.30
30-32	0.18 ± 0.03	0.50 ± 0.14	5.2 ± 0.40
32-34	0.15 ± 0.02	0.44 ± 0.11	4.5 ± 0.30
34-36	0.12 ± 0.02	0.24 ± 0.09	3.8 ± 0.30
36-38	0.15 ± 0.02	0.39 ± 0.11	4.0 ± 0.30
38-40	0.22 ± 0.02	0.29 ± 0.10	3.7 ± 0.30
40-42	0.19 ± 0.02	NA	3.6 ± 0.30
42-44	0.14 ± 0.02	0.19 ± 0.09	4.5 ± 0.30
44-46	0.15 ± 0.03	0.30 ± 0.13	4.5 ± 0.40
46-48	0.22 ± 0.02	NA	4.1 ± 0.30
48-50	0.29 ± 0.03	0.54 ± 0.10	3.3 ± 0.40
50-52	0.26 ± 0.02	0.52 ± 0.12	3.3 ± 0.30
52-54	0.25 ± 0.03	0.37 ± 0.13	3.3 ± 0.40
54-56	0.23 ± 0.03	0.70 ± 0.20	3.3 ± 0.40
56-58	0.15 ± 0.03	0.53 ± 0.17	3.6 ± 0.40
58-60	0.09 ± 0.03	0.45 ± 0.13	4.5 ± 0.40
60-62	0.11 ± 0.02	0.39 ± 0.08	3.9 ± 0.30
62-64	0.09 ± 0.02	0.45 ± 0.12	4.3 ± 0.30
64-66	0.06 ± 0.02	0.36 ± 0.12	4.3 ± 0.40
66-68	0.04 ± 0.01	0.29 ± 0.10	4.7 ± 0.30
68-70	0.05 ± 0.02	NA	4.1 ± 0.30
70-74	0.07 ± 0.01	0.33 ± 0.10	3.6 ± 0.20

Table A-1 Radioisotope concentrations in Middle Loch vibracore CA (con't)

Depth (cm)	Radioisotope concentrations (pCi/g)		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Older (1930 - 1950)		
74-78	ND	0.28 ± 0.12	4.5 ± 0.50
78-82	ND	ND	5.4 ± 0.40
82-86	0.02 ± 0.02[c]	0.21 ± 0.13	5.6 ± 0.40
86-90	0.03 ± 0.02[c]	0.03 ± 0.11[c]	5.4 ± 0.30
90-94	0.04 ± 0.02[c]	0.10 ± 0.11[c]	5.3 ± 0.30
94-98	0.01 ± 0.01[c]	ND	4.3 ± 0.20
98-102	ND	0.32 ± 0.13	4.3 ± 0.40
102-106	0.05 ± 0.02	0.21 ± 0.10	3.1 ± 0.40
106-110	ND	0.32 ± 0.13	1.9 ± 0.40
110-114	NA	0.20 ± 0.08	NA
	Historical (prior to 1930)		
114-118	NA	0.09 ± 0.06[c]	NA
118-122	NA	ND	NA
126-130	NA	0.10 ± 0.09[c]	NA
138-142	NA	0.08 ± 0.08[c]	NA

[a] NA = not analyzed; ND = not detected. (See Table 4 for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediment.

[c] These concentrations are so low compared to error bands that they are, in effect, considered not detected.

Table A-2. Radioisotope concentration in Middle Loch vibracore CI Recent (1950 - 1985)

