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Title:

OU3 Sediment Dating and Sedimentation Rates

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MASTER

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INTRODUCTION

Environmental Technologies at Rocky Flats Environmental Technology Site (RFS) investigated the sediment history of Standley Lake, Great Western Reservoir, and Mower Reservoir using ^{137}Cs and $^{239,240}Pu$ global fall-out as dating indicators. These Colorado Front Range reservoirs have been the subject of study by various city, state and national agencies due to suspected Department of Energy Rocky Flats Plant impacts (Figure 1). We performed sediment dating as part of the RCRA Facility Investigation/Remedial Investigation Report for Operable Unit 3 (RFI/RI Report OU3) (EG&G 1994). A sediment chronology profile assists scientist in determining the year of sedimentation for a particular peak concentration of contaminants.

Radioisotope sediment dating for the three reservoirs indicated sedimentation rates of 0.7 to 0.8 in./yr. for Standley Lake (SL), 0.9 in./yr. for Great Western Reservoir (GWR), and 0.3 in./yr. in Mower Reservoir (MR). RFS sediment dating for Operable Unit 3 compared favorably with the Hardy, Livingston, Burke, and Volchok Standley Lake study (Hardy et al. 1978).

This report describes the cesium/plutonium sediment dating method, estimates sedimentation rates for Operable Unit 3 (OU3) reservoirs, and compares these results to previous investigations.

THEORY OF CESIUM AND PLUTONIUM DATING

Isotopes introduced into the atmosphere by natural and manmade methods descend to the earth's surface by precipitation and dry fallout. The fission products, ^{137}Cs and $^{239,240}Pu$, of nuclear weapons testing and nuclear power facilities, are frequently used to determine sedimentation rates and depositional history (Matsumoto and Wong 1977; Krishnaswami and Lal 1978).

Peak weapons testing during 1962-63 maximized cesium and plutonium in the atmosphere and subsequent fallout and are often used as a stratigraphic marker (Robbins and Edgington 1975). One of the primary assumptions in sediment dating is that maximum cesium and plutonium in a sediment core represent peak weapons testing during 1962-1963. Another is constant sedimentation rates prevail throughout the core. A third is no migration of cesium and plutonium occurs through the sediment column.

Nuclear reactors also contribute to cesium deposits, but the aerial fallout is usually localized (Krishnaswami and Lal 1978). Cesium is an abundant component of discharges during accidents at nuclear power facilities such as Chernobyl in 1986 and Three Mile Island in 1979 (Gilbert 1989). Increased cesium content may be apparent in more recently deposited sediment layers coinciding with these incidents.

Contaminants were released to the environment during several periodic events at RFS. During the history of activities, releases of contaminants into the environment occurred due to early operational practices during the 1950's and 1960's, holding pond reconstruction between 1970-1973, and an airborne radionuclide release during a building fire in 1969. Recent studies illustrated plutonium concentrations over normal global fallout in the 1969 sedimentation year for GWR and SL creating an independent dating marker (Thomas and Robertson 1981 and Hardy et al. 1978). The 1969 fire was used as the plutonium peak for this study. Cesium was not a product of any RFS influenced activities, so OU3 reservoir sediments contain only global cesium fallout peaking in 1963 (Thomas and Robertson 1981).

In most ponds, reservoirs, and lakes, cesium and plutonium are removed to the sediments via adsorption almost immediately. Removal to the sediments is driven by processes such as 1) adsorption to particulate matter present in the water column (clay minerals and organic matter); 2) direct adsorption to epilimnion sediments; and 3) scavenging by organisms (Anderson et al. 1987; Nittrouer et al. 1979; Hakonson and Whicker 1974).

Once cesium and plutonium are incorporated within the solid phase of the sediment, they are usually resistant to redistribution. Mechanisms that may cause redistribution include bioturbation, erosion, slumping, unreported human activity on the sediment bed, and irregular processes of deposition (Robbins et al. 1977).

The sampling process can cause further disturbances that affect the distribution of radionuclides and other chemical components (Anderson et al. 1987; Gilbert 1989). Some examples of sampling disturbances include:

1. Disturbance of the sediment/water interface by turbulence created by the gravity coring apparatus;

2. Compaction of the sediment caused by the impact of the gravity coring device;

3. Inadequate suction within the free-fall gravity coring device leading to segmentation of the sample core;

4. Small sample volume from the free-fall gravity coring device.

Disturbances 1 and 2 can create unpredictable and erratic activities of cesium and plutonium through the top layers of a sediment core. Therefore, other methods of dating are used. A third isotopic dating method, such as measuring the decay of naturally occurring ^{210}Pb, can verify cesium and plutonium dating. A fourth method of verification includes comparing historic sediment studies when available.

^{210}Pb dating is an applicable dating method for OU3 reservoirs, but for the OU3 study, small sample sizes for each core increment limited the number of parameters analyzed. Lack of adequate sample size prevented ^{210}Pb dating measurement. To verify cesium/plutonium dating results, RFS used historic sediment dating information from studies performed by Hardy et al. (1978), EPA (1973), Thomas and Robertson (1981), and Rockwell (1985).

Hardy et al. (1980) applied a fifth method of dating verification by performing an analysis of isotopic ratio data which can support peak cesium fallout identification. Hardy et al. verified the influence of RFS debris vs. global fallout by determining ^{241}Am and

$^{239,240}Pu$ ratios. Additionally, $^{239,240}Pu$ to ^{137}Cs ratio values can correspond to RFS influences and lack thereof. Radionuclide ratio analysis is beyond the scope of this report but can be found in the OU3 RFI/RI report (EG&G 1995).

METHODOLOGY

This report describes sediment dating, core selection, coring equipment limitations, dating methodology, and statistical analysis. Sampling locations, strategies and field methods for OU3 reservoir sediment samples are discussed in detail in the OU3 RFI/RI report (1995).

The United States Geological Survey (USGS) extracted 12 cores from the three reservoirs, and RFS dedicated 4 SL cores, 5 GWR cores, and 3 MR cores to chemical analysis and sediment dating (Figure 2). Two cores from GWR and MR met the required criteria of optimum sampling location within the reservoir, sufficient core thickness, and adequate sample size. One SL core met the required criteria.

Sampling from the deepest areas of the reservoir optimizes sediment dating accuracy, due to minimized sediment disturbances. If deeper portions of a lake are anoxic, which can occur in the hypolimnion of some lakes during stratification, there will be a reduction in the number of large benthic fauna communities which would normally mix the sediments (Anderson et al. 1987). Sediment mixing due to human or biological disturbances is minimal in the deepest areas and radionuclides concentrate in this area.

Due to a loss of suction in the free-fall gravity coring apparatus, some of the 12 cores failed to retain sufficient thickness to reach the 1962 peak cesium/plutonium activities. For dating purposes, RFS rejected cores with insufficient sediment thickness.

After rejecting cores based on the above criteria, RFS used 2 cores from GWR and MR and one core from SL to determine sediment history. The second SL core had minimal sample size for chemical analysis, and cesium analysis could not be performed.

The field crew sectioned each core into 2 in. increments with separate laboratory analysis performed on each increment. This step provides cesium and plutonium activities for 2 in. sediment layers.

The widely established cesium/plutonium dating method is based on selecting the peak cesium and plutonium activities within a core increment. With the following assumptions, the sediment horizon corresponds to peak atmospheric testing in 1962 and the 1969 RFS fire (Gilbert 1989):

1. By allowing time for aerial deposition, peak cesium activity within the sediment corresponds to the year 1963, while peak plutonium in GWR and SL corresponds to 1969;

2. Cesium and plutonium are absorbed to the sediments almost immediately and do not remain in the water column;

3. Migration of cesium and plutonium within the sediments after deposition is insignificant;

4. Annual sedimentation rate is constant.

The horizon of maximum cesium activity establishes the location of 1963 sedimentation. The year of sedimentation for each core increment is established by determining the length of sediment between the top of the core and the top of the layer of peak cesium activity. To determine sedimentation rates, the length is divided by the number of years elapsed between 1963 and the date of core recovery (Gilbert 1989).

Plutonium dating is performed in the same manner, but for this study, the layer of maximum activity corresponds to the 1969 fire. Again, the length from peak plutonium to the top is divided by the number of years elapsed between 1969 and the date of core recovery.

Historic reservoir sediment studies supplemented cesium and plutonium dating methods by comparing incremental results. RFS compiled information from studies by EPA (1973), Hardy et al. (1978 and 1980), Thomas and Robertson (1981), and Rockwell International (1985).

Sampling strategies for each study included extracting cores at various locations within GWR and SL (Figures 2 through 4). For dating comparisons, RFS selected data from cores retrieved from the deepest areas of the reservoirs, near the center of the dam. In none of the studies did the core sampling locations exactly match the OU3 sampling locations. These Front Range reservoirs are located in flat drainage valleys and are relatively flat near the dam, and since these radionuclides are resistant to redistribution, sedimentation rates and radionuclide distributions are similar (Wolaver 1989).

Thomas and Robertson dated GWR sediments using the cesium method, while Hardy et al. dated SL sediments using both the cesium and plutonium methods. RFS used both cesium and plutonium for OU3 sediment dating and a comparison with historic studies.

EPA (1973) and Rockwell International (1985) reported incremental radionuclide activities without sediment dating, because the objective of these studies was to report where higher radionuclide concentrations existed. For these studies, we identified cesium or plutonium peaks within cores in the deepest reservoir areas and dated the core increments in the same manner as the OU3 cores. Cesium data was not always available.

Core retrieving methods for these historic studies were similar to OU3 coring methods. In each study, a gravity-type corer retrieved cores of varying diameter. Varying diameters allow for various sample sizes for analysis without changing the sampling quality, but may minimize core depth. Each sampling event is susceptible to equipment limitations such as surficial disturbances and sediment compaction.

RESULTS

Figures 5 through 9 illustrate the variation of cesium and plutonium with depth, and peak activities. Tables 1 through 6 summarize activities and dating results for cores within each of the reservoirs. Instrument counting error is illustrated with error bars in the figures and enumerated in the tables.

The SL cesium activities peaked at the 18 to 20 in. increment. Cesium in both of the GWR cores peaked at the 24 to 26 in. increment. MR cesium activities peaked in both cores at the 6 to 8 in. increment. Plutonium peaked at different intervals than the cesium in each core indicating another source other than fall-out. SL, GWR, and MR deposited sediments at 0.7 to 0.8 (0.75 average), 0.9, and 0.3 in./yr. respectively.

All values reported for cesium and plutonium have an associated error value comprised of counting error and analytical error. The random nature of radioactive disintegrations and laboratory error are estimated with the error value, as seen in Figures 5 through 9 and Tables 1 through 6.

RFS statistically compared the similarity between cesium activities of core pairs in GWR and in MR. The difference between the measured cesium values was derived, and a paired t-test was used to determine whether there was a difference between the core pairs.

