THE HISTORY OF PLUTONIUM AND CESIUM - 137 CONTAMINATION OF THE OB RIVER DELTA SEDIMENTS

by

George P. Panteleyev

M.S., Geology and Geochemistry
Moscow State University, 1988

submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

at the
Massachusetts Institute of Technology
and the
Woods Hole Oceanographic Institution

May, 1995

Signature of Author _____
Joint Program in Oceanography and Oceanographic Engineering
Massachusetts Institute of Technology/
Woods Hole Oceanographic Institution

certified by _____
Dr. Frederick L Sayles
Woods Hole Oceanographic Institution

and _____
Dr. Hugh D. Livingston
Woods Hole Oceanographic Institution
Thesis Co-supervisor

Accepted by _____
Dr. Daniel J. Repeta,
Chairman, Joint Committee for Chemical Oceanography
Massachusetts Institute of Technology / Woods Hole Oceanographic Institution

PREFACE

Woods Hole
17 December, 1995

On June 8, 1995 George P. Panteleyev lost his life while leading an expedition on the Ob River, Siberia. Gera, as he was known to his many friends, was in the final stages of completing this thesis when he left for Siberia, intending to submit it on his return. We have intentionally changed little in the thesis that Gera left with us; we have completed the editing that was included in the third draft he had prepared and added some missing figures and text. The thesis is Gera's in its entirety, while we take responsibility for the editorial errors that escaped notice.

We have not presumed to attempt to acknowledge the help that Gera received from his many friends, although we know he would have done so in his usual thoughtful and thorough manner. It is simply too personal an aspect of a thesis for someone else to undertake and we do not feel it would be appropriate. We are certain he would have emphasized the enduring support and encouragement he received from his wife Natasha, his parents Alla and Pavel, and his brother Shasha. In the Acknowledgement, we have limited ourselves to noting the sources of financial support that made Gera's research possible and this thesis a reality. We would like to note here the help of Joanne Goudreau and Joanna Ireland that was essential to completing the thesis.

The research that forms the basis of Gera's thesis was always intended to be more than a Master's thesis and will be a significant contribution to knowledge about the distribution, fate and transport of artificial radionuclides in river systems in general and the Ob watershed in particular. It also stands as a success story in the realm of post-Cold War scientific cooperation between American and Russian scientists. This was an area which interested Gera greatly and the success that this project has achieved is due in large part to his vision, enthusiasm and energy.

We take this opportunity to express our appreciation and gratitude for the dedication which Gera brought to his research and to pay tribute to him for the central role he played so well in the development and conduct of the Ob River Project. His thesis represents the product of his efforts and is a fitting testimonial to his knowledge, ability, and skill.

We are proud to have had the opportunity to work with Gera, to learn from him, and to share his vision of Russian-American cooperation in environmental research; he is sorely missed in our laboratory. We extend our deepest sympathy to Natasha, and to Alla, Pavel and Sasha, whose loss defies understanding.

Hugh D. Livingston

Frederick L. Sayles

ABSTRACT

Much of the nuclear activity of the Former Soviet Union took place within or adjacent to the confines of the Ob River drainage basin. These activities include weapons production and reprocessing at Chelyabinsk-65 (also called Chelyabinsk-40 and Mayak) and the Siberian Radiochemical Plant of Tomsk-7, nuclear weapons testing at Semipalatinsk and uranium mining and milling on the Ishym River. These sites have been the locations of accidental and planned releases of major amounts of radioactive materials since the dawn of the nuclear era. More important, these sites contain vast amounts radioactive waste, in storage, released to the environment, and injected into geologic formations at relatively shallow depth. In total there is thought to be on the order of 2.5 billion curies of radioactive materials presently located within the Ob River basin. Since the Ob is one of the largest rivers flowing into the Arctic, there has been considerable concern over past delivery of radioactive contaminants to the Arctic and the potential for much larger future releases.

This project was initiated as part of the Arctic Nuclear Waste Program (ANWAP), administered through the Office of Naval Research, to attempt to characterize the time history of radioactive contaminant transport in the Ob River and to identify the sources of those contaminants. The project has focused on the use of sediment cores to define the distributions of the particle reactive isotopes Cs-137, Pu-239,240, and Pu-238 with depth in sediments. To preserve a temporal record, the sediments need to be deposited more or less continuously and to not be subject to mixing. Meeting these criteria led to a focus on sampling in the shallow "sor" and oxbow lakes that are abundant in the flood plain of the Ob delta as sources of undisturbed sediment.

To gain access to the lakes on the flood plain it was necessary to design and build a shallow draft vessel that could navigate the shallow channels and marshes that connect the lakes to the main channels and still accommodate coring operations. An inflatable catamaran was built for this purpose and used during the month of July, 1994 for field operations. A Russian Fisheries Protection vessel served as a base of operations and means of transport between stations for the catamaran. Samples were collected at 17 sites from the delta to the Ob Estuary. Eight of the cores collected were analyzed in detail for the isotopes noted above and for Pb-210; seven of these were from the Ob delta and estuary, and one was from the Taz estuary, a river with no nuclear facilities in its watershed.

The patterns of distribution of Cs-137 with depth in most of the cores are very similar. Distributions of Pu-239,240 closely follow those of Cs-137. The depth distribution pattern in the Taz is also essentially the same as those observed in the Ob cores. All of the cores are characterized by relatively low surface activities, a strong subsurface maximum, and activities that decrease sharply to below detection beneath the maximum. The depth of the subsurface maximum varies in response to differing sedimentation rates as do the absolute activities observed in a given core. Consistent with the similarity of the Cs-137 and Pu-239,240 distributions, Pu-239,240/Cs-137 ratios are

constant in most cores; they are also very similar in all of the cores, save possibly for the Taz which is slightly higher. The distributions are qualitatively similar to those reported in other areas and attributed to a global fallout source. Time scales of deposition established on the basis of excess Pb-210 are consistent with a fallout source, placing the introduction of Cs-137 and Pu-239,240 at approximately 1950 and the subsurface maxima at around 1963, the time of maximum fallout deposition reported for Fairbanks and Anchorage, Alaska. The Pu/Cs ratios, corrected to 1994, are also consistent with a fallout origin and much greater than that reported for contaminated sediments in the vicinity of the weapons plants in this region.

These studies support several conclusions regarding the deposition of the radioactive contaminants studied and the sources of these nuclides.

1) The sediments of many "sor" and oxbow lakes on the flood plain preserve a record of particle reactive contaminant transport down the Ob River. There is little or no evidence of mixing of the record in many of the cores collected. These sediments should preserve the temporal histories of other particle reactive contaminants as well.

2) Based on the patterns and time scale of deposition, the Pu/Cs ratios, and the similarity of the Ob and Taz distributions, the primary source of the Cs-137 and Pu isotopes in these sediments is global fallout.

3) Uncertainties in the analyses could permit perhaps 25% of the isotopes studied to be derived from a Mayak-like source. However, the data do not require any source other than global fallout. Consequently, we conclude that local sources make little if any contribution to these sediments.

ACKNOWLEDGEMENTS

(Please see Preface)

Financial support for the research that forms the basis of this thesis and has supported the thesis itself has come from several sources and is gratefully acknowledged:

1. The Ocean Ventures Fund of the Woods Hole Oceanographic Institution.

2. The Education Program of the Woods Hole Oceanographic Institution.

3. The Office of Naval Research through the Arctic Nuclear Waste Assessment Program, Grant No N00014-93-1-0641.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

Introduction

Understanding the geochemistry of Siberian rivers is an important task which will help to constrain the global water balance and cycles of chemical elements, and provide information about the influence of the Arctic Ocean on the global climate. Understanding the behavior of artificial radionuclides in the Arctic is of environmental concern, especially with the end of the Cold War and revelations about practices of handling radioactive materials in the nuclear states. Among the important issues related to radioactivity in the Arctic are the types, amounts and fates of artificial radionuclides delivered to the Arctic Ocean by Siberian rivers. The answers to these questions are controversial and remain largely unknown.

In this study we address radioactive contamination of the Ob River Delta by particle reactive artificial radionuclides. The Ob River has been subject to serious accidental and intentional releases of radioactivity in the past and has a potential for catastrophic future releases due to the estimated storage of in excess of 2.5 billions curies of radioactivity within the confines of its watershed. The time history of radionuclide transport to date is assessed by examining the radionuclide distributions in high accumulation rate, unmixed freshwater sediment in the Ob River Delta and Estuary. These studies allow us to address the transport, behavior, sources and fate of particle reactive radionuclides in the transition zone from the continent to the Arctic Ocean.

1-A. Ob River System

The Ob is one of the biggest rivers in the world, draining an area of 2.5 million km^2 which includes the areas of West Siberian, the Central and North Kazakhstan plains, and the Ural and Altay Mountains (Fig. 1). The Ob flows into the Kara Sea with a mean annual discharge of about 390 km^3 (Voskresenskiy, 1963). The total annual sediment discharge by the Ob river (19.9×10^6 tons) is about 1/3 smaller (30.2×10^6 tons) than the

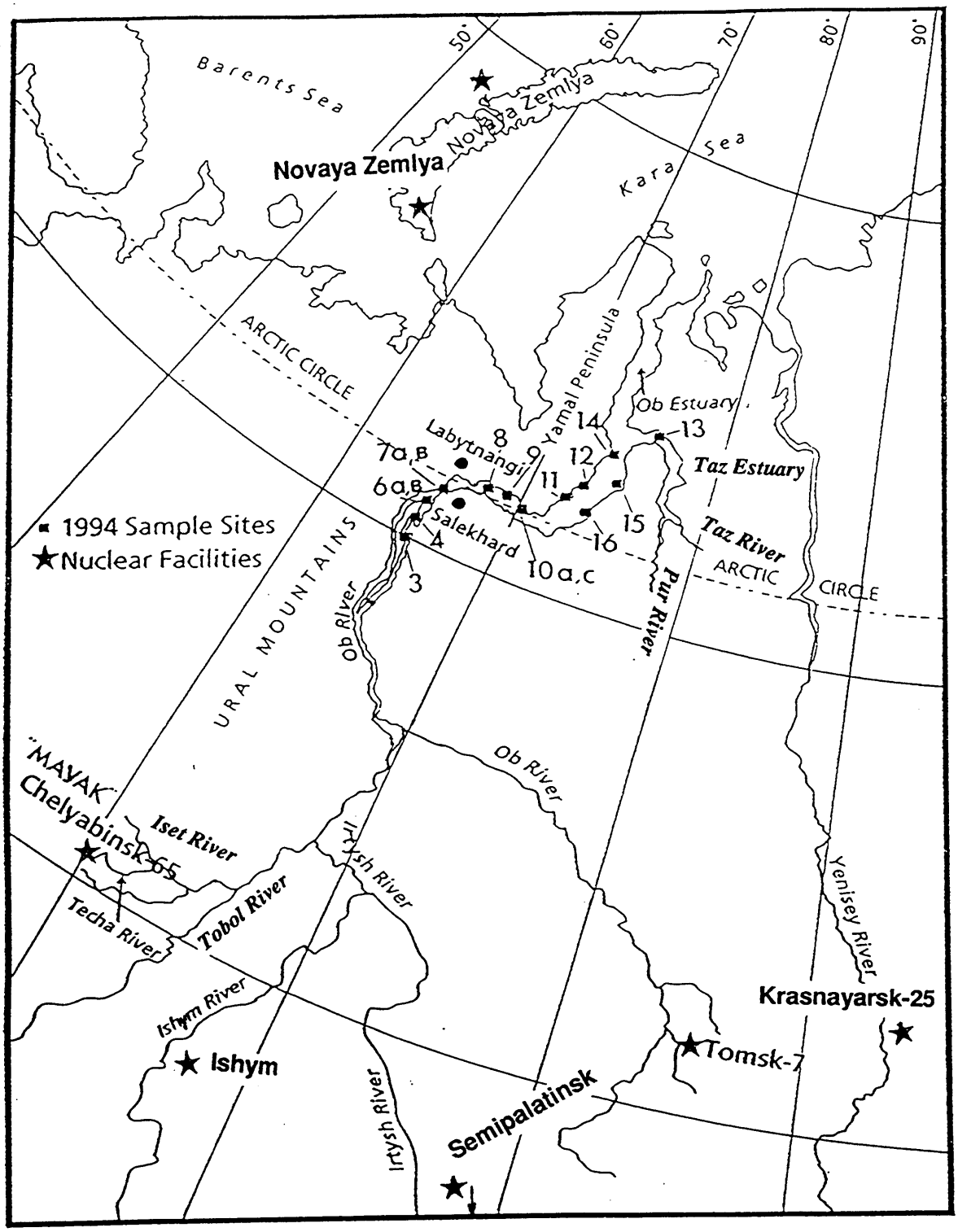


Fig. 1. Map of the Ob River main tributaries and sampling locations of the Joint Russian-American Expedition "Ob Estuary -1994".

discharge of dissolved chemical components (Nesterova, 1960). The estuary of the Ob River (also known as Obskaya Guba) is a complex region, 800 km long and 35 to 82 km wide, with an average depth of 10-12 meters. The Taz Estuary, at the mouths of the Taz and Pur rivers forms an eastward extension of the Ob Estuary halfway to the Kara Sea. An important characteristic of the Ob Estuary is that all year around the southern part (south of 69°N, including theTaz Estuary) contains only fresh water. Even during the low-flow winter period and high wind tides, a net flow of 1-3 cm/sec towards the Kara Sea is maintained (Ivanov, 1980).

1-B. Sources of Radioactivity

There are many sources of radioactivity to the Ob River. The largest source of artificial radioactive elements globally dispersed in the environment is fallout from atmospheric nuclear weapons testing. Most atmospheric testing was carried out at the end of 50's and in the early 60's, prior to the Limited Test Ban Treaty of 1963. There are two test sites of this kind in close proximity to the Ob watershed. One is the nuclear facility on Novaya Zemlya Island to the north of the Ob Estuary (Fig. 1) where the Soviet Union conducted 90 atmospheric tests, including the largest atmospheric nuclear explosion in history, a 50 megaton blast in 1961, and 42 underground explosions. The other is the Semipalatinsk Testing Site situated in headwaters of the Irtysh River, a southern tributary of the Ob River where 132 tests were carried out. These two sites contributed substantially to the global fallout and possibly to the close-in fallout of the Ob River watershed. In addition, Chelyabinsk-40 (also known as Chelyabinsk-65 and "Mayak"), a nuclear weapons production facility, the Siberian Radiochemical Plant (Tomsk-7), and the Ishym Uranium Ore Mine are located in the headwaters of the Ob River basin. These sites have a known history of accidental and intentional releases of radioactivity. Also, fallout from the Chernobyl accident may have contributed slightly to the radioactive contamination of the Ob river system. The extent to which radioactivity from these sources has been carried down the Ob and delivered to the Ob Estuary and, eventually, to the Arctic Ocean is largely unknown.

1-C. Radionuclide Time History Reconstruction in Fresh Water Sediments

The distribution of artificial radionuclides with depth in unmixed estuarine and lacustrine sediments has been used by many researchers to reconstruct time histories of radionuclide inputs to drainage basins, and to determine their sources, transport, fate and geochemical behavior (Olsen et. al., 1978,1981; Hardy et. al., 1980; Breteler et. al., 1984; Beasley and Jennings, 1984; Beasley, 1987). Also, Smith and Ellis (1982) have used Pb-210 and the fallout radionuclides, Cs-137, Pu-238 and Pu-239,240 to resolve the annual cyclicity in the estuarine sedimentation patterns of the Saguenay Fjord (Canada) and to identify the source function for sediment inputs. Krey (1976), used mass spectrometric techniques to identify the origins of plutonium in soil samples. Their identification is based on the fact that plutonium from different sources is characterized by distinct isotopic ratios. Pu of cumulative fallout origin has characteristic ratios for the isotopes comprising the material. As of January of 1971, these atom ratios were as follows: Pu-240/Pu-239=0.176$\pm$0.014; Pu-241/Pu-239=0.0086$\pm$ 0.0017; Pu-242/Pu-239=0.0044$\pm$0.0011; Pu-240/Pu-242=40$\pm$10). Plutonium from reactors or fuel reprocessing plants carries an isotopic signature characteristic of "low burn-up" Pu; atom ratios are typically near: Pu-240/Pu-239 = 0.06; Pu-241/Pu-239= 0.0043; Pu-242/Pu-239P= 0.00014; Pu-240/Pu-242 =454 (Sanders and Boni, 1980). Thus, using two-component mixing theory (Faure, 1986) it is possible to estimate the contribution of each Pu source to the total Pu in a sample. Beasley (1987) has shown that the Pu-239,240 sediment inventory derived from fallout, the total inventory of Cs-137 in the sediments, and the Pu-239,240/Cs-137 activity ratio in global fallout, assuming that the Pu-239,240/Cs-137 activity ratios remain unchanged during the erosional and depositional processes, permit one to calculate the Cs-137 in sediments that has come from reactors and other land sources. The cooling of nuclear reactors with river water and its subsequent return to the river provides a wide spectrum of radioactive transition elements to the river water. Perkins et al. (1966) have studied a series of radionuclides in the waters of Columbia River that are the products of activation of river water constituents and corrosion products of the Hanford reactor cooling system. Most are short-lived radionuclides, the exceptions being relatively long-lived Mn-54, Co-

60, Zn-65, and Ru-106. Perkins et al. (1966) proposed that a study of the behavior of these radionuclides is useful in understanding the processes that take place in rivers since they provide important information in regard to their stable chemical analogs; i.e. their transport, sorption, and fate. The series of studies of the Columbia River and its estuary (Perkins et al., 1966; Foster, 1972; Beasley and Jennings, 1984; Beasley 1987) provide a relevant case study. However, an important contrast exists: the unique arctic weathering environment will certainly condition the behavior of transition and radioactive elements.

CHAPTER TWO

Sources of Radioactivity in the Ob River Watershed

As noted above, there are several possible sources of radioactivity to the Ob River Delta sediments. For some of them, like global fallout, the contribution to the Ob River watershed varies with latitude. Others, like accidental and intentional releases from the "MAYAK" Nuclear Production Facility, the Siberian Radiochemical Plant at Tomsk-7, the Chernobyl Nuclear Power Plant accident, the Novaya Zemlya and Semipalatinsk testing sites, as well as the other possible sources, are likely to influence only parts of the Ob River watershed. Here I present the brief overview of the available information about these sources.

2-A. Global Fallout Radioactivity

Artificial radioactivity was introduced to the atmosphere with the development and testing of the first nuclear device at the end of 1940's. Since then, artificial radionuclides have been dispersed around the globe.

Detonation of many nuclear devices in the atmosphere lead to the injection of fission products into the stratosphere. The altitude and location of the injection depend on the total yield of the device, detonation conditions and test location. After the debris is injected into the upper stratosphere, it slowly moves by gravitational settlement into the lower stratosphere and is dispersed by eddy diffusion around the globe. If a test occurs at temperate latitudes, the debris may be injected into the lower polar stratosphere. The debris would be transported into the troposphere mainly during the following spring (Larsen, 1985). The exchange between the polar stratosphere and the troposphere at temperate latitudes is accelerated in the late winter and early spring. This exchange results in increased fallout during this time period. The half-residence time (the time required for half the debris to be transported out of the stratosphere) is dependent on the season,

altitude and latitude of the injection into the stratosphere. Fallout from tests in the tropical latitudes conducted by the United States and the United Kingdom deposited more slowly than did debris from Soviet union tests that were conducted in the Arctic or at 50 degrees North latitude (Larsen, 1985).

The global atmospheric fallout of radionuclides has a strong latitudinal dependence, with the maximum fallout being in the mid-latitudes and minimum fallout towards the pole and equator (Hardy et al., 1973). For example, the cumulative fallout of Pu-239,240, as measured from the Pu inventory in soils, in the latitude belt of 70-80 degrees North (0.08 dpm/cm^2) is only about 16 percent of that in the 40-50 degrees North belt. Similarly, for other radionuclides derived from nuclear weapons tests, such as Sr-90, the fallout flux in the 70-80 degrees North belt is only about 8% of the value at mid-latitudes (Joseph et al., 1979).

The relative amounts of different radionuclides which are produced during nuclear tests do not vary over a wide range: Pu-239,240 activity is about 2-3 percent of the fission product Sr-90 radioactivity, and the Pu-238 activity from nuclear tests and a 1964 satellite power source burn-up is only 2 to 3 percent of the Pu-239,240 activity (Hardy, 1974).

2-A-1. Sr-90 and Cs-137 in Global Fallout

In 1954 a global network of fallout observation stations was established through the efforts of the HASL, now known as Environment Measurement Laboratory of the US Department of Energy (Hardy, 1977, Monetti & Larsen, 1991). The continuous record of monthly direct fallout deposition of Sr-90 was obtained for many locations around the world. Figure 2, provides a graphic illustration of annual deposition of Sr-90 in the Northern Hemisphere. The two maxima in the fallout deposition coincide with the maximum activity in atmospheric testing in 1956-1958 and 1962-1964 (Zander & R. Araskog, 1973). These nuclear tests delivered the bulk of artificial radioactivity to the atmosphere.

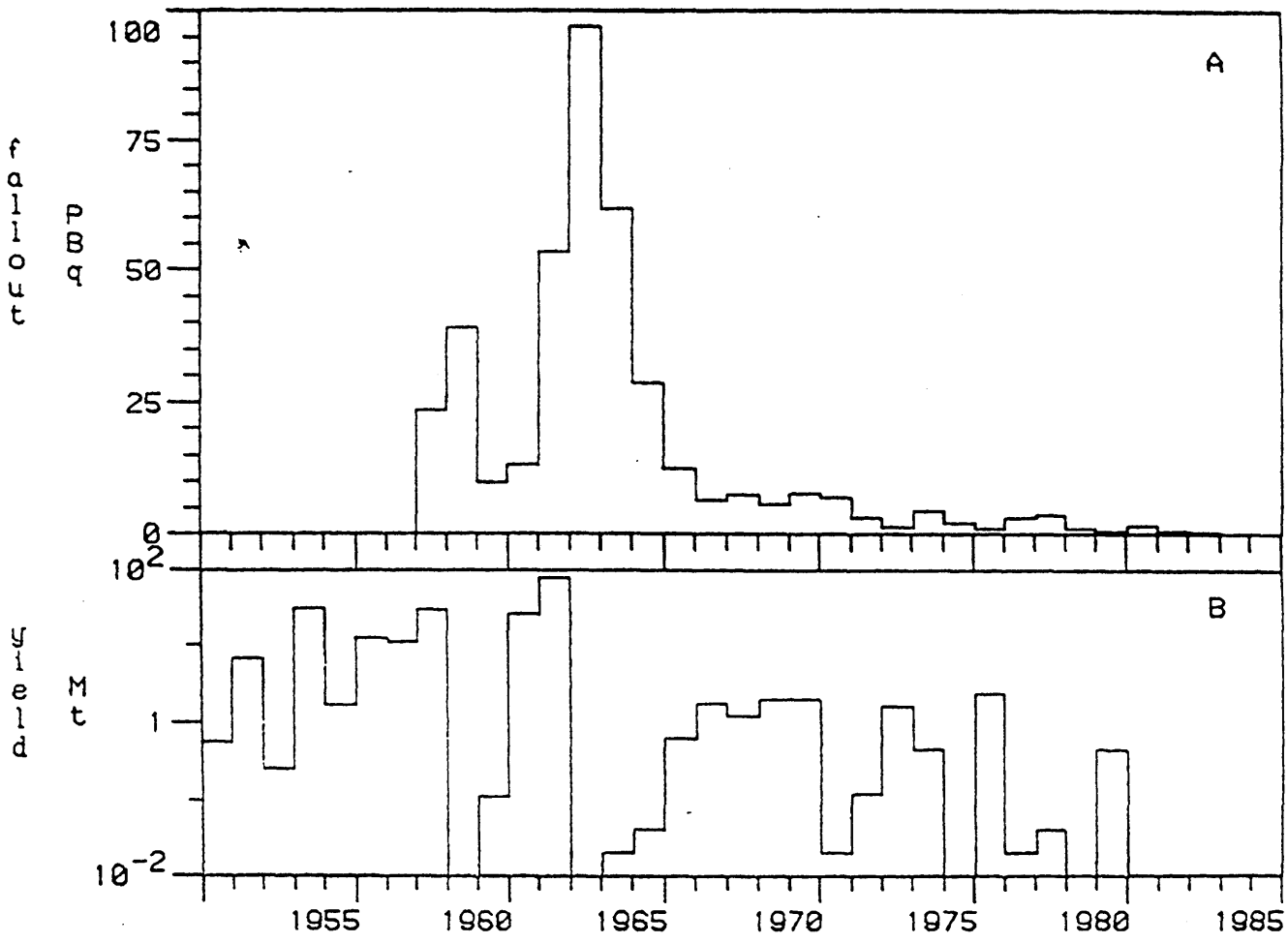


Fig. 2. A. Annual Deposition of Sr-90 in the Northern Hemisphere.
B. Annual Estimated Fission Yield of Atmospheric Nuclear Tests in the Northern Hemisphere.
(Larsen R. J. 1985, Worldwide Deposition of Sr-90 Through 1983. USDOE Report EML-444).

Larsen (1985) reported the record of Sr-90 fallout deposition for several locations around the globe. The Anchorage and Fairbanks sampling sites in Alaska are at 61° to 63°N, only slightly south of our sampling locations in the Ob River Delta and Estuary. The fallout data for these two locations (Fig. 3, 4) provide an estimate of the amount of Sr-90 which was delivered as direct fallout to the Ob River area.

Cs-137 has not been continuously measured by the EML (HASL) sampling network. However, during 1965-1966, an effort was made to estimate the deposition of this isotope from atmospheric nuclear tests (Hardy 1973). Based on these observations, Hardy (1973) concluded that the temporal and latitudinal variations in the Cs-137/Sr-90 ratio are random and that the average ratio could be assumed to be 1.6 ± 0.2. Bowen et al. (1974) summarized a large number of the seawater samples collected in and about Atlantic Ocean from 1966 to 1972 and concluded that the mean open ocean ratio was 1.43.

The variation of Cs-137/Sr-90 ratio through time (Fig. 5) in the ice shelf of Antarctica from the beginning of the Nuclear Age was presented by Koide et al. (1979). During the first stage of nuclear tests (1950-1959), they stated that Cs-137 was produced in a relatively greater amounts with the Cs-137/Sr-90 ratio varying between 1.05 and 3.05 and averaging 1.57. In later stage nuclear tests, they suggested that the Cs-137 yield was lower relative to Sr-90 and the ratio varied between 0.85 - 1.45 with an average ratio of around 1.2. However, these findings are not in agreement with other studies of global fallout in many countries.

Mr. Matthew Monetti of the USDOE Environment Measurement Laboratory provided me with the raw data on Sr-90 fallout deposition for the two Alaskan sites. Figures 6 and 7 represent a reconstructed time record of Cs-137 direct fallout deposition for the Fairbanks and Anchorage. The Sr-90 data for the period from 1954 to 1960 (when there was no EML observation at these locations) were estimated from the correlation (0.9776 and 0.9077 respectively) between the available Sr-90 data at EML in New York City and the Alaskan sampling sites. The Sr-90 data were converted to Cs-137 record

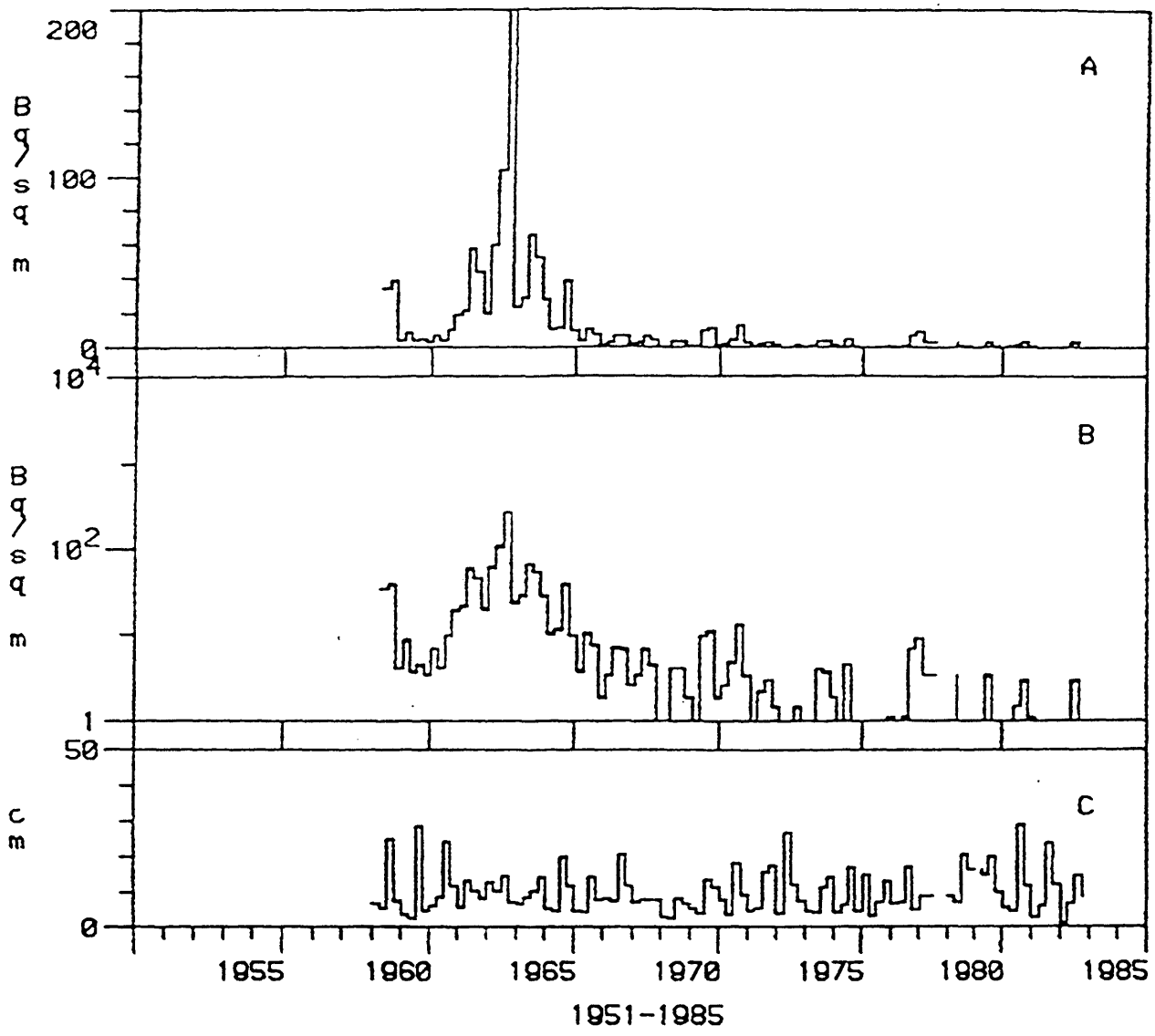


Fig. 3. A. Annual Deposition of Sr-90 (Bq/m2 on linear scale) in Alaska, Anchorage.
B. Annual Deposition of Sr-90 (Bq/m2 on semi-log scale) in Alaska, Anchorage.
C. Atmospheric precipitation (cm) in Alaska, Anchorage
(Larsen R. J. 1985, Worldwide Deposition of Sr-90 Through 1983. USDOE Report EML-444).