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
0-4	0.14 ± 0.02	1.65 ± 0.16	1.6 ± 0.23
4-8	0.18 ± 0.01	NA	1.9 ± 0.18
8-12	0.16 ± 0.01	0.87 ± 0.11	2.0 ± 0.18
12-16	0.17 ± 0.01	NA	1.8 ± 0.19
16-20	0.18 ± 0.01	NA	1.9 ± 0.20
20-24	0.14 ± 0.01	1.27 ± 0.13	1.4 ± 0.19
24-28	0.15 ± 0.02	NA	1.7 ± 0.18
28-32	0.22 ± 0.01	NA	1.7 ± 0.10
32-36	0.25 ± 0.02	1.01 ± 0.11	1.5 ± 0.17
36-40	0.24 ± 0.01	NA	1.9 ± 0.18
40-44	0.24 ± 0.01	NA	2.0 ± 0.14
44-48	0.26 ± 0.01	NA	1.6 ± 0.11
48-52	0.26 ± 0.01	1.20 ± 0.12	1.8 ± 0.17
52-56	0.28 ± 0.02	NA	1.6 ± 0.18
56-60	0.16 ± 0.01	NA	1.0 ± 0.18
60-64	0.17 ± 0.02	NA	1.0 ± 0.18
64-68	0.22 ± 0.02	1.87 ± 0.16	1.2 ± 0.16
68-72	0.20 ± 0.03	NA	1.7 ± 0.36
72-76	0.38 ± 0.02	0.81 ± 0.09	2.0 ± 0.29
76-80	0.34 ± 0.02	0.93 ± 0.11	1.9 ± 0.18
80-84	0.32 ± 0.02	NA	1.5 ± 0.28
84-88	0.27 ± 0.02	NA	2.1 ± 0.26
88-92	0.28 ± 0.03	1.33 ± 0.12	1.9 ± 0.29
92-96	0.21 ± 0.02	NA	2.3 ± 0.27
96-100	0.21 ± 0.01	0.98 ± 0.10	2.0 ± 0.18
100-104	0.18 ± 0.02	NA	1.8 ± 0.25
104-108	0.19 ± 0.03	NA	1.4 ± 0.23
108-112	0.21 ± 0.02	0.39 ± 0.09	2.3 ± 0.30
112-116	0.20 ± 0.02	NA	1.5 ± 0.22
116-120	0.27 ± 0.02	NA	1.7 ± 0.21
120-124	0.23 ± 0.02	1.36 ± 0.13	1.3 ± 0.24
124-128	0.29 ± 0.02	NA	1.8 ± 0.29
128-132	0.38 ± 0.02	2.10 ± 0.14	1.3 ± 0.18
148-152	0.37 ± 0.02	1.74 ± 0.12	2.1 ± 0.19
196-200	0.30 ± 0.02	NA	2.3 ± 0.19
216-224	0.27 ± 0.02	NA	2.2 ± 0.18

[a] NA = not analyzed

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediment.

Table A-3. Radioisotope concentrations in Middle Loch vibracore CX

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Recent (1950-1985)		
0-4	0.22 ± 0.02	1.46 ± 0.13	5.8 ± 0.30
4-6	0.19 ± 0.04	1.50 ± 0.19	7.0 ± 0.60
6-8	0.17 ± 0.04	1.74 ± 0.20	7.5 ± 0.60
8-10	0.22 ± 0.06	1.14 ± 0.22	5.5 ± 0.70
10-12	0.17 ± 0.05	0.86 ± 0.20	5.6 ± 0.60
12-14	0.19 ± 0.04	1.34 ± 0.19	4.4 ± 0.60
14-16	0.21 ± 0.05	1.35 ± 0.23	5.1 ± 0.70
16-18	0.34 ± 0.05	1.04 ± 0.22	7.2 ± 0.70
18-20	0.17 ± 0.05	0.88 ± 0.20	6.1 ± 0.70
20-22	0.16 ± 0.05	0.97 ± 0.20	5.6 ± 0.70
22-24	0.20 ± 0.05	1.05 ± 0.21	7.0 ± 0.70
24-26	0.17 ± 0.05	1.00 ± 0.21	5.1 ± 0.60
26-28	0.20 ± 0.05	0.92 ± 0.19	5.0 ± 0.50
28-30	0.24 ± 0.04	1.11 ± 0.19	5.7 ± 0.50
30-32	0.25 ± 0.04	0.85 ± 0.17	4.6 ± 0.60
32-34	0.31 ± 0.03	1.14 ± 0.24	5.0 ± 0.30
34-36	0.41 ± 0.04	1.09 ± 0.16	5.0 ± 0.50
36-38	0.26 ± 0.04	0.69 ± 0.14	5.1 ± 0.50
38-40	0.20 ± 0.03	0.84 ± 0.16	6.2 ± 0.50
40-42	0.25 ± 0.03	0.53 ± 0.16	5.5 ± 0.40
42-44	0.20 ± 0.03	0.41 ± 0.11	4.7 ± 0.40
44-46	0.17 ± 0.03	NA	3.5 ± 0.40
46-48	0.38 ± 0.03	0.70 ± 0.13	5.2 ± 0.50
48-50	0.30 ± 0.04	NA	4.8 ± 0.50
50-52	0.20 ± 0.03	NA	4.9 ± 0.40
52-54	0.27 ± 0.04	1.16 ± 0.16	5.6 ± 0.50
54-56	0.24 ± 0.03	NA	4.4 ± 0.40
56-58	0.29 ± 0.03	NA	5.0 ± 0.40
58-60	0.36 ± 0.03	NA	5.2 ± 0.40
60-62	0.34 ± 0.03	0.41 ± 0.09	4.4 ± 0.40
62-64	0.27 ± 0.03	NA	4.3 ± 0.40
64-66	0.22 ± 0.03	NA	4.8 ± 0.40
66-68	0.21 ± 0.04	0.82 ± 0.16	5.1 ± 0.60
68-70	0.15 ± 0.03	NA	5.2 ± 0.40
70-72	0.16 ± 0.03	0.58 ± 0.15	2.6 ± 0.50