The paired t-test hypothesized that the mean difference between the duplicate pairs was zero (H_O: U_d=0). The mean difference was not significantly different from zero and there was no significant difference between core pairs (Table 7). There is significant confidence that the core pairs are approximately the same when compared layer by layer.

RFS compared sediment dating results for the 1992 OU3 sampling with EPA (1973), Hardy et al. (1978), Thomas and Robertson (1981), and Rockwell International (1985). Some studies characterized GWR sediments, others SL sediments, but previous MR core samples did not exist before the OU3 sampling (Table 8 and Appendices A-1 through A-5). EPA data includes plutonium for SL and GWR; Hardy et al, includes cesium/plutonium for SL; Thomas and Robertson data include cesium for SL and GWR; Rockwell data include plutonium for GWR.

EPA retrieved 12 cores from GWR and two cores from SL. From these, RFS selected data from those cores near the middle of the dam for comparison (GWR core #11c and SL core #14c). Hardy et al. retrieved one core from the center of SL. Thomas and Robertson retrieved 10 cores from GWR and one core from SL, and of these, RFS selected core #A-3 in GWR and core #5 in SL. RFS selected core KB#4 from four Rockwell International gravity cores from GWR.

Appendices A-1, A-2, and A-3 illustrate a comparison of the OU3 SL sediment core with EPA , Hardy et al., and Thomas and Robertson. EPA and Thomas and Robertson recorded plutonium activities, therefore, we dated these cores using the 1969 RFS fire plutonium peak. Both cesium and plutonium activities were available for dating the Hardy et al. cores.

The intermittent nature of EPA core horizons for SL interfered with identifying the EPA recorded plutonium activities. The available data placed peak plutonium at the 12 inch depth, which is appropriately labeled as the RFS fire in 1969, but this sedimentation rate is suspect because 6 in./yr. is abnormally high.

The OU-3 and EPA cores did not correspond unilaterally for SL cores (Table 8 and Appendix A-1). EPA reported a sedimentation rate of 1.1 to 1.5 in./yr. based on all their cores, which more favorably compare to the OU3 average sedimentation rate of 0.75 in./yr.

Peak plutonium reported by Hardy et al. allowed for a fair comparison with OU3 SL dating (Table 8 and Appendix A-2). OU3 derived sedimentation rates of 0.75 in./yr. were slightly lower than the 1.2 in./yr. Hardy rate. The Thomas and Robertson cesium-derived sedimentation rate of 1 in./yr. is a reasonable comparison to the 0.75 OU3 rate (Table 8 and Appendix A-3).

Appendix A-4 and A-5 illustrate the comparison of Thomas and Robertson (1981) and Rockwell International (1985) investigations of Great Western Reservoir. The Rockwell core dating matched the OU3 1992 core dating remarkably well, with sedimentation rates of 1.2 and 0.9 in./yr. respectively (Appendix A-5). Data from the Thomas and Robertson study did not compare to the OU3 study (Appendix A-4).

DISCUSSION

Within each core, peak cesium and peak plutonium occurred at different depths (Tables 1 through 6). Based on former Front Range reservoir sediment study results, we can identify the cesium peak as 1963 peak global fallout, and the plutonium peak as the RFS 1969 fire. Different plutonium and cesium peak intervals in the OU3 cores confirm that different events affected plutonium activities other than atmospheric testing.

OU3 cesium and plutonium dating schemes compared well (Tables 1 through 6). Intervals of plutonium peaks corresponded primarily to deposition periods from 1968 to 1969 as a result of recorded air borne releases from the plant. Sediment dating for these cores is confirmed based on the fact that peak plutonium usually occurred in the 1969 interval as determined from cesium dating.

The agreement between core pairs in GWR and MR is quite favorable. Peak cesium horizons and dating results matched in the GWR and MR core pairs (Table 7). The paired t-test verified that cesium activities at each incremental depth were consistent between cores in each pair. Consistency between cores indicates minimal sediment mixing from bioturbation, erosion, slumping, or irregular processes of deposition. Minimal sediment mixing prevents excessive radionuclide movement, and more reliable sediment dating.

MR is a relatively flat and shallow reservoir. At shallow depths, we expected to find bioturbation due to crayfish, midge larvae, or earthworms, but the similarity between cores does not suggest a bioturbation problem. Core #SED08992 was taken at a water depth of only 5 ft, while #SED08892 was 400 ft away at a water depth of 6 ft.

The MR sedimentation rate was low relative to SL and GWR (0.3 vs. 0.9 and 0.75 in./yr. respectively). Other Colorado Front Range reservoirs deposit sediments at rates of 0.49 to 2.5 in./yr. (Wolaver 1989, EPA 1973, Hardy et al. 1980, Thomas and Robertson 1981, and Rockwell International 1985). Rates vary from reservoir to reservoir based on the size of the drainage basin, methods of water transport into the reservoir (conduit, manmade ditch, or natural waterway), reservoir residence time, and surrounding vegetative cover.

One reason for low sedimentation in MR is that it is smaller than GWR and SL, with more vegetation surrounding the lake. Vegetative cover protects the reservoir banks from erosion and contributes to low sedimentation rates. Another reason is MR receives water periodically from Rocky Flats Lake (near Colorado Hwy. 93) and Pond C-1 on the RFS property, both of which serve as settling ponds upstream from MR. A third is that GWR and SL receive water from a much larger drainage basin (Clear Creek) that includes significant spring runoff which allows for high suspended solids. The MR drainage basin originates within RFS boundaries and has very little spring runoff.

Another explanation for low sedimentation rates relates to the location of the cesium and plutonium peaks within the two cores. Sediment winnowing in the shallow MR water can cause redistribution of these radionuclides, so the peak activities of cesium/plutonium may not be in the layer of original deposition (Anderson et al. 1987). However, there was high correlation between the two MR cores, which suggests minimal sampling or winnowing disturbance.

As previously mentioned, all values reported for cesium and plutonium have an associated error value. Scientists performing sediment dating usually accept the midpoint as the true value (Robbins and Edgington 1975 and Krishnaswami and Lal 1978). It is possible in our sediment cores that the "real" peak activity falls within the error interval of a sediment layer other than the layer with the peak midpoint activity. We analyzed these differences for cesium in each reservoir core.

In SL, it is possible that the "real" peak cesium occurred in the 16 or 18 in. layer. The result of this scenario is that sedimentation rates would be decreased to 0.5 - 0.6 in./yr. In turn, dating using the 16 or 18 in. layer for peak activity creates a sediment layer dating difference of 3 to 6 yrs. The sedimentation rates based on the 16 and 18 in. layer are significantly lower than the midpoint peak derived rate (0.7 in./yr.) and previous reports (1.1 - 2.5 in./yr.) (EPA 1973 and Hardy et al. 1980).

Error intervals for the GWR cores indicate that the "real" peak may be in a sediment increment above or below the layer of peak midpoint activity. This translates into a faster or slower sedimentation rate than the recorded peak midpoint activity derived sedimentation rate (0.8 - 1.0 in./yr.) and sediment layer dating could be as much as 1 year different.

The overlap of MR error intervals reveals a slower sedimentation rate than the peak midpoint interval (only 0.07 - 0.20 in./yr.) with a sediment layer dating difference of 23 yrs. Sedimentation rates based on the peak midpoint value are already low, and based on sedimentation rates for other Front Range reservoirs, it is difficult to justify lower rates.

EPA, Hardy et al., and Thomas and Robertson core-sampled SL with various results. The location of peak plutonium in the EPA study was abnormal. Cores were extracted in 1970, possibly too early for a 1969 RFS fire plutonium peak and the depth of the sediment core was also inadequate. Another cause of this unusual distribution may be the coring device. A gravity core can disturb surficial sediments and prevent a realistic representation of plutonium deposition. The plutonium peak may not be a result of the 1969 fire, but a sub-peak.

OU3, Hardy et al., and Thomas and Robertson sedimentation rates for SL are fairly comparable. Where they are different, it is our opinion that the OU3 cores are the most representative because of the length of the OU3 cores as compared to the historic study cores. Sometimes, it is not possible to extract a long sediment core, and we found that the OU3 cores were longer than cores from the previously mentioned historic studies. Logically, the longer cores represent the best average sedimentation rate since more years of sedimentation are represented.

Another reason for variation between studies may reflect variable annual sedimentation rates. With cesium/plutonium dating, we assume that annual sedimentation rates are the same. This assumption may label a sediment increment as a given year, but be off by a couple of years due to varying sedimentation rates.

The GWR study comparisons with OU3 results include Thomas and Robertson (1981) and Rockwell International (1985) (Table 8 and Appendices A-4 and A-5). OU3 compares with these two historic studies, but poorly at best.

Summarizing and comparing historic sediment information revealed inconsistencies that arise between designated horizons for different studies. One study out of five allowed a year for year match of sediment horizons with the OU3 plutonium sediment dating (i.e.. Hardy et al.). The other four were offset on horizon dating, sometimes from as little as 2 to as many as 6 years (Appendix A).

Factors that cause horizon date variability include: 1) laboratory analysis technique and error; 2) replicating the sampling location within the reservoir; 3) the possibility that radionuclides migrate to some degree; 4) sedimentation is assumed to be constant from year to year (but in nearly all watersheds, this is a gross assumption), and 5) cores taken at different years with different thicknesses represent a snapshot of different sedimentation years.

CONCLUSIONS

Aerial fallout from peak weapons testing during 1963 and the 1969 RFS fire provided sediment markers within cores extracted from GWR, SL, and MR. Peak activities of

^{137}Cs and $^{239,240}Pu$ provided a means to date core horizons for one SL core, two GWR cores, and two MR cores.

SL, GWR, and MR sedimentation rates based on the OU3 study are 0.75, 0.9, and 0.3 in./yr., respectively. Core pairs from GWR and MR were compared using a paired t-test and it was confirmed there was no difference between the core pairs. Therefore, sediment dating between the core pairs from each reservoir was identical. This analysis indicates that the sampling process and migration minimally affected the distribution of cesium and plutonium.

Historic sediment information from GWR and SL provided a second comparison. Historic information on MR is very limited, and previous sediment core data are non-existent. RFS compared GWR and SL sediment dating results for the 1992 OU3 sampling with previous studies performed by EPA (1973), Hardy et al. (1980), Thomas and Robertson (1981), and Rockwell International (1985).

Comparing historic sediment data for SL with the OU3 study proved to be successful with the Hardy et al. study. Plutonium dating for the OU3 and Hardy et al. sediment intervals was nearly identical. Only one study out of five allowed a year for year match of sediment horizons. The other four were offset on horizon dating, sometimes two years and as much as six years (Appendix A).