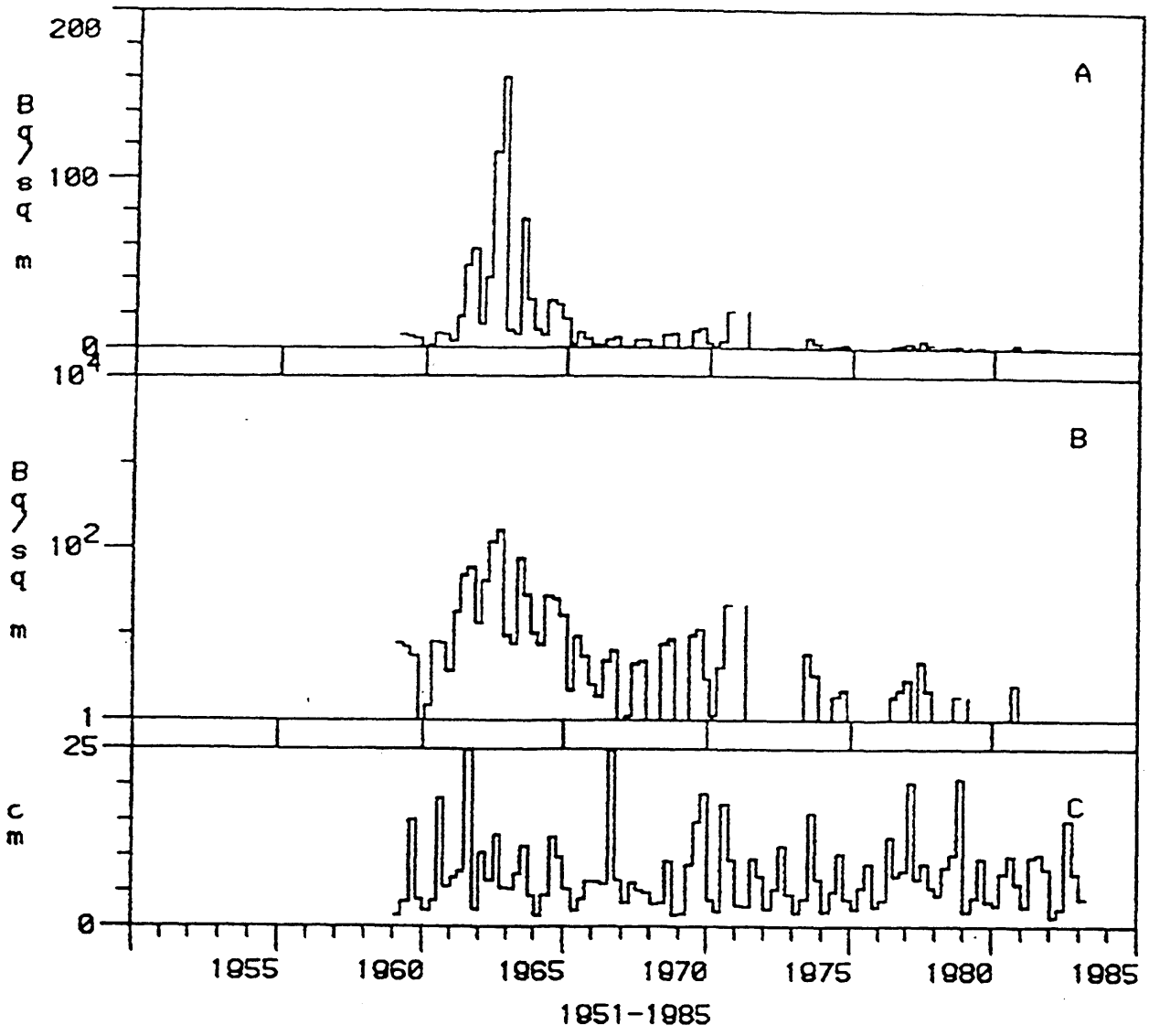


Fig. 4. A. Annual Deposition of Sr-90 (Bq/m2 on linear scale) in Alaska, Fairbanks.
B. Annual Deposition of Sr-90 (Bq/m2 on semi-log scale) in Alaska, Fairbanks.
C. Atmospheric precipitation (cm) in Alaska, Fairbanks.
(Larsen R. J. 1985, Worldwide Deposition of Sr-90 Through 1983. USDOE Report EML-444).

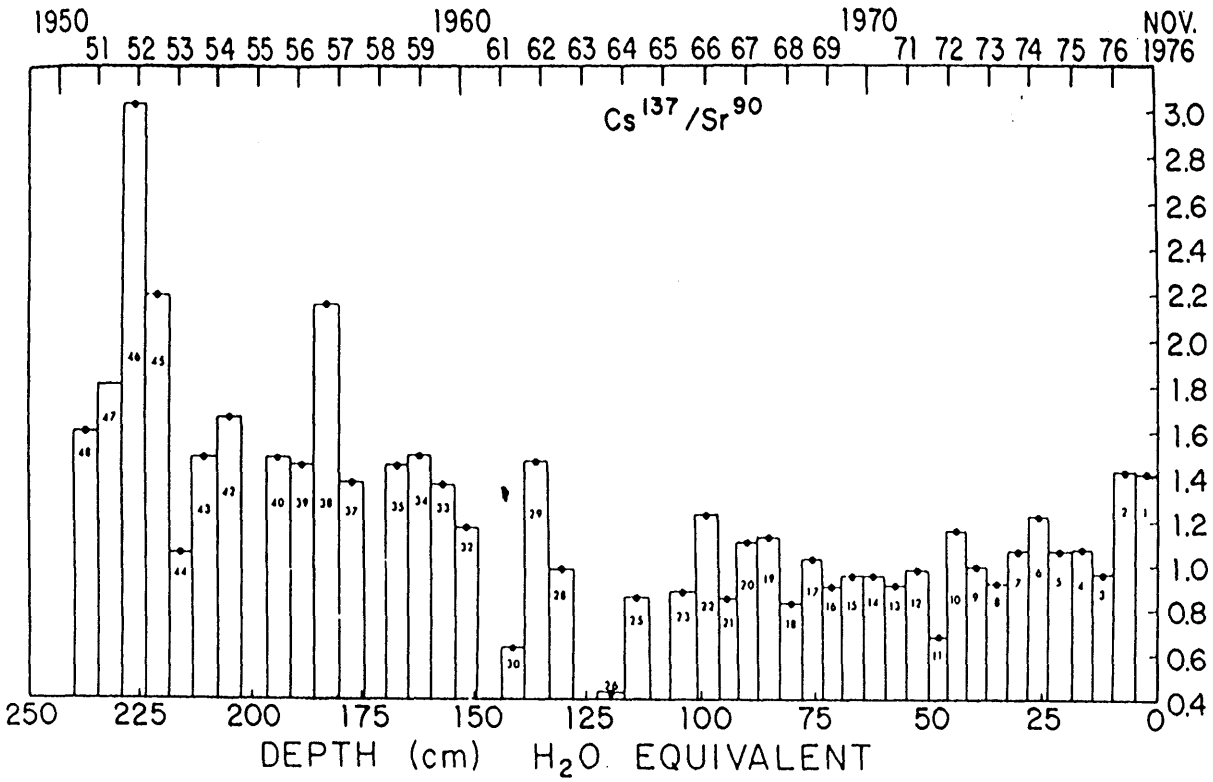


Fig. 5. Cs-137/Sr-90 activity ratio as a function of depth and Pb-210 age in the ice shelf. The Cs-137 and Sr-90 values are decay corrected to the time of deposition.
(Koide et al. 1979, Depositional history of artificial radionuclides in the Ross ice shelf, Antarctica. Earth and Planetary Science Letters, 44 pp. 205-223)

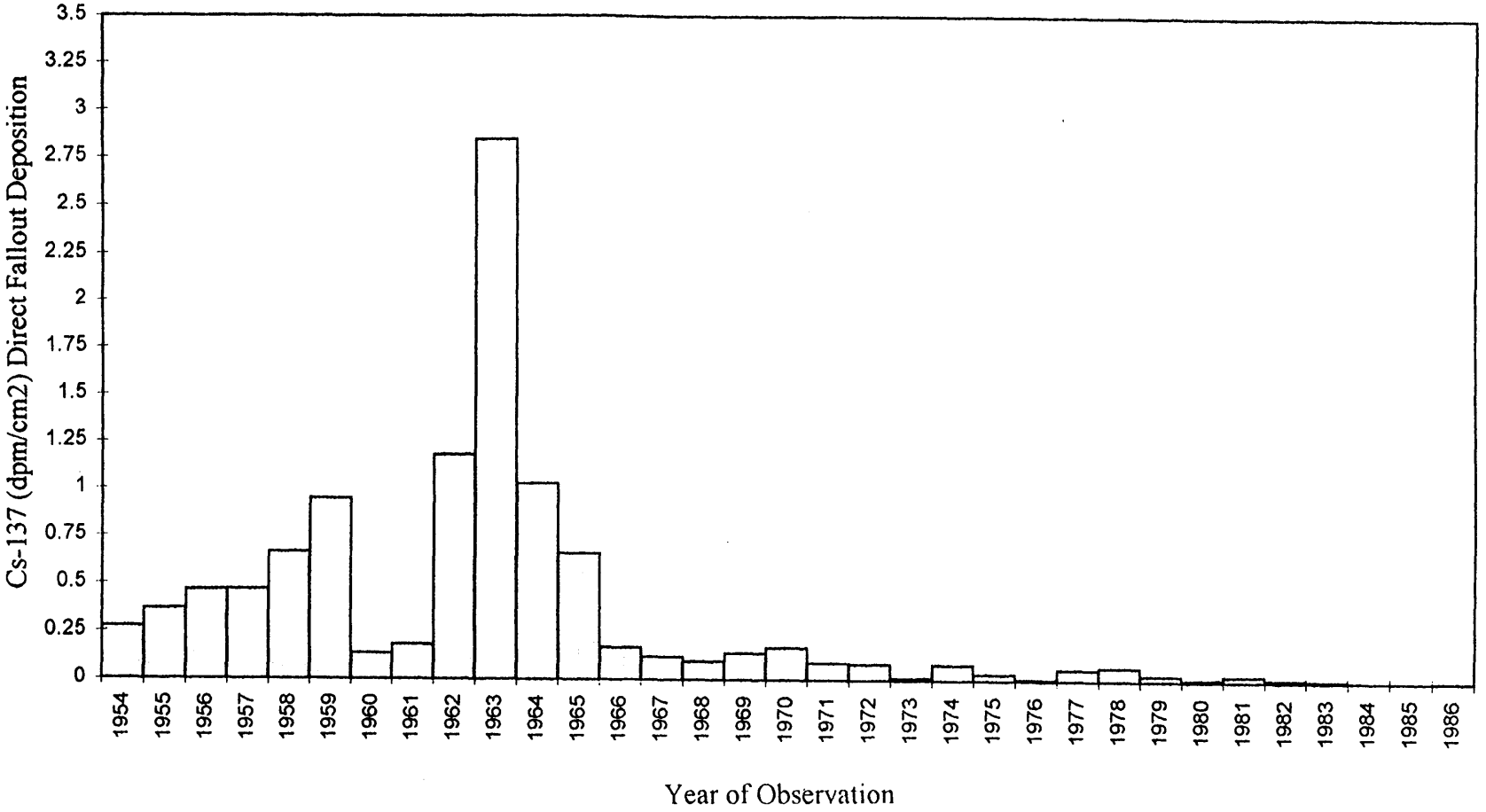


Fig. 6. Cs-137 Direct Fallout Deposition (dpm/cm2) at Fairbanks, Alaska.
Data calculated from Sr-90 direct fallout deposition at EML observation site
(Sr-90 data - M. Monetti personal communication)

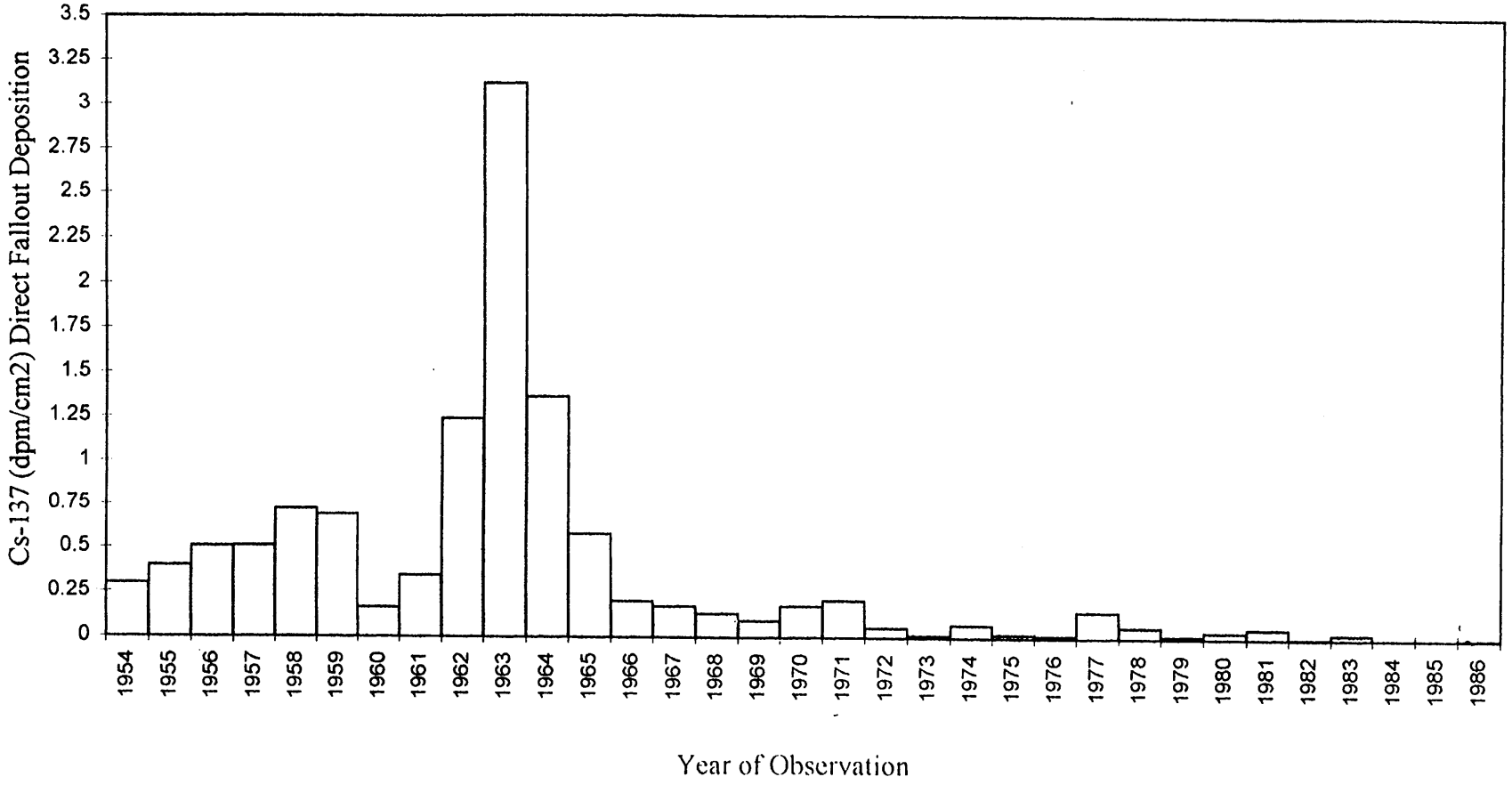


Fig. 7. Cs-137 Direct Fallout Deposition (dpm/cm2) at Anchorage, Alaska.
Data calculated from Sr-90 direct fallout deposition at EML observation site
(Sr-90 data - M. Monetti personal communication)

using the average Cs-137/Sr-90 fallout deposition ratio of 1.57 (Koide et al., 1979) for the period between 1954-59 and 1.45 starting in 1960 (Harley et al., 1965). The data are characterized by two maxima: in 1958-59 and 1962-65 that follow the maxima in atmospheric nuclear tests. From these data the expected inventory of direct fallout deposition of Cs-137 at the study sites was calculated. The decay corrected inventories for 1994 of Cs-137 direct fallout deposition for Fairbanks and Anchorage are 5.08 and 5.57 dpm/cm^2, respectively.

Based on the data collected at a global network of samplings stations, EML compiled the average Sr-90 deposition in 10 degree latitude bands for the Northern and Southern hemispheres (Hardy, 1971). Given the latitudinal similarity of the Alaskan sites to the Ob River Delta and Estuary, I assume that direct fallout deposition in Alaska provides a proxy for direct fallout deposition at the Ob River Delta sampling locations.

2-A-2. Plutonium in Global Fallout

Plutonium contamination of the environment on a global basis is primarily the result of the atmospheric nuclear weapons testing. There are localized areas where plutonium contamination has occurred through accidents or releases from nuclear facilities, however, the total amount released in this manner is on the order of curies, while the global fallout source amounts to hundreds of thousands of curies (Hardy. 1974). The plutonium distribution from nuclear tests, also called "background" plutonium, serves as the baseline against which the contribution to the environment from other sources can be assessed.

It is widely accepted that Pu-239 and Pu-240 are considered together as Pu-239,240 due to the analytical difficulty of distinguishing these two isotopes by conventional alpha spectrometry. The isotope plutonium 238 has been also widely measured in global fallout.

Most of the Pu-239,240 now dispersed around the world was produced by the nuclear tests conducted through 1965. The above ground tests by the republic of China

and France since 1965 have contributed an additional ten percent to the global inventory. Figure 8 shows the inventory of Pu-239,240 in the stratosphere as a function of time. Hardy (1974) provided separate curves for Northern and Southern hemispheres. After the intensive period of testing in 1961 and 1962, the levels of Pu-239,240 declined with a half residence time of 10 to 11 months until 1967, more slowly thereafter.

The Pu-238 contribution to total plutonium fallout radioactivity is relatively small, comprising only about 2 to 3% of the total. About 9 kCi of Pu-238 reached the stratosphere as a result of the weapons tests. However, the introduction of 17 kCi of Pu-238 into the atmosphere as a result of the failed launch of the Transit Navigational Satellite (SNAP-9A) on April 21, 1964, provided an important radioactive marker. The satellite re-entry to the atmosphere resulted in complete burn up of the generator and introduction of about 1 kg of Pu-238 to the atmosphere in the form of small particles at an altitude of about 50 km. The stratospheric inventories of Pu-238 (Fig. 9) studied by Hardy (1974) clearly indicated that by mid-1970 >95% of the SNAP Pu-238 had been deposited on the Earth's surface.

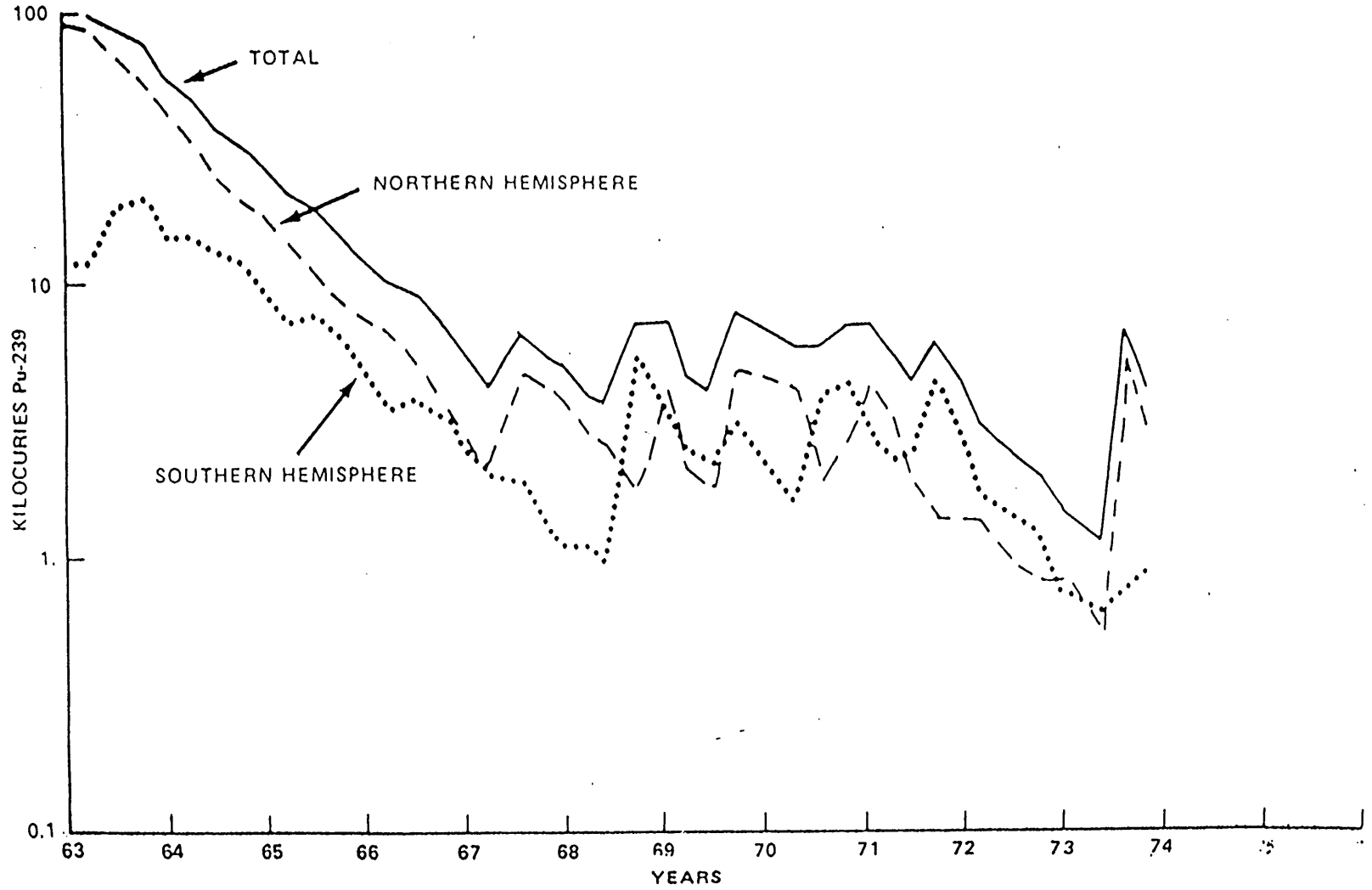


Fig. 8. Stratospheric Inventory of Pu-239,240.
(Hardy E. P. 1974, Worldwide distribution of plutonium. Part of the AEC presentation at the EPA Plutonium Standards Hearings. Washington, D. C., December 10-11, 1974.)

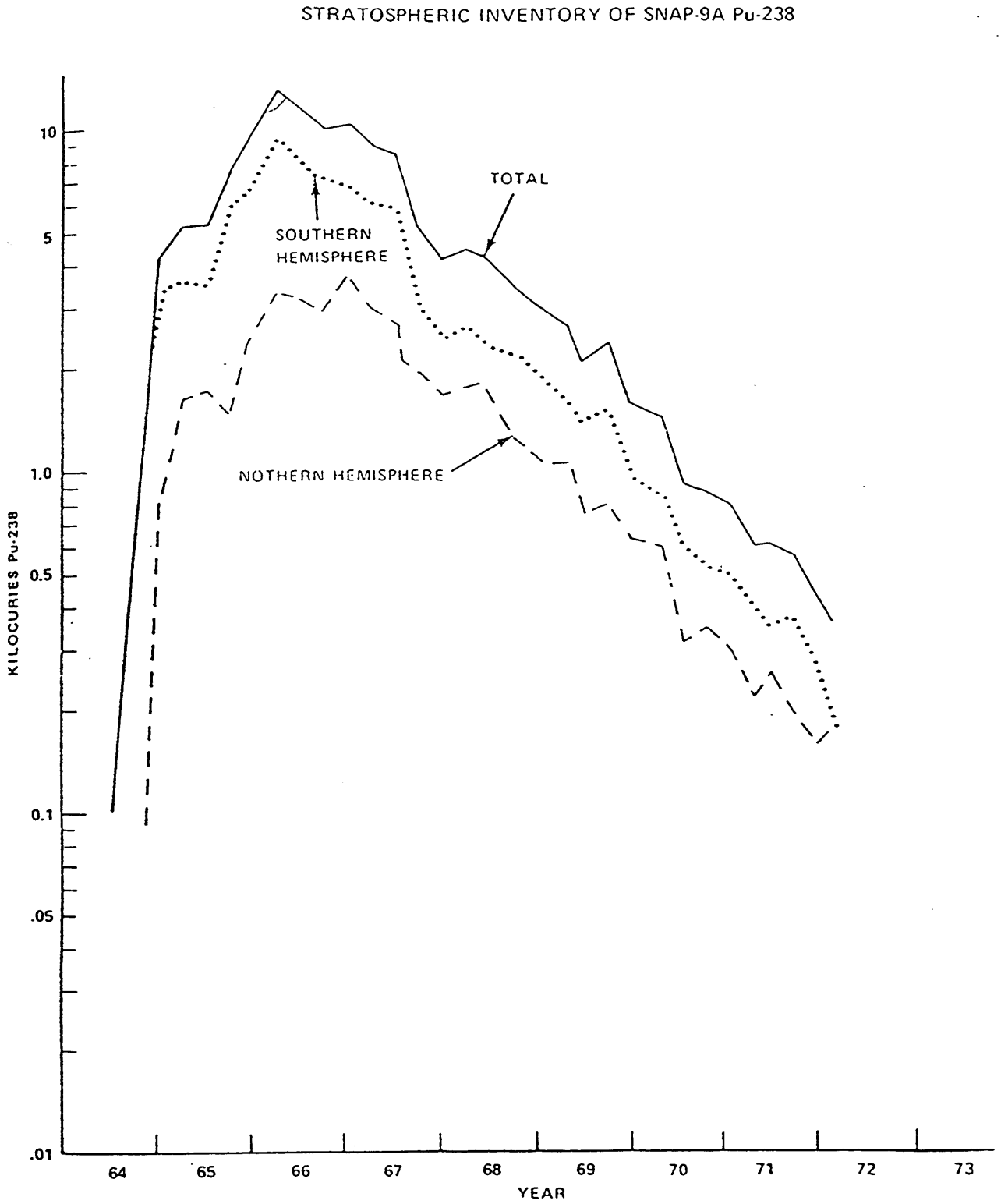


Fig. 9. Stratospheric Inventory of SNAP-9A Pu-238.
(Hardy E. P. 1974, Worldwide distribution of plutonium. Part of the AEC presentation at the EPA Plutonium Standards Hearings. Washington, D. C., December 10-11, 1974.)

Based on a worldwide soil sampling program carried out in 1970-1971 by Hardy et al. (1973) the inventory of Pu-239,240 and Pu-238 fallout was established (Table 1).

Table 1. Inventory (kCi) of Pu-239,240 and Pu-238 Fallout (Hardy et al., 1973)

	Pu-239,240	Pu-238 Weapons	Pu-238 SNAP-9A
N. Hemisphere	256±33	6.1±0.8	3.1±0.8
S. Hemisphere	69±14	1.6±0.3	10.8±2.1
Global	325±36	7.7±0.9	13.9±2.2

Total global Pu-239,240 deposition was 325±36 kCi, and weapons Pu-238 was 7.7±0.9 kCi. Hardy et al. (1973) estimate of SNAP-9A Pu-238 deposition, 13.9±2.2 kCi, is in reasonable agreement with 17 kCi that was contained in the satellite. Over 75% of the total SNAP Pu-238 was deposited in the Southern hemisphere, whereas only about 20% of the Weapons Pu-238 fallout occurred in that hemisphere. The SNAP accident release of Pu-238 almost tripled the global deposition of this isotope of plutonium.

2-A-3. Global Fallout Pu-238/Pu-239,240 Ratios

The activity ratios of fallout plutonium (Pu-238/Pu239,240) derived from the weapons testing have changed with time. Koide et al. (1979) discussed the Pu-238/Pu-239,240 ratio variation in the Ross Ice Shelf in great detail (Fig. 10). The initial U.S. tests performed in 1950-51 were high Pu-238/Pu-239,240, low yield fission bombs. The testing of the first hydrogen bomb (Mike-Ivy Test) in 1952 resulted in a very low Pu-238/Pu-239,240 ratio of 0.1% recorded in the Ross Ice Shelf. Tests performed between 1953 and 1963 produced Pu-238/Pu-239,240 ratios of 2.0 - 2.7% with an average of 2.5%.

Due to the introduction of SNAP Pu-238 in 1964, the Pu-238/Pu239,240 ratio of fallout deposition in 1970 in the Northern hemisphere increased to 3.6%, and in the Southern Hemisphere it was 17.8% (HASL, 1975). In 1970, the global average activity

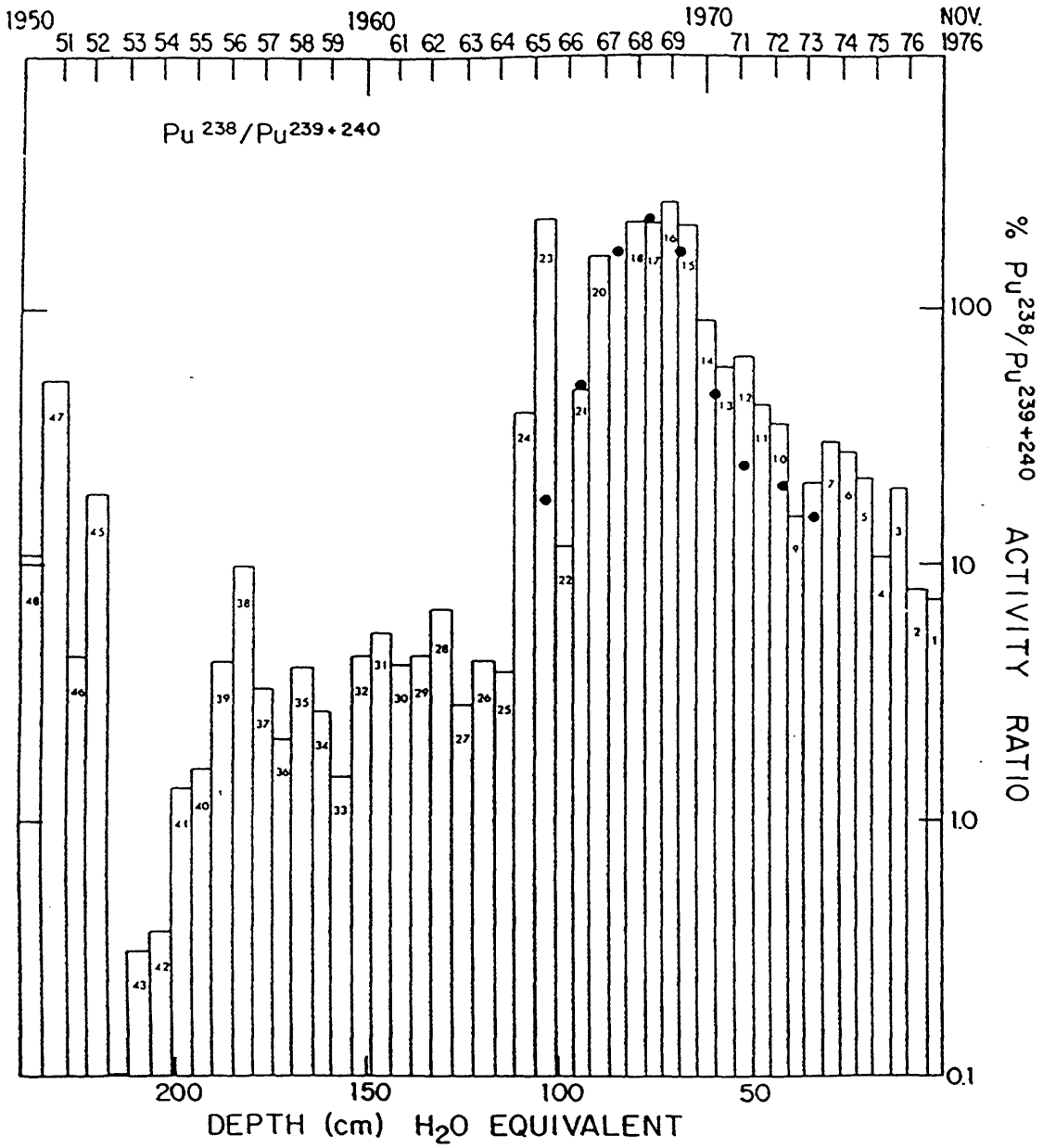


Fig. 10. The Pu-238/Pu-239,240 activity ratio as a function of depth and age. The heavy circles are unpublished data for plutonium in atmospheric particulates measured by the Environmental Measurements Laboratory of the U.S. Department of Energy (H. Volchok, personal communication). The value of sample 44 is slightly greater than 0.1.

(Koide et al. 1979, Depositional history of artificial radionuclides in the Ross ice shelf, Antarctica. Earth and Planetary Science Letters, 44 pp. 205-223)

ratio of fallout deposition increased from 2.4% to 6.6%. Aakrog et al. (1989) assumed global fallout average Pu-238/Pu-239,240 ratio for 1987 to be about 4.0%.

Table 2 presents Pu-238/Pu-239,240 ratios calculated from (Hardy et at., 1973) soil sample analyses for the Northern and Southern Hemispheres.

Table 2. Median Global and Latitudinal Distribution of Weapon and SNAP-9A - Pu-238/Pu-239,240 ratios for the Northern and Southern Hemispheres (Derived from Hardy et al., 1973). Results in parentheses were derived by extrapolation. Error terms are standard deviations.

Hemisphere	Latitude Band Deg.	238/239,240 Weapons Tests	238/239,240 SNAP-9A	238/239,240 Test+SNAP-9A
Northern	90-80	(0.020±0.013)	(0.010±0.004)	(0.030±0.024)
	80-70	0.025±0.004	(0.003±0.001)	(0.028±0.019)
	70-60	0.024±0.022	0.016±0.014	0.040±0.005
	60-50	0.024±0.005	0.010±0.003	0.034±0.012
	50-40	0.024±0.007	0.012±0.006	0.036±0.019
	40-30	0.023±0.011	0.014±0.010	0.037±0.028
	30-20	0.024±0.003	0.011±0.004	0.035±0.013
	20-10	0.025±0.013	0.013±0.010	0.038±0.032
	10-0	0.023±0.013	(0.008±0.004)	(0.031±0.018)
Southern	0-10	0.023±0.023	0.033±0.032	0.057±0.068
	10-20	0.022±0.008	0.200±0.129	0.222±0.154
	20-30	0.023±0.014	0.179±0.130	0.203±0.173
	30-40	0.023±0.010	0.153±0.068	0.175±0.0.97
	40-50	0.023±0.020	0.197±0.161	0.220±0.226
	50-60	(0.025±0.015)	(0.220±0.152)	(0.245±0.195)
	60-70	(0.020±0.013)	(0.220±0.149)	(0.240±0.202)
	70-80	(0.033±0.035)	(0.267±0.189)	(0.300±0.368)
	80-90	(0.100±0.040)	(0.400±0.256)	(0.500±0.320)
Northern Hemisphere. Median		0.024±0.004	0.012±0.003	0.036±0.011
Southern Hemisphere. Median		0.023±0.006	0.157±0.044	0.180±0.061
Global. Median		0.024±0.004	0.043±0.008	0.066±0.015

The data from Table 2 show that Pu-238/Pu-239,240 ratios for the Northern hemisphere (0.036±0.011) derived from the analysis of soil samples (Hardy et al., 1973) are in good agreement with the mean ratio of 0.038 in 1972-1973 for Buzzards Bay cores and 0.036 for Wilkinson Basin (Gulf of Maine) reported by Livingston and Bowen (1979).