Table A-3. Radioisotope concentrations in Middle Loch vibracore CX (con't)

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Older (1930 - 1950)		
72-74	0.02 ± 0.02[c]	NA	3.9 ± 0.40
74-76	0.04 ± 0.02[c]	NA	4.0 ± 0.40
76-78	0.03 ± 0.01[c]	0.51 ± 0.13	4.3 ± 0.20
78-80	0.01 ± 0.02[c]	0.53 ± 0.15	4.4 ± 0.40
80-84	ND	NA	3.3 ± 0.30
84-88	0.06 ± 0.02	0.45 ± 0.10	3.9 ± 0.30
	Historical (prior to 1930)		
88-92	NA	ND	NA
92-96	NA	0.10 ± 0.08[c]	NA
96-100	ND	0.05 ± 0.08[c]	3.8 ± 0.30
100-104	ND	NA	2.7 ± 0.30
271-275	ND	NA	3.7 ± 0.30

[a] NA = not analyzed; ND = not detected (See Table 4 in text for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediments.

[c] These concentrations are so low in comparison to the error bands that they are, in effect, not detected.

Table A-4. Radioisotope concentrations in Middle Loch gravity core GD

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[a]	^{40}K
	Recent (1950-1985)		
0-2	0.22 ± 0.08	1.03 ± 0.18	6.8 ± 0.90
2-5	0.27 ± 0.04	0.95 ± 0.16	4.6 ± 0.50
5-10	0.28 ± 0.04	1.26 ± 0.18	4.1 ± 0.50
10-15	0.22 ± 0.03	0.89 ± 0.13	3.1 ± 0.30
15-20	0.25 ± 0.03	0.83 ± 0.12	2.1 ± 0.30
20-25	0.24 ± 0.03	0.92 ± 0.16	3.9 ± 0.40
25-30	0.23 ± 0.03	0.72 ± 0.13	3.0 ± 0.40
30-35	0.26 ± 0.03	0.55 ± 0.13	4.9 ± 0.40
35-40	0.17 ± 0.04	0.65 ± 0.15	3.9 ± 0.50
40-45	0.08 ± 0.03	0.22 ± 0.13	4.6 ± 0.50
	Older (1930-1950)		
45-50	0.03 ± 0.02[c]	0.16 ± 0.11	4.0 ± 0.40
50-55	0.01 ± 0.03[c]	0.10 ± 0.11[c]	3.1 ± 0.40
55-60	ND	0.22 ± 0.09	3.8 ± 0.40
60-63	0.05 ± 0.05[c]	0.14 ± 0.10[c]	3.2 ± 0.50

[a] ND = not detected (See Table 4 in text for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediments.

[c] These concentrations are so low compared to the error bands that they are, in effect, not detected.

Table A-5. Radioisotope concentrations in Middle Loch gravity core GE

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Recent (1950-1985)		
0-2	0.12 ± 0.06	2.79 ± 0.16	8.7 ± 0.80
2-5	0.15 ± 0.02	0.81 ± 0.14	6.0 ± 0.31
5-10	0.13 ± 0.03	0.67 ± 0.13	5.3 ± 0.40
	Older (1930-1950)		
10-15	0.03 ± 0.01[c]	0.60 ± 0.09	3.7 ± 0.30
15-20	0.03 ± 0.02[c]	0.38 ± 0.10	2.9 ± 0.40
	Historical (prior to 1930)		
20-25	ND	ND	2.7 ± 0.20
25-30	0.03 ± 0.01[c]	0.01 ± 0.06[c]	2.2 ± 0.20
30-35	ND	0.01 ± 0.09[c]	3.6 ± 0.20

[a] ND = not detected (See Table 4 in text for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediments.