Summarizing and comparing historic sediment information revealed inconsistencies that arise between designated horizons for different studies. Factors that cause horizon date variability include: 1) laboratory analysis technique and error; 2) replicating the sampling location within the reservoir; 3) the possibility that radionuclides migrate to some degree; 4) sedimentation is assumed to be constant from year to year, and 5) cores taken at different years with different thicknesses represent a snapshot of different sedimentation years.

We believe the OU3 cores are representative of sedimentation rates for the assigned time period. The SL cores were 2 to 4 in. longer and GWR cores 8 in. longer than any of the historic studies, providing a better average annual sedimentation rate. There was strong correlation between GWR and MR core pairs, and the one SL OU3 core compared favorably with the Hardy et al. study.

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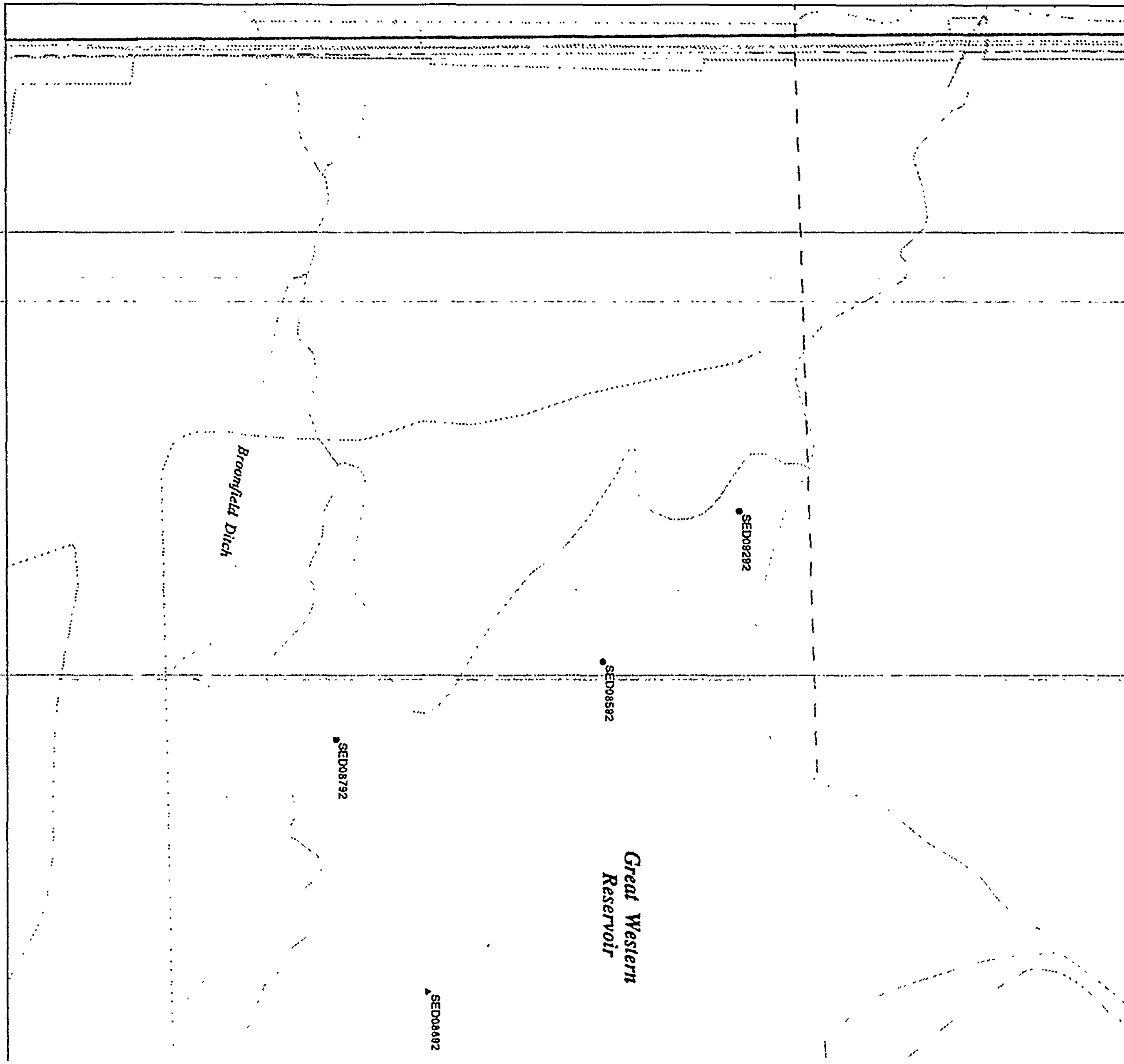

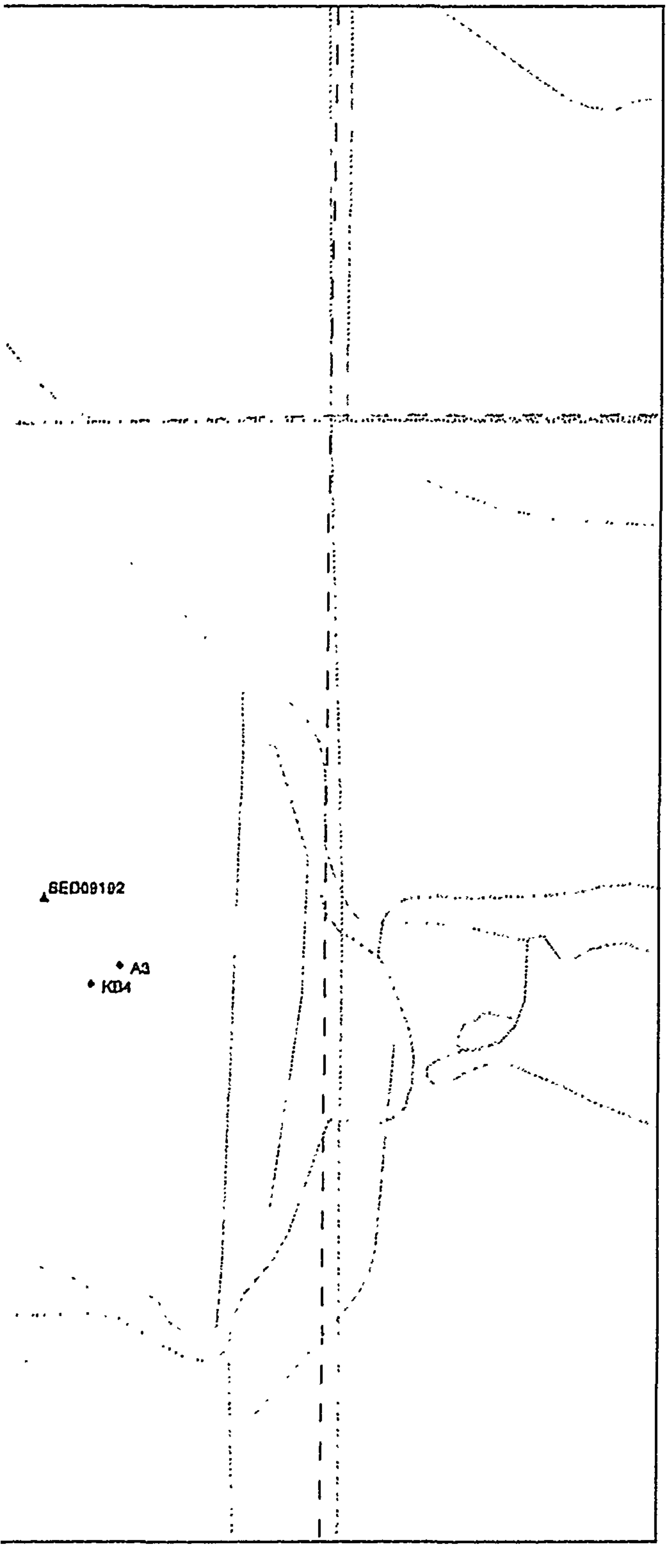

Figure 2
Approximate Locations of OU3 and Historical Sediment Cores

OPERABLE UNIT 3
IHSS 200 Great Western Reservoir
ROCKY FLATS PLANT
U.S. Department of Energy

Legend

- OU3 sediment core sample
- OU3 core sample used for sediment age dating
- A3 Battelle PNL (Thomas and Robertson, 1981.)
- KB4 Rockwell, 1985.

Mapping Sources:
Jefferson County Mapping Dept.
EG&G Rocky Flats
U.S. Geological Survey
CH2M HILL, Inc.

N

Polyconic projection. 1927 North American datum.
Colorado central zone state plane coordinate system.

EG&G ROCKY FLATS

CH2M HILL

MAP FILE NAME: 1M3.EPS | Drawn by: D. Moreno | August 04, 1994 | EG&G Age Dating Appendix (Sediment Report) Figure 3
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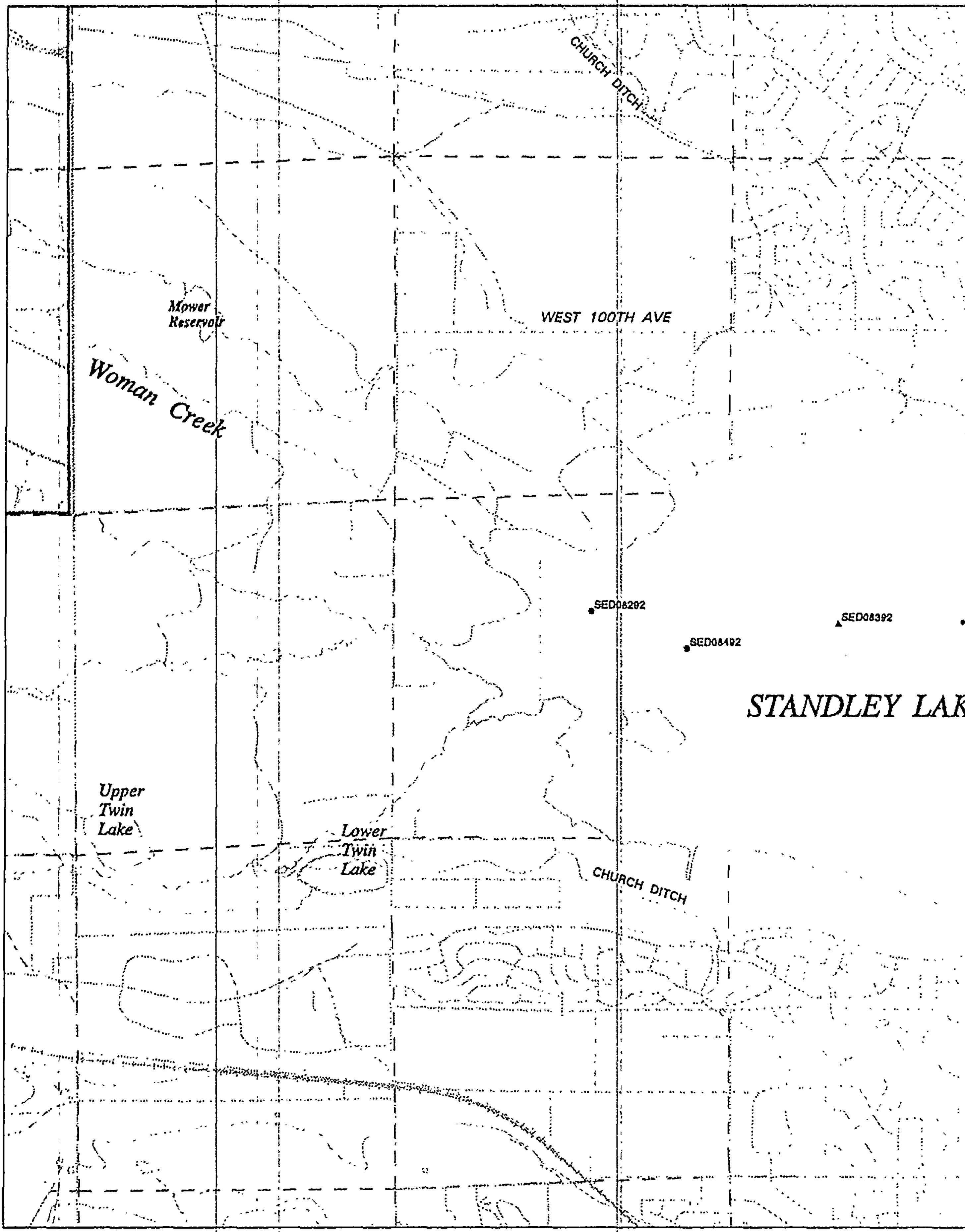