2-A-4. Global Fallout Pu-239,240/Cs-137 Ratios

The Pu-239,240/Cs-137 ratio in global fallout was estimated using different approaches which included analysis of stratospheric air, wet and dry fallout precipitation, soils, water, suspended matter and sediment samples. There are considerable differences in the Pu-239,240/Cs-137 fallout ratio estimates made by different observers. The Pu-239,240/Cs-137 deposition ratio recorded in the Ross Ice Shelf showed quite a substantial variation (Fig. 11) ranging from 0.008 to about 0.050 (Koide et al., 1979), averaging 0.013. Thomas and Perkins (1974) reported the results of a long series of analyses of atmospheric particulates collected at Richland, Washington beginning in1962 when the effects of the last and most extensive test series by U.S. and U.S.S.R. had begun to show up in the atmospheric fallout. Their value was between 0.005 - 0.011 averaging at 0.008. Krey et al. (1975) reported analyses of the stratospheric particulate samples collected from aircraft in a framework of "Project Airstream" during the early part 1960's; the Pu-239,240/Cs-137 ratio averaged 0.0126±0.0013. It may be assumed that these samples represent the source term for the ground level samples. Livingston and Bowen (1979) suggested that the origin of the discrepancy between the ratios reported by these two laboratories may be a result of calibration discrepancies.

It is important to establish representative Pu-239,240/Cs-137 global fallout ratios for our analysis. From the discussion above we see that the Pu-239,240/Cs-137 ratio in Antarctic Ice Sheet (0.013 - Koide et al., 1979) is in good agreement with the stratospheric average value (0.0126±0.0013 Krey et al., 1975) and also agrees with the average ratios of 0.013 reported by Bowen et al. (1971) and - 0.012 by Gavini (1978) which was measured in wet and dry fallout deposition at Woods Hole, Massachusetts

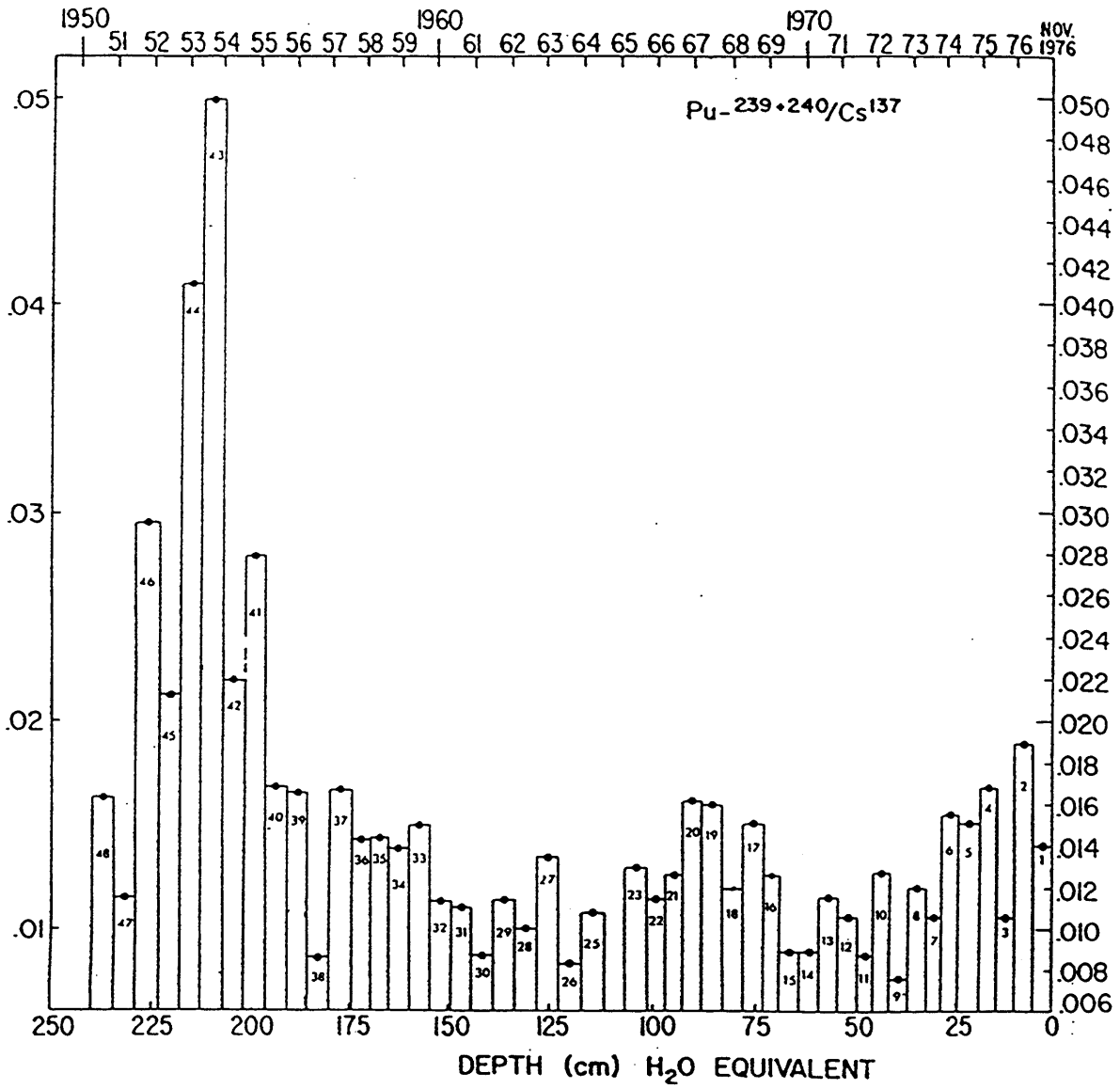


Fig. 11. The Pu-239,240/Cs-137 activity ratio as a function of depth and Pb-210 age in the Ross Ice Shelf. The Cs-137 values are decay corrected to the time of deposition.
(Koide et al. 1979, Depositional history of artificial radionuclides in the Ross ice shelf, Antarctica. Earth and Planetary Science Letters, 44 pp. 205-223)

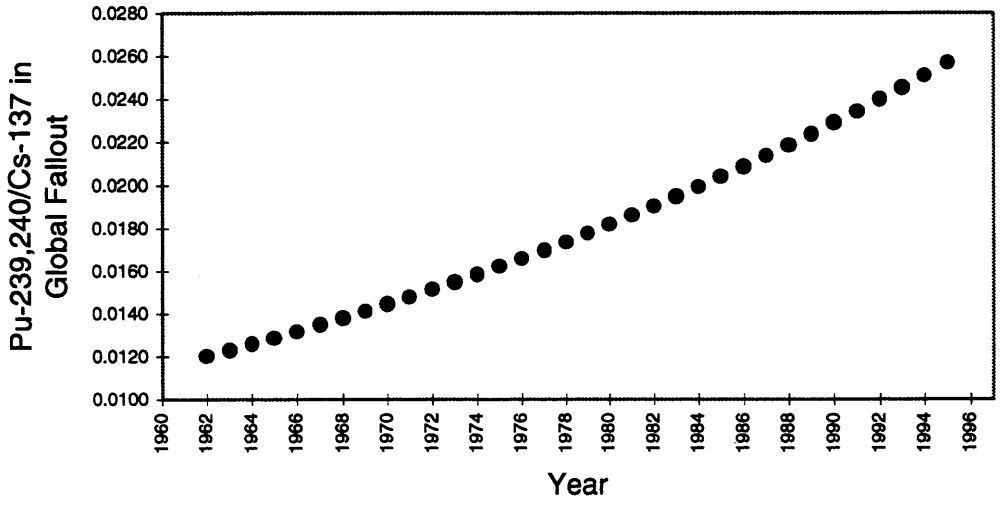
(June 1976 to December 1977). In contrast, a Pu-239,240/Cs-137 ratio of 0.010 to 0.035 (average - 0.023) was reported by Thein et al., 1980 for 1978-79 for the rain delivery of fallout radioactivity to the Mediterranean Sea.

Another way of establishing the Pu-239,240/Cs-137 ratio is to analyze soil samples. Bunzl and Kracke (1988) reported the results for fallout radionuclides in soils from forests and grasslands in Bavaria (FRG). Even though the accumulated inventory of Cs-137 and Pu-239,240 varied by about 30% between the samples collected at forest and grassland sites, the resulting Pu-239,240/Cs-137 ratio was not statistically different. For 1984, the Pu-239,240/Cs-137 value of 0.018 ± 0.0024 was found, which is very similar to the 0.0178 ratio observed in Great Britain by Cawse (1983).

The Pu-239,240/Cs-137 ratio in water, suspended matter and sediments of freshwater lakes without additional landbased radioactivity sources were studied at many locations in North America and Europe (Wahlgren and Nelson, 1975; Alberts & Wahlgren, 1981; Edgington & Robbins, 1975; Wan et al., 1987). Alberts and Wahlgren (1981) reported suspended matter Pu-239,240/Cs-137 ratios of 0.0207 ± 0.0128 for the Great Lakes in 1976. The Great Lakes surface water Pu-239,240/Cs-137 value in 1973 was 0.0118 ± 0.0035 (Wahlgren and Nelson, 1975). A Pu-239,240/Cs-137 ratio of 0.01647 ± 0.0054 was found in Lake Michigan sediments in 1972-74 by Edgington and Robbins (1975). Wan et al. (1987) analyzed a sediment core from the Greifensee lake Switzerland and found Pu-239,240/Cs-137 ratio of 0.0185 in 1983. Most of these studies reported Pu-239,240/Cs-137 ratios within the range 0.009-0.035. It is interesting to note, that on average, the Pu-239,240/Cs-137 ratio in large water bodies were higher that that of global fallout estimates based on air, direct fallout and soil samples estimates. I propose that an as yet unquantified plutonium-cesium fractionation process could be responsible for the Pu-239,240/Cs-137 ratio variation in the large lakes and that it is not unreasonable to observe such a variation.

From the discussion above we can conclude that on average the fallout Pu-239,240/Cs-137 ratio was in a range of 0.011-0.013 in 1962 and is best represented by air, direct precipitation and soil sample analyses. The Pu-239,240/Cs-137 ratio in large lakes show slight variations - typically higher values and in some cases these could be a result of a plutonium - cesium fractionation process. The older the age of the fallout deposit, the higher the ratio should be due to the natural decay of Cs-137 (half-life 30.1 yr.) compared with that of Pu-239 (half-life 24,400 yr.) or Pu-240 (half-life 6,600 yr.). Figure 12 presents the expected change in fallout Pu-239,240/Cs-137 ratio due to the natural decay of Cs-137 isotope.

Fig. 12. Change in Pu-239,240/Cs-137 ratio in Global Fallout
due to the natural decay of Cs-137 isotope.
Calculation assumes a 1962 origin for all material.
Pu-239,240/Cs-137 initial 1962 ratio - 0.012.



The expected direct fallout Pu-239,240 inventory at Fairbanks and Anchorage has been computed from Cs-137 inventories (5.08 and 5.57 dpm/cm^2 respectively) and the average Pu-239,240/Cs-137 ratio (0.0264 - average estimate) as 0.134 and 0.147 dpm/cm^2 respectively.

2-B. Chernobyl Accident Fallout

On April 26, 1986 the Unit 4 reactor at the Chernobyl Nuclear Power Plant in the Soviet Union became unstable and released the largest quantity of radioactive material to the atmosphere resulting from an industrial accident (Levi 1986, Buesseler 1987). On the order of 2.7 MCi of Cs-137 and 216 kCi of Sr-90 were released to the environment (Aarkrog et al., 1993). The contamination from this source has been measured throughout the Northern hemisphere. Along with Cs-137, the activation product Cs-134 was also released. The ratio of Cs-134/Cs-137 was about 0.5 at the time of release. Due to the short half-life of Cs-134 (2.06 yr.) - about 94% of Cs-134 had decayed by 1994. It has been assumed that the "Chernobyl" fallout signal was dominated by volatile radioactive isotopes like Iodine, Cesium, and depleted in refractory isotopes like Plutonium and Neptunium (Hohenemeser et al., 1986).

Table 3. Estimated Averaged Inventories of Radionuclides in Soils of the Urals from Global, "Chernobyl" Fallout, Kyshtym* and Unreported Sources in the Urals.

(Data calculated from Aarkrog et al., 1992)

	Fallout Global *dpm/cm2*	Fallout Chernobyl *dpm/cm2*	Kyshtym* Accident *dpm/cm2*	Unreported Sources. Ural *dpm/cm2*	Total Deposit *dpm/cm2*
Cs-137	14.1	6.6	3.0	46.5	70.2
Pu-239,240	0.312	0	?	0.588	0.930

*-Kyshtym accident will be described below.

Aarkrog et al. (1992) estimated the contribution of "Chernobyl" Cs-137 in Chelyabinsk region, Ural Mountains (headwaters of the western tributaries of the Ob river) to be about 7 to 10% of the total Cs-137 (Table 3). According to their estimate, the inventory of Cs-137 in analyzed soil samples were represented by global fallout - 18 to

22%; "Chernobyl" fallout - 7-10%; and Kyshtym[1] accident and unreported local sources in the Urals 66 to 75% (Aakrog et al., 1992). The substantial amount of non-fallout radioactivity found in the soil samples in the Urals is a particular concern of my investigation and will be addressed in the following discussion.

2-C. Local Sources of Radioactivity in the Ob River Watershed

In the introduction, we outlined the many potential sources of radioactivity located in the Ob River watershed such as the Chelyabinsk-40 (also known as Chelyabinsk -65 and "MAYAK") Nuclear Production Facility, the Siberian Radiochemical Plant (widely known as Tomsk-7), the Ishym Uranium Ore Mine on the lower reaches of the Ishym River, and the Semipalatinsk Nuclear Testing Sites (Fig. 1). They are known to be significant contributors to the radioactive contamination of the environment of the Ob River watershed. However, knowledge about the releases of radioactivity is difficult to assess and incomplete. Additional sources could include close-in fallout from Novaya Zemlya and Semipalatinsk Nuclear Test sites as well as "peaceful" nuclear explosions.

2-C-1. Sources in the South Ural Mountains: Chelyabinsk Region

The "MAYAK" Nuclear Production Facility is located 70 km north of Chelyabinsk in the southern Ural mountains (Fig. 1). The plant covers an area of 90 sq. km and is operated by the Ministry of Nuclear Energy of the Russian Federation.

There are three known major events which contributed significantly to the radioactive contamination of the Ural Mountains.

---

[1] * Information on the Kyshtym accident will be discussed in the next section.

2-C-1-1. Techa River

Direct discharge of medium and low level liquid radioactive waste into the Techa river occurred during the early part of "MAYAK" operation in 1949-1952. During that period about 76 million cubic meters of waste were discharged into the Techa River with a total activity of 2.76 MCi (Fig. 13, 14). Short lived radionuclides were released along with Sr-90 and Cs-137 ,the latter two contributed 11.6 and 12.2%, of the total respectively (Aarkrog et al., 1993). In 1994 the environmental contamination from this source has decayed to 108 kCi of Sr-90 and 113 kCi of Cs-137. It is assumed that the main portion of radionuclides was deposited in the Techa River bed and floodplain within 100 to 150 km from the point of discharge. Figure 15 presents the Cs-137 inventory data (Ci/km^2) along the Techa river compiled by the Institute of Global Climate and Ecology of the Russian Academy of Sciences. At the locations close to and at "Mayak" the levels of contamination exceed 40 Ci/km^2.

In 1993, Aarkrog et al. (1993) wrote: "It is still an open question how much of the activity discharged throughout the years to the Techa river which remains in the Techa-Iset-Tobol-Irtysh-Ob river system and how much of that has entered the Arctic Ocean". They estimated that between 27 and 270 kCi of Sr-90 and Cs-137 may have gone to the Arctic Ocean. Khotuleva et al., (1993) reported that little has been published on alpha-emitting isotopes such as Pu-239,240 in the Techa river. The Committee of the Academy of Sciences (1991) which investigated the radioactive contamination in the Chelyabinsk region found plutonium in the sediments of the Techa river. The conclusion was that the Techa river is simultaneously a depositional site and is a main secondary source of such radionuclides as Cs-137, Sr-90 and Pu-239,240 to the Iset-Tobol-Irtysh-Ob river system.

Trapeznikov et al., (1993a) studied radioactive contamination of the Techa river. They estimated that at present the sediments and flood plain of the Techa river (between 50 and 250 km from Mayak) contain: Sr-90 - 8 Ci; Cs-137 > 162 Ci and Pu-239,240 - 0.2 Ci in the upper 10 cm layer of sediment. At the moment it is difficult to evaluate the

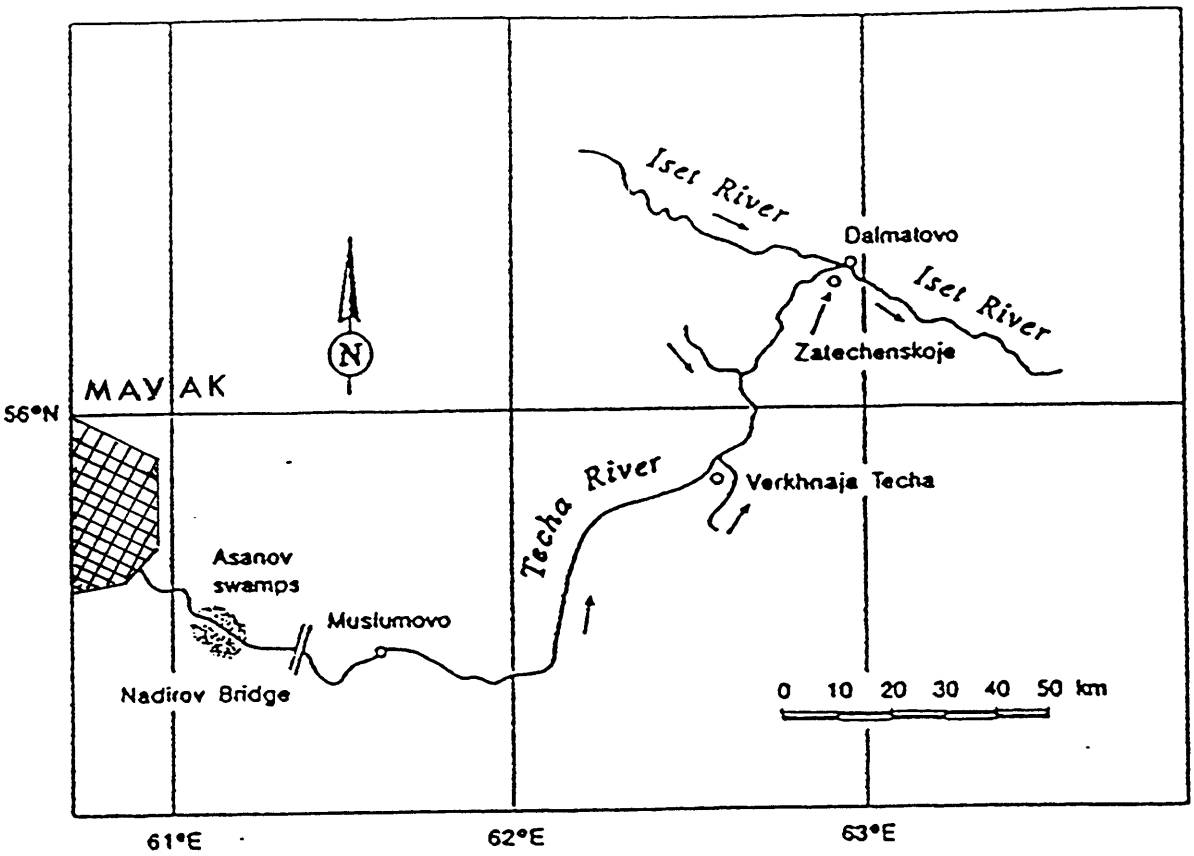


Fig. 13. Techa River

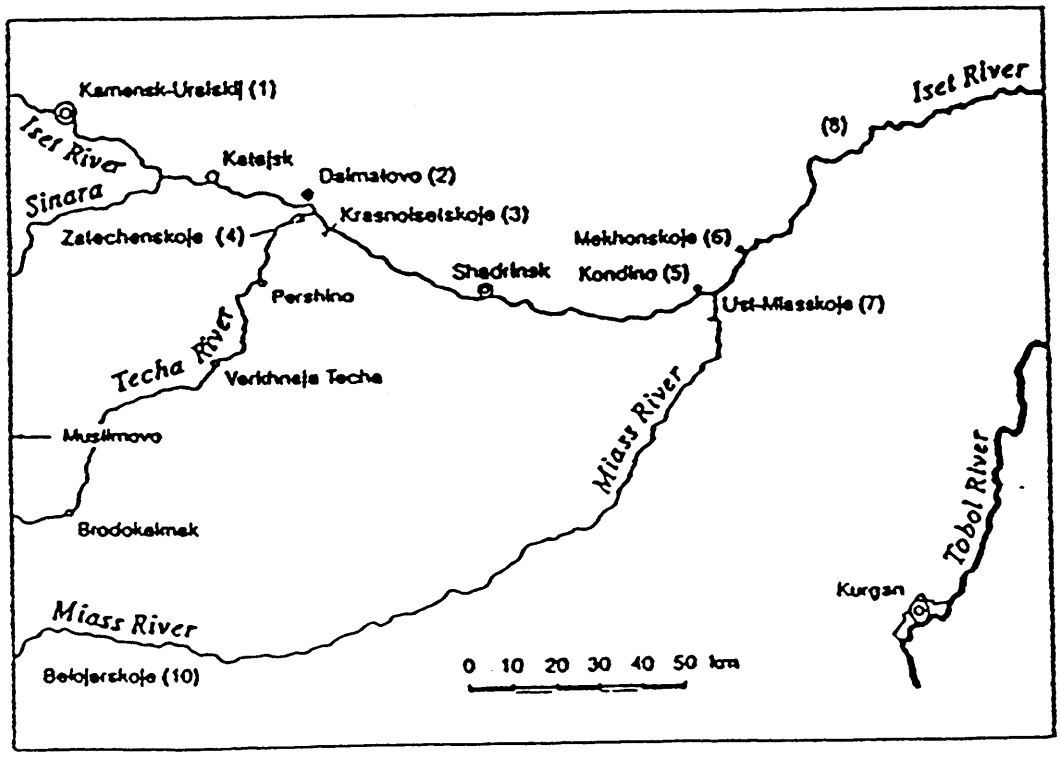


Fig. 14. Iset River.

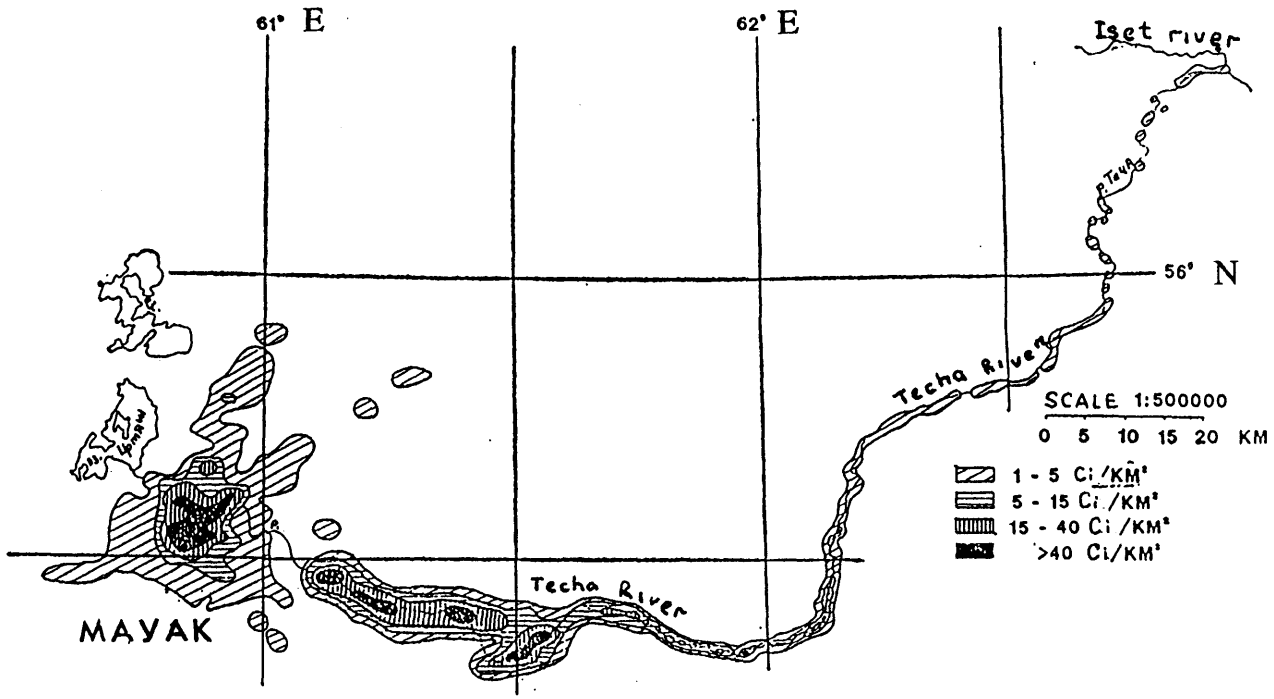


Fig. 15. Density of Cs-137 contamination (Ci/km2) of the Techa river in 1993 as a result of direct discharge of medium and low level radioactive waste by "Mayak" Nuclear Production Facility during 1949-1952.
(Data of the Institute of Global Climate and Ecology, Russian Academy of Sciences)

importance of these numbers because much of the radioactivity is stored within the 50 km zone from "Mayak" and also could be preserved in the sediment layers below 10 cm horizon which were not sampled by Trapeznikov et al., (1993a). The possibility that sedimentation rates at accumulation sites in the rivers could be high enough to bury the most contaminated sediments under the less contaminated layers is well described in the literature (Breteler et al., 1984).

The Pu-239,240/Cs-137 and Pu-238/Pu-239,240 ratios for the contaminated sediments of the Techa river were reported by Trapeznikov et al. (1993a) and are presented in Table 4.

Table 4. Radionuclide ratios in the Techa River sediments in July 1990. Data from Trapeznikov et al. (1993a, 1993b)

Location	Sediment type	Sr-90/Cs-137	Pu239,240/Cs137	Pu238/Pu239,240
Nadirov Brd.	Sand & silt	0.082	0.0017	0.012
Muslimovo	Silt	0.013	0.0008	0.012
	Sand	0.315	0.0012	0.051
V. Techa	Silt	0.023	0.0017	
	Sand	0.245	0.0025	
Zatechensk	Silt	1.670	0.0053	
	Sand	1.053	0.0023	

It is apparent from Table 4 that the Pu-239,240/Cs-137 ratio in silts (0.0024 ± 0.0020) is generally low compared to the fallout ratio -0.0264. The Pu-239,240/Cs-137 ratio in the heavily contaminated sediments along the Techa river is generally low, between 0.0008 and 0.0017. With the distance from the "Mayak" facility along the Techa river we see an increase in the ratio reaching 0.0053 suggesting that global fallout source contribution already is present and significant. From the knowledge of the total Cs-137 release into the Techa River during 1949-1952 and assuming that the

Pu-239,240/Cs-137 described above represents the 1990 ratio, Pu-239,240 contributed about 300 Ci to radioactive contamination. This is probably the most significant present source of plutonium to the Ob River system.

2-C-1-2. Kyshtym Accident. September 29, 1957

The Kyshtym accident occurred on September 29, 1957 when a tank containing high-level radioactive waste exploded dispersing about 1 MCi of nuclear fission products of which Ce-144 (half-life 285 day) and Zr-95 (half-life 64 day) accounted for 91%. The amount of Sr-90 was 27 kCi while Cs-137 amounted to 0.35 kCi (Nikipelov et al., 1989; Romanov et al., 1990; Trabalka & Auerbach, 1990). An area of 15,000 square kilometers was contaminated to the north-east of the "Mayak" facility (Fig. 16). Nikipelov et al. (1989) characterized the radionuclide composition of waste which was dispersed out of the exploded storage tank. Cs-137 contribution was only 0.036% and Pu-239,240 was measurable (Table 5).

Table 5. Radionuclide composition of the dispersed radioactive waste of the Kyshtym accident. (Nikipelov et al., 1989)

Radionuclide	Half-life	Percent activity (%)
Sr-89	51 days	Trace
Sr-90	28.6 years	2.7
Y-90	64.1 hours	2.7
Zr-95+Nb-96	65 days	24.9
Ru-106+Rh-106	1 year	3.7
Cs-137	30 years	0.036
Ce-144+Pr144	286 days	66
Pm-147	2.6 years	Trace
Eu-155	5 years	Trace
Pu-239,240	>6000 years	Trace

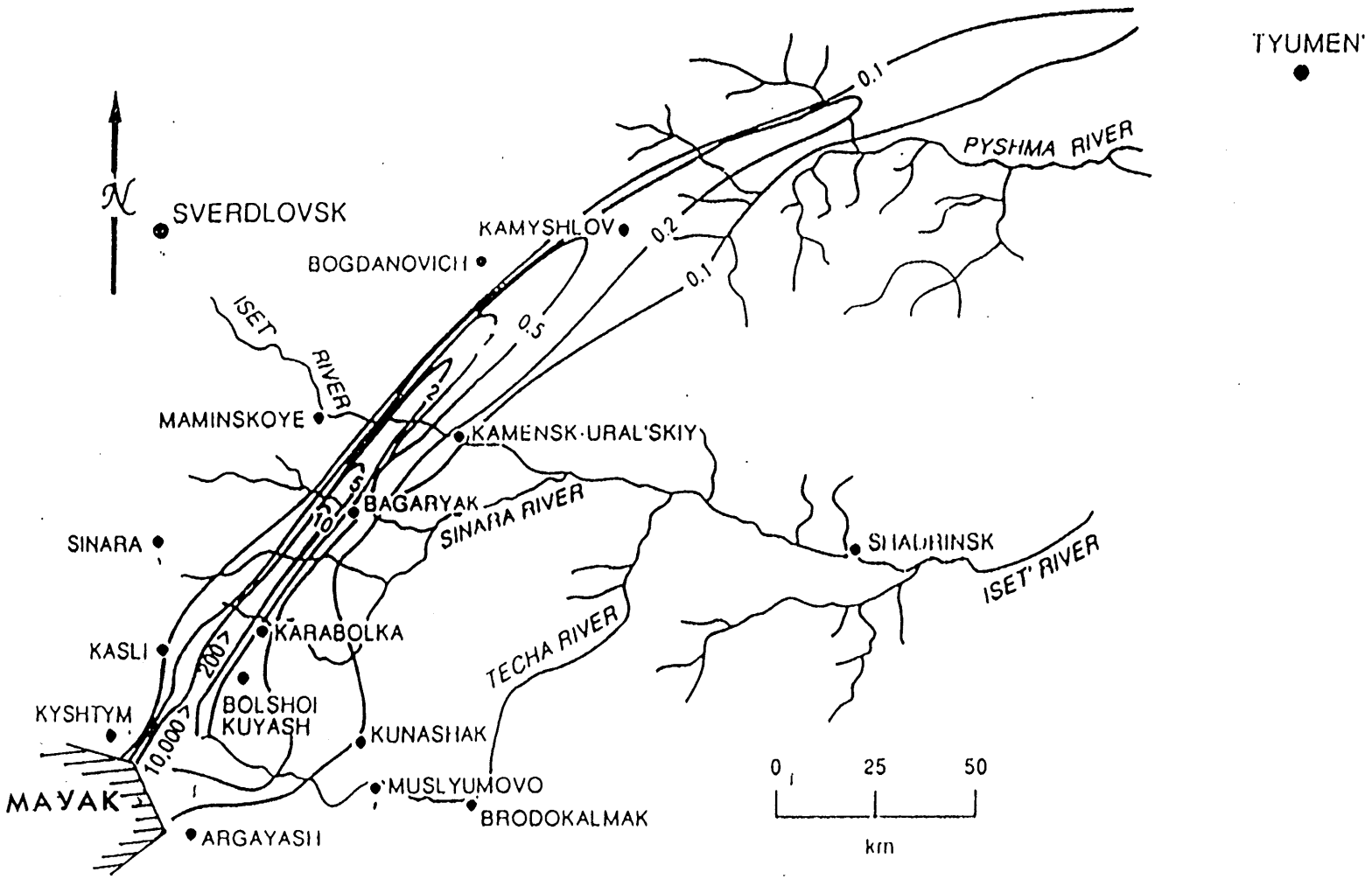


Fig. 16. Isopleths of Sr-90 concentration (Ci/km2) resulting from high-level nuclear waste explosion in 1957 (15,000-23,000 km2 at > 0.1 Ci/km2) and another release in 1967 that contaminated an additional 1800 km2 (note large bulge at the southern end of the contamination zone).