[c] These concentrations are so low compared to the error bands that they are, in effect, not detected.

Table A-6. Radioisotope concentrations in Middle Loch gravity core GG Recent (1950-1985)

Depth (cm)	Radioisotope concentrations (pCi/g)		
	^{137}Cs	Excess ^{210}Pb[a]	^{40}K
0-5	0.18 ± 0.04	0.86 ± 0.15	4.9 ± 0.60
5-10	0.24 ± 0.04	1.00 ± 0.17	4.5 ± 0.60
10-15	0.13 ± 0.05	0.91 ± 0.14	2.9 ± 0.70
15-20	0.29 ± 0.06	0.91 ± 0.19	5.2 ± 0.70
20-25	0.15 ± 0.04	0.80 ± 0.10	5.0 ± 0.60
25-30	0.11 ± 0.04	0.78 ± 0.18	4.5 ± 0.50
30-35	0.12 ± 0.03	0.72 ± 0.16	3.6 ± 0.50
35-40	0.18 ± 0.05	0.60 ± 0.13	3.8 ± 0.50
40-45	0.19 ± 0.04	0.73 ± 0.13	6.0 ± 0.60
45-50	0.13 ± 0.04	0.44 ± 0.19	4.8 ± 0.60
50-55	0.14 ± 0.04	0.43 ± 0.14	6.6 ± 0.50
55-60	0.08 ± 0.02	0.11 ± 0.14	3.2 ± 0.30

[a] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediments.

Table A-7. Radioisotope concentrations in Middle Loch gravity core GH

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Recent (1950-1985)		
0-2	0.16 ± 0.04	1.31 ± 0.20	2.9 ± 0.50
2-5	0.23 ± 0.06	1.04 ± 0.11	1.3 ± 0.60
5-10	0.18 ± 0.03	0.97 ± 0.15	4.7 ± 0.50
10-15	0.18 ± 0.04	0.85 ± 0.15	3.0 ± 0.70
15-20	0.06 ± 0.02	0.37 ± 0.10	2.4 ± 0.30
	Older (1930-1950)		
20-25	0.02 ± 0.01[c]	0.15 ± 0.08	2.6 ± 0.20
25-30	ND	0.15 ± 0.09	3.0 ± 0.30
30-35	0.01 ± 0.01[c]	0.07 ± 0.07[c]	4.0 ± 0.30
35-40	0.01 ± 0.01[c]	0.17 ± 0.09	3.1 ± 0.20
	Historical (prior to 1930)		
40-45	ND	ND	3.1 ± 0.30
45-50	0.04 ± 0.01[c]	ND	3.4 ± 0.30

[a] ND = not detected (See Table 4 in text for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by the uranium in the sediments.

[c] These concentrations are so low compared to the error bands that they are, in effect, not detected.