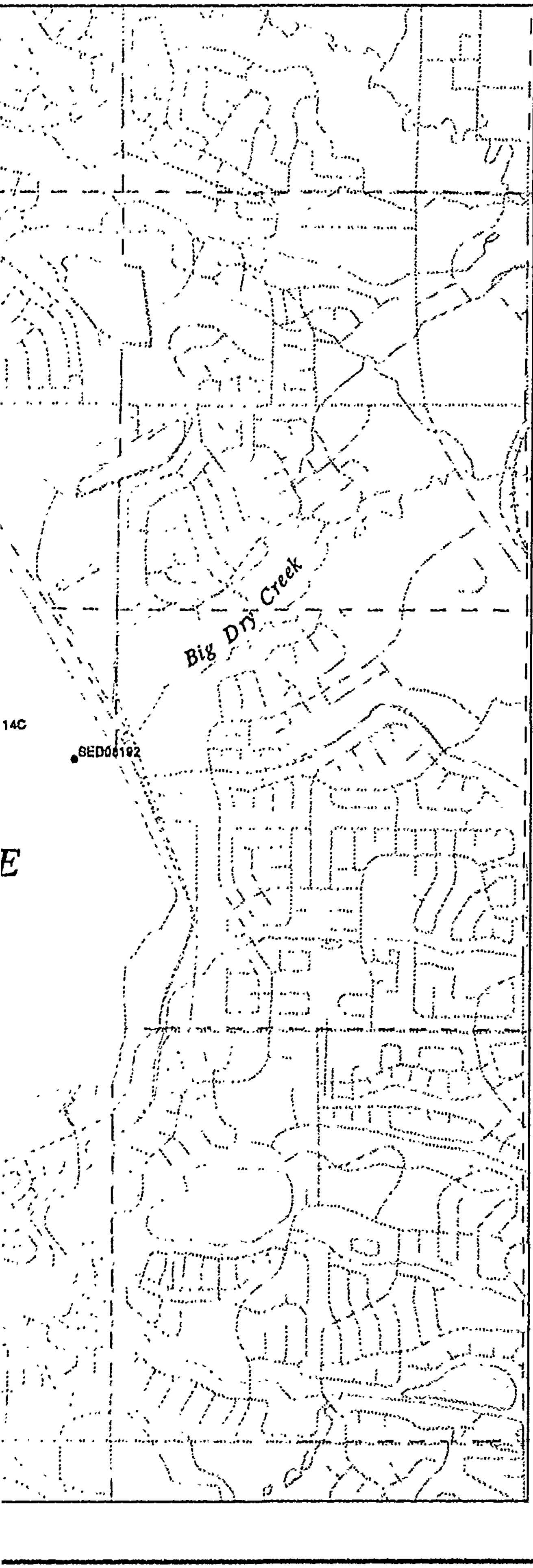

Figure 3
Approximate Locations of OU3 and Historical Sediment Cores

OPERABLE UNIT 3
IHSS 201 Standley Lake
ROCKY FLATS PLANT
U.S. Department of Energy

Legend

- OU3 sediment core sample
- ▲ OU3 core sample used for sediment age dating
- ◆ 5 Battelle PNL (Thomas and Robertson, 1981.)
- ◆ 14C EPA, 1970.

Mapping Sources:
Jefferson County Mapping Dept.
EG&G Rocky Flats
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CH2M HILL, Inc.

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Polyconic projection. 1927 North American datum.
Colorado central zone state plane coordinate system.

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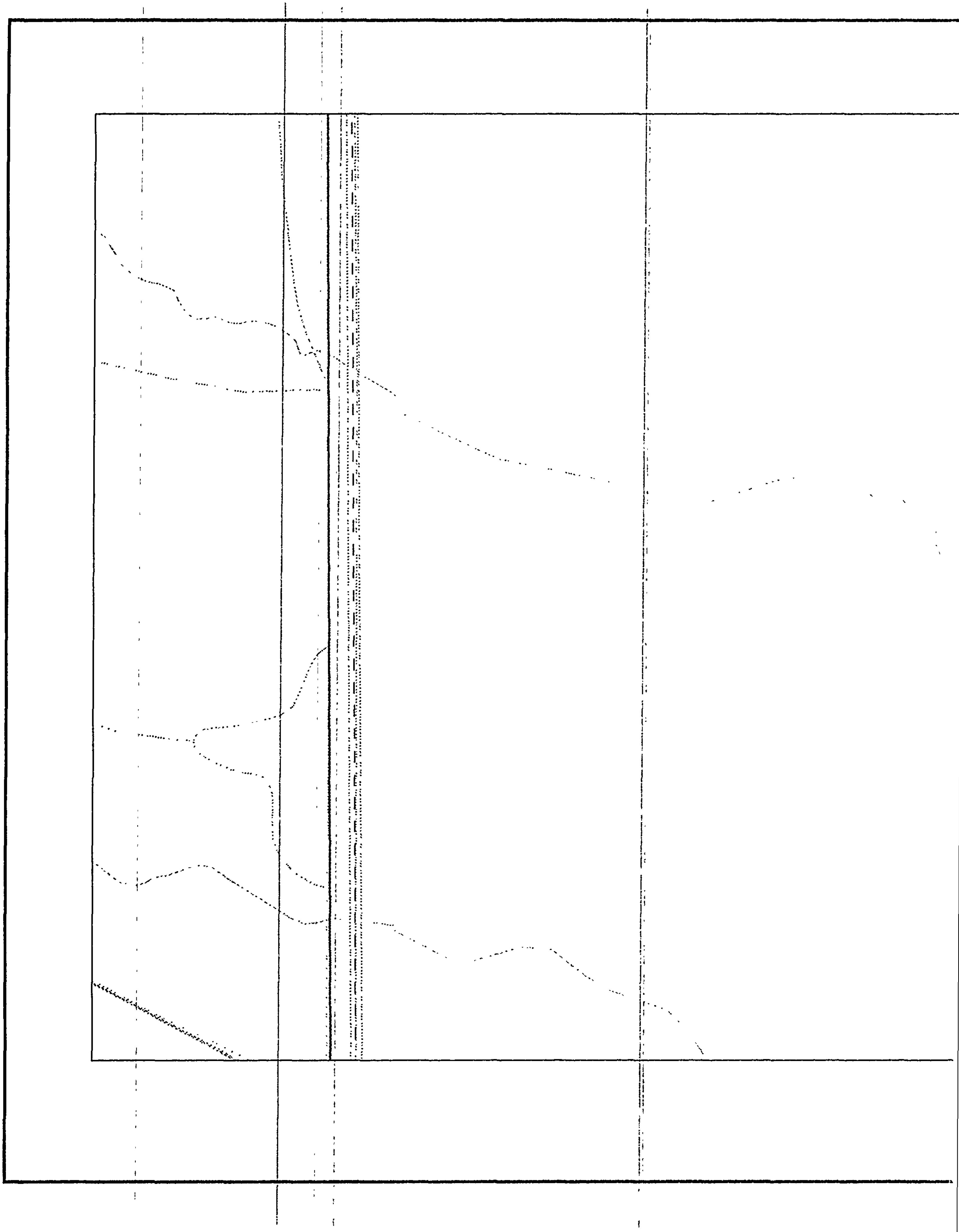