Trabalka J. R., S. I. Auerbach (1990). One western prospective of the 1957 Soviet nuclear accident. In Proceedings of "Seminar on Comparative Assessment of the Environmental Impact of radionuclides Released during three major Nuclear Accidents: Kyshtym, Windscale, Chernobyl". Luxemburg, 1-5 October 1990. EUR 13574. pp. 41-69.

Trabalka and Auerbach (1990) made a review of available information about the Kyshtym accident and also concluded that in the Kyshtym accident the release of Cs-137 was small and the Sr-90+Y-90/Cs-137 activity ratio was about 150:1. Pavlotskaya et al., (1992) reported their study of plutonium soil contamination performed in 1980-1982 after the Kyshtym accident in the Southern Urals. They concluded that, in contrast to Sr-90, the Pu-239,240 contamination density within a few kilometers of the axis of the path (Fig. 16) was low and only about 4 to 9 times in excess of the expected global fallout levels (0.44 to 0.83 dpm/cm^2). Most of the Pu-239,240 was deposited near the exploded tank. The Pu -239,240 concentrations close to the explosion site were 44 to 76 dpm/cm^2; 70 dpm/cm^2 at 0.5-1 km and 3.6 dpm/cm^2 at 9 km from the axis of the path (Pavlotskaya et al., 1992). The Pu-238/Pu-239,240 ratios reported along the Kyshtym accident path are practically the same as the global fallout ratio and vary between 0.030 and 0.050.

It is important to estimate the amount of Pu-239,240 released during the accident. By assuming the same deposition pattern for Sr-90, Cs-137 and Pu-239,240 during the Kyshtym accident, and by knowing the Pu-239,240/Sr-90+Y-90 ratio (Pavlotskaya et al., 1992) of deposition (0.000024) and Sr-90+Y-90/Cs-137 ratio in the dispersed waste (150), we can estimate the Pu-239,240/Cs-137 ratio (0.0036). This ratio is very similar to the Pu-239,240/Cs-137 ratio (0.0034) found in the contaminated sediments of the Techa river by Trapeznikov et al. (1993) and is much lower than the expected global fallout ratio of 0.024 in 1994. Based on the Pu-239,240/Cs-137 ratio and total amount of released Cs-137 (0.35 kCi) the estimated release of Pu-239,240 would be about 1.05 Ci.

One of the conclusions from the soil study performed by Pavlotskaya et al. (1992) is that Pu-239,240 migrated mostly in a downward direction with little lateral migration in a soil profile. This result predicts that we should not expect substantial amounts of "Kyshtym" plutonium migrating towards creeks and small rivers along the trail of the Kyshtym accident. A similar conclusion was reached by Romanov et al. (1990) for Cs-137 and Sr-90 migration within the "Kyshtym" radioactive path. Only 2 to 3 % of total

deposited Cs-137 and Sr-90 was transported by water and wind processes out of the contaminated area.

2-C-1-3. Lake Karachay Wind Transfer

The discharge of medium and low level radioactive waste into the Techa river was stopped with the diversion of waste to Lake Karachay in October 1951. The lake eventually accumulated 120 MCi of radioactivity (Laverov 1995), including 97 MCi of Cs-137 and 20 MCi of Sr-90. In 1967, as a result of extreme drought, part of the lake bottom was exposed to the atmosphere and a gusty wind dispersed about 600 Ci of radioactivity onto the surrounding environment, covering an area of 1800 km^2. This contamination overlapped the southeastern side of the radioactive path left from the Kyshtym accident (Fig. 16). The exact radionuclide composition of the 1967 accident is hard to access due to the lack of available information, however, we can assume that the isotopic ratios in the lake sediments should be similar to the ones found in the Techa river.

Lake Karachay is the main potential source of radioactive contamination for the Ob River system, as well as of the air and adjacent territories of the "Mayak" facility (Aarkrog et al., 1993). After the 1967 accident, a plan was developed to decrease the lake surface by filling it with soil and hollow concrete blocks. This work decreased exposure of radioactive waste to the atmosphere and the aerosol dispersion by a factor of 5-10. Laverov (1995) reported that by spring 1995 about 80% of the lake surface was sealed. The coverage of Lake Karachay should be completed in 1998. This work did not alleviate another problem - contamination of groundwater with radioactive waste. At present a lens of highly contaminated salts, which has formed at the lake bottom, has propagated to a distance of 2-3 km from the reservoir at a rate of 80 meters per year. This lens of radioactive material is also a potential threat to the environment should its waters reach the surface.

Overall, the operation of the "Mayak" facility in the south Urals for more that 45 years has led to local accumulation of extremely high amounts of radionuclides and to significant contamination of various regions in the Ural Mountains. Overall, the site contains over 1 billion curies of radioactivity, of which 120 MCi are disposed in the open natural environment in liquid form.

2-C-2. Siberian Radiochemical Plant (Tomsk-7)

The Siberian Radiochemical Plant (Tomsk-7) is located 15 kilometers northwest of the city of Tomsk on the Tom river (Fig. 1). Tomsk-7 is the largest facility for plutonium, uranium and transuranium production in Russia (Lystsov et al., 1993). In general, only scarce information is available concerning possible contamination and nuclear incidents at Tomsk-7. However, it was recently revealed that large amounts of low level radioactive waste were disposed of underground at this site. 259 wells were drilled to depths of up to 400 meters to dispose and monitor radioactive waste. This has taken place at "Area -18" and "Area-18A" disposal sites at the Tomsk-7 nuclear facility (Laverov 1995). Although the exact amount of radioactivity at Tomsk-7 is unknown, there were reports that about 1 to 1.5 billion curies are stored and disposed of at this facility.

Recently, an accident was reported at the Tomsk-7 facility. On April 6, 1993 overpressure occurred in a tank containing uranium-nitrate solution. This caused gases to burst through the top of the tank, displacing the cover of the containment cell. An explosion followed when a caustic mixture of air and gas caused an electrical short-circuit. The facility was heavily damaged. The total amount of released radioactivity was estimated at 100 to 400 Ci (Lystsov et al., 1993). An area of 1500 m^2 near the building was contaminated. Of the order of 1.35 Ci of Pu-239,240 was released to the environment. The implications for the Ob river contamination as a result of this accident, however, are hard to access due to the availability of little information. The likely scenario for the fate of plutonium during this accident is probably similar to the fate of plutonium

released during the Kyshtym accident - retained by soils along the radioactive path (Tcherkezian, 1993, personal communication).

Another type of radioactivity released to the environment as a result of industrial activities of the Tomsk-7 facility is activation products. There are five flow-through type reactors at the site. Vakulovsky (1995, personal communication) revealed that the studies conducted by the Scientific Production Association "Typhoon" in the 1970's found short lived activation products in the sediments and waters of the Ob river downstream from Tomsk-7. The radioactive contamination was similar to that observed on the Yenisey river as a result of the industrial activity at the Krasnoyarsk-25 nuclear production facility (Vakulovsky 1995, Nosov et al., 1993). At present, all nuclear fuel production reactors are closed.

2-C-3. Ishym Uranium Ore Mine

Publicly available information about the existence of the Ishym Uranium Ore mining facility in the middle reach of the Ishym river (Fig. 1) became known during the ONR Arctic Nuclear Waste Assessment Program Workshop held at the Woods Hole Oceanographic Institution on May 1-5, 1995. Academician N. P. Laverov (1995) revealed that this facility is a potential source of radioactivity to the Ob river and the Arctic. The character of radioactive contamination could include low level radioactive waste containing uranium and thorium and their radioactive daughter isotopes. The extent of operation as well as the amount of radioactivity at this facility is unknown.

2-C-4. Nuclear Testing Sites: Novaya Zemlya and Semipalatinsk

There are two additional sources of radioactivity which could contribute to the overall radioactive contamination of the Ob river watershed: the Semipalatinsk and Novaya Zemlya Nuclear Testing Sites. There were a variety of nuclear tests performed at these two sites including high altitude, low altitude and ground atmospheric explosions as

well as underground and underwater tests. There is a good possibility that these tests, especially low altitude, ground level and underground ones which vented to the atmosphere, could have contributed to the close-in fallout around the testing site.

2-C-4-1. Novaya Zemlya Nuclear Testing Site

The energy release from the atmospheric tests at Novaya Zemlya amounted to 235 Mt of TNT. The major part of the released radioactivity was injected into the stratosphere and thus became global fallout deposited worldwide. However, a few Novaya Zemlya tests might have produced some local and regional fallout in the Arctic (Aarkrog et al., 1993). Measurements of Cs-137 at the southern testing site of the southern island of the Novaya Zemlya archipelago (Fig. 1) showed local deposition of 2.4 to 36 dpm/cm^2. At the northern test site (southern part of the northern island of Novaya Zemlya) 24 to 240 dpm/cm2 were observed. The expected Cs-137 deposition at this latitude from global fallout would be about 6 dpm/cm^2.

2-C-4-2. Semipalatinsk Nuclear Testing Site

Information on radioactive contamination of the Irtysh River watershed (tributary of the Ob river Fig. 1) as a result of the Semipalatinsk Nuclear Testing Site activity is very limited (Laverov 1995, personal communication). This is the site where the first nuclear test was performed by the USSR in August 29, 1949. During the period 1949-1962, 124 explosions were conducted (8 at high altitude, 91 atmospheric and 25 ground tests). The Semipalatinsk Testing Site was the main base for conducting ground explosions which resulted in radioactive contamination of large territories surrounding the test site. As a result of 25 on-land nuclear explosions, the contribution of Cs-137, Sr-90 and Pu-239,240 may amount to 35 kCi, 19 kCi and 6.2 kCi respectively (Aarkrog et al., 1993). This source of radioactive contamination is potentially significant; however, previous findings about the rate of plutonium migration in soils will probably create a time lag before the radioactivity will make it to the river.

2-D Summary of the Isotopic Ratios of Different Sources

The summary of the estimated range of isotopic ratios which characterize different sources of radioactivity to the Ob river watershed is presented in Table 6.

Table 6. Estimated isotope ratios of radioactivity sources in the Ob river watershed in 1994.

	Pu239,240/Cs137	Pu238/Pu239,240	Cs137/Sr90
Global Fallout + SNAP 9A	0.0264	0.026±0.040	1.45 (1.57 in 1949-59)
Chernobyl Fallout (Aarkrog 1988)	0.0001 - 0.00001	0.5	100
MAYAK Facility			
Techa river (Trapeznikov et al., 1993a)	0.0034	0.012±0.050	2.36
Kyshtym accident (Pavlotskaya 1992)	0.0036	0.030±0.050	0.014
Karachay lake wind event	as Techa river?	as Techa river ?	as Techa river ?
Tomsk - 7	?	?	?
Novaya Zemlya Test Site	as global fallout ?	as global fallout ?	as global fallout ?
Semipalatinsk Test Site	as global fallout ?	as global	as global fallout ?
Ishym Uranium Mine	-	-	-

CHAPTER THREE

Characteristics of the Ob River, Delta and Estuary

The Ob River annual water discharge cycle is characterized by low winter flow and a spring-summer flood starting in May, peaking in June, and slowly decreasing towards the end of the summer (Ivanov, 1980). The mean annual suspended load of the Ob varies along the river and seasonally, being about 500 mg/l near Barnaul City and about 40 mg/l in the delta at Salekhard.

3-A. Water and Sediment Runoff, Sediment Accumulation

Contemporary sediments forming delta island and channel beds represent a "sandwich" structure incorporating sheets of sandy loam, loam, sand, sometimes clays and peat with a thickness between several millimeters and 10 centimeters (commonly 0.2-3 cm). Each of these layers has been deposited during one flood season. Makeev (1988) estimated that "sor" or oxbow lakes could receive up to 10 cm of accumulated sediment during one extreme flood season, while, on average, the sediment accumulation rate in the delta is 0.2-0.4 cm/yr. for the last 300 years.

The sedimentation conditions in the lower reaches and delta of the Ob are influenced by river and sediment runoff and ice conditions. The sedimentation processes in the Ob estuary are a function of wind-wave, tide activity, and, within the northern part - geochemical processes. The average annual water discharge of the Ob and Taz rivers is 530 km^3 (16800 m^3/sec). It fluctuates between 410 and 713 km^3 (13000-22600 m^3/s) (Fig. 17, 18). The annual runoff is characterized by stable low flow in winter and extended spring-summer flood (Fig. 19). The level of water discharge falls to its lowest values by the end of April. The flood starts at the end of April - beginning of May, and reaches a maximum by the end of May - beginning of July. The duration of the flood event varies between 110 (1963) and 186 (1947) days. The beginning of freeze-up is

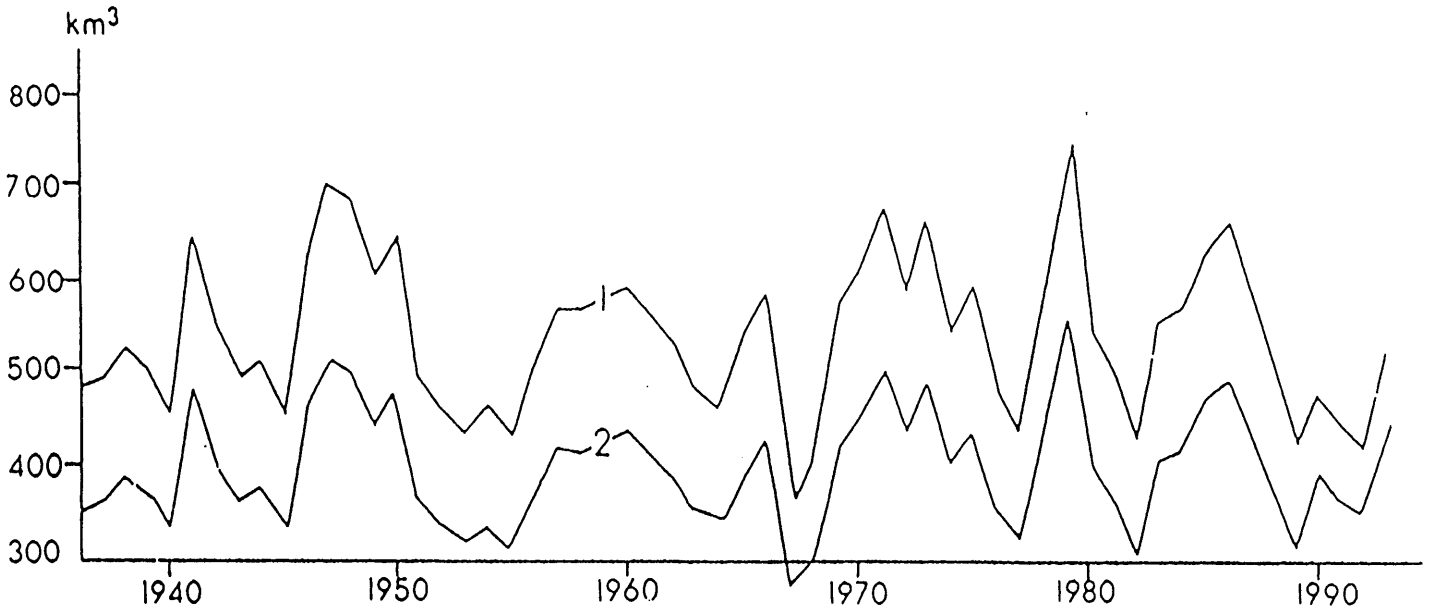


Fig. 17. Long-term fluctuation in the annual average freshwater runoff into the Kara sea from the Ob river and Estuary. 1. Ob Estuary freshwater runoff. 2. Ob river runoff.

Ivanov V. V. (1980) Hydrologic regime of lower reaches and mouths of West Siberian rivers, and estimates of its variations from territorial redistribution of water resources. (In Russian), Problems of the Arctic and Antarctic, issue 55, pp. 20-43.

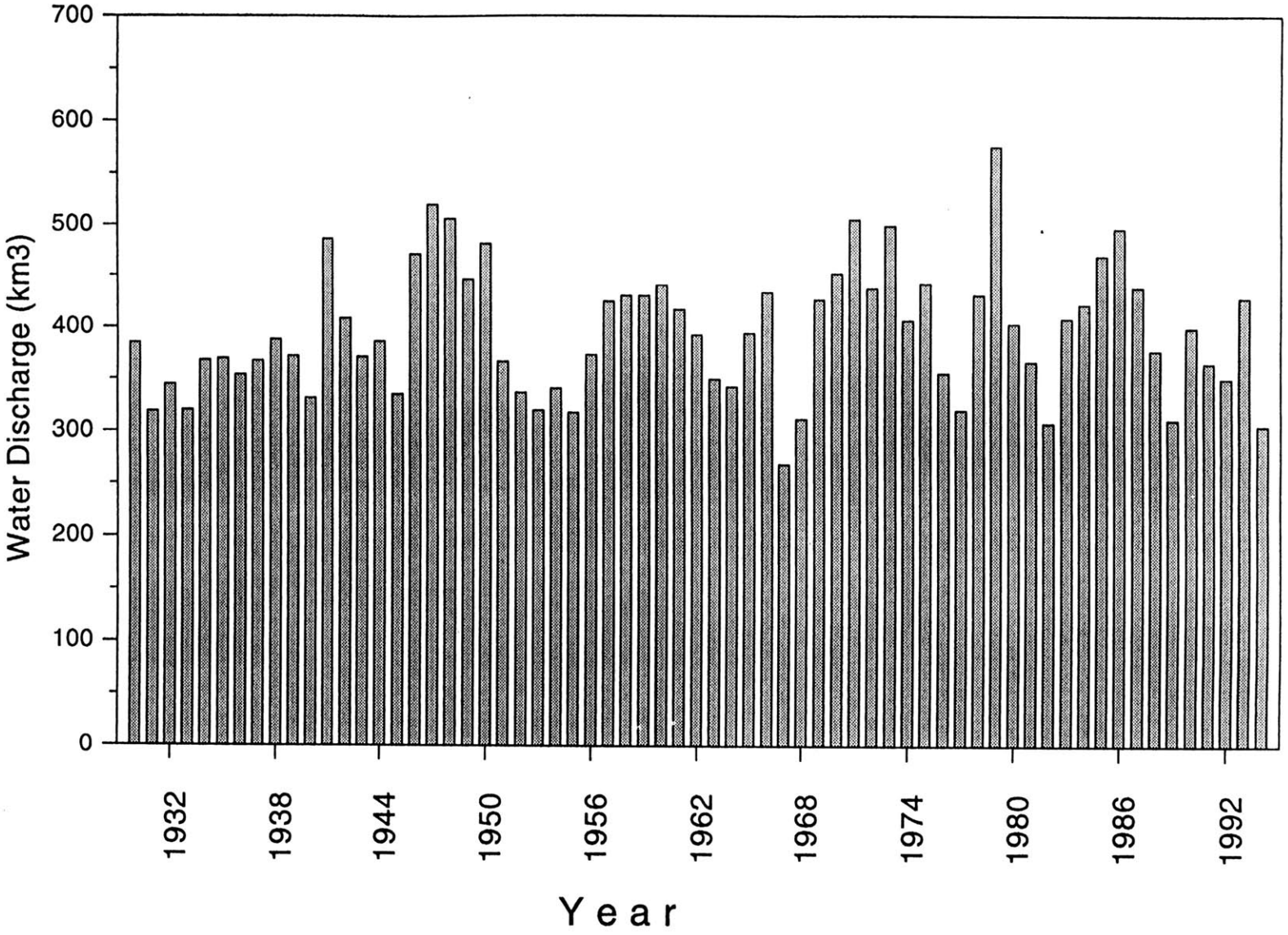


Fig. 18. Long-term fluctuation in the annual Ob river annual runoff.
Data from State Hydrological Network (RUSSIA)

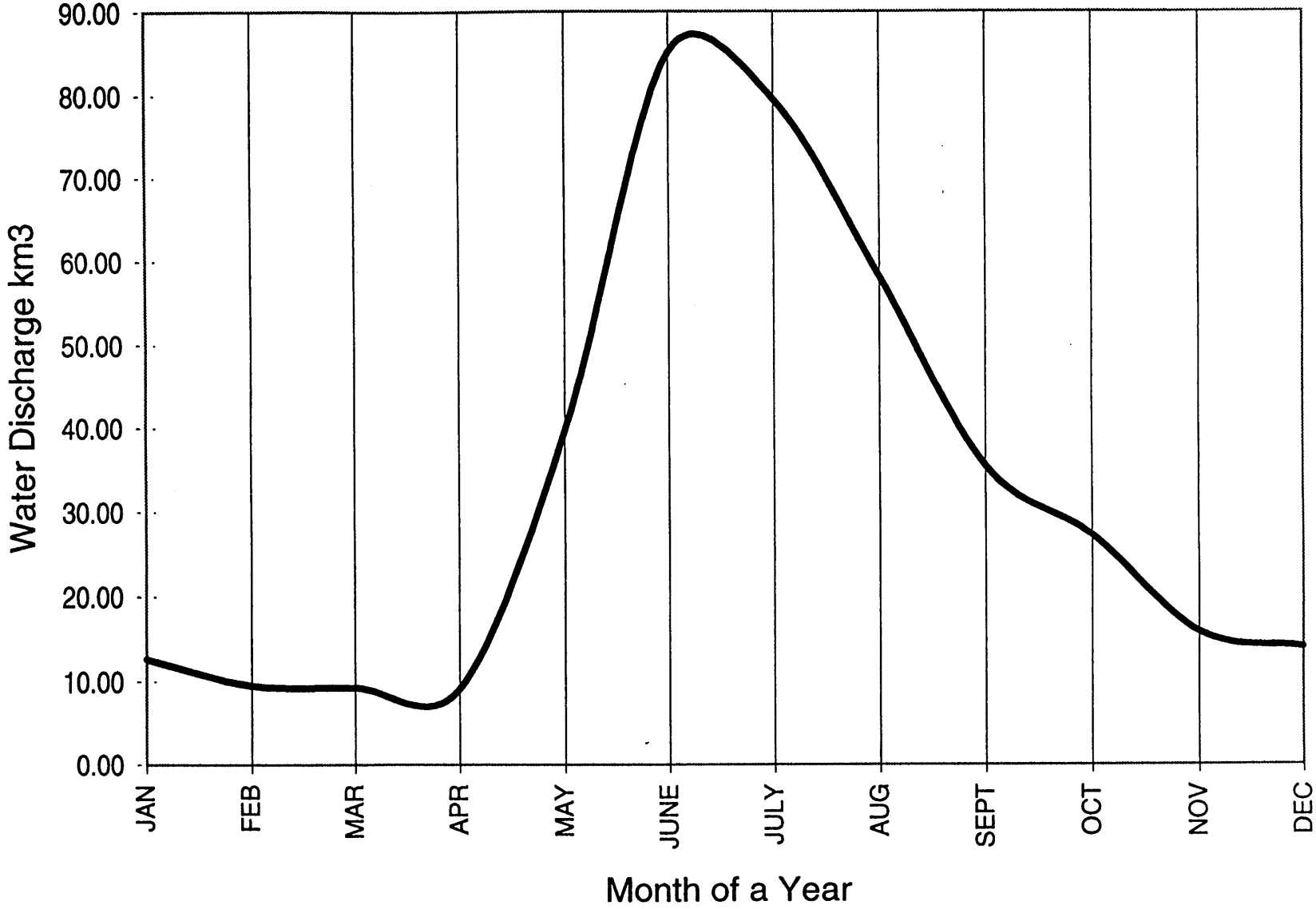


Fig. 19. The Ob River annual averaged (1930-1994) water discharge cycle at Salekhard.
Data from State Hydrological Network (RUSSIA)

preceded by a short period of low water with relatively stabilized discharges (Ivanov et al., 1995). The variation of annual runoff is quite dramatic. High-water years show a relative reduction in the spring runoff and increase in the summer-fall (Fig. 20).

The average annual sediment load discharge near Salekhard amounts to $16x10^6$ tons. In general, the annual sediment discharge variation correlates with the water discharge (Fig. 21). Most of the sediment arrives with the spring-summer flood, which in some years continues until September (Fig. 22). During the flood period, almost 80% of the annual sediment runoff is discharged. Suspended sediments are dominated by the 0.05-0.01 mm (40-50%) and <0.01 mm (25-35%) size fractions. The average particle size of suspended sediments was 0.03-0.06 mm (Ivanov 1995).

The basic sources of sediment supply into the Ob delta are the Ob river itself and material from bank erosion. The suspended sediment discharge into the Ob Estuary is estimated at 15 million tons; 90% of this amount is stored at the outer rim of the delta.

The processes of sediment deposition in the Ob River Delta are complicated. Ivanov et al. (1995) have characterized sediment size composition in the different parts of the Ob delta. The main branches of the Ob river in the delta have a general tendency to contain coarse (0.3 mm) size sediments at the upper reach of the branch and finer size (0.16 mm) sediments at the mouth. This size reduction was attributed to the possibility that fine sediments are carried further by river flow. A size variability also exists during the flood season, when most of the coarse size sediments are transported during the flood maxima. Because of the hydraulic resistance of river banks, the river flow is weaker in these areas. This process effectively creates a favorable environment for finer sediment deposition.

"Sor" and oxbow lakes receive two sorts of sediment: suspended sediments from the Ob River and "local" material of river bank erosion. The amount of upstream sediment is determined by the amount of suspended sediment load of the Ob, the period of lake

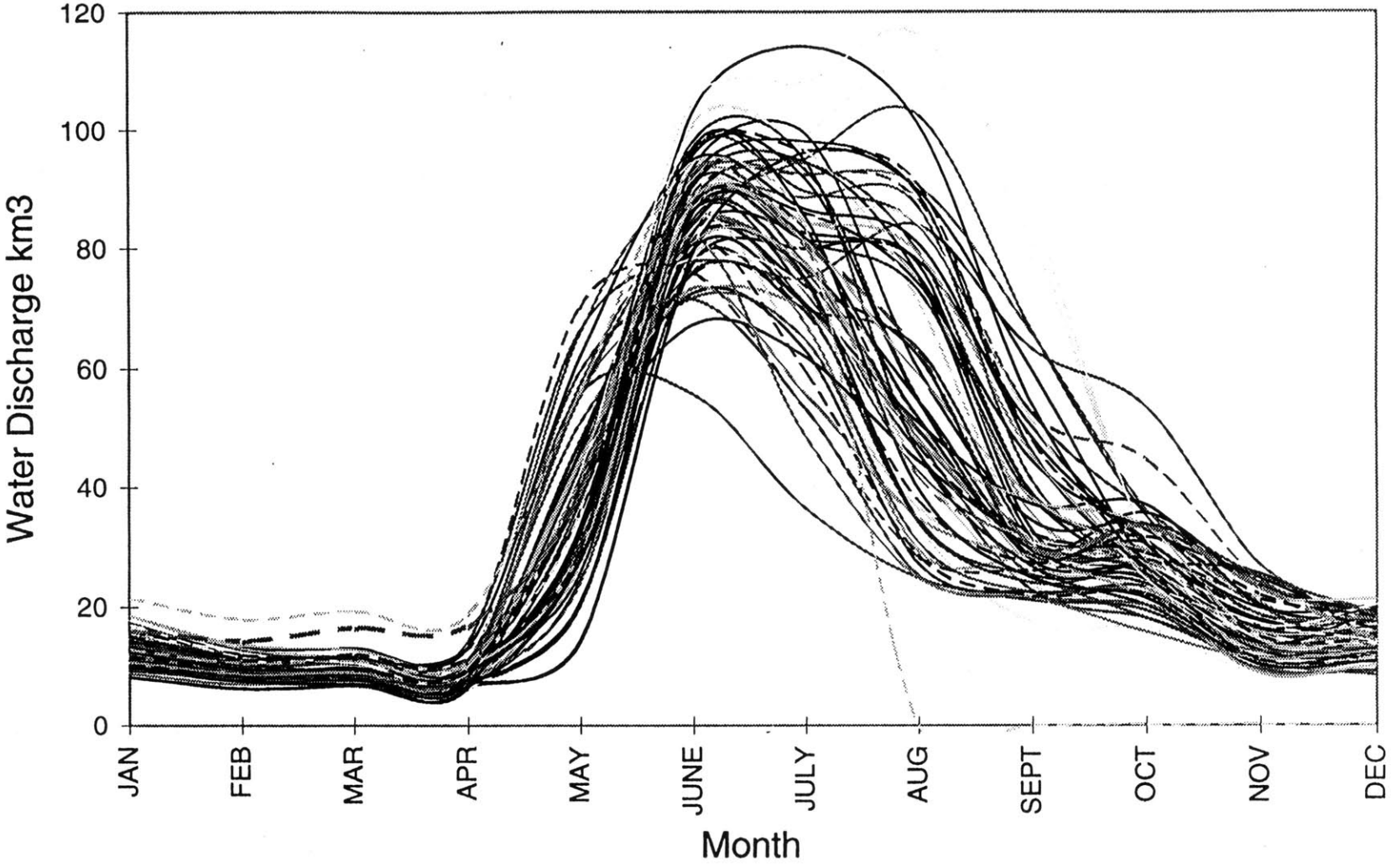


Fig. 20. The Ob River annual water discharge variability. Each line represents one year of observation. Data from State Hydrological Network (RUSSIA)

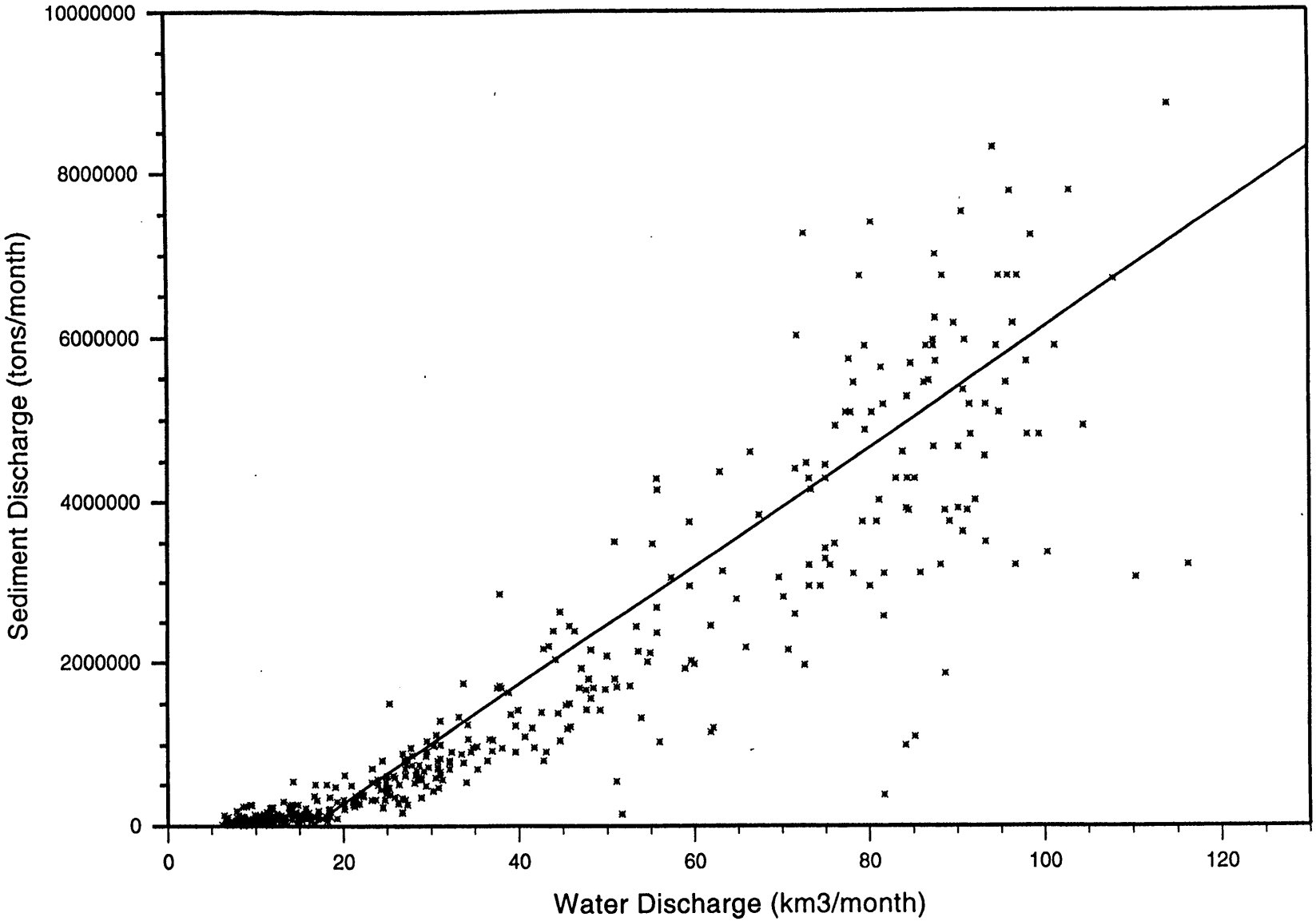


Fig. 21. The Ob River annual water discharge vs. sediment discharge (1930-1994) at Salekhard. Data from State Hydrological Network (RUSSIA)

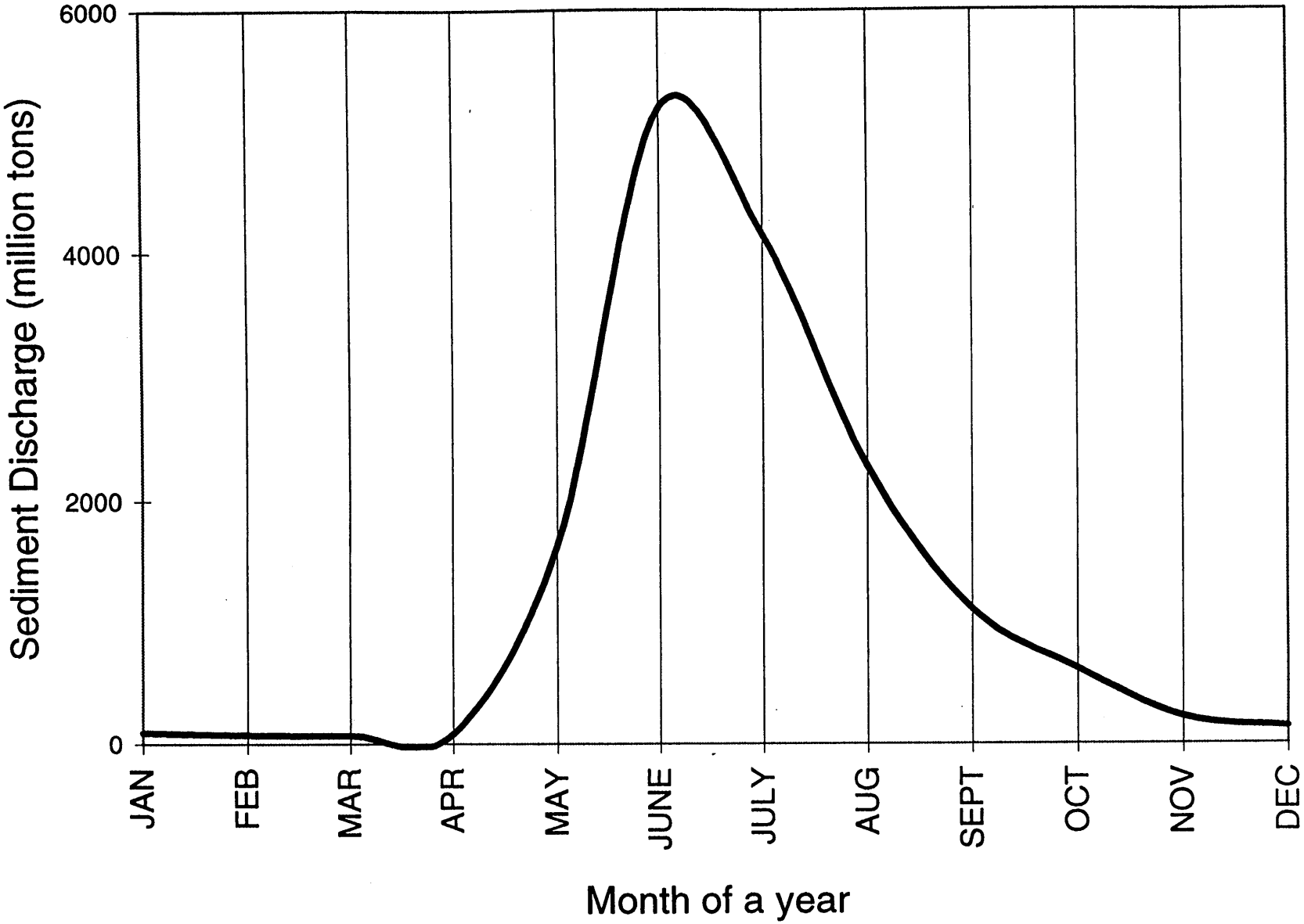


Fig. 22. Long-term fluctuation in the annual Ob river sediment discharge.
Data from State Hydrological Network (RUSSIA)

flooding and the degree of isolation. The amount of "local" material depends on the rate of thermal abrasion of bank terraces, their height, composition, and the ice content of the deposit forming their structure. Bottom sediments contain sand, silt and clay materials with large amounts of fine plant organic debris. It was observed that the larger the lake the higher the probability that it will contain sandy sediments, while the deeper it is the more likely there will be fine grained sediment accumulating.