Table A-8. Radioisotope concentrations in West Loch vibracore WL-2

Depth (cm)	Radioisotope concentrations (pCi/g)[a]		
	^{137}Cs	Excess ^{210}Pb[b]	^{40}K
	Recent (1950-1985)		
0-2	0.28 ± 0.04	0.43 ± 0.10	4.0 ± 0.64
2-4	0.20 ± 0.03	0.57 ± 0.14	4.0 ± 0.63
4-6	0.19 ± 0.03	0.63 ± 0.13	3.7 ± 0.54
6-8	0.20 ± 0.03	0.52 ± 0.12	5.6 ± 0.51
8-10	0.23 ± 0.03	0.71 ± 0.13	2.6 ± 0.52
10-12	0.11 ± 0.03	0.54 ± 0.09	3.7 ± 0.49
12-14	0.22 ± 0.02	0.46 ± 0.10	3.8 ± 0.44
14-16	0.17 ± 0.03	0.39 ± 0.10	5.8 ± 0.49
16-18	0.13 ± 0.02	0.31 ± 0.10	3.5 ± 0.48
18-20	0.15 ± 0.03	0.48 ± 0.12	3.6 ± 0.41
20-22	0.20 ± 0.03	0.39 ± 0.10	5.2 ± 0.49
22-24	0.16 ± 0.03	0.20 ± 0.10	4.4 ± 0.52
24-26	0.23 ± 0.02	0.46 ± 0.11	3.3 ± 0.42
26-28	0.21 ± 0.02	0.36 ± 0.13	4.2 ± 0.50
28-30	0.20 ± 0.02	0.30 ± 0.11	5.0 ± 0.42
30-32	0.18 ± 0.02	0.17 ± 0.13	4.3 ± 0.45
32-34	0.26 ± 0.03	0.39 ± 0.13	3.0 ± 0.61
34-36	0.21 ± 0.03	0.24 ± 0.08	5.1 ± 0.58
36-38	0.09 ± 0.02	0.23 ± 0.12	4.5 ± 0.48
38-40	0.04 ± 0.02[c]	0.21 ± 0.12	6.6 ± 0.61
40-44	0.06 ± 0.02	0.26 ± 0.12	4.4 ± 0.43
	Older (1930-1950)		
44-48	ND	0.22 ± 0.08	5.6 ± 0.48
48-52	0.01 ± 0.02[c]	0.06 ± 0.12[c]	3.9 ± 0.44
52-56	NA	0.10 ± 0.10[c]	NA
56-60	0.01 ± 0.02[c]	0.24 ± 0.11	4.0 ± 0.33

[a] NA = not analyzed; ND = not detected (See Table 4 in text for detection limits.)

[b] Excess ^{210}Pb means the concentration above that accounted for by uranium in the sediments.

[c] These concentrations are so low compared to the error bands that they are, in effect, not detected.

APPENDIX B
TRACE METAL LEVELS IN PEARL HARBOR SEDIMENT

Table B-1. Trace metal levels in Middle Loch vibracore CA

	Trace metal levels (µg/g)					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
		Recent (1950-1985)				
0-4	210	220	0.22	150	58	280
8-10	210	230	0.28	150	70	290
20-22	210	210	0.29	160	88	320
30-32	220	210	0.31	170	39	210
32-34	280	170	0.26	220	47	200
38-40	300	200	0.26	220	45	240
44-46	250	200	0.24	220	35	240
48-50	220	200	0.23	160	45	210
52-54	200	230	0.47	150	42	280
58-60	270	290	0.55	250	46	290
66-68	320	310	1.7	260	79	290
70-74	310	170	0.29	220	14	190
		Older (1930-1950)				
74-78	300	250	0.83	360	33	300
78-82	280	230	0.36	400	23	320
86-90	290	220	0.83	400	40	330
94-98	290	250	0.57	370	42	320
102-106	1500	1000	0.21	150	3700	5900
106-110	280	250	0.29	140	98	520
		Historical (prior to 1930)				
122-126	340	160	0.19	210	10	160
146-150	340	150	0.07	200	4	160
166-170	330	160	0.18	210	5	160
202-206	270	120	0.16	170	2	120
222-226	390	150	0.02	270	3	160

Table B-2. Trace metal levels in Middle Loch vibracore CX

Depth (cm)	Trace metal levels (µg/g)					
	Cr	Cu	Hg[a]	Ni	Pb	Zn
		Recent (1950-1985)				
0-4	230	5400	NA	170	285	910
8-10	170	230	NA	120	77	480
10-12	190	220	NA	130	123	450
20-22	170	200	NA	130	67	380
30-32	220	180	NA	170	56	290
32-34	230	170	NA	180	66	250
38-40	240	180	NA	190	368	270
44-46	250	170	NA	160	46	200
48-50	250	200	NA	170	51	400
52-54	220	190	NA	170	468	510
58-60	230	160	NA	160	27	180
66-68	220	250	NA	140	62	260
70-72	230	230	NA	150	69	250
		Older (1930-1950)				
76-78	230	270	NA	140	54	190
78-80	240	250	NA	150	41	190
		Historical (prior to 1930)				
88-92	270	130	NA	170	7	90
96-100	280	130	NA	160	4	86
108-112	300	140	NA	170	7	99
120-124	260	120	NA	160	2	63
148-152	250	98	NA	130	2	60
168-172	260	100	NA	160	2	59
188-192	260	100	NA	150	1	56