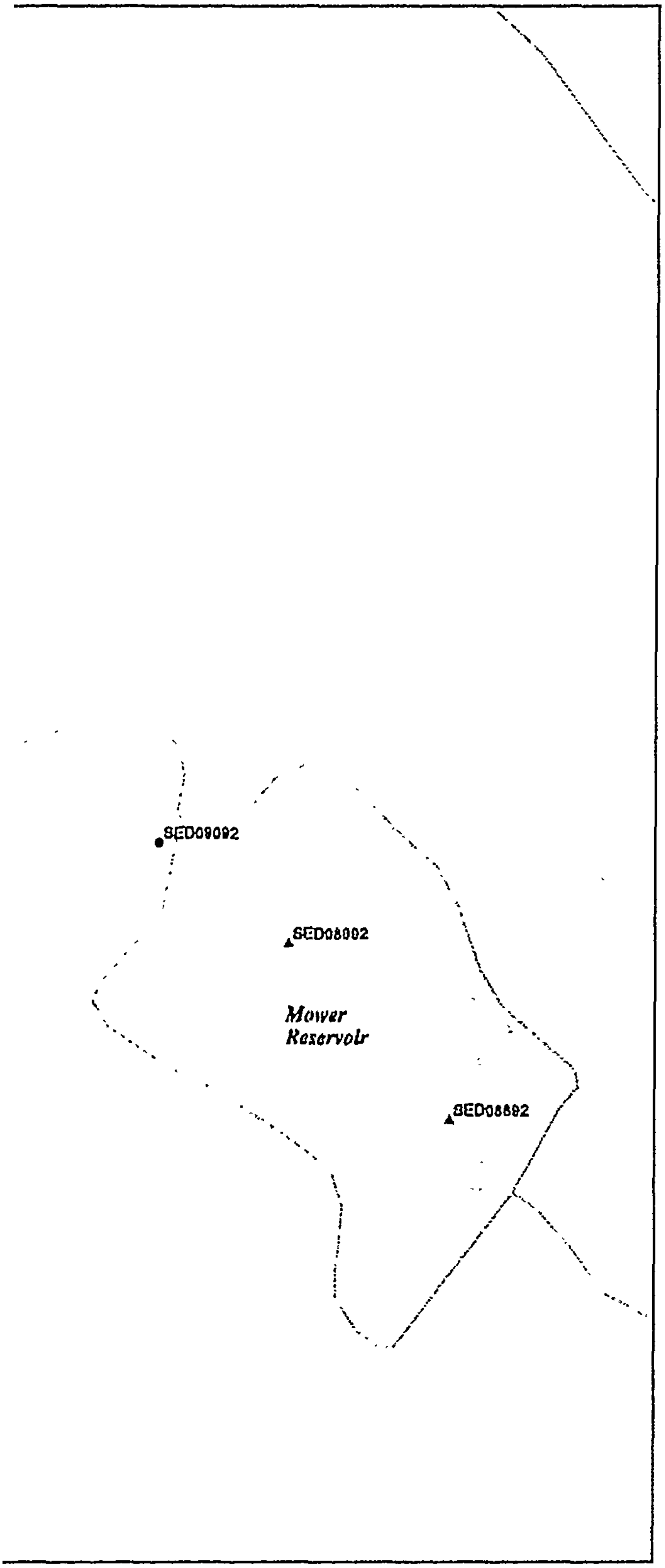


Figure 4
Approximate Locations of OU3 Sediment Cores

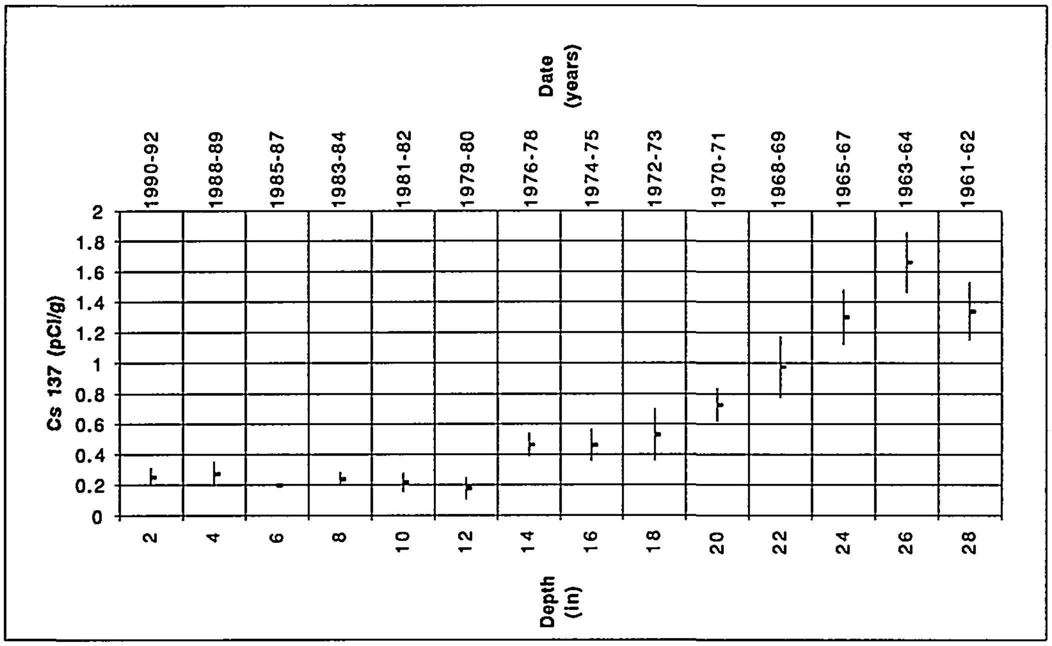
OPERABLE UNIT 3
IHSS 202 Mower Reservoir
ROCKY FLATS PLANT
U.S. Department of Energy

Legend

- OU3 sediment core sample
- OU3 core sample used for sediment age dating

Mapping Sources:
Jefferson County Mapping Dept.
EG&G Rocky Flats
U.S. Geological Survey
CH2M HILL, Inc.

Polyconic projection. 1927 North American datum.
Colorado central zone state plane coordinate system.



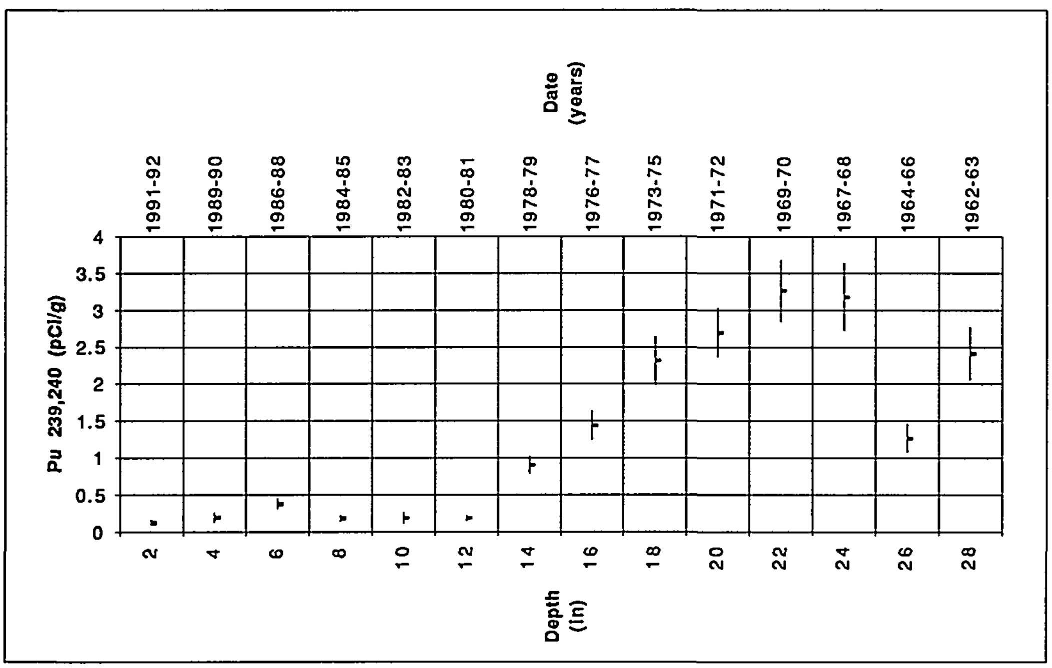
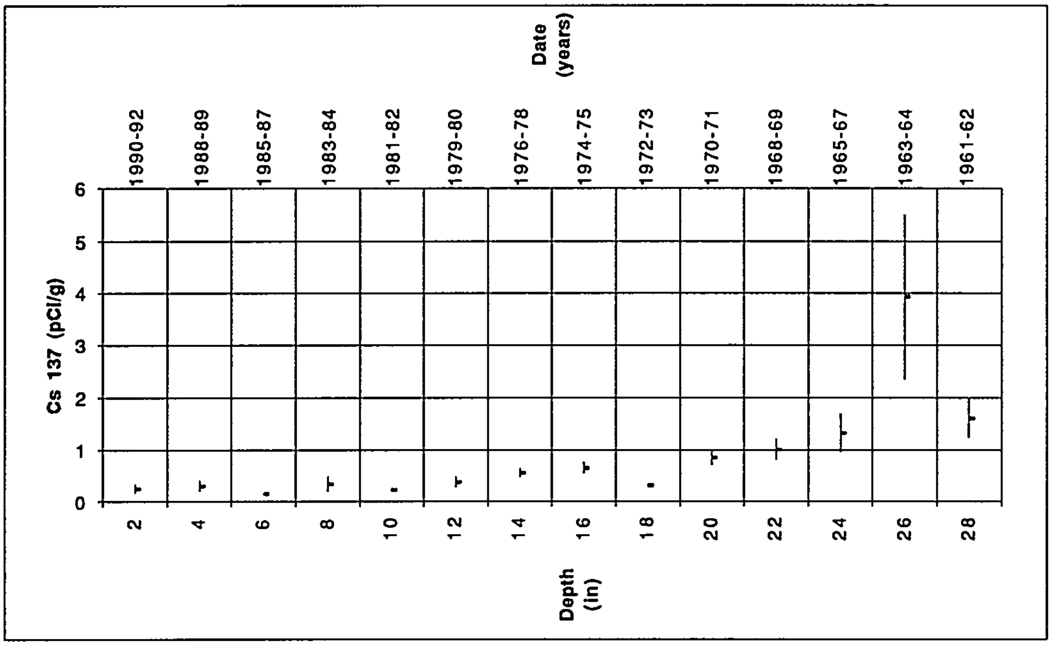


Figure 6. Depth distribution of Cs-137 and Pu-239,240 in Great Western Reservoir sediment based on Core # SED 08692. Corresponding sediment layer dates are illustrated for cesium or plutonium dating. For data points where there are no confidence intervals, the value was below the detection limit.