Mead (1995, personal communications) has addressed the question of sediment transport, exchange and its residence time in the river system. Actively sinuous rivers like the Irtysh usually compensate for erosion on the outer banks of their bends by depositing materials on the point bars of the inner banks. In the case of the Irtysh river, the estimated amount of sediment redeposition is about 2/3 of the eroded material. Although the reasoning of Mead (1995) is based on many assumptions, the discussion implies several things. First, the bulk sediment discharge - which relates to the quantity of radionuclides on suspended sediment passing the Ob-Irtysh confluence - is about half of that which is passing the confluence of the Irtysh and Tobol rivers. Second, the loss of about 40% of the sediment transport between Belogorie (confluence of the Ob and Irtysh rivers) and Salekhard implies massive sediment deposition to the floodplain. The process is reversible and it would be wise to assume that a portion of material which passes through Salekhard was resuspended in the flood plain upstream. The sediment deposition-resuspension process between river and its floodplain could lead to the delay and dilution of the downstream propagation of the radioactive signals from the upstream nuclear facilities.

3-B. Ob Delta and Ob and Taz estuaries

The Ob-Taz estuarine zone is a complicated natural system located at the mouth of the Ob, Nadym, Pur and Taz rivers (Fig. 23). The Ob and Taz form an estuary which is characterized by several morphological features: the bars of the Ob, Nadym, Pur and Taz rivers; the shallow (4-20 meters) southern (south of 69° N) portion of the Ob estuary which contains freshwater all year long; and a deeper (8-35 meters) part, filled with

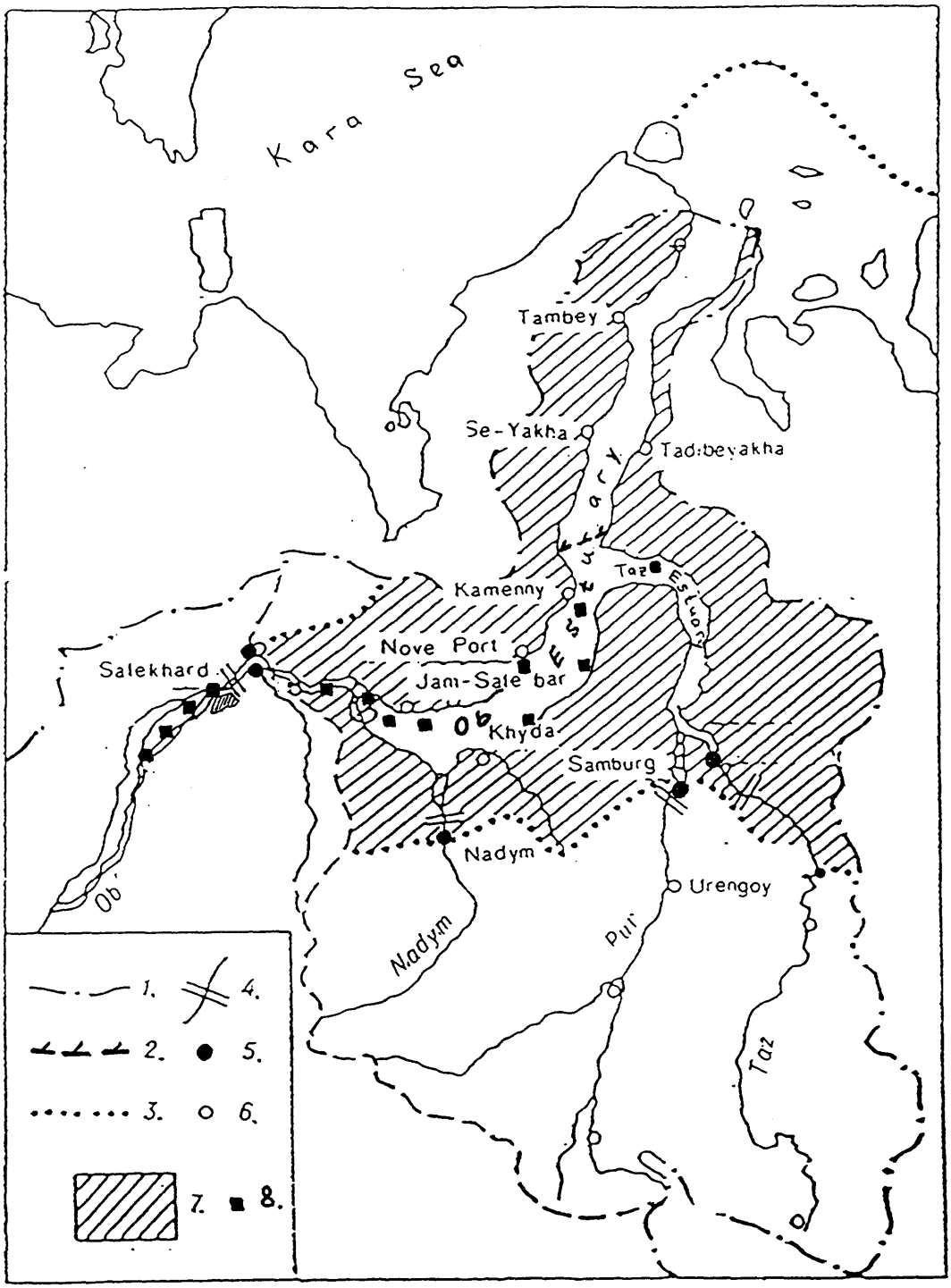


Fig. 23. Map of the Ob river Delta, Ob and Taz estuaries and the Taz Estuary drainage Basin. 1. Drainage boundary; 2. Southern boundary of sea water intrusion at the bottom during winter. 3. Boundary of river water propagation into the Kara Sea. 4. Boundary of river mouth. 5. Outlets of large rivers at sites with runoff measurements. 6. Hydrological stations. 7. Area of uncharacterized runoff. 8. "Ob Estuary-1994" sampling locations.

Ivanov. V. V., O. N. Medkova, V. M. Makeev (1995) Characteristic features of sedimentation process in lower reaches and mouth of the Ob river. Data report prepared at the request of the Woods Hole Oceanographic Institution on behalf of "Ob River Project".

brackish water (north of 69° N). The propagation of the brackish waters into the Ob estuary depends upon seasonal variations of the river runoff, thermohaline conditions, wind-wave action and ice conditions in the estuary. The Ob estuary extends for 800 km (Fig. 23) and covers an area about 40,800 km^2. The Taz estuary extends for 300 km and covers 7,760 km^2 (Ivanov 1968).

The mouths of the Ob, Nadym, Pur and Taz rivers have well-developed deltas (Ivanov et al., 1980). The Ob Delta is characterized by a complex network of channels which interconnect two main branches: the Khamanelskaya Ob and Nadymskaya Ob. Between the branches of the Ob there are over 50 islands (Fig. 24). The overall length of the Ob mouth area is 279 km including 143 km in the delta itself. The total delta area is 3250 km^2, of which about 60% is covered by water (Ivanov et al., 1995). The Ob river floodplain above and below Salekhard is 3-6 m high. It characterized by numerous channels of various-size and lakes (100 meters to several kilometers) of different genesis (oxbow, "sor") with depths up to 5 meters. Most of this area is under water during flood season which occurs on average in late May. In some areas the floodplain is almost 20 km wide. The material forming the banks and the floodplain is commonly in the permafrost state (Makeev et al., 1988). Portions of thawed ground are located beneath the bed of large water streams and lakes. "Sor" lakes as well as oxbow lakes are a characteristic feature of the floodplain of the Ob delta. "Sor" lakes are of isometric shape, 2-3 m deep, with widths ranging from hundreds of meters to several kilometers (Fig. 25).

3-C. Ice in the Ob river Delta and Estuary

Freezing starts in October. In the lower reaches of the Ob River delta, ice forms along coasts and bars. After reaching a certain size, ice forced by the winds and currents detaches from shore and drifts towards the estuary. In the oxbow and "sor" lakes, the ice formation process starts at the same time, however, because of the enclosed nature of the lakes, they freeze solid in a reasonably short time. The ice thickness ranges between 100-

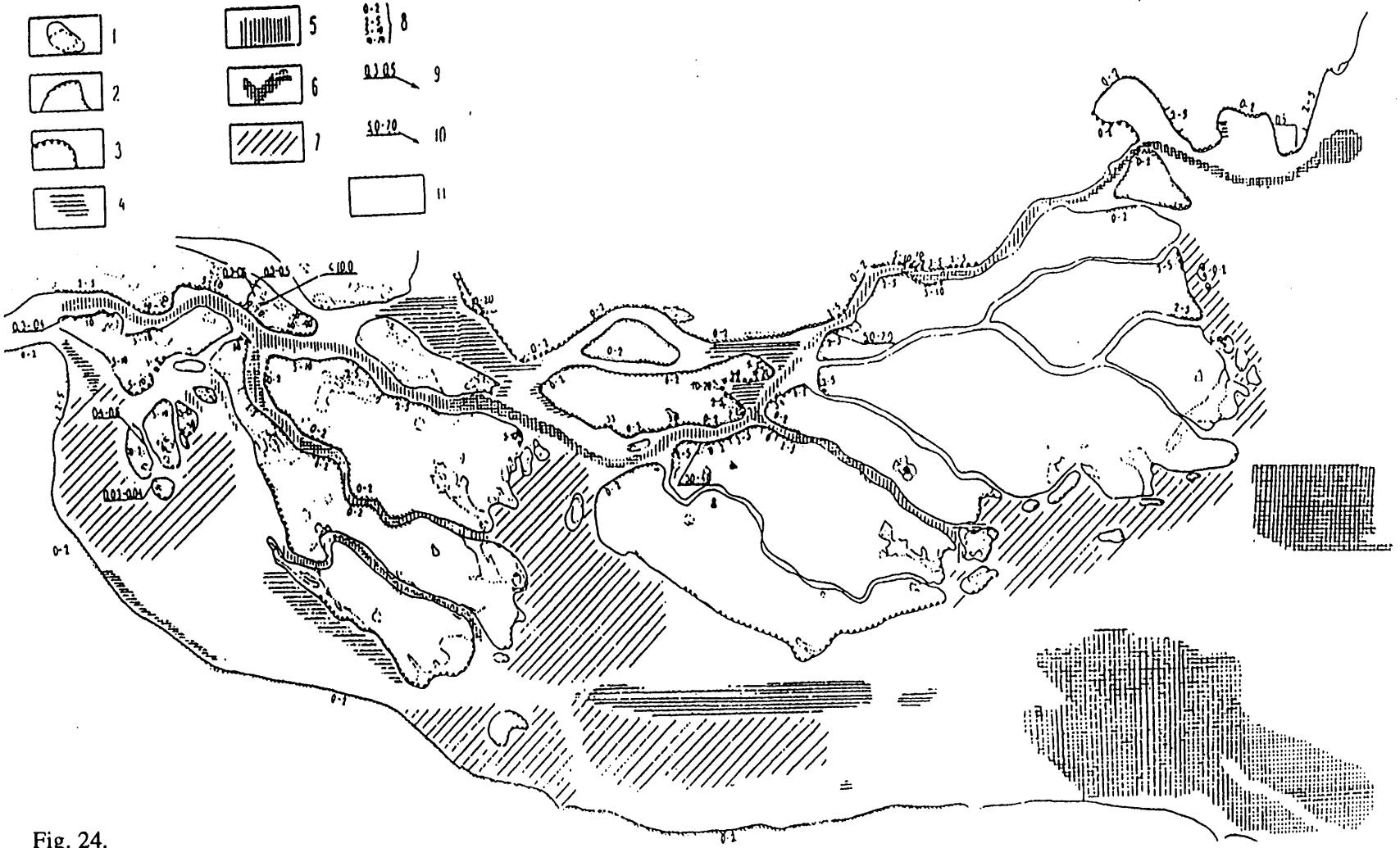


Fig. 24.
Map of the Ob Delta dynamics. 1. Portion of flood plain flooded at average annual flood rise; 2. Eroding banks; 3. Accumulating banks; 4. Sediment accumulation zones; 5. Sediment erosion zones. 6. Stable sediment zones - no erosion or accumulation. 7. Areas of prevailing accumulation (data from aerial observations); 8. Coastal line deformation rate; 9. Sediment deposition rate on the banks; 10. Thickness of silt deposition in lowland floodplain; 11. Data unavailable.
Ivanov. V. V., O. N. Medkova, V. M. Makeev (1995) Characteristic features of sedimentation process in lower reaches and mouth of the Ob river. Data report prepared at the request of the Woods Hole Oceanographic Institution on behalf of "Ob River Project".

Fig. 25. Morphological types of arctic environment lakes in the Ob River Delta. Satellite picture of one of the tributaries of the Ob river. 1. "Sor" lake. 2. Oxbow lake.

150 cm in the Ob delta, 90-230 cm in the freshwater part and 130-250 cm in the brackish water part of the Ob estuary (Ivanov et al., 1995).

Ice thickness is of great importance for the preservation of the sediment record in the oxbow and "sor" lakes. If the ice thickness is less than the depth of the lake then ice cover remains afloat during the whole winter period, and does not disturb the sediments on the bottom. If, on the other hand, the thickness is greater than the lake depth, ice cover may freeze to the bottom and incorporate sediment in itself. During the spring flood season the ice detaches from the bottom carrying away incorporated sediment. This process destroys the sediment record in the lakes. However, in enclosed and semi-enclosed lakes ice would probably stay within the lake depositing the sediment back to the bottom. It is interesting to speculate, that in such enclosed lakes, the floating ice gradually (due to the thawing process) releases incorporated sediment back into the water which could fall to the bottom, layer after layer, effectively reinstating the sediment record. This process, were it to occur, could explain some inconsistencies in records observed in the sediments (see further discussion).

The ice breakup in the Ob delta on average starts in spring in May, and, due to the complexity and wide distribution of river channels, ice dam formation is rarely observed. The break up of coastal ice in the Ob Estuary starts from the center of the estuary as a result of thermal heating with little mechanical destruction. It was observed that most of the ice which originated in the southern part of the estuary does not make it out into the Kara sea. Most of this ice melts away by the time it reaches the northern part of the estuary (Doronina et al., 1976, Ivanov & Makeev, 1990).

CHAPTER FOUR

Joint Russian-American Expedition "Ob Estuary - 1994"

Sampling in the Ob River Delta and Estuary

Sedimentation processes in the Ob delta and the Ob and Taz estuaries are dependent on geological-geomorphological and hydrological conditions, geomorphological structure, water and sediment runoff, ice conditions and wind-wave action. To assess the history of accumulation of particle reactive radioactive isotopes of plutonium and cesium arriving from the Ob watershed into the Ob Delta and Estuary, as well as to the Taz Estuary from the Taz River watershed we collected sediment cores at 15 locations (Fig. 1). Our journey began at the small Siberian city of Salekhard, which is located at the mouth of the Ob River. From there, we traveled some 800 kilometers collecting sediment samples in the delta and estuary. Our approach was to sample numerous oxbow lakes (Fig. 26, 27). These annually flooded lakes are characterized by a low flow environment and were expected to preserve the sediment transported there each year.

The key to the success of the sampling was the design and construction of a collapsible catamaran boat. It was christened "Ob-Venture". "Ob Venture" is a shallow draft sampling platform that consists of a deck with an A frame, resting on two inflatable pontoons (Fig. 28, 29), designed to meet a number of criteria that are quite unusual for sediment sampling vessels.

It should be suitable for:

1. Transport over long distances by air, train or any other transportation means within Russia in small 5 ton capacity steel containers;
2. Easy to assemble and disassemble with simple hand tools;
3. Light enough, so six people could handle it by hand;
4. Sturdy enough to carry 4 people;
5. Capable of delivering 2 meter long cores and handling a 400 kg coring device with an A-frame.
6. Shallow draft; 10-20 cm.

Fig. 26. "Sor" lake in the Ob River Delta.

Fig. 27. Oxbow lake in the Ob River Delta.

Fig. 28. "Ob Venture" IT FLOATS !, Woods Hole, May 23, 1994.

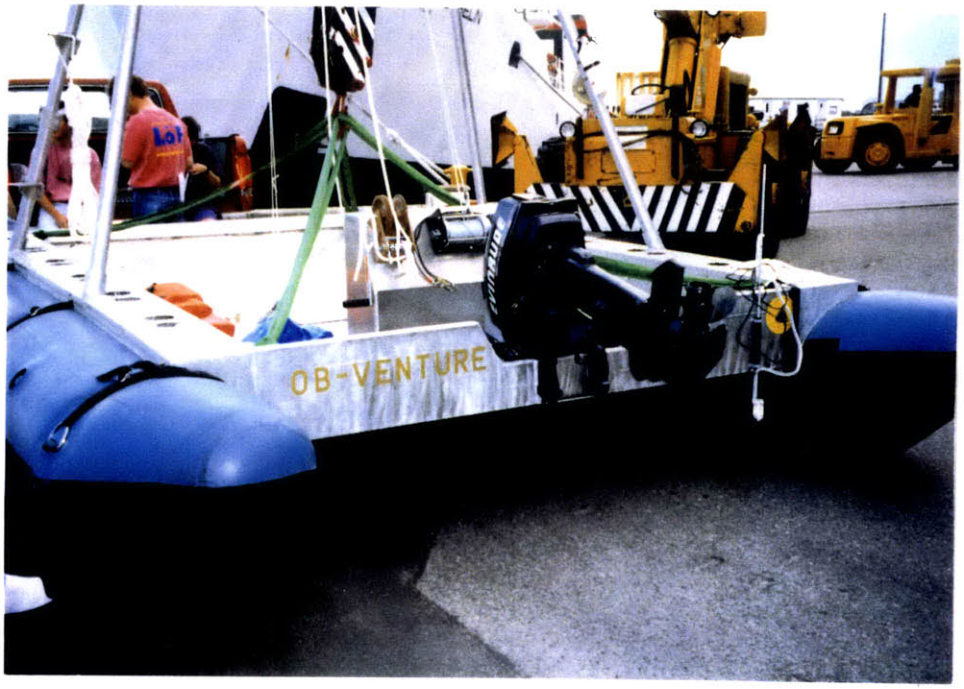


Fig. 29. "Ob Venture": Outboard Motor; Manual and Electric Winch; Depth Sounder.

With the help, enthusiasm and effort of many people at the Woods Hole Oceanographic Institution, Atlantic Branch of USGS and MIT we were able to construct "Ob-Venture" from scratch within 5 weeks in April-May 1994.

For our sampling program we chartered the Russian fisheries' protection vessel RS300 # 168 to serve as a mother ship for the "Ob-Venture". High-resolution maps and aerial photographs were used to identify locations for sampling. "Ob-Venture" is equipped with a Global Positioning System and a Depth Sounder. The GPS was used for navigational purposes and provided us with precise coordinates of the sampling locations. The depth sounder was used to obtain a knowledge of the bathymetry of each lake. After entering each lake, we made several transects surveying it completely for the deepest location.

The quality of the sediment core was a critical component of the program. A gravity corer (>200 kg) was slowly lowered through the central well of the "Ob-Venture" into the lake bottom (Fig. 30, 31). It was designed by S. Smith, G. Panteleyev, and F. Sayles - WHOI, based on design ideas provided by M. Bothner, USGS Atlantic Branch. Battery and manual powered winches were used to retrieve the core from the sediment. The manual winch gave more control over the gravity core and delivered better samples. A carefully designed valve (M. Bothner - USGS Atlantic Branch) of the gravity corer, prevented the sediment from falling out of the core barrel. The core barrels were made of clear plastic allowing us to make a visual assessment of the quality of the core upon retrieval. It took us about one hour to collect a high quality core. Sediment cores were transported in a vertical position and prepared for sectioning at 1 centimeter intervals aboard the ship. The sediment samples were preserved in 8 ounces jars and were shipped to the Woods Hole Oceanographic Institution for radiochemical analysis.

Fig. 30. "Ob Venture" Sediment coring in progress.

Expedition "Ob Estuary - 1994".

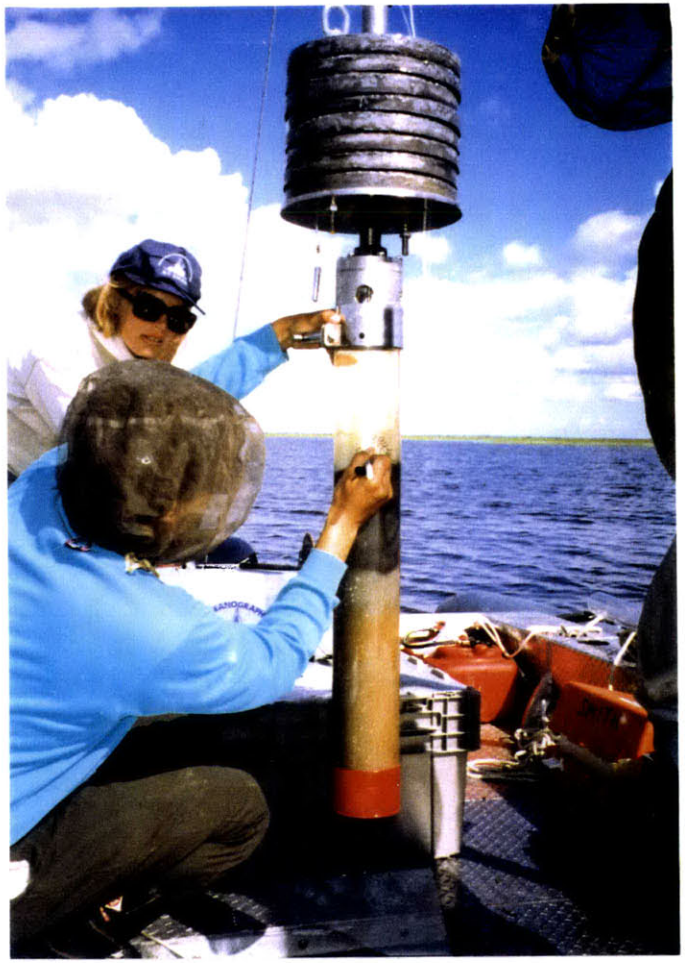


Fig. 31. "Ob Venture" Sediment corer.

Expedition "Ob Estuary - 1994".

There were many organizations and people involved in the organization of the Joint Russian-American Expedition "Ob Estuary -1994". Here I would like to name just few of them who helped tremendously during the expedition:

Dr. V. Shishmarev - Environment Protection Committee of Salekhard, Russia.

V. Chusovitin - Chief Inspector of Fisheries Protection of Salekhard, Russia

S. Smith - Woods Hole Oceanographic Institution

O. Medkova - Arctic & Antarctic Research Institution of St. Petersburg, Russia.

M. Monetti - US DOE Environmental Measurements Laboratory.

The summary of the sediment core locations is presented in Table 7.

Table 7. Summary of sediment core locations collected during Joint Russian-American Expedition: "Ob Estuary-1994"

ID	Sample site	Water depth m	Core lengh cm	Cs-137 depth penetr. cm.	Lat. Coord. North	Long. Coord. East	Date coll.	Numb sampl
Ob94-3	Hashgort "Sor" Lake connected to main channel by wide water body.	1.9	78.5	11.5	65 28.855	65 40.655	21-Jul-94	60
Ob94-4	Khanty Pytlyarsky "Sor" Lake connected to the main body by shallow channel.	2.1	46.0	16.0	65 47.385	65 52.050	22-Jul-94	42
Ob94-6a	Langytlor "Sor" Lake. Core in open part of the lake.	1.3	65.0	12.0	65 39.007	65 04.881	24-Jul-94	58
Ob94-6b	Langytlor "Sor" Lake. Core surrounded by grasses.	1.0	77.5	6.0	65 39.520	65 06.726	24-Jul-94	66
Ob94-7a	Nentinsky "Sor" Lake. Core in small partially enclosed lake.	1.0	60.5	12.0	65 41.066	65 32.771	25-Jul-94	54
Ob94-7b	Nentinsky "Sor" lake. Core in small enclosed lake on a side.	1.5	48.0	18.0	66 40.035	68 32.521	25-Jul-94	46
Ob94-8	Oxbow lake adjusted to the main river channel. Enclosed from one side.	4.0	128.0	25.0	66 48.814	69 24.439	26-Jul-94	67
Ob94-9	Taliyun "Sor" Lake separated by long channel from the main river.	1.0	58.0	15.0	66 48.364	69 32.652	27-Jul-94	52
Ob94-10a	Endatasata. "Sor" Lake separated by long channel from the main river	2.5	96.5	61.0	66 46.751	70 57.880	28-Jul-94	97
Ob94-10c	Endatasata. "Sor" Lake separated by series of lakes and channels from the main riv	1.4	46.5	15.0	66 47.071	70 44.670	28-Jul-94	47
Ob94-11	Noviy port bay. Ob Estuary.	1.2	47.0	9.0	67 43.596	67 02.839	29-Jul-94	47
Ob94-12	Nakhodka bay. Ob Estuary	1.2	67.0	10.0	67 15.552	72 06.160	30-Jul-94	61
Ob94-13	Taz Estuary in the middle of the estuary, near "Bukhta Dvykh Chumov"	5.3	107.0	12.0	69 05.370	76 43.028	31-Jul-94	59
Ob94-14	Ob Estuary. Mys Kamenniy. Grab sample Surface sediment	17.1	3.0	3.0	68 25.525	73 49.887	1-Aug-94	1
Ob94-15	Ob Estuary. Jamburg settlement. Grab sample. Surface sediment	6.0	3.0	3.0	67 53.989	74 47.744	1-Aug-94	1
Ob94-16	Ob Estuary. Grab sample from the southern part of the Ob Estuary.	5.0	5.0	3.0	66 51.416	73 12.038	2-Aug-94	1
Ob94-17a	Labendigo "Sor" lake. Lake separated by another lake from the main channel. Grass	0.7	50.0	6.0	66 42.671	70 12.962	3-Aug-94	50
Ob94-17b	Labendigo "Sor" lake. Lake connected to the main channel.	1.2	52.0	12.0	66 42.390	70 10.471	3-Aug-94	50

CHAPTER FIVE
METHODS AND DATA

5-A. Analysis of Cs, Pb and Pu isotopes and data quality

The overall approach to the analysis of the sediment cores from the Ob delta made use of well established methods of radionuclide analysis. Two general techniques were used:

1. Gamma spectrometry - high resolution Ge detectors were used on the sediment sections of each core directly, to determine concentrations of Cs-137 and Pb-210 (in excess of that supported by its parent, Ra-226).

2. Radiochemical analysis - after non-destructive gamma spectrometric analysis, sub-samples of the sediment sections were analyzed for Pu-239,240 and Pu-238 by classical radiochemical methods using hot nitric acid leaching, anion exchange purification and electrodeposition of sources for alpha spectrometric determination.

The strategy for the analyses involved a preliminary screening measurement to scope out the rough distribution of down core Cs-137 concentrations. The undried sediment sections in clear plastic jars were placed directly on the Ge detector and the gamma spectra measured. The relative down core concentration of Cs-137 so obtained was used to prioritize the order of analysis of the samples by core and within a core. Water content of the samples was determined by weight difference before and after drying. After weighing each undried sample, it was dried at 65 deg C (determined by the melting point of the jars) for 2 days and reweighed. Following drying, each section was carefully homogenized by grinding in a mortar and pestle.

The dried samples were subsequently analyzed for Cs-137, Pb-210 and other isotopes by the technique summarized below. Thereafter, 20 gram sub-samples of each

section were taken for radiochemical analysis of Pu isotopes - either in Woods Hole or via the intercomparison exercise discussed later.

A few sections of core Ob94-8 were analyzed sequentially - for intercomparison of the Cs-137 determination - in our laboratory in Woods Hole and at the U.S. Department of Energy's Environmental Measurements Laboratory in New York. This was arranged through Matthew Monetti who had participated in the 1994 field program.

5-B. Cs-137, Pb-210 and Ra-226 analysis by gamma spectrometry

Several detectors were available for these analyses. All counting was accomplished in standard 8 ounce plastic jars. As the amount of sample varied from section to section, corrections based on counting geometry (essentially sample thickness) and internal self-absorption were made. The counting efficiency of each detector, as a function of the energy of the gamma lines used, was determined using "standard pitchblend ore" from the Environmental Protection Agency laboratories in Las Vegas, Nevada with a certified ^{238}U activity of 6.03×10^3 dpm/g.

The geometry correction for each detector and each gamma line was determined by repeated measurements of different amounts of this reference sample with resultant increasing sample thickness. The self-absorption corrections were made by comparison of the reduction of the counting rate at the various lines used of a standard source (uranyl nitrate; 1.4μCi; uranium series activity) placed on top of each sample.

The Pb-210 concentration in each sample derives from two independent sources. The first is the Pb-210 which is in equilibrium with its radiogenic precursors supported by Ra-226. These are part of the natural series radionuclides in the soils and sediments of the watershed associated with the decay of U and Th.. The second is Pb-210 derived from atmospheric fallout of Pb-210 produced from Rn-222 released to the atmosphere from the earth's surface. It is this latter component, the so-called excess Pb-210, which can be used

to derive age estimates of undisturbed layers in accumulating sediments. The total Pb-210 activity was directly determined by quantification of the activity of the 46.5 KeV line. The excess Pb-210 was determined by subtracting the supported Pb-210 (estimated from the measured amount of Ra-226) from total Pb-210. The Ra-226 concentration was estimated from the equilibrium concentrations of its decay products with measurable gamma lines, Pb-214 and Bi-214. Equilibrium was established by sealing the sample container to prevent loss of Rn-222 and delaying counting the sample for two weeks. A discussion of the differences between Ra-226 estimated from Pb-214 and Bi-214 can be found in the next chapter.