[a] NA = not analyzed

Table B-3. Trace metal levels in Middle Loch gravity core GD

	Trace metal levels (µg/g)					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
			Recent (1950-1985)			
0-5	250	150	0.29	170	32	240
5-10	230	140	0.32	170	34	220
10-15	240	140	0.26	170	36	230
15-20	250	150	0.53	170	43	260
20-25	250	140	0.33	160	35	260
25-30	260	140	0.30	170	31	220
30-35	260	130	0.34	150	27	210
35-40	240	130	0.38	150	37	230
40-45	210	110	0.54	130	35	200
			Older (1930-1950)			
45-50	230	130	0.34	150	28	200
50-55	250	130	0.43	140	21	200
55-60	240	120	0.39	140	28	200
60-63	250	120	0.42	140	22	190

Table B-4. Trace metal levels in Middle Loch gravity core GE

	Trace metal levels (µg/g)					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
		Recent (1950-1985)				
0-5	240	140	0.37	150	39	250
5-10	220	130	0.35	140	30	250
		Older (1930-1950)				
10-15	280	110	0.19	140	9	150
15-20	280	100	0.21	170	10	170
		Historical (prior to 1930)				
20-25	310	120	0.19	190	4	150
25-30	300	110	0.09	170	3	140
30-35	280	100	0.08	170	2	150

Table B-5. Trace metal levels in Middle Loch gravity core GG
Recent (1950-1985)

	Trace metal levels (µg/g)					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
0-5	220	160	0.35	150	51	280
5-10	220	150	0.33	150	43	250
10-15	230	160	0.31	160	46	260
15-20	220	160	0.40	160	46	270
20-25	200	150	0.36	150	46	270
25-30	200	150	0.38	160	45	280
30-35	230	200	0.39	190	88	290
35-40	250	210	0.30	230	63	310
40-45	240	200	0.26	200	43	340
45-50	230	180	0.41	180	32	260
50-55	240	190	0.48	180	44	270
55-60	240	180	0.70	160	56	240

Table B-6. Trace metal levels in Middle Loch gravity core GH

	Trace metal levels (µg/g)					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
			Recent (1950-1985)			
0-5	230	170	0.48	160	38	290
5-10	230	160	0.53	150	58	260
10-15	240	180	0.56	160	48	300
15-20	180	120	0.33	110	28	230
			Older (1930-1950)			
20-25	180	120	0.37	100	48	220
25-30	200	110	0.66	110	22	210
30-35	250	120	0.60	150	22	200
			Historical (prior to 1930)			
35-40	250	100	0.37	150	10	170
40-45	270	110	0.37	160	10	130
45-50	270	100	0.16	170	14	130
50-55	260	100	0.16	160	3	120
55-58	270	110	0.17	180	5	170

Table B-7. Trace metal levels in Middle Loch gravity core WL-2

	Trace metal levels (µg/g)[a]					
Depth (cm)	Cr	Cu	Hg	Ni	Pb	Zn
		Recent (1950-1985)				
0-2	NA	125	NA	NA	38	157
2-4	NA	122	NA	NA	37	172
4-6	NA	114	NA	NA	36	163
6-8	NA	110	NA	NA	37	160
8-10	NA	107	NA	NA	38	161
10-12	NA	115	NA	NA	35	161
12-14	NA	105	NA	NA	34	166
14-16	NA	108	NA	NA	34	167
16-18	NA	106	NA	NA	38	164
18-20	NA	97	NA	NA	35	166
20-22	NA	106	NA	NA	36	174
22-24	NA	101	NA	NA	37	164
24-26	NA	99	NA	NA	34	170
28-30	NA	99	NA	NA	36	175
30-32	NA	102	NA	NA	34	167
32-34	NA	105	NA	NA	37	174
36-38	NA	104	NA	NA	30	167
38-40	NA	108	NA	NA	25	172
40-44	NA	104	NA	NA	19	180
		Older (1930-1950)				
44-48	NA	105	NA	NA	23	175
48-52	NA	86	NA	NA	18	147
52-56	NA	90	NA	NA	20	160
56-60	NA	83	NA	NA	20	150

[a] NA = not analyzed.

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