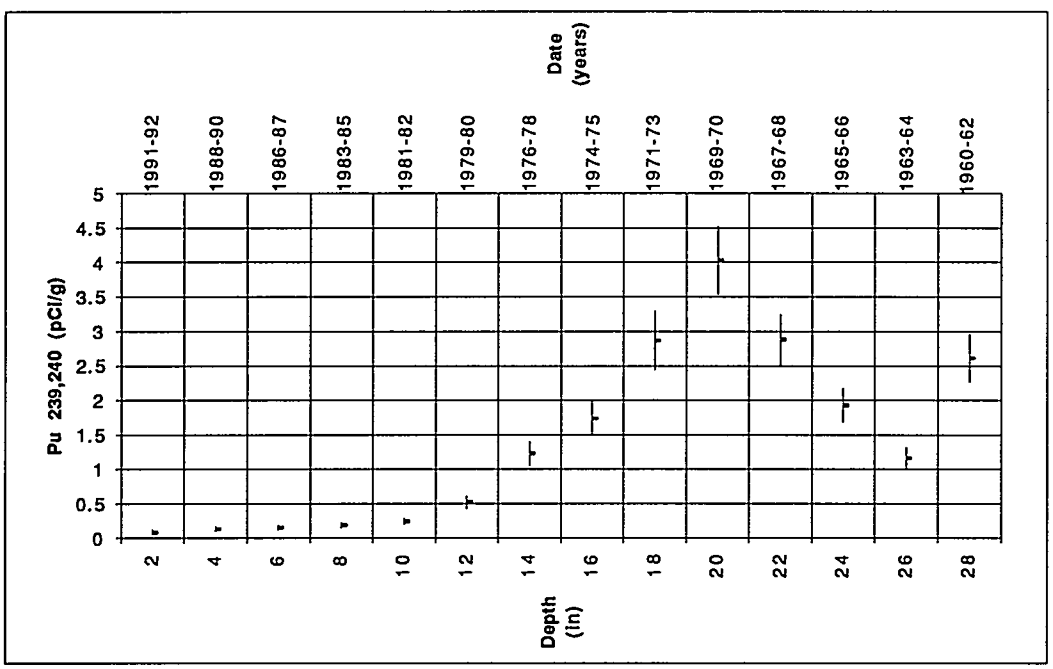
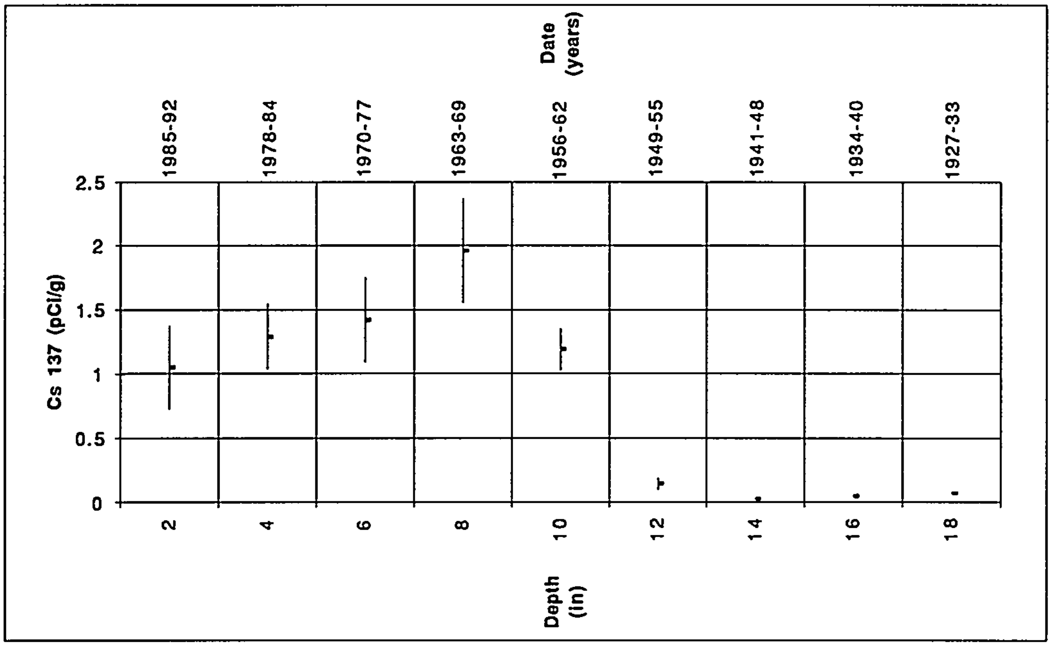


Figure 7. Depth distribution of Cs-137 and Pu-239,240 in Great Western Reservoir sediment based on Core # SED 09192. Corresponding sediment layer dates are illustrated for cesium or plutonium dating. For data points where there are no confidence intervals, the value was below the detection limit.



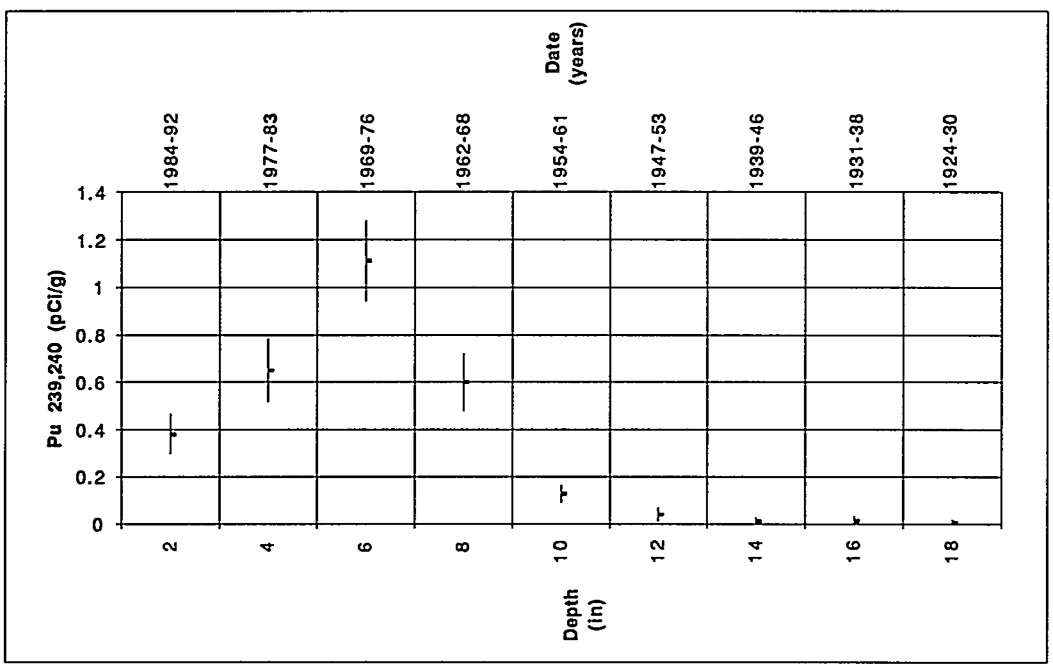
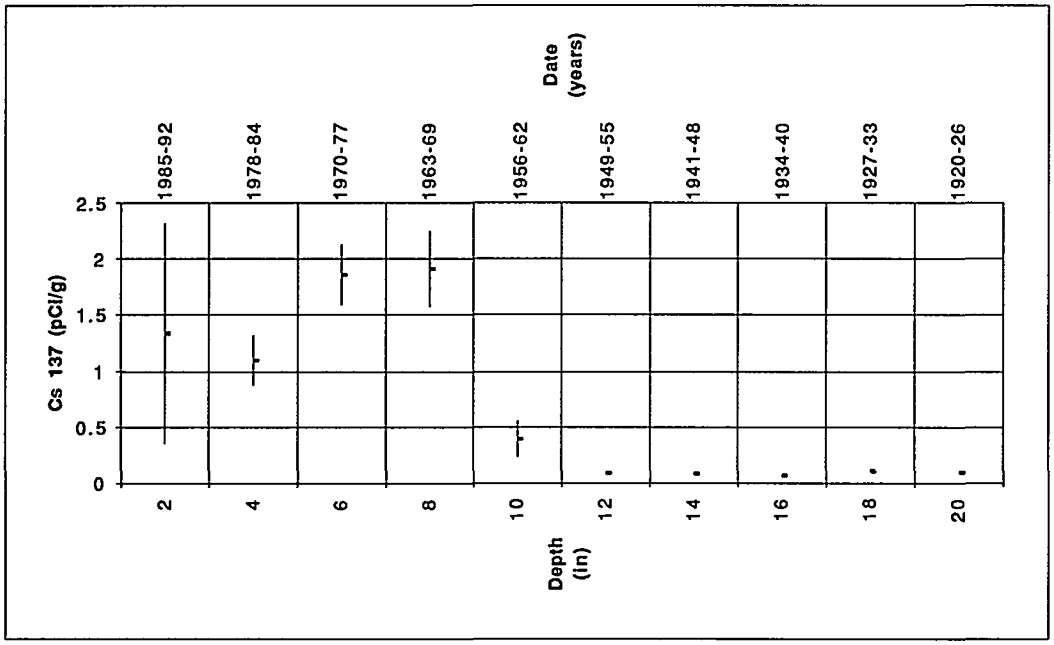


Figure 8. Depth distribution of Cs-137 and Pu-239,240 in Mower Reservoir sediment based on Core # SED 08992. Corresponding sediment layer dates are illustrated for cesium or plutonium dating. For data points where there are no confidence interval, the value was below the detection limit.



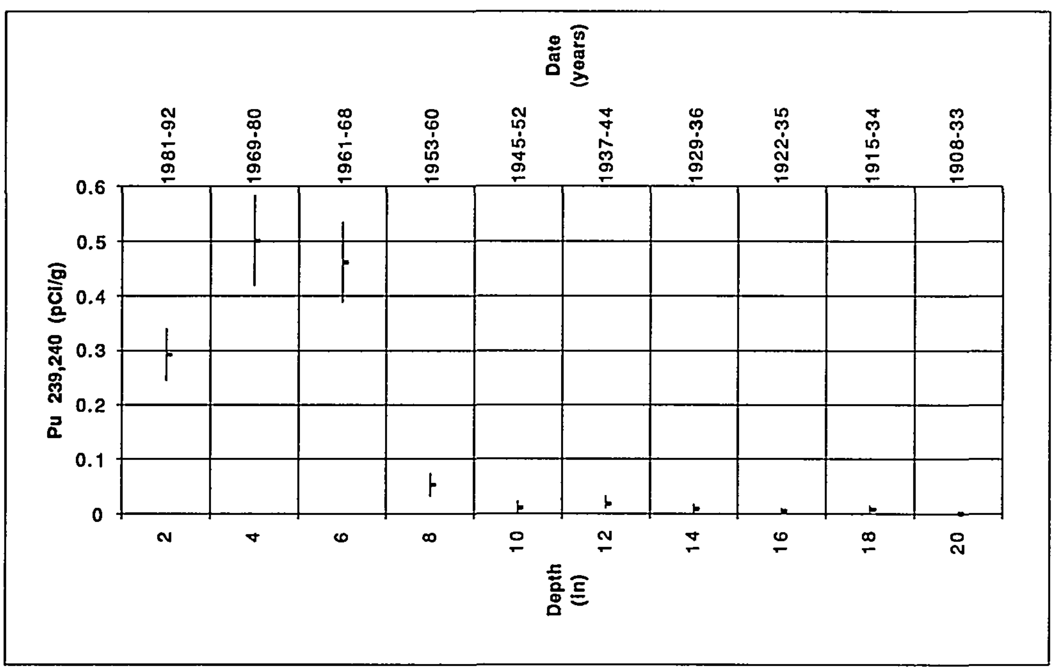


Figure 9. Depth distribution of Cs-137 and Pu-239,240 in Mower Reservoir sediment based on Core # SED 08892. Corresponding sediment layer dates are illustrated for cesium or plutonium dating. For data points where there are no confidence intervals, the value was below the detection limit.

Table 1. Standley Lake Cs-137 and Pu-239,240 sediment activity and errors based on 1992 OU3 sediment core samples.

LOCATION NUMBER	Depth (inches)	Cs-137 (pCi/g)	Error (pCi/g)	Pu-239,240 (pCi/g)	Error (pCi/g)
SED08392	2	0.36	u (3)	0.0249	0.0128
	4	0.34	u (3)	0.028	0.0114
	6	0.397	0.124	0.0412	0.0145
	8	0.614	0.182	0.0505	0.0187
	10	0.765	0.287	0.0705	0.0218
	12	0.716	0.221	0.0796	0.022
	14	0.946	0.242	0.139	0.032
	16	1.29	0.35	0.265	0.046
	18	1.4	0.21	**0.38(2)**	**0.063**
	20	**1.61(1)**	**0.23**	0.101	0.025
	22	0.534	0.088	0.0408	0.0158

Note:
1. Core's peak cesium activity.
2. Core's peak plutonium activity.
3. u = below instrument detection limit.