5-C. Pu-239,240 and Pu-238 analysis

The method applied in these analyses is one which has been in use in the radiochemical group at Woods Hole and in many other laboratories for many years. As mentioned above, it involves a radiochemical separation of Pu isotopes from other alpha emitting radio-elements in the sediment followed by alpha spectrometric analysis with solid state detectors as described by Livingston et al. (1975).

5-D. Intercomparison analyses

In order to extend the number of samples analyzed, and to provide an element of quality control, some samples were analyzed in other laboratories.

For the measurement of Cs-137 by gamma spectrometry, nine samples of dried and mixed sections from core Ob94-8 were analyzed both in Woods Hole and at the Environmental Measurements Laboratory in New York (in collaboration with Mathew Monetti). The results of this intercomparison are shown in Figure 32. Although the results track generally together, there is a sytematic difference between the two data sets. The EML activities are consistently ~17% lower than the WHOI measurements. The reasons for this difference have not been established but there is no reason to believe that

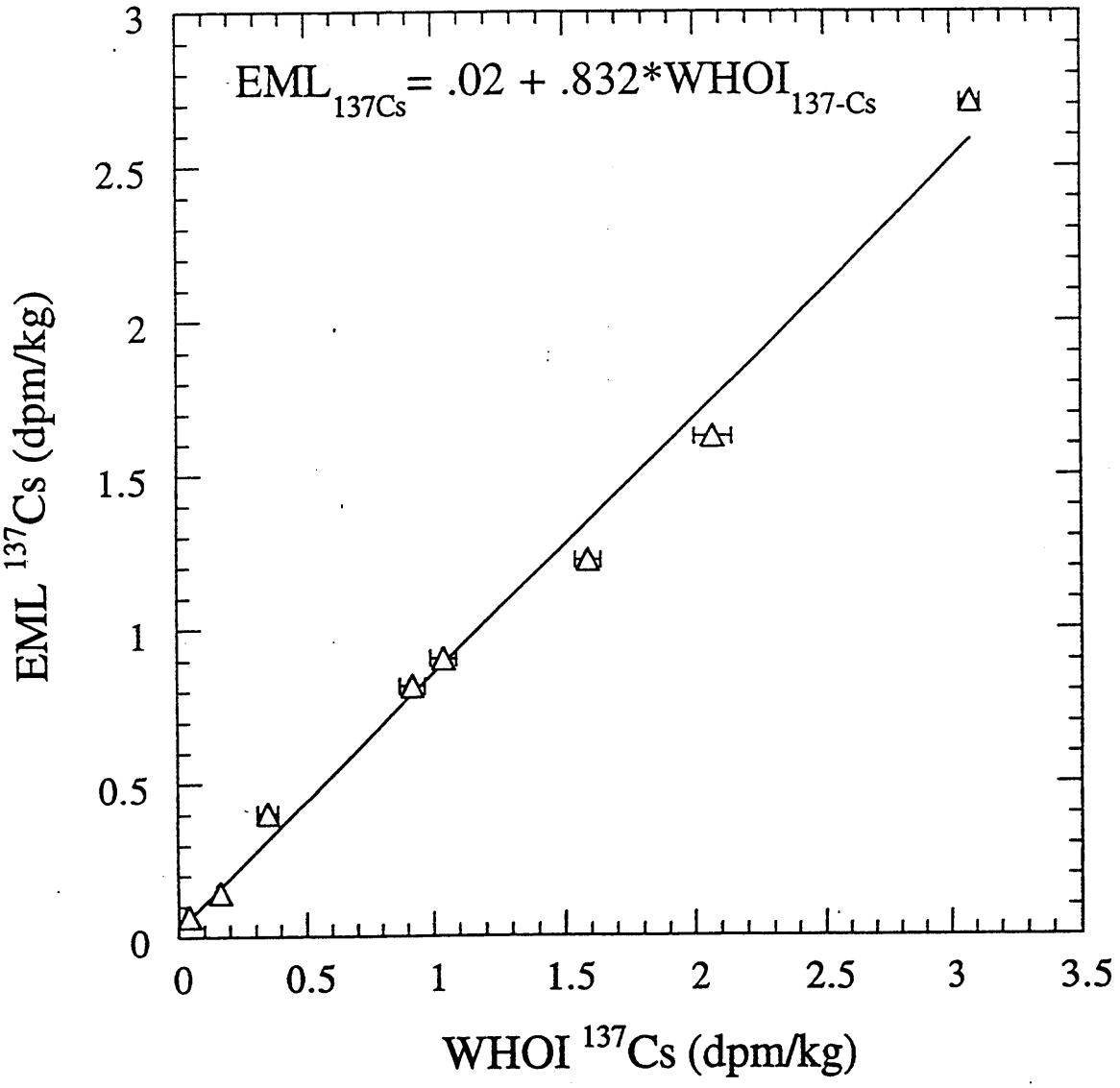


Fig. 32. Comparison of cesium data measured at Woods Hole Oceanographic Institution (WHOI) and at the Environmental Measurements Laboratory (EML) of the Department of Energy.

one data set is superior to the other. This discrepancy should be kept in mind in evaluating the data. As the Woods Hole data are used throughout this thesis, it is necessary to remember that the Cs-137 concentrations, inventories and ratios to other radionuclides could have uncertainties somewhat larger than the indicated measurement uncertainties.

For intercomparison of radiochemical analyses of Pu isotopes, splits of dried and homogenized sections from several cores were sent to two laboratories in addition to those analyzed in Woods Hole. The other measurements were made in laboratories at the Institute of Oceanology, Sopot, Poland (Dr. Ryszard Bojanowski) and at the Radium Institute in St. Petersburg, Russia (Professor Yuri Kuznetsov). In general, the agreement between the three laboratories was good. The data from the Radium Institute had larger uncertainties because of the small size (7 grams) used for analysis and the relatively short periods of alpha spectrometry measurement. On the other hand, the data from Dr. Bojanowski's laboratory had lower uncertainties, similar to those obtained in the data set from Woods Hole. The data sets from Poland and Woods Hole are plotted against each other in Figure 33 and it may be seen that the agreement is such that a high degree of confidence in all the Pu data reported in this work is assured.

5-E. Data and Figures

The analytical data for each core analyzed are presented in Appendix 1.

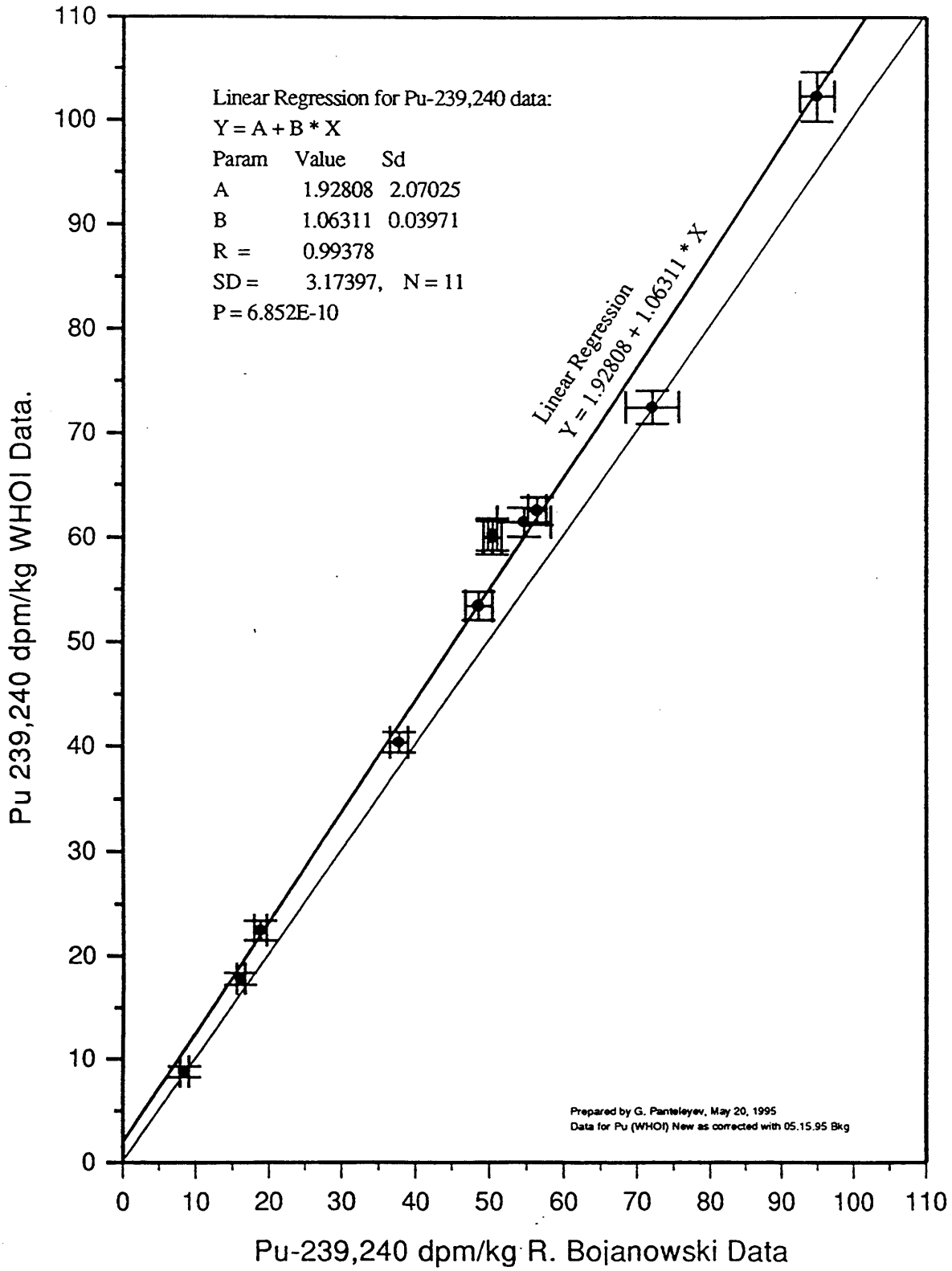


Fig. 33. Comparison of plutonium data measured at Woods Hole Oceanographic Institution (WHOI) and at the Institute of Oceanology, Sopot, Poland (R. Bojanowski).

CHAPTER SIX

The History of Plutonium and Cesium-137 Contamination of the Ob River Delta Sediments

The goal of the present study is to assess the history of radionuclide contamination of the Ob River Delta sediments that resulted from Cold War activities of the Former Soviet Union and eventually estimate the potential supply of land derived radioactivity to the Arctic Ocean. The approach is to reconstruct the history of radioactive contamination of the Ob River delta using Cs-137, Pu and Pb isotopes and estimate different source contributions using Pu-239,240/Cs-137 and Pu-238/Pu-239,240 ratios. The potential sources supplying radioactivity to the Ob delta sediments (global/close-in fallout, discharges to the Techa river, the Kyshtym accident and the Lake Karachay wind event at Mayak, and the activities and accident at Tomsk-7) have been described in chapter 2.

There are two types of radioactive elements which, by their geochemical behavior in fresh water, represent long term environmental threats: soluble and particle reactive. Soluble isotopes, like Sr-90, remain essentially dissolved in river water and can travel with water flowing downstream. Large quantities of Sr-90 were measured in the river waters by the Radium Institute of St. Petersburg (Kuznetsov, Vakulovskiy - personal communications) throughout the Techa-Iset-Tobol-Irtysh-Ob river system during the 1970's. The source of this Sr-90 was attributed to be from global fallout. Cesium and plutonium are particle reactive elements in fresh water and strongly bond to the fine grained particles in the rivers. Because of this property, they travel through the river system mainly along with the suspended load.

Because of the nature of intentional releases and accidents at "Mayak" and Tomsk-7 (see discussion above) the main concern is the radioactivity stored in the floodplain and bed of the Techa River. The river directly connects to the Ob through the network of its tributaries: the Iset, Tobol and Irtysh rivers (Fig. 1). In the future, in case of radioactive storage reservoir overflow or dam failure at the "Mayak" facility, the Techa river will be a

likely recipient of large amounts of radioactivity (up to 120 MCi). This radioactivity has the potential to reach the Arctic Ocean traveling some two thousands kilometers through the Techa-Iset-Tobol-Irtysh-Ob-Ob Estuary river system.

"Sor" and oxbow lake receive sediment and radionuclides through at least three possible pathways: direct fallout from the atmosphere (this could include aeolian input, global and close-in fallout), sediment transport from surrounding flood plains and river banks, and ownstream sediment transport which carries particle reactive radionuclides in sorbed form. The latter process could bring radionuclides from upstream nuclear facilities.

6-A. Results and Discussion

Eight sediment cores from the Ob flood plain and one from the Taz were analyzed, representing 8 different locations. More than two hundred samples were analyzed for Cs-137, Pb-210; Pb-214; Bi-214; Pu-239,240 isotopes and Pu-238. Pu-239,240/Cs-137 and Pu-238/Pu-239,240 ratios were calculated for many samples. Inventories were estimated for the cores where data are sufficient. Excess Pb-210 data were used in a constant activity/sedimentation model to date the cores. Data on wet density, water content, isotopes, ratios and dates are presented in Appendix 1. Table 8 lists analyses performed on the cores selected cores for this work. At the moment, a full set of information on Cs-137, Pb-210, Pb-214, Bi-214 and Pu isotopes exists only for cores Ob94-8; Ob94-9; and Ob94-13. Analyses of Cs-137 were completed for Ob94-10A, Ob94-7A and Ob94-7B, while Pb-210, Pb-214 and Bi-214 are only available for the latter two. Pu data were obtained on a few samples in core Ob94-7B and Ob94-10A.

Table 8. Number of sections per core analyzed for different isotopes

Core ID	Cs-137	Pb-210	Pb-214	Bi-214	Pu-239,240	Pu-238
Ob94-3	10	9	9	9	7	7
Ob94-4	14	12	12	12	-	-
Ob94-7A	15	15	15	15	-	-
Ob94-7B	21	23	23	23	6	6
Ob94-8	16	17	17	17	17	16
Ob94-9	14	18	18	18	16	16
Ob94-10A	60	-	-	-	-	-
Ob94-13	13	17	17	17	14	14

6-B. Sediment Cs-137 Profiles

All of the sediment cores I analyzed show a more or less consistent Cs-137 distribution pattern: low Cs-137 activity at the surface, an increase with depth and then an exponential decrease downcore until the activity is unmeasurable. The data (except core Ob94-10A) are plotted on the same scale (Fig. 34-41). Surface sediment Cs-137 values vary between 0.22 and 3.3 dpm/g. The position of the main Cs-137 maxima in the core varies between 2 and 51 cm depth in the sediment.

The continuous record of atmospheric radioactive fallout that exists for the Environmental Measurements Laboratory (EML) network stations around the world, could be used to explain the general shape of a Cs-137 sediment core profile. The annual Cs-137 direct fallout deposition records were reconstructed for Fairbanks and Anchorage in chapter 2 (Fig. 6 and 7). This basic pattern can be seen at all sites in the Northern hemisphere and fits well with the history of atmospheric nuclear weapons tests (Larsen, 1984). The estimated sediment Cs-137 distribution, from the direct fallout deposition pattern, could be inferred from fallout deposition record if it is plotted on a vertical axis and it is decay corrected to 1994.

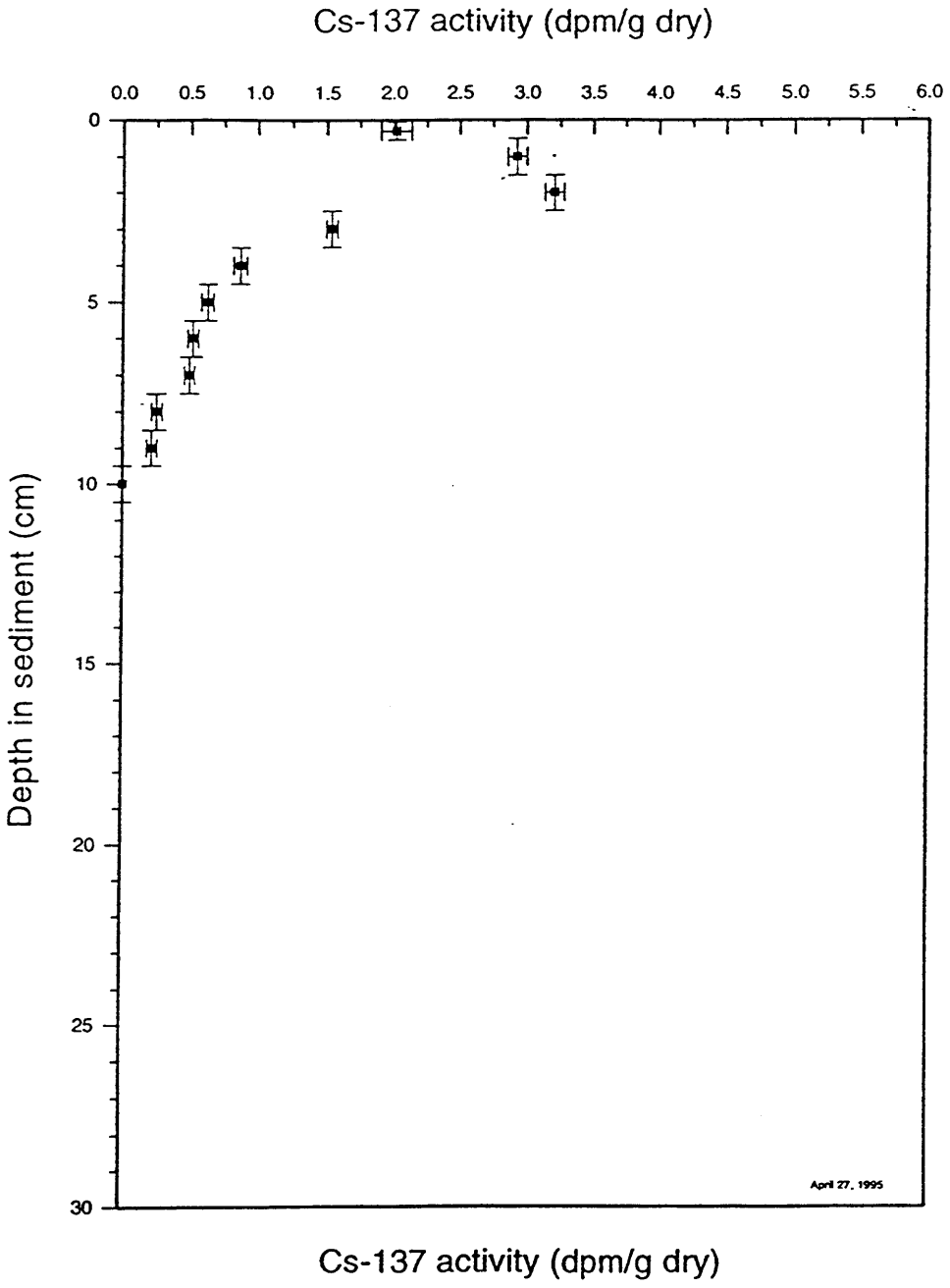


Fig. 34. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-3, collected in the Ob River Delta.

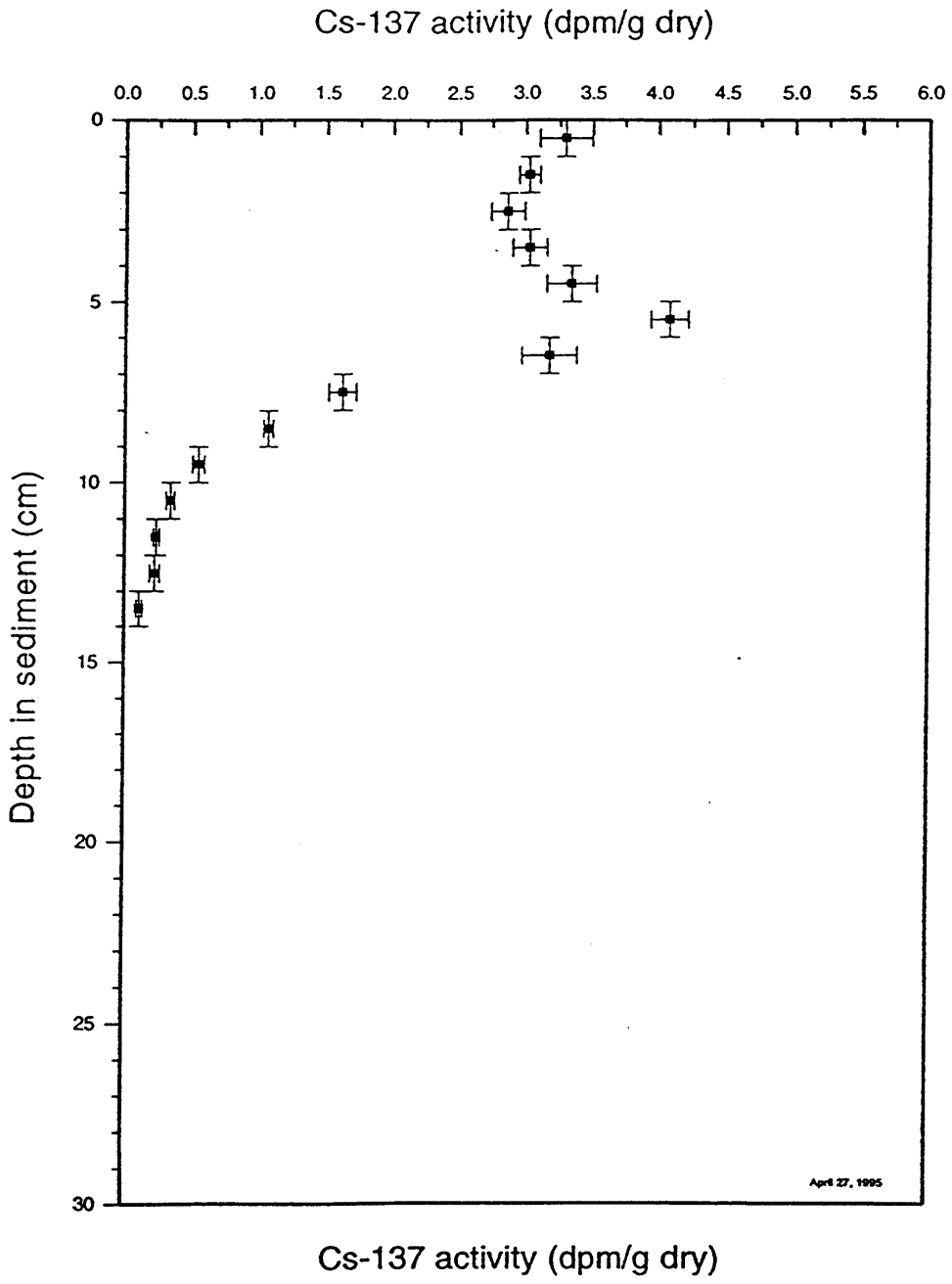


Fig. 35. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-4 collected in the Ob River Delta.

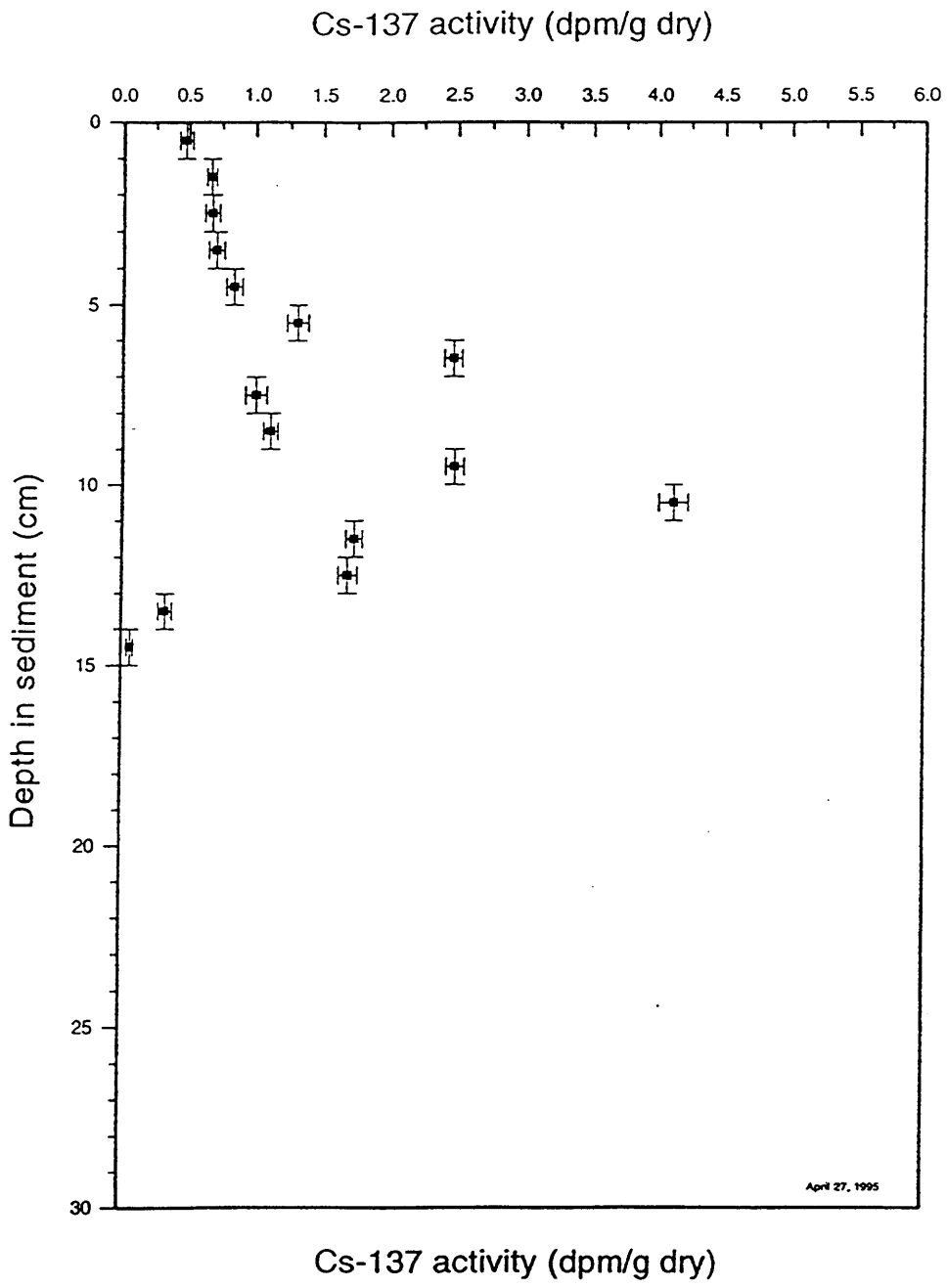


Fig. 36. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-7A collected in the Ob River Delta.

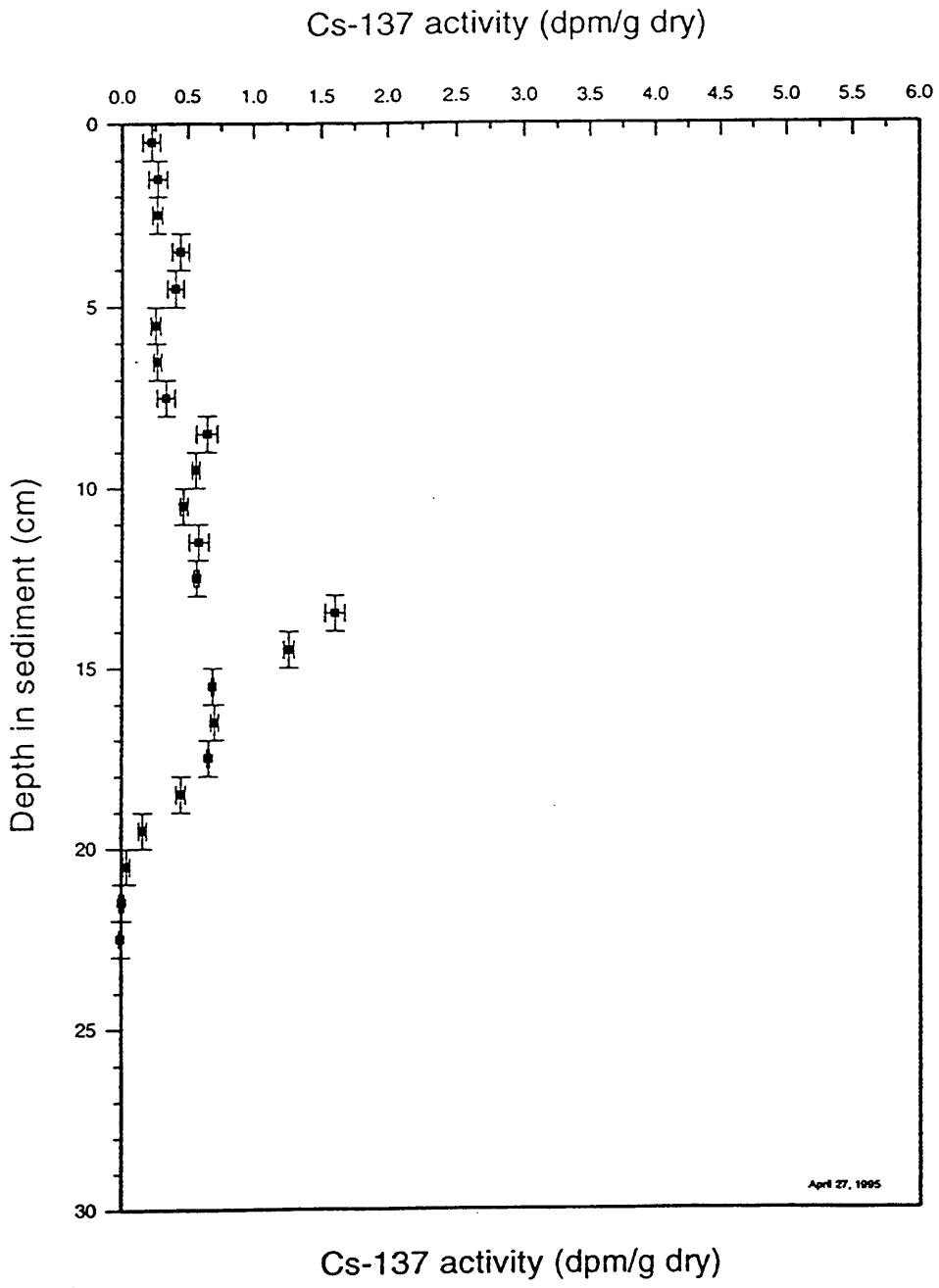


Fig. 37. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-7B collected in the Ob River Delta.

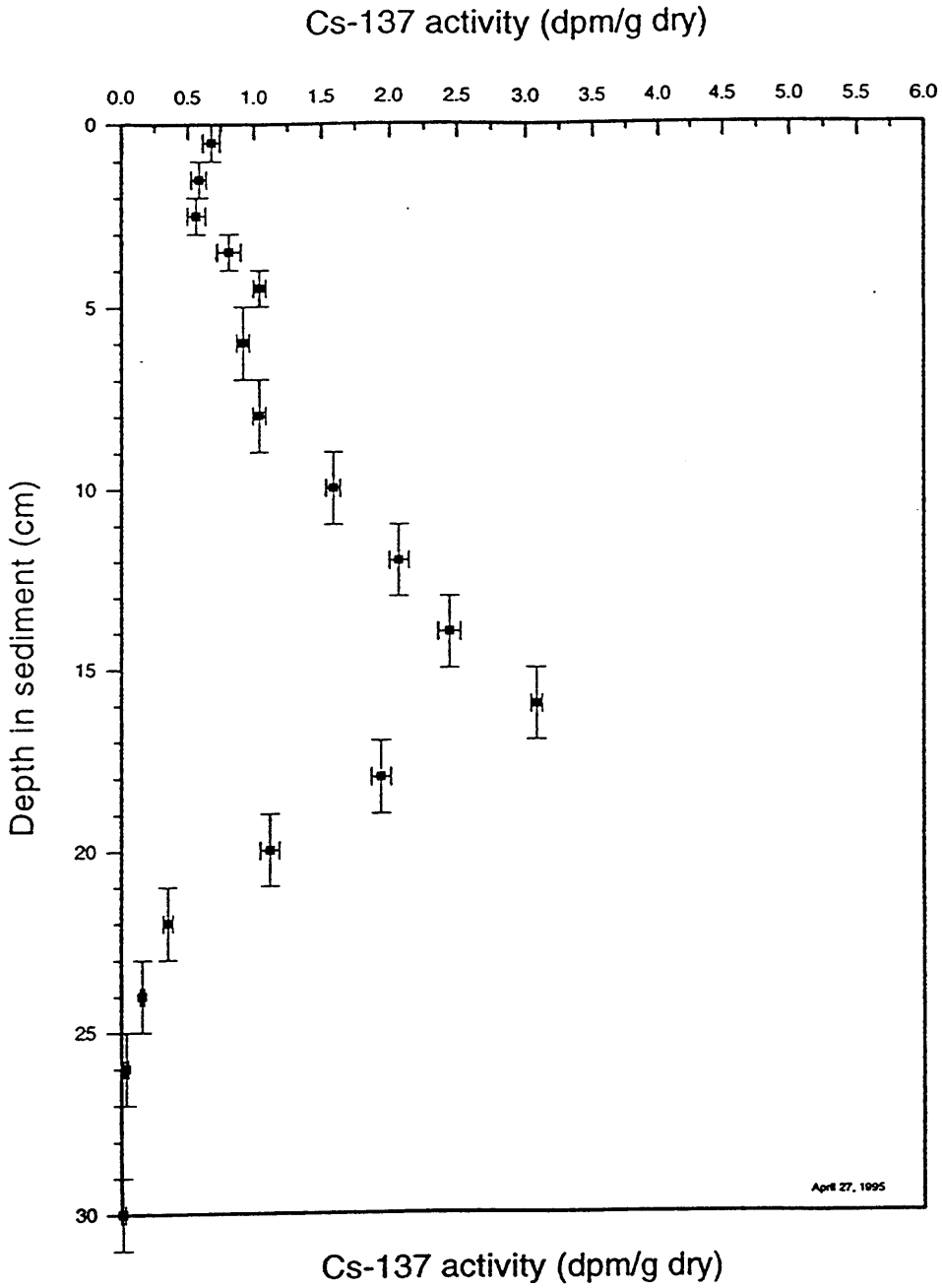


Fig. 38. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-8 collected in the Ob River Delta.