Table 2. *Standley Lake Cs-137 and Pu-239,240 sediment dating based on 1992 OU3 sediment core samples.*

LOCATION NUMBER	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)
SED08392	2	1989-92	1989-92
	4	1986-88	1987-88
	6	1983-85	1983-86
	8	1980-82	1981-82
	10	1978-79	1979-80
	12	1975-77	1976-78
	14	1972-74	1974-75
	16	1969-71	1971-73
	18(3)	1966-68	**1969-70**
	20(2)	**1963-65**	1966-68
	22	1960-62	1964-65

Note:
1. The cesium and plutonium based sedimentation rates for Standley Lake based on core #SED08392 are 0.7 and 0.8 in/yr respectively.
2. Core's peak cesium activity interval.
3. Core's peak plutonium activity interval.

Table 3. Great Western Reservoir Cs-137 and Pu-239,240 sediment activity and errors based on 1992 OU3 sediment core samples.

LOCATION NUMBER	Depth (inches)	Cs-137 (pCi/g)	Error (pCi/g)	Pu-239,240 (pCi/g)	Error (pCi/g)
SED08692	2	0.252	0.056	0.1246	0.033
	4	0.272	0.075	0.1915	0.0623
	6	0.2	0 (3)	0.3745	0.0694
	8	0.238	0.043	0.1809	0.046
	10	0.214	0.062	0.1875	0.0775
	12	0.176	0.072	0.1887	0.0403
	14	0.462	0.076	0.8958	0.125
	16	0.461	0.104	1.437	0.2
	18	0.528	0.173	2.313	0.325
	20	0.725	0.109	2.698	0.335
	22	0.975	0.2	**3.263(2)**	**0.421**
	24	1.3	0.18	3.183	0.459
	26	**1.66(1)**	**0.2**	1.266	0.192
	28	1.34	0.19	2.413	0.36
SED09192	2	0.248	0.077	0.0891	0.034
	4	0.299	0.11	0.134	0.034
	6	0.16	u	0.154	0.038
	8	0.34	0.136	0.191	0.043
	10	0.23	u	0.243	0.051
	12	0.379	0.099	0.519	0.091
	14	0.55	0.09	1.23	0.18
	16	0.651	0.109	1.74	0.24
	18	0.31	u	2.87	0.43
	20	0.848	0.142	**4.03(2)**	**0.5**
	22	1.01	0.21	2.88	0.37
	24	1.33	0.38	1.93	0.25
	26	**3.93(1)**	**1.58**	1.16	0.16
	28	1.61	0.38	2.61	0.35

Note:
1. Core's peak cesium activity.
2. Core's peak plutonium activity.
3. u = below instrument detection limit.

Table 4. Great Western Reservoir Cs-137 and Pu-239,240 sediment dating based on 1992 OU3 sediment core samples.

LOCATION NUMBER	Depth (inches)	Cs dated Sediment Age (years)	Pu dated Sediment Age (years)
SED08692	2	1990-92	1991-92
	4	1988-89	1989-90
	6	1985-87	1986-88
	8	1983-84	1984-85
	10	1981-82	1982-83
	12	1979-80	1980-81
	14	1976-78	1978-79
	16	1974-75	1976-77
	18	1972-73	1973-75
	20	1970-71	1971-72
	22	1968-69	**1969-70(3)**
	24	1965-67	1967-68
	26	**1963-64(2)**	1964-66
	28	1961-62	1962-63
SED09192	2	1990-92	1991-92
	4	1988-89	1988-90
	6	1985-87	1986-87
	8	1983-84	1983-85
	10	1981-82	1981-82
	12	1979-80	1979-80
	14	1976-78	1976-78
	16	1974-75	1974-75
	18	1972-73	1971-73
	20	1970-71	**1969-70(3)**
	22	1968-69	1967-68
	24	1965-67	1965-66
	26	**1963-64(2)**	1963-64
	28	1961-62	1960-62

Note:
1. The cesium and plutonium based sedimentation rate for GWR based on cores #SED08692 and #SED09192 is 0.9 in./yr.
2. Core's peak cesium activity interval.
3. Core's peak plutonium activity interval.

Table 5. Mower Reservoir Cs-137 and Pu-239,240 sediment activity and errors based on 1992 OU3 sediment core samples.

LOCATION NUMBER	Depth (inches)	Cs-137 (pCi/g)	Error (pCi/g)	Pu-239,240 (pCi/g)	Error (pCi/g)
SED08892	2	1.34	0.98	0.292	0.048
	4	1.1	0.22	**0.502(2)**	0.082
	6	1.86	0.27	0.462	0.073
	8	**1.91(1)**	0.34	0.0214	0.0214
	10	0.396	0.161	0.0122	0.0122
	12	0.093	u (3)	0.0147	0.0147
	14	0.088	u	0.00871	0.00871
	16	0.068	u	0.00642	0.00642
	18	0.11	u	0.00761	0.00761
	20	0.099	u	0.00427	0.00427
SED08992	2	1.05	0.32	0.3811	0.0836
	4	1.29	0.25	0.6509	0.132
	6	1.42	0.33	**1.112(2)**	0.17
	8	**1.96(1)**	0.41	0.6001	0.121
	10	1.19	0.16	0.1281	0.038
	12	0.143	0.043	0.04021	0.029
	14	0.026	u	0.01186	u
	16	0.051	u	0.01393	u
	18	0.073	u	0.00779	u

Note:
1. Core's peak cesium activity.
2. Core's peak plutonium activity.
3. u = below instrument detection limit.

Table 6. Mower Reservoir Cs-137 and Pu-239,240 sediment dating based on 1992 OU3 sediment core samples.

LOCATION NUMBER	Depth (inches)	Cs dated Sediment Age (years)	Pu dated Sediment Age (years)
SED08892	2	1985-92	1981-92
	4	1978-84	**1969-80(3)**
	6	1970-77	1961-68
	8	**1963-69(2)**	1953-60
	10	1956-62	1945-52
	12	1949-55	1937-44
	14	1941-48	1929-36
	16	1934-40	1922-35
	18	1927-33	1915-34
	20	1920-26	1908-33
SED08992	2	1985-92	1984-92
	4	1978-84	1977-83
	6	1970-77	**1969-76(3)**
	8	**1963-69(2)**	1962-68
	10	1956-62	1954-61
	12	1949-55	1947-53
	14	1941-48	1939-46
	16	1934-40	1931-38
	18	1927-33	1924-30

Note:
1. The cesium and plutonium based sedimentation rate for Mower Reservoir based on cores #SED08892 and SED08992 is 0.3 in./yr.
2. Core's peak cesium activity interval.
3. Core's peak plutonium activity interval.

Table 7. Paired t-test on core pairs within Great Western Reservoir and Mower Reservoir.

Location	LOCATION NUMBER	Mean Difference	DF	t-Value	P-Value
Great Western Reservoir	SED08692 SED09192	-0.221	13	-1.374	0.1928
Mower Reservoir	SED08892 SED08992	0.026	8	0.23	0.8236

Table 8. Summary of OU3 and historic sediment dating (refer to Appendix 1-5).

STUDY	Standley Lake SAMPLED	Standley Lake SEDIMENTATION RATE COMPARISON WITH OU3 (OU3 : Study) (in./yr.)	Standley Lake OU3 SEDIMENT DATING COMPARISON	Great Western Reservoir SAMPLED	Great Western Reservoir SEDIMENTATION RATE COMPARISON WITH OU3 (OU3 : Study) (in./yr.)	Great Western Reservoir OU3 SEDIMENT DATING COMPARISON
EPA 1970	YES	0.7-0.8 : 6.1	POOR + 3 yr	YES	-	Core Thickness Inadaquate
Hardy et al. 1978	YES	0.7-0.8 : 1.24-1.28	GOOD + 0 to 1 yr	NO	-	-
Thomas and Robertson 1981	YES	0.7-0.8 : 0.98	FAIR +0 to 2 yrs	YES	0.9 : 1.48	FAIR +1 to 2 yrs
Rockwell International 1985	NO	-	-	YES	0.9 : 1.20	FAIR + 2 yrs
Rockwell International (Broomfield analysis)1985	NO	-	-	YES	-	Core Thickness Inadaquate

Note: When possible, sedimentation rates were based on cores taken from the deepest reservoir area.

Appendix A-1. Comparison of Standley Lake Pu dating by OU3 (1992) and EPA (1970).

	OU3 (1992)			EPA core #14c	
LOCATION NUMBER	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)	Depth (inches)	Pu Dated Sediment Age (years)
SED08392	0-2.0	1989-92	1989-92		
	2.0-4.0	1986-88	1987-88		
	4.0-6.0	1983-85	1983-86		
	6.0-8.0	1980-82	1981-82	0-2.25	1970
	8.0-10.0	1978-79	1979-80	2.25-4.25	1970
	10.0-12.0	1975-77	1976-78		1970
	12.0-14.0	1972-74	1974-75	7.25-8.25	1969
	14.0-16.0	1969-71	1971-73		1969
	16.0-18.0	1966-68	**1969-70(2)**	**11.25-12.25(1)**	**1969(2)**
	18.0-20.0	**1963-65(1)**	1966-68	12.25-14.75	1968
	20.0-22.0	1960-62	1964-65		

Note:
1. Core's peak cesium activity interval.
2. Core's peak plutonium activity interval.
3. OU3 (1992) sedimentation rate is 0.7-0.8 in./yr.
4. EPA (1970) sedimentation rate based on core 14C is 6.13 in./yr. They recorded sedimentation rates of 1.1-1.61 in./yr. based on all their cores.

Appendix A-2. Comparison of Standley Lake Cs and Pu dating by OU3 (1992) and Hardy (1980).

	OU3 (1992)			Hardy et al. core #1		
LOCATION NUMBER	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)
SED08392	0-2.0	1989-92	1989-92			
	2.0-4.0	1986-88	1987-88			
	4.0-6.0	1983-85	1983-86			
	6.0-8.0	1980-82	1981-82			
	8.0-10.0	1978-79	1979-80			
	10.0-12.0	1975-77	1976-78	0-2.36	1975-76	1975-76
	12.0-14.0	1972-74	1974-75	2.36-4.72	1973-75	1973-75
	14.0-16.0	1969-71	1971-73	4.72-7.87	1971-73	1971-73
	16.0-18.0	1966-68	**1969-70(2)**	7.87-10.24	1969-70	**1969-70(2)**
	18.0-20.0	**1963-65(1)**	1966-68	10.24-12.6	1967-1968	1967-68
	20.0-22.0	1960-62	1964-65	12.6-14.96	1965-1966	1965-67
				14.96-18.11	**1962-64(1)**	1963-65
				18.11-19.69	1961-62	1962

Note: 1. Core's peak cesium activity interval.
2. Core's peak plutonium activity interval.
3. OU3 (1992) sedimentation rate is 0.7-0.8 in./yr.
4. Hardy (1980) recorded a sedimentation rate of 1.3 in./yr.

Appendix A-3. Comparison of Standley Lake Cs and Pu dating by OU3 (1992) and Thomas and Robertson (1981).

	OU3			Thomas and Robertson core #5	
LOCATION NUMBER	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)	Depth (inches)	Cs Dated Sediment Age (years)
SED08392	0-2.0	1989-92	1989-92		
	2.0-4.0	1986-88	1987-88	0-1.97	1974
	4.0-6.0	1983-85	1983-86	1.97-3.94	1973
	6.0-8.0	1980-82	1981-82	3.94-5.91	1972
	8.0-10.0	1978-79	1979-80	5.91-7.87	1971
	10.0-12.0	1975-77	1976-78	7.87-9.84	1969
	12.0-14.0	1972-74	1974-75	9.84-11.81	1967
	14.0-16.0	1969-71	1971-73	11.81-13.78	1966
	16.0-18.0	1966-68	**1969-70(2)**	13.78-15.75	1964
	18.0-20.0	**1963-65(1)**	1966-68	**15.75-17.72**	**1963(1)**
	20.0-22.0	1960-62	1964-65	17.72-19.69	1962

Note: 1. Core's peak cesium activity interval.
2. Core's peak plutonium activity interval.
3. OU3 (1992) sedimentation rate is 0.7-0.8 in./yr.
4. Thomas and Robertson (1981) sedimentation rate based on core #5 is 0.98 in./yr.

Appendix A-4. Comparison of Great Western Reservoir Cs and Pu dating by OU3 (1992) and Thomas and Robertson (1981).

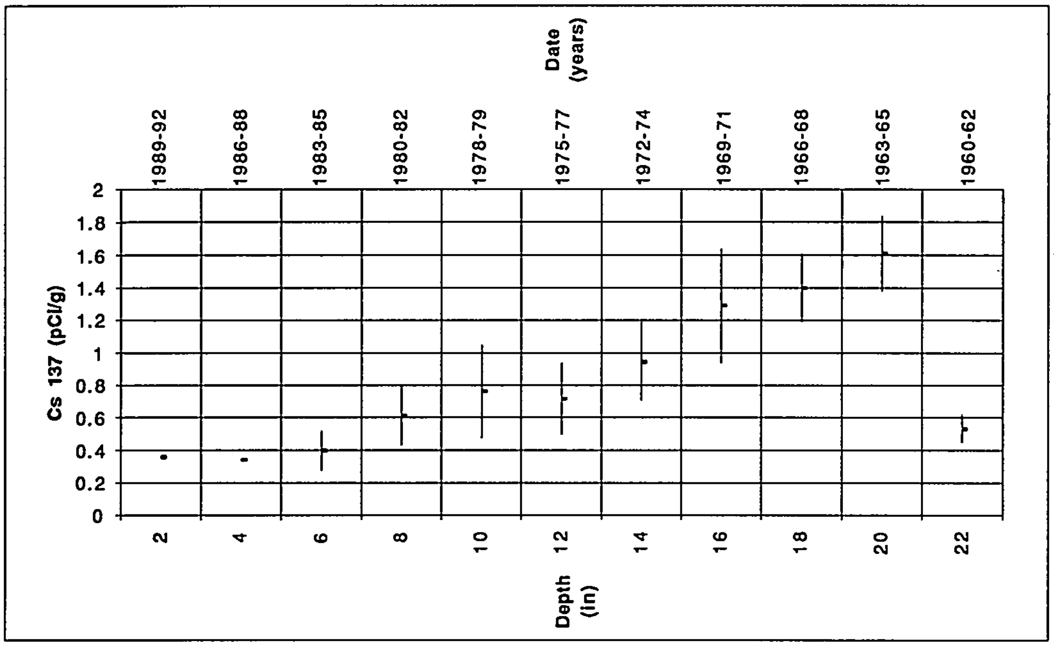
	OU-3			Thomas and Robertson core #A-3	
LOCATION NUMBER	Depth (inches)	Cs Dated Sediment Age (years)	Pu Dated Sediment Age (years)	Depth (inches)	Cs Dated Sediment Age (years)
SED08692	2	1990-92	1991-92		
	4	1988-89	1989-90		
	6	1985-87	1986-88		
	8	1983-84	1984-85		
	10	1981-82	1982-83	0-1.97	1974
	12	1979-80	1980-81	1.97-3.94	1973
	14	1976-78	1978-79	3.94-5.91	1972
	16	1974-75	1976-77	5.91-7.87	1971
	18	1972-73	1973-75	7.87-9.84	1969
	20	1970-71	1971-72	9.84-11.81	1967
	22	1967-69	**1969-70(2)**	11.81-13.78	1966
	24	1965-66	1967-68	13.78-15.75	1964
	26	**1963-64(1)**	1964-66	**15.75-17.72**	**1963(1)**
	28	1961-62	1962-63	17.72-19.69	1962
SED09192	2	1990-92	1991-92		
	4	1988-89	1988-90		
	6	1985-87	1986-87		
	8	1983-84	1983-85		
	10	1981-82	1981-82	0-1.97	1974
	12	1979-80	1979-80	1.97-3.94	1973
	14	1976-78	1976-78	3.94-5.91	1972
	16	1974-75	1974-75	5.91-7.87	1971
	18	1972-73	1971-73	7.87-9.84	1969
	20	1970-71	**1969-70(2)**	9.84-11.81	1967
	22	1967-69	1967-68	11.81-13.78	1966
	24	1965-66	1965-66	13.78-15.75	1964
	26	**1963-64(1)**	1963-64	**15.75-17.72**	**1963(1)**
	28	1961-62	1960-62	17.72-19.69	1962

Note:
1. Core's peak cesium concentration interval.
2. Core's peak plutonium concentration interval.
3. OU3 (1992) sedimentation rate based on core #SED09192 is 0.9 in./yr.
4. Thomas and Robertson (1981) sedimentation rate based on core A-3 is 1.48 in./yr.

Appendix A-5. Great Western Reservoir OU3 (1992) Cs/Pu dating compared to Pu dating from Rockwell International (1985).

	OU3			RI core KB#4	
LOCATION NUMBER	Depth (inches)	Cs dated Sediment Age (years)	Pu dated Sediment Age (years)	Depth (inches)	Pu dated Sediment Age (years)
SED08692	2	1990-92	1991-92		
	4	1988-89	1989-90		
	6	1985-87	1986-88	0-2	1983
	8	1983-84	1984-85	2-4	1982
	10	1981-82	1982-83	4-6	1980-81
	12	1979-80	1980-81	6-8	1978-79
	14	1976-78	1978-79	8-10	1976-77
	16	1974-75	1976-77	10-12	1974-75
	18	1972-73	1973-75	12-14	1972-73
	20	1970-71	1971-72	14-16	1970-71
	22	1967-69	**1969-70(2)**	**16-18**	**1969 (2)**
	24	1965-66	1967-68	18-20	1967-68
	26	**1963-64(1)**	1964-66		
	28	1961-62	1962-63		
SED09192	2	1990-92	1991-92		
	4	1988-89	1988-90	0-2	1983
	6	1985-87	1986-87	2-4	1982
	8	1983-84	1983-85	4-6	1980-81
	10	1981-82	1981-82	6-8	1978-79
	12	1979-80	1979-80	8-10	1976-77
	14	1976-78	1976-78	10-12	1974-75
	16	1974-75	1974-75	12-14	1972-73
	18	1972-73	1971-73	14-16	1970-71
	20	1970-71	**1969-70(2)**	**16-18**	**1969 (2)**
	22	1967-69	1967-68	18-20	1967-68
	24	1965-66	1965-66		
	26	**1963-64(1)**	1963-64		
	28	1961-62	1960-62		

Note: 1. Core's peak cesium concentration interval.
2. Core's peak plutonium concentration interval.
3. OU3 SED09192 (1992) Sedimentaion rate is 0.9 in./yr.
4. Rockwell International (1985) sedimentaion rate is 1.2 in./yr. based on core KB #4.



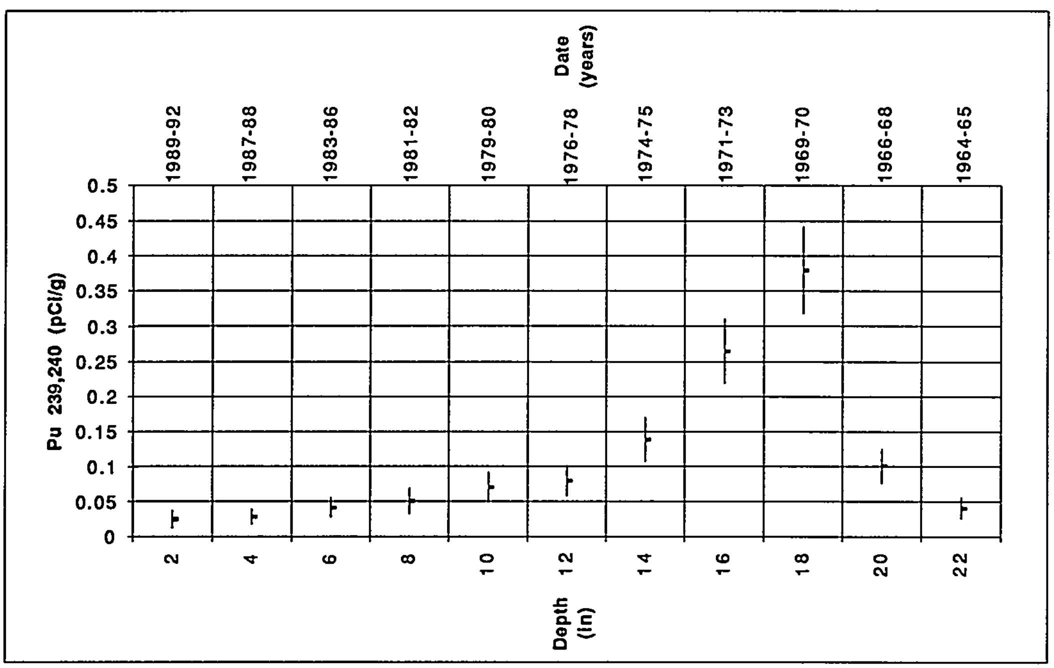


Figure 5. Depth distribution of Cs-137 and Pu 239,240 in Standley Lake sediment based on Core # SED08392. Sediment layer dates are illustrated for cesium or plutonium dating. For data points where there are no confidence intervals, the value was below the detection limit.