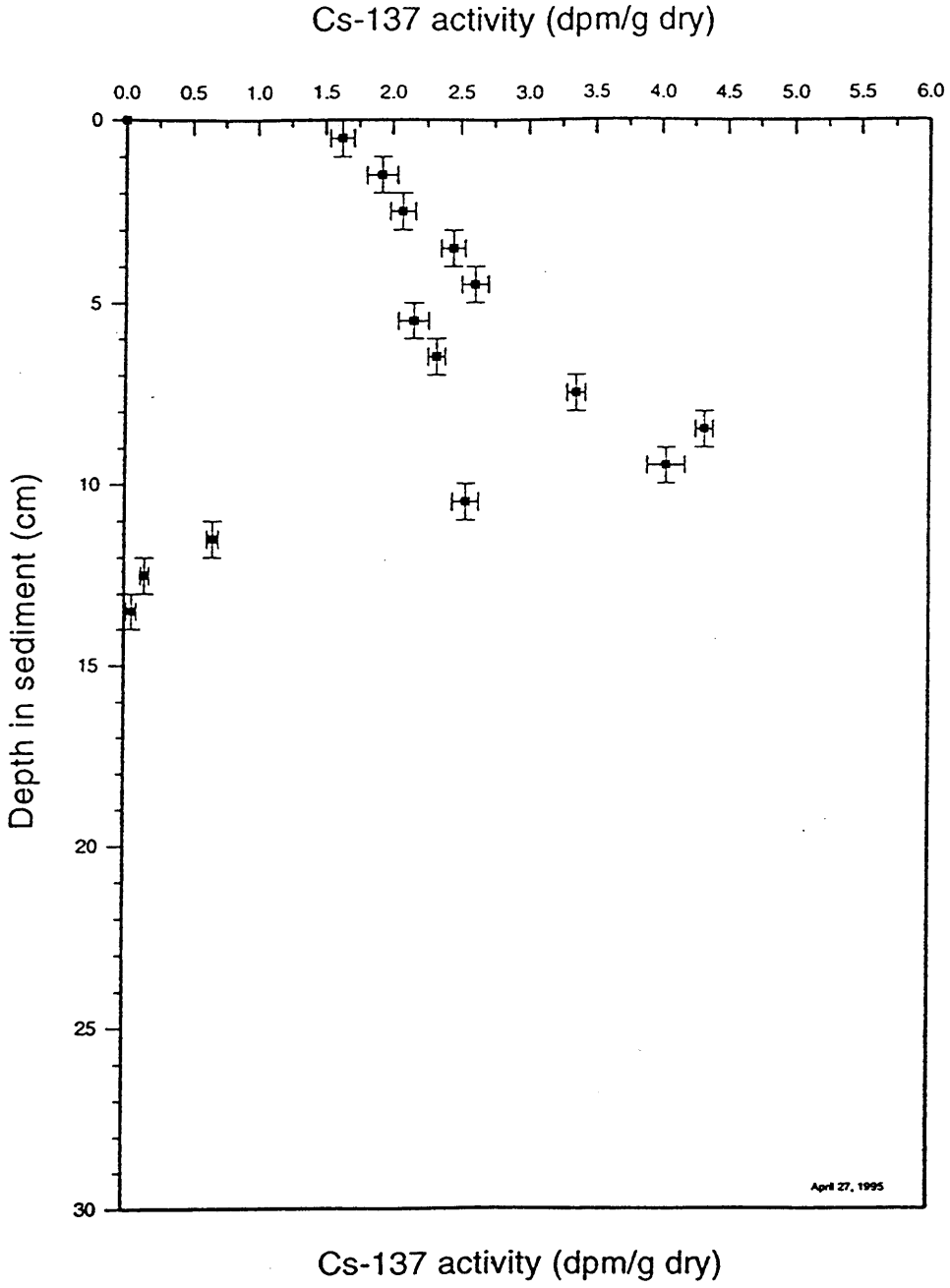


Fig. 39. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-9 collected in the Ob River Delta.

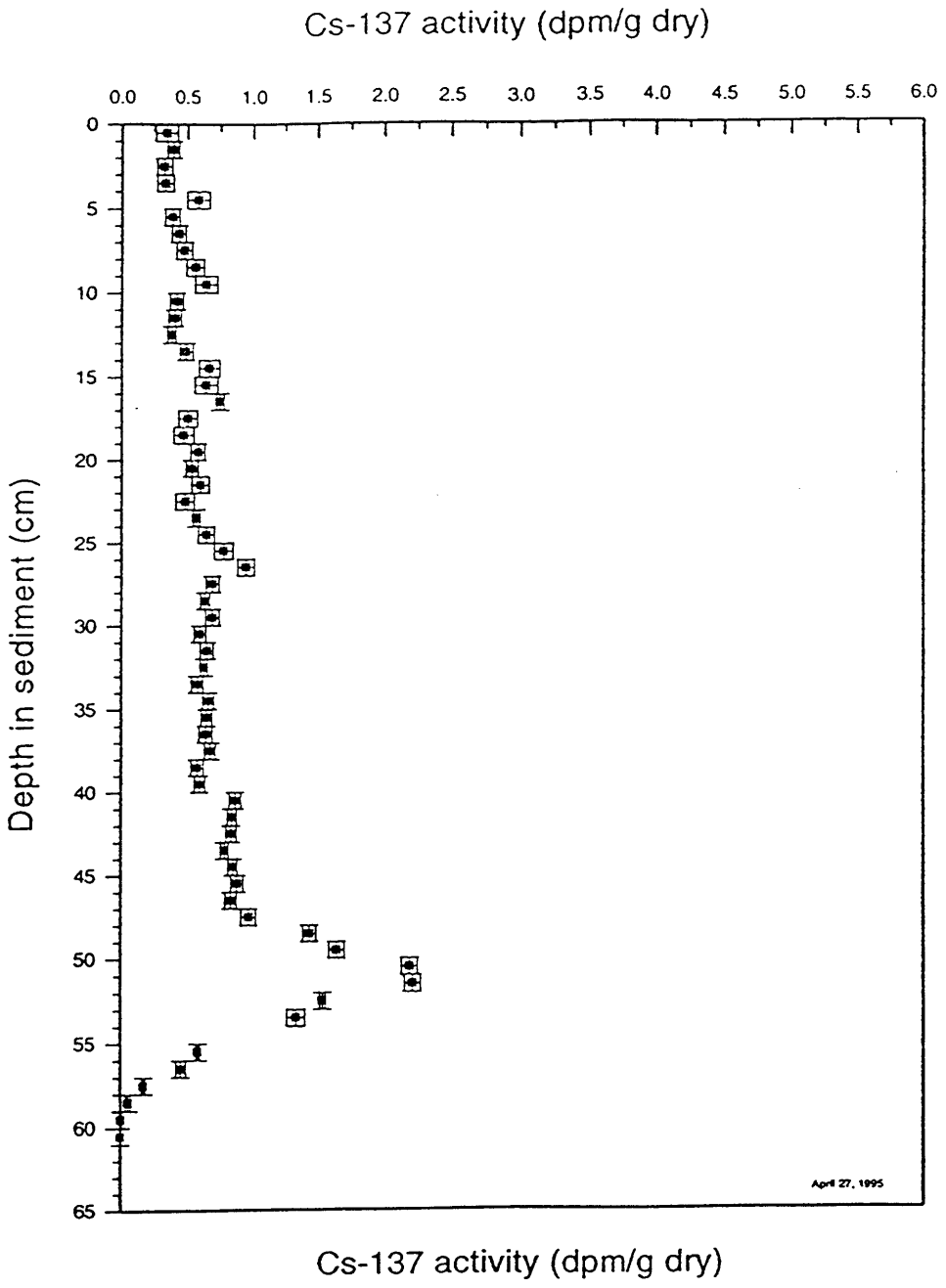


Fig. 40. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-10A collected in the Ob River Delta.

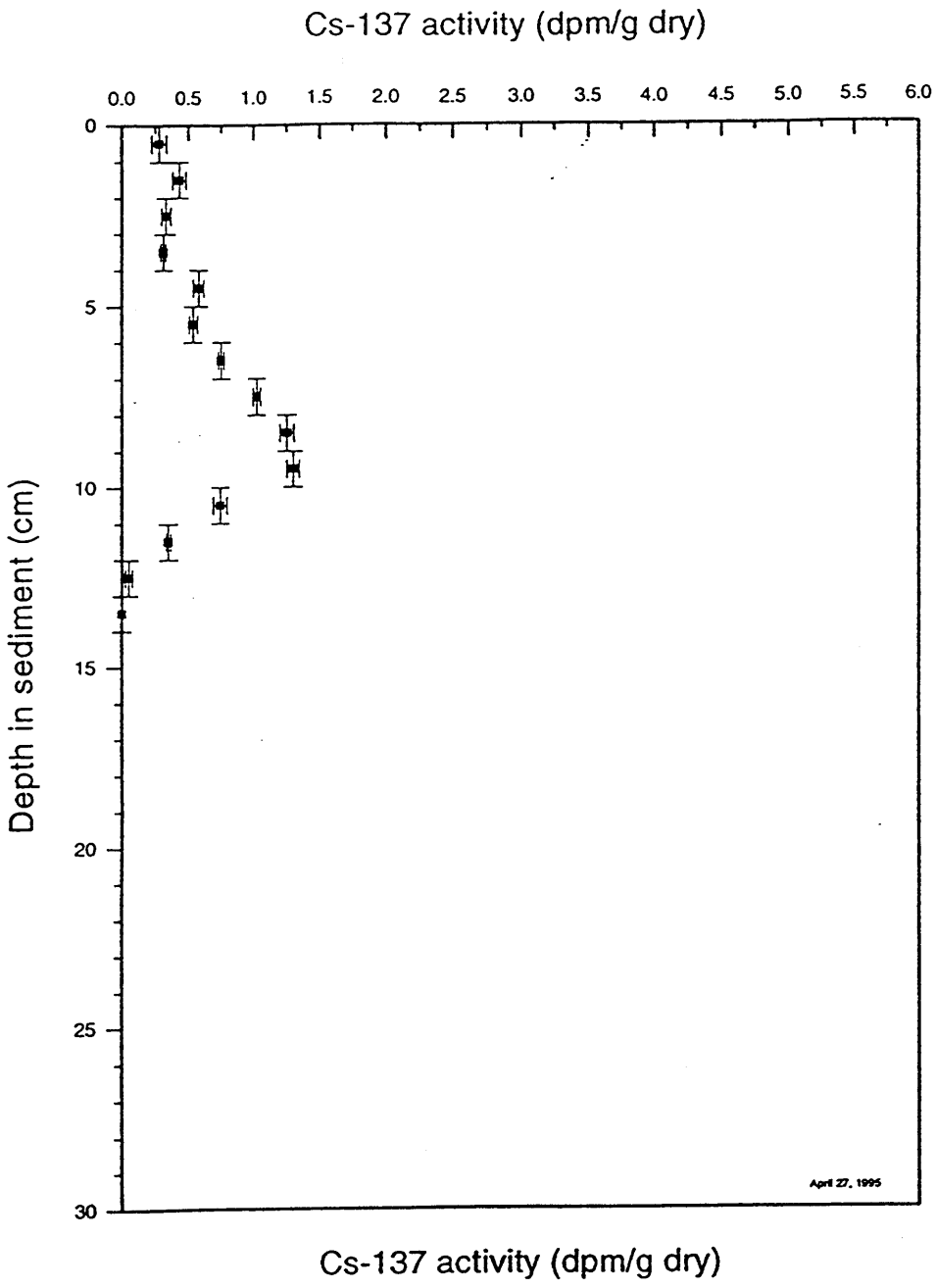
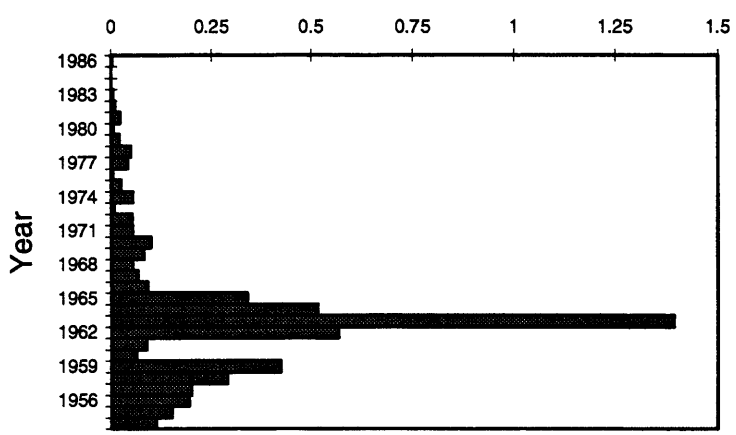


Fig. 41. Downcore Cs-137 activity (dpm/g) distribution. Station Ob94-13 collected in the Taz Estuary.

Fig. 42. Cs-137 direct fallout deposition in hypothetical ideal core at Fairbanks, Alaska (data decay corrected for 1994)



A "perfect" core, that is, one with no mixing or diffusion and with no time-delayed focusing (wash-in) due to erosion from the watershed, taken in 1994 at Fairbanks Alaska, would in principle have a Cs-137 profile closely matching the one in Figure 42. Miller and Heit (1986) analyzed Cs-137 profiles sediment cores from many lakes in the US. Two major categories of sediment cores were designated: those with a double peak structure with a minor peak below the main one and those with only one resolvable main peak. Most of the cores fall into second category.

Various factors should be considered when assessing the quality of sediment cores. An estimate of the sedimentation rate of the core could be made from the observed Cs-137 penetration depth. This is possible, if one assumes that the sediment accumulates continuously or, as is more likely for the lakes in the Ob Delta, in a pulse mode and that sediment mixing and cesium diffusion are negligible in these fresh water sediments. Because there was no Cs-137 in the environment in the pre-nuclear age, the bottom of the Cs-137 profile would theoretically coincide with the first nuclear test in 1945 with a delay of about 1 year due to the pattern of atmospheric-stratospheric circulation and exchange (see. Chapter 2.). However, due to the fact that these were low altitude tests, the amounts of Cs-137 introduced to the stratosphere and hence dispersed to the

environments around the globe were small. Through 1945-1949 there were about nine nuclear tests with a total yield of about 200 kt TNT (Zander and Araskog, 1978). The first thermonuclear test, Ivy-Mike, (15 Mt TNT) introduced substantial amounts of radionuclides into the global environment in 1951. In 1994 there should be less than 32.4% of the Cs-137 deposited at the beginning of nuclear-age because its half-life is 30.1 years. Also, the gamma-spectrometric method of Cs-137 detection is not very sensitive and I was unable to measure activities below 0.04 dpm/g, with an error of more that 50 %. Bearing all this in mind one can estimate that the Cs-137 penetration depth could be dated at 1950 which agrees with the estimate by Miller and Heit (1986).

The first main series of nuclear tests was completed by the US and USSR in 1958. During 1959-1960 there were no known tests by these two countries. The next major series started in October 1961 with the highest yield ever tested (58 Mt TNT) in November at the Novaya Zemlya Testing Site. This series ended with the 1963 Partial Test Ban Treaty. These two series produce the two maxima in the direct fallout deposition record shown in Fig. 42.

Miller and Heit (1986) observed these two maxima in the Cs-137 sediment records in Cayuga-Lake, Ithaca, New York and Deer Creek Reservoir, Heber City, Utah (Fig. 43). The reason these two peaks are resolved in the cores are two fold: sedimentation rate and wash-in factor. Average sedimentation rates were estimated for Cayuga-Lake and Deer Creek Reservoir at 0.79 cm/yr. and 2.50 cm/yr. respectively. The high sedimentation rate at Deer Creek appears to be a result of substantial sediment focusing from the surrounding watershed. This flux of sediment brings 105 dpm/cm^2 of Cs-137 from the surrounding region compared to the expected direct fallout of only 22.2-33.3 dpm/cm^2. I speculate that the reason the peaks are resolved is explained by 1) the short time the fine grained sediment was exposed to the atmospheric fallout on the surrounding territory before being transported to the bottom of Deer Creek and 2) little or no sediment mixing and diffusion. The sediment core from Cayuga-Lake, on the other hand, has an inventory Cs-137 of 41.7

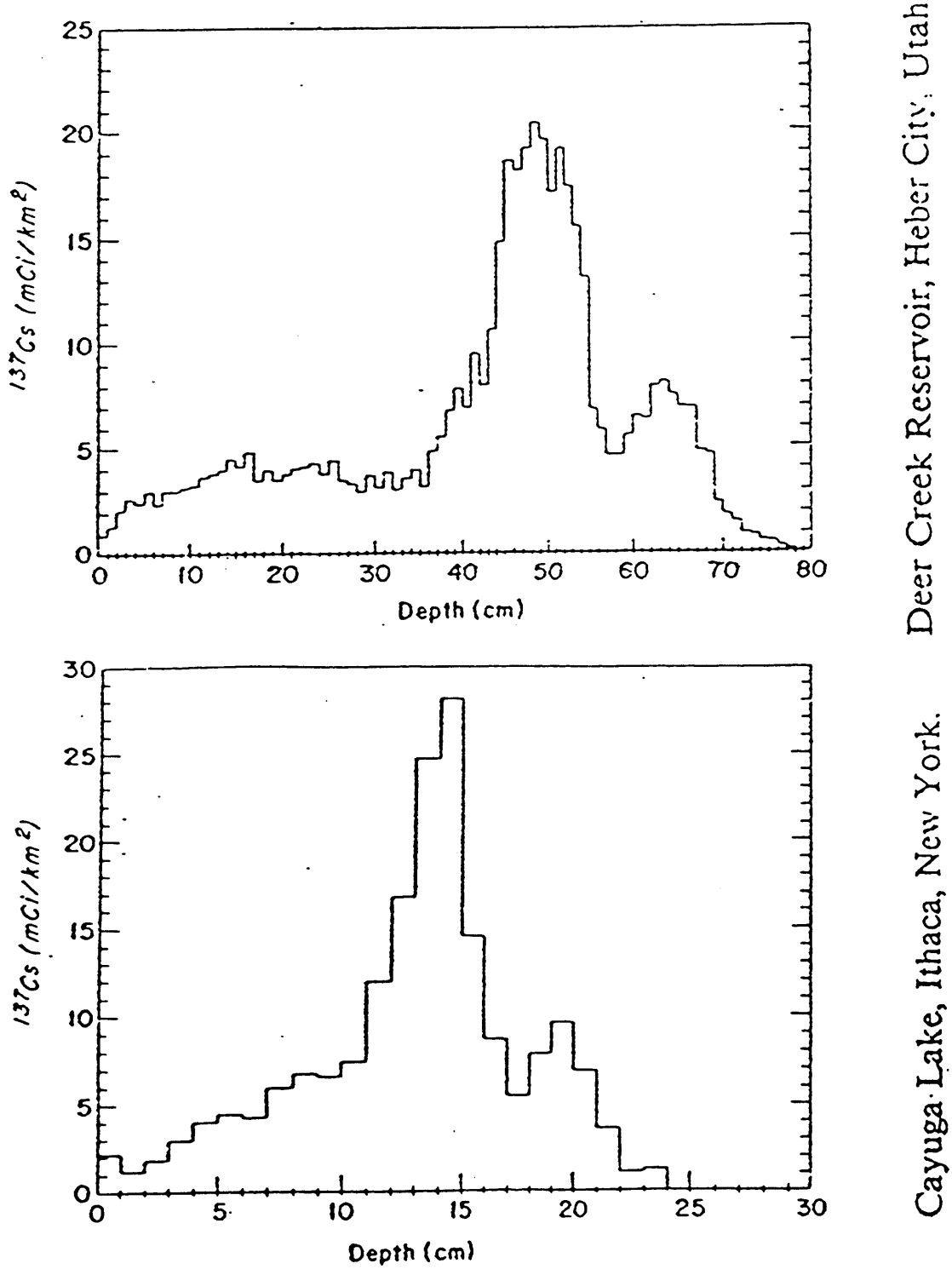


Fig. 43. Cs-137 inventory in sediment cores at Cayuga Lake (Ithaca, New York) and Deer Creek Reservoir, (Heber City, Utah).

Miller K. M., M. Heit (1986). A time resolution methodology for assessing the quality of lake sediment cores that are dated by Cs-137. Limnology and Oceanography. 31 pp. 1292-1300.

dpm/cm^2 which is only slightly higher than expected from direct fallout. The sedimentation rate is also slower and thus sediment focusing plays a lesser role.

Many other cores analyzed by Miller and Heit (1986) showed only one resolved peak (Fig. 44). Three processes are likely responsible for this: sediment mixing, diffusion and delayed focusing (wash-in).

The diffusion process, although always in operation, will play an important role in the environments where the sedimentation rate is low. Robbins et al. (1979) reported the effective molecular diffusion coefficient D_e to be 5.8*10E-5 cm^2/day (0.02 cm^2/yr.) and concluded that unless the presence of organisms somehow enhance the exchange of Cs-137 between sediments and pore water, the migration of Cs-137 via molecular diffusion should be very small. Sediment mixing by bioturbation is another well known process affecting oxygenated estuarine and open ocean sediments. In fresh water environments, the bioturbation process is in general much slower due to the relatively small abundance (compared to an estuary) of benthic burrowing organisms. The most prominent feature of sediment cores when the bioturbation process is underway, is a subsurface layer of relatively homogenous Cs-137 activity (Robbins et al., 1977). This feature should also be observed for other radioactive and non-radioactive particle-bound element distributions, due to the fact that in most cases, sediment burrowing organisms feed entirely on the sediment. Robbins et al. (1977) found this layer to be 3-6 cm in the sediment cores collected at Lake Huron in 1975. Unlike in estuarine sediments, bioturbation in fresh water environments could be present or inhibited within the same water body (Robins and Edgington, 1975). Heit and Miller (1987) have observed bioturbation in some lakes in the Adirondack Region and not in others. Diffusion, bioturbation and mixing by mechanical means are internal processes that could change the shape of the Cs-137 depth distribution.

Delayed focusing (wash-in), could be observed most prominently in the sediments with large "excess" radionuclide inventories. By the "excess" inventory I mean, the inventory of a radionuclide in excess of that expected from direct wet and dry fallout

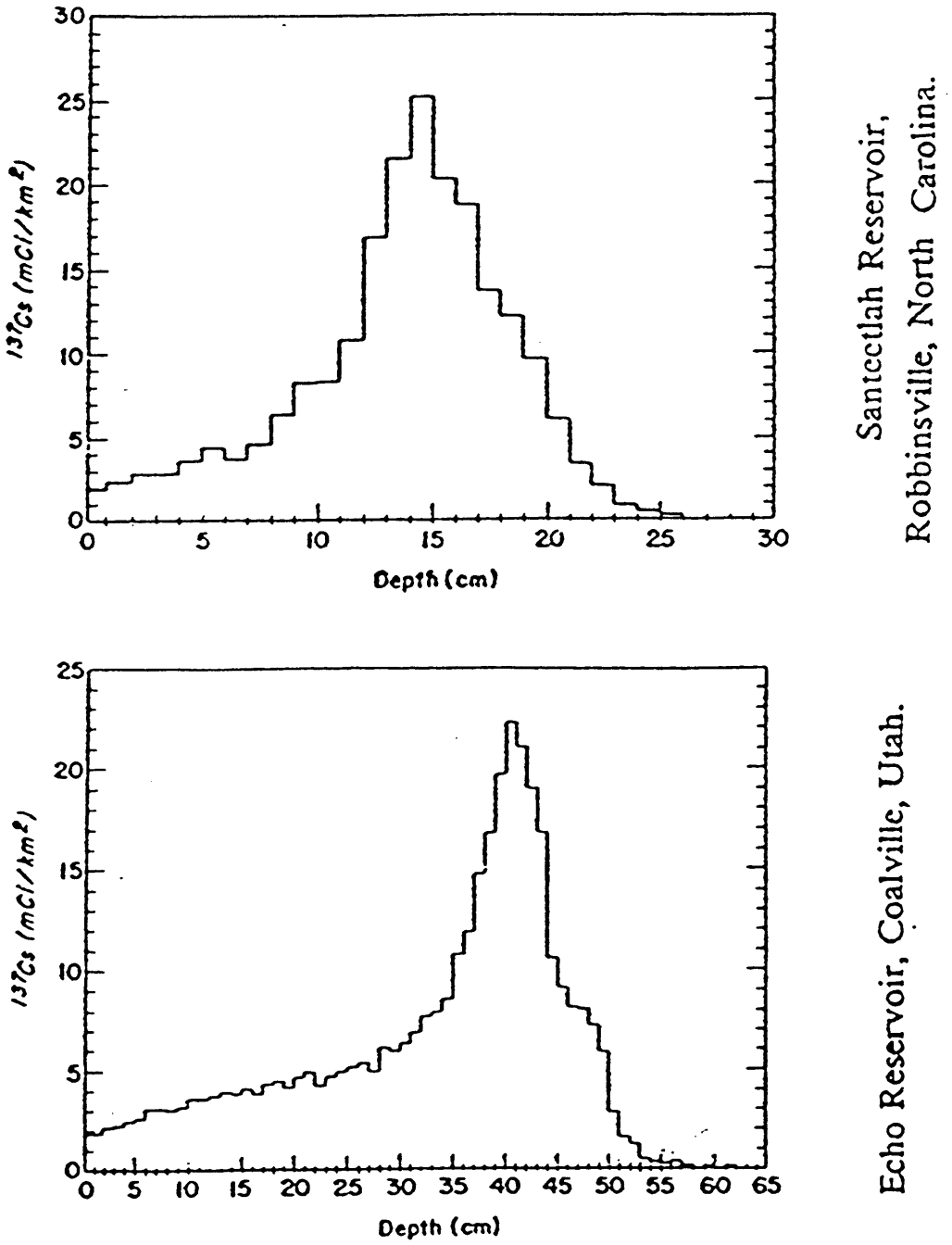


Fig. 44. Cs-137 inventory in sediment cores at Echo Reservoir (Coalville, Utah) and Santeetlah Reservoir (Robbinsville, North Carolina)

Miller K. M., M. Heit (1986). A time resolution methodology for assessing the quality of lake sediment cores that are dated by Cs-137. Limnology and Oceanography. 31 pp. 1292-1300.

delivery. This "excess" is a delayed input of radioactive material resulting from erosion and runoff in the watershed. Radionuclides sorbed on the surface of sediment particles can spend many deposition-resuspension cycles in a river or lake as well as continued sorption/desorption between water and particles. In addition to the above, soil processes could delay the signal even further. Smith et al. (1987) estimated the residence times for Cs-137 and Pu within the soil component of the Saguenay drainage basin (Quebec, Canada) to be 1000 and 3000 yr., respectively, and their flushing times through the water column component to be about 1 year. The net effect on the profile in the sediment core would be basically opposite to that produced by direct deposition, i.e. an upward tail forms. This feature was observed many times in sediment cores at many locations (Breteler et al., 1984; Wan et al., 1987; McCall et al., 1984; Smith and Ellis 1982; Hardy et al., 1980, Livingston, 1979 (unpublished Great Lakes data)).

The Ob Delta cores show several important features. First, there is generally no upper sediment layer with constant Cs-137 activity and thus it may be assumed that bioturbation and mechanical mixing processes are insignificant. Most of the cores have pronounced Cs-137 maxima which are located at varying depths in the sediment cores from different sites. Almost all the cores (except the ones believed to be disturbed) show one or several small Cs-137 peaks above the main maxima at different locations (Fig. 34-41). The main Cs-137 peak closely resembles that observed in the sediments with only one source of radioactivity - global fallout.

Cs-137 penetration depths for the Ob delta sediment cores are presented in Table 9. From these data I can estimate Cs-137 penetration depth derived average sedimentation rates over the period since the introduction of Cs-137. These vary from 0.23 to 1.38 cm/year, assuming the Cs-137 penetration depths represent sediment layers deposited in 1950 (Table 9).

Table 9. Estimated sedimentation rates using different techniques

Core ID	Cs-137 penetration depth *1			Cs-137 main maxima *2		
	Cs-137 penetration depth	Sedimentation Rate	Estimated Cs-137 main maximum depth	Cs-137 maximum depth	Sedimentation Rate	Estimated Cs-137 penetration depth
	cm.	cm/yr	cm.	cm.	cm/yr	cm.
Ob94-3	9.5	0.216	6.7	2.0	0.065	2.8
Ob94-4	14.0	0.318	9.9	6.5	0.210	9.2
Ob94-7a	15.0	0.341	10.6	10.5	0.339	14.9
Ob94-7B	21.0	0.477	14.8	13.5	0.435	19.2
Ob94-8	27.0	0.614	19.0	16.0	0.516	22.7
Ob94-9	14.0	0.318	9.9	8.5	0.274	12.1
Ob94-10A	60.0	1.364	42.3	51.0	1.645	72.4
Ob94-13	13.0	0.295	9.2	9.5	0.306	13.5

*1 Cs-137 penetration depth assumed to coincide with global fallout deposition in 1950.
*2 Cs-137 main maxima assumed to coincide with global fallout deposition in 1963.

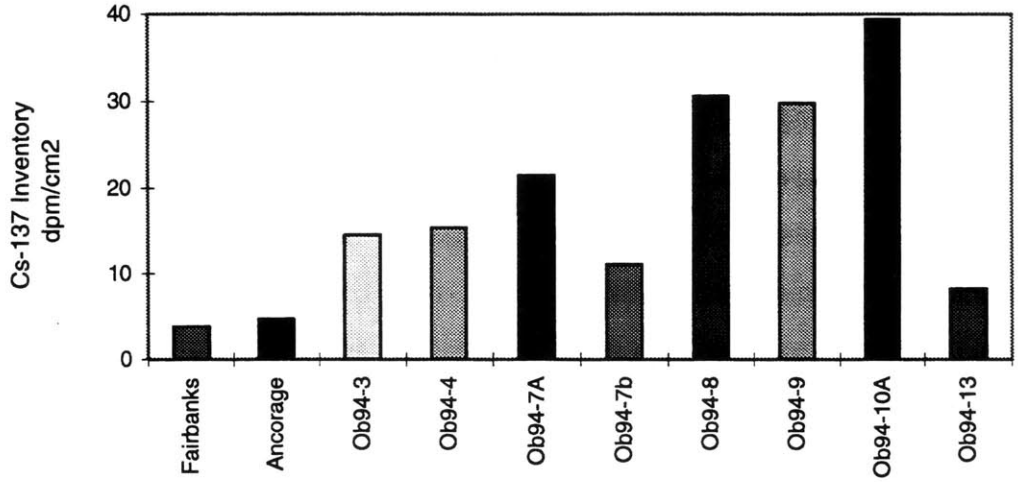
The large Cs-137 maxima can also be used to estimate average sedimentation rates if one assumes that these maxima represent layers deposited in 1963, when the maximum in global fallout was observed (Table 9). This technique has been widely used to date sediment cores (Breteler et al., 1984; Hardy et al., 1980).

The largest inconsistencies in the two estimates of sedimentation rates are observed for cores Ob94-3 and Ob94-4 where they differ by factors of 3.7 and 1.5 times, respectively. A careful examination of the shapes of the radionuclide profiles in these cores and the relative position of the main maxima leads to the conclusion that these cores were affected by the some kind of erosional process and lost several recently deposited sections of the sediment column. Two processes could explain such a loss: ice erosion and/or water erosion. It is difficult to distinguish between these two processes without collecting additional information on these specific sites. One way to resolve this, would be by making ice thickness measurements at these two locations during winter time, to see if

the process of ice erosion as was described by Ivanov et al. (1995) could be inferred. Cores Ob94-3 and Ob94-4 will be used as a contrast to well preserved cores in the later discussion.

Using the available data on Cs-137 distributions, inventories were calculated for seven sediment cores in the Ob Delta; one in the Taz estuary and the anticipated direct fallout deposition pattern at Fairbanks and Anchorage Alaska. Inventories are plotted in Fig. 45. First, it is obvious that all of the inventories in sediment cores from Siberia exceed that expected from direct fallout. Second, the degree of inventory excess over direct fallout varies from core to core. The core from the Taz estuary has the lowest Cs-137 inventory and exceeds that expected from direct fallout by only about 60%. Cores Ob94-8, Ob94-9 and Ob94-10A have the highest Cs-137 inventories, and, following from the above discussion on sediment focusing, I can speculate that these two cores should have highest sedimentation rates. However this is true only for cores Ob94-8 and Ob-94-10A. The reason that core Ob94-9 has a high Cs-137 inventory and a low sedimentation rate is difficult to explain if one considers only sediment focusing; implying, that the greater the amount of the sediment brought by river water into the oxbow or "sor" lake, the higher the quantity of sorbed Cs-137 will be deposited at the site. There are many other possible reasons that could explain such a pattern in core Ob94-9. Apart from core disruption, it is possible to speculate that on average, core Ob94-9 could has higher content of fine grained material than the other high inventory cores and consequently a greater quantity of sorbed and incorporated Cs-137. The fact that Cs-137 is preferentially retained by certain layer silicates such as micas, vermiculite and interleaved mica-illites (Francis and Brinkley 1976), is consistent with this theory. To answer this specific question one would have to perform mineralogical and grain size analysis of sediment samples.

Fig.45. Cs-137 inventories (dpm/cm2) calculated for the Ob Delta; Taz estuary sites and estimated for direct Global fallout at Fairbanks and Anchorage, Alaska..



The apparently undisturbed cores, (Ob94-7A, Ob94-7b, Ob94-8, Ob94-9, Ob94-10A, Ob94-13) can be subdivided into two groups. There are two main reasons for such subdivision: analytical considerations and interpretation. The first group - cores for which all analyses are already completed - are Ob94-8; Ob94-9 and Ob94-13. They are also relatively easy to interpret. The second group - cores Ob94-7A, Ob94-7B and Ob94-10A, will be used as complementary data sets. Also, these cores have more complicated Cs-137 records than can easily be explained based on the available data.

All of the high quality cores show one main maxima at about 2/3 of the Cs-137 penetration depth in the sediment. These cores can be subdivided into two subgroups by the shape of the bottom part of the main peak. Cores Ob94-7A and Ob94-7B show pronounced "shoulders" just below the main peak, while Ob94-10A, Ob94-8 and Ob94-9 reveal an exponential-like decline in Cs-137 concentration. I can speculate that cores with the "shoulder" (Ob94-7A and Ob94-7B) represent areas where the record of the two main nuclear tests series can be partially resolved. However, at the moment, the data sets do not permit any definite conclusions. Cores Ob94-8, Ob94-9, Ob94-10A as well as the disturbed cores, (Ob94-3, Ob94-4), display exponential like Cs-137 decay patterns.

This pattern is well documented for typical sediment cores which have received delayed focused (wash-in) artificial radioactivity of global fallout origin.

The Cs-137 record in all cores above the main maxima show at least one small peak. At the moment, it difficult to speculate about the reasons for the appearance of these maxima. More data is needed for Pu in cores Ob94-7A, Ob94-7B and for Pb-210 in Ob94-10A to provide reasonable explanations.

Apart from the general similarity of the observed Cs-137 sediment profiles in the Ob River Delta to the global fallout Cs-137 deposition pattern and sediment records found in the other locations in Europe and North America, the comparison of the core Ob94-8 from the Ob River Delta and core Ob94-13 from the Taz Estuary is instructive. The Taz Estuary core was collected as a "control core" and it was hoped that it would provide a radionuclide record of fallout origin. The Taz and Pur- rivers are relatively pristine and drain the east side of the Ob Estuary watershed. There are no nuclear facilities on these rivers and the radioactivity in them must be of global or close-in fallout origin. Core Ob94-13 from the Taz estuary has almost exactly the same relative downcore profile as core Ob94-8 from the Ob River Delta. Their very different sedimentation rates and inventories do not alter the general pattern and relative positions of the main and secondary maximas. Based on the Cs-137 penetration depth dating, the main maxima in core Ob94-8 could be dated as 1969, which is about 6 years later than one would expect for the main portion of global fallout. This and the fact that the Cs-137 inventory in this core is 5 times higher than expected direct fallout inventory suggests that the delayed focusing (wash-in) process is at work here. Similar dating of core Ob94-13 from the Taz Estuary leads to an estimate that the main Cs-137 maxima was deposited in 1962, which is close to the 1963 maximum in fallout from nuclear testing in 1961-1962. The Cs-137 inventory for this core is only 60% higher than expected direct fallout suggesting that the delayed focusing (wash-in) process plays a much smaller role at this site.

The minor near surface Cs-137 maxima in these two cores are real. Cs-137 depth penetration dating and main maxima dating methods give dates between 1985 - 1987 for core Ob94-8 and one of 1989 for the Taz Estuary core Ob94-13. It is tempting to suggest that this peaks are of the same origin and the Chernobyl accident immediately comes to mind. However, there are two reasons that argue against Chernobyl hypothesis. The first is that the Chernobyl fallout cloud atmospheric dispersion pattern is well documented, and it is hard to imagine that there was substantial unrecorded fallout cloud that went to the Taz and Pur rivers watersheds, which are more than 2000 thousands kilometers from the point of release of radioactivity from Chernobyl. Second, the fact that Pu-239,240 also shows small maxima at this depth in the cores almost certainly excludes the Chernobyl theory - due to the fact that the Chernobyl release was dominated by volatile radioactive isotopes and plutonium releases were very small. Thus, one needs to look for another explanation of this event. One possible source of this radioactivity maxima could be from close in fallout. There is now information about venting accidents at the Novaya Zemlya Testing site (Bjurman et al. (1990), Anonymous (1992)).

I believe that the environmental setting of the "sor" or oxbow lakes within the Ob Delta and Taz Estuary is of great importance for the interpretation of core profiles. Cores Ob94-8 and Ob94-13 were at the deepest sites, 4 and 5.3 meters respectively. They were also in the best position to entrap the sediment material which passes through the Ob Delta and Taz Estuary. Core Ob94-8 was located at a point at about 1 km from the main branch of the Ob river and which was open on one side to it. Core Ob94-13 was located in the center of the Taz estuary. In contrast, core Ob94-9 was located in a lake that is separated from the main river by a long (3 km) shallow channel with an average depth of 1.0 meters and could easily be affected by the ice breakup (Ivanov et al., 1995).

Core Ob94-9, also from the Ob River Delta, shows a Cs-137 distribution pattern similar to Ob94-8 and Ob94-13. However, as was described above, there is an unexplained discrepancy between the low sedimentation rate and high Cs-137 inventory in Ob94-9. The relative position of the main Cs-137 maximum in the core is consistent with

the estimate made by utilizing the Cs-137 penetration depth dating technique. However, the position of a secondary subsurface maxima is questionable and hard to explain. If one assumes constant sedimentation rate at this site this peak will coincide with an event dated at 1979. Although venting from Novaya Zemlya could be linked to this peak, an event at this time horizon does not show up in other cores like Ob94-8 or Ob94-13. If one assumes that the subsurface peak dates at 1987 (like in Ob94-8 and Ob94-13), the main fallout maxima will be dated as 1981 which is unrealistic. Thus it is concluded, that there is a lot more going on in the core Ob94-9 than can be explained and there is a good chance that this core was somehow disturbed.

6-C. Pb-210 Dating

The chronologies established so far using Cs-137 methods were based on the assumption that there is a constant or regularly pulsing flux of sediment from the river system to the particular oxbow or "sor" lake. The analysis of water and sediment discharge data which was presented in chapter 3 suggests that this is not the case and that the relationship is much more complicated. It is possible to address the question of sediment flux fluctuation using sophisticated modeling techniques proposed by Smith and Ellis (1982), Smith et al. (1987), however, this effort is beyond the scope of this work. Slow diffusion and lack of bioturbation were two other assumptions for establishing Cs-137 chronologies.

The importance of careful analysis of Cs-137 profiles cannot be understated. My initial hypothesis, that I am dealing with a signal mostly from fallout, was supported by the general shape of the Cs-137 profiles. Also, it became possible through this analysis to eliminate from consideration some cores. These cores, in my opinion, have inconsistencies about their parameters that are hard to explain without additional data, either on the characteristics of the particular sampling location, or new measurements. As a result of this process it became possible to identify two cores, Ob94-8 and Ob94-13, from the Ob

Delta and Taz Estuary respectively, which could help us address the main question of this study ie. what are the sources of radioactive contamination in the Ob Delta sediments?

The Pb-210 excess method of establishing sediment accumulation chronology is a widely used standard technique in freshwater as well as coastal and open ocean sediments (Yokoyama and Nguten, 1980, Krishnaswami and Lal, 1978; Krishnaswami et al, 1971 McCall et al., 1984; and references therein). There are several variations of the method, however, all of them are based on the fact that Pb-210 is a naturally occurring radioactive isotope with a half life of 22.1 years. Pb-210 is produced as a result of decay of Ra-226 - another naturally occurring isotope of the U-238 series. Ra-226 (half-life 1622 yr.) alpha decays into Rn-222 - a naturally occurring radioactive noble gas. Rn-222 has a half- life of about 3.8 days which is sufficient for it to escape to the atmosphere from soils or other materials present on the Earth surface. In the atmosphere, Rn-222 alpha decays into Po-218 (half-life 3.05 min.) and eventually, through a chain of alpha and beta decays into Pb-210. Pb-210, or its parent short-lived radioisotopes, are effectively removed from the atmosphere by wet and dry deposition, creating a flux of unsupported Pb-210 to the earth's surface. Unsupported, or excess Pb-210, means that it is present in the media in excess of Pb-210 which is in secular equilibrium with its long-lived parent - Ra-226. The flux or amount of excess Pb-210 precipitation per unit area depends on the wind pattern over land masses. The larger the land mass over which the atmospheric air mass passes and the longer it takes, the higher the flux of Pb-210 to the earth's surface. It is assumed that, due to the annual cyclicity of weather patterns for a particular location, the average annual atmospheric flux of excess Pb-210 is constant with minor variability for particular locations. In water systems - Pb-210 is a particle reactive element. After deposition on the water surface, Pb-210 bonds to particles. Their movement through the river or any other water system defines the eventual fate of Pb-210. All these characteristics of excess Pb-210 lead to its use in establishing sediment chronology.

Pb-210 decays at a constant rate (half-life 22.1 yr.) and by measuring Pb-210excess downcore, one can establish the age of deposition of this sediment by using a simple model:

$$N=No*exp(-\lambda t),$$

where N = Pb-210ex activity at the time of observation; No = Pb-210 initial activity at time T = 0; λ= radioactive decay rate constant and t = time elapsed since the sediment deposition.

There are many modifications of this approach, but most of them utilize one of two assumptions: constant Pb-210 excess activity or constant flux from the atmosphere. There are two main reasons why one cannot use the constant flux approach. First, there are no direct observations of atmospheric Pb-210 fluxes at or near the Ob river delta. An attempt to use estimates from observations made in the other Arctic locations will certainly fail due to the complicated character of prevailing wind and weather patterns in the Arctic. Second, sediment focusing processes would certainly complicate the picture. Due to insufficient analytical data, I, unfortunately, cannot calculate expected Pb-210 excess inventories for sediment profiles. As was discussed above for Cs-137, focusing (wash-in) could bring up to 5 times more Cs-137 into the lake than is expected from fallout.

Another approach is to assume that the sediment, which is brought into the particular oxbow or "sor" lake has constant Pb-210ex activity. It is critical to understand that this is major assumption. Sediment grain size distribution, particle residence time in the water column, creation and disappearance of river branches and many other factors could influence the Pb-210ex activity of the sediment. Understanding these limitations, the sampling sites in the Ob river delta were carefully chosen. Downcore distributions of Pb-210ex in the Ob river delta (Ob94-8) and Taz Estuary (Ob94-13) cores are presented in Figures 46 and 47. It is interesting to note that the surface Pb-210ex activity among all the cores varies between 3.48 and 7.74 dpm/g. This fact supports the idea that the

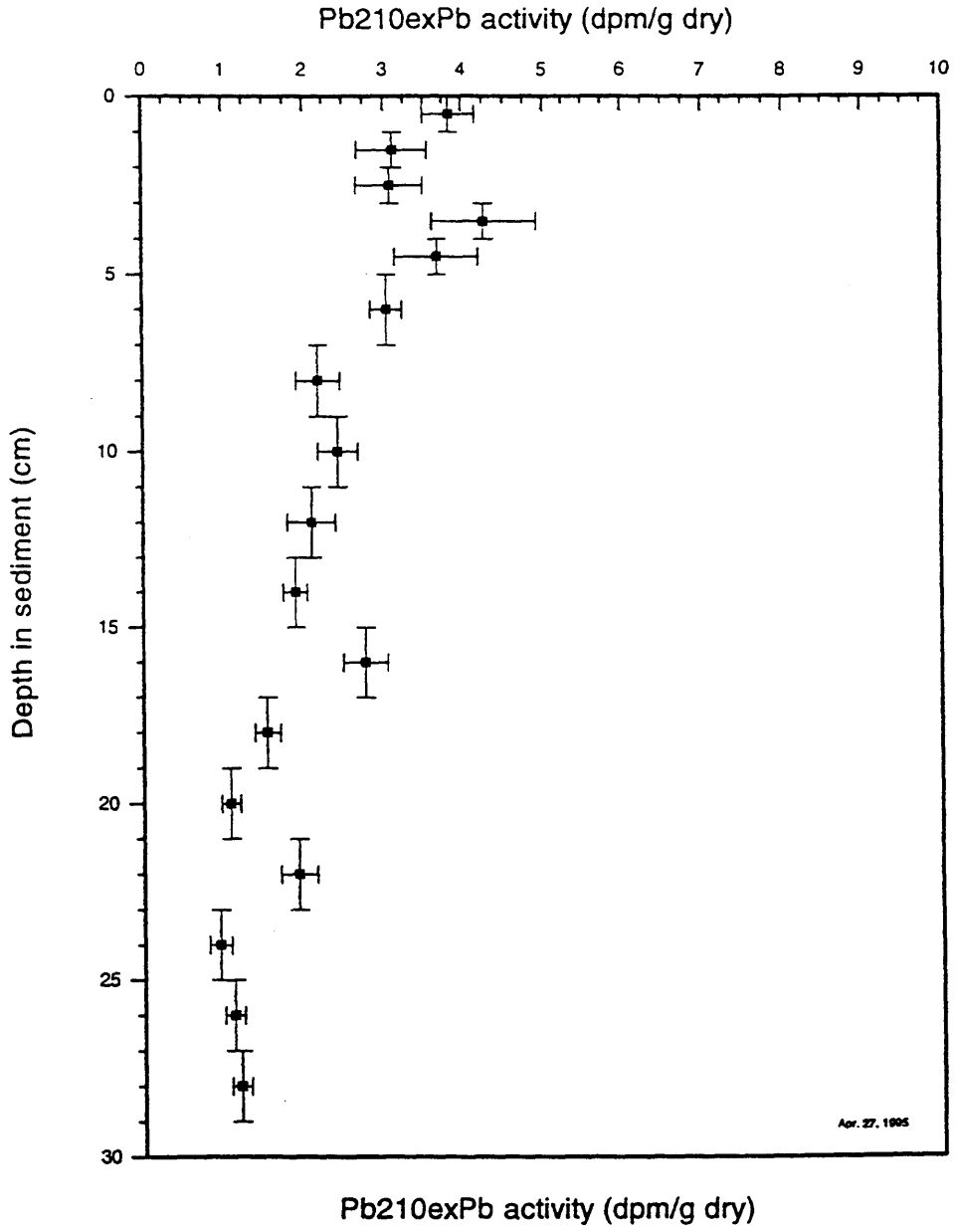


Fig. 46. Downcore Pb-210ex (dpm/g) distribution in the core Ob94-8 collected in the Ob River Delta in 1994.

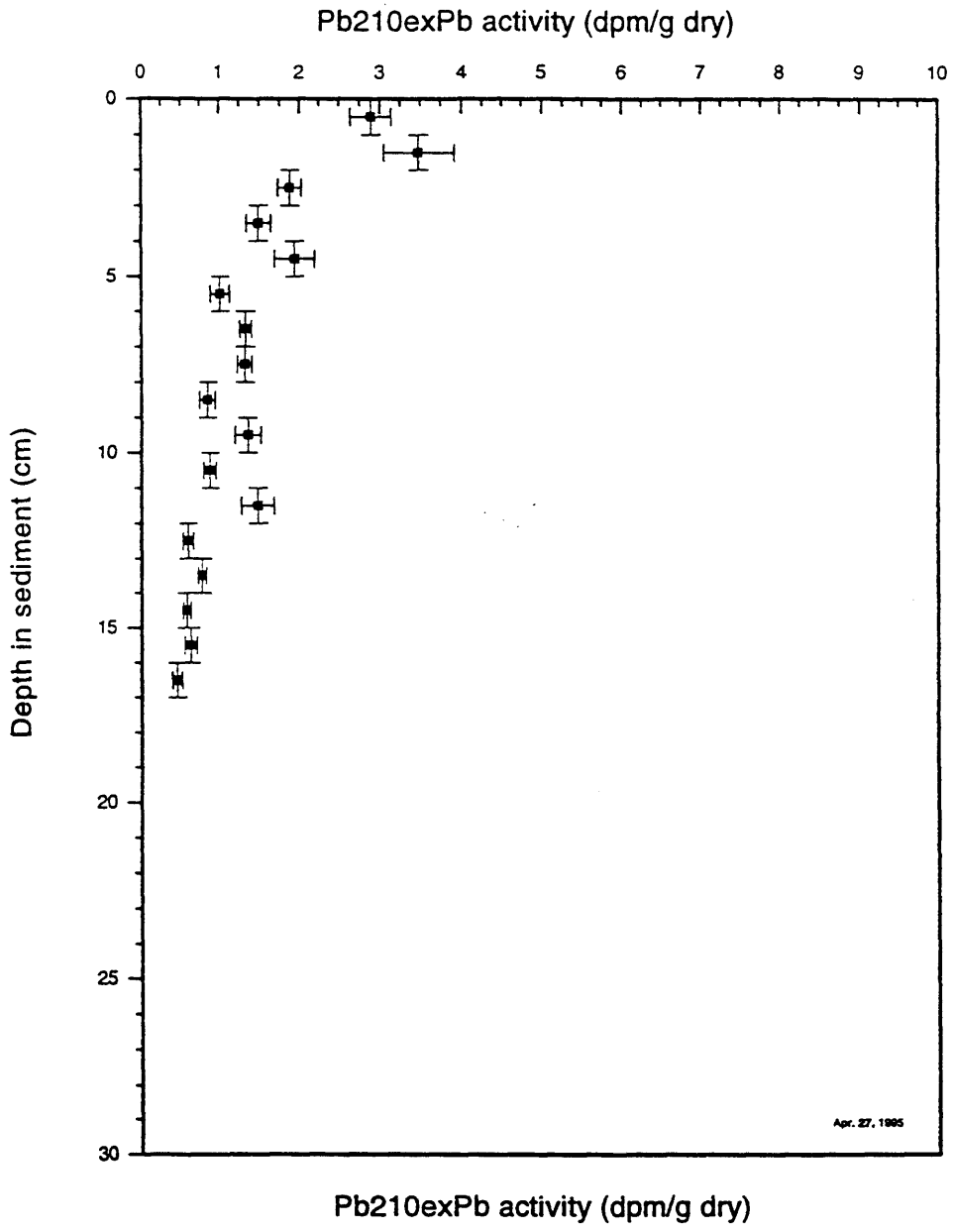


Fig. 47. Downcore Pb-210ex (dpm/g) distribution in the core Ob94-13 collected in the Taz Estuary in 1994.

constant activity approach can be used only for specific lakes and not throughout the Ob delta.

In contrast to Pb-210ex, Pb-214 (which in secular equilibrium with Ra-226) can be compared across the Ob Delta. Figures 47 to 51 show that the Pb-214 activity is almost constant within and between the cores. Calculations showed that the variations Pb-214 activity (in dpm/g) in the cores (Ob94-3 - 1.164±0.121; Ob94-4 - 1.153±0.332; Ob94-8 - 1.236±0.185; Ob94-9 - 1.245±0.237) are statistically insignificant. Core Ob94-13, from the Taz Estuary (Fig. 51) showed a Pb-214 activity of 1.046±0.150 dpm/g, which is at the lower end of the spectrum. From this, one can conclude that the sediment material which is present in the Ob Delta lakes is probably of the same origin. Second, it can be speculated that there is a possibility that the Taz Estuary sediments might be depleted in Ra-226. Differences in sediment mineralogical, grain size and chemical composition could help explain the observed differences in Pb-210ex activities in the lakes.

From the discussion above, it is obvious that there are two components to Pb-210ex in the sediment: direct fallout and transported or focused. Having this in mind, I assume that the constant Pb-210ex activity model should work, either in cases when the direct Pb-210ex deposition flux component is smaller or higher than the transported component. Although, a modeling study could test this assumption, I can only empirically assess this problem.

Figures 52 and 53 show Pb-210ex profiles for core Ob94-8 and figures 54 and 55 for core Ob94-13. They also show constant activity and constant sediment accumulation model derived curves. Both Pb-214 and Bi-214 radioisotopes (figures 49 and 51) were used as a Ra-226 proxy (assuming secular equilibrium) to derive excess Pb-210. Due to the relatively large analytical errors (10.2 - 11.3% for Pb-214 derived Pb-210ex (Pb-210ex = Pb-210total-Ra-226(Pb-214)) and 11.9 -13.5% for Bi-214 derived Pb-210ex (Pb-210 = Pb-210total-Ra-226(Bi-214)), the agreement between the age estimates is not very good. The Pb-214 and Bi-214 measurements are, in general, characterized by large

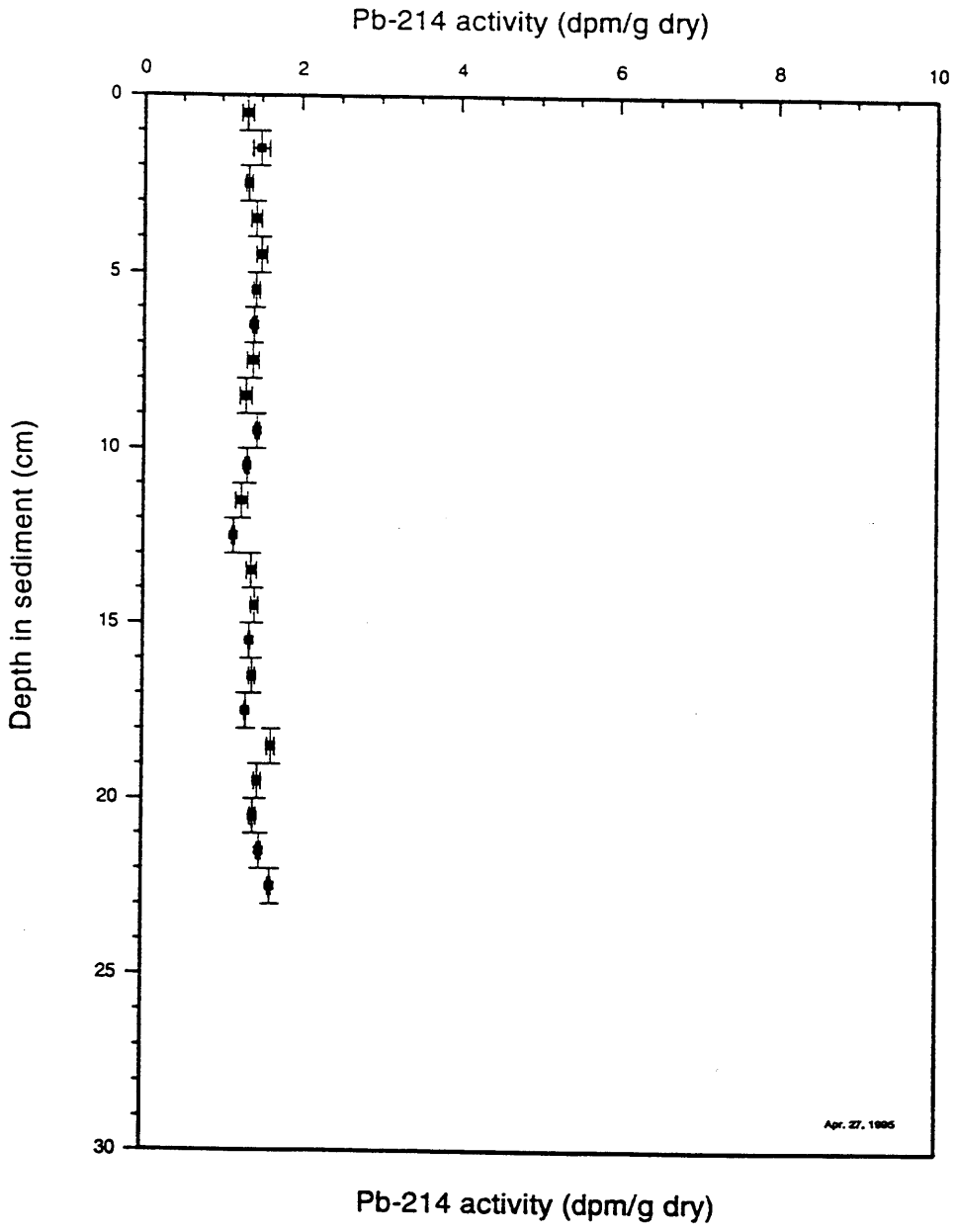


Fig. 48. Downcore Pb-214 (dpm/g) distribution in the core Ob94-7B collected in the Ob River Delta in 1994.

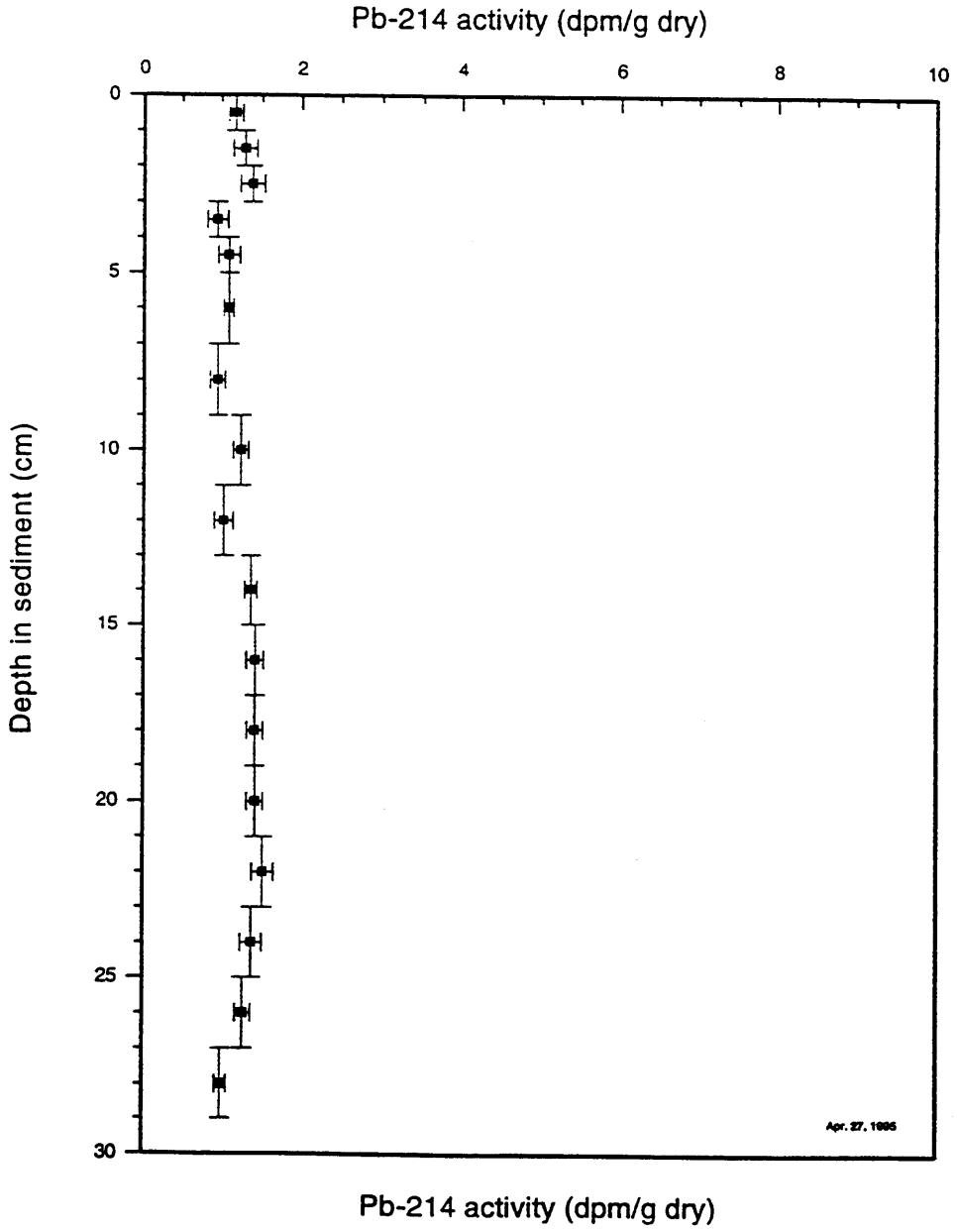


Fig. 49. Downcore Pb-214 (dpm/g) distribution in the core Ob94-8 collected in the Ob River Delta in 1994.

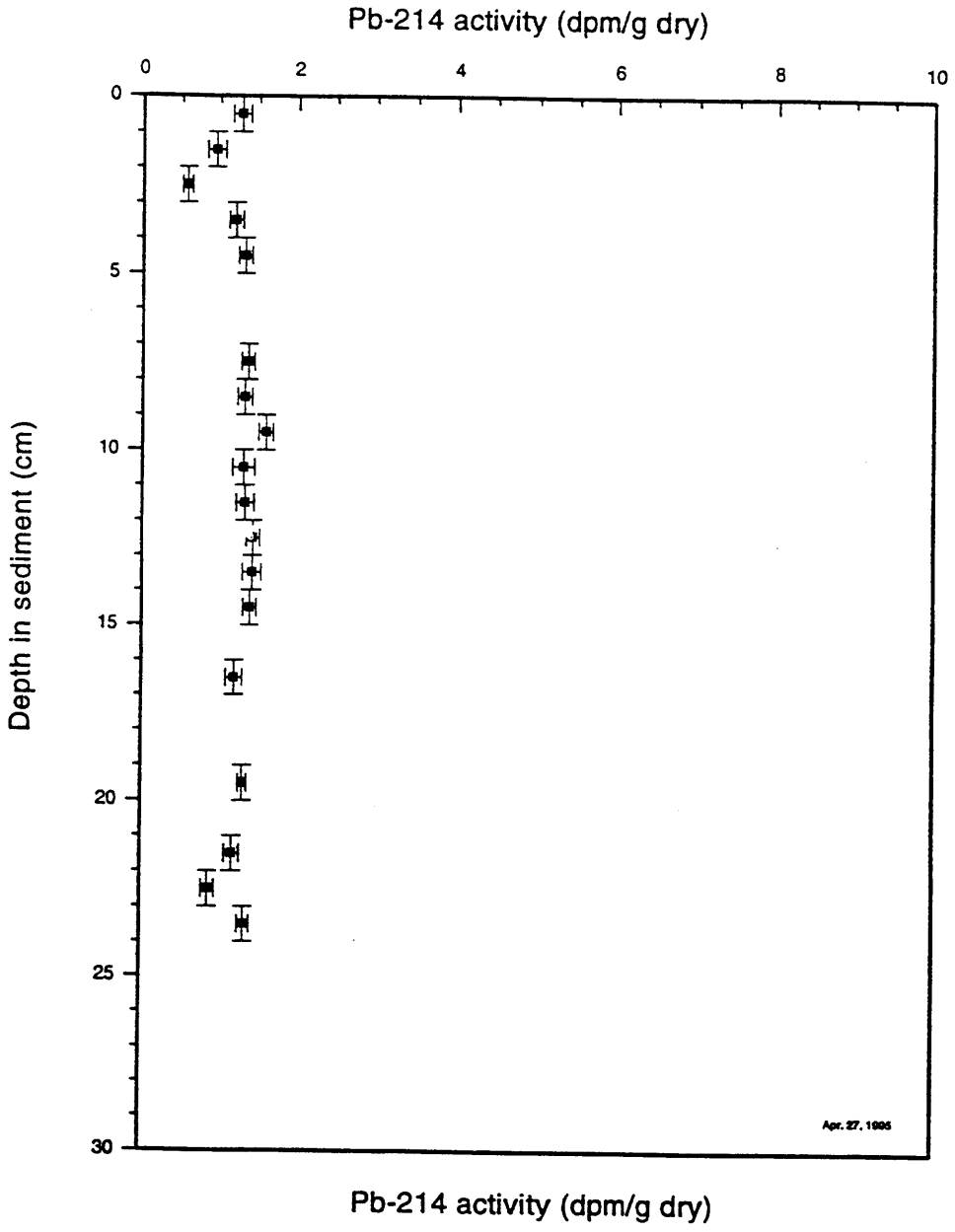


Fig. 50. Downcore Pb-214 (dpm/g) distribution in the core Ob94-9 collected in the Ob River Delta in 1994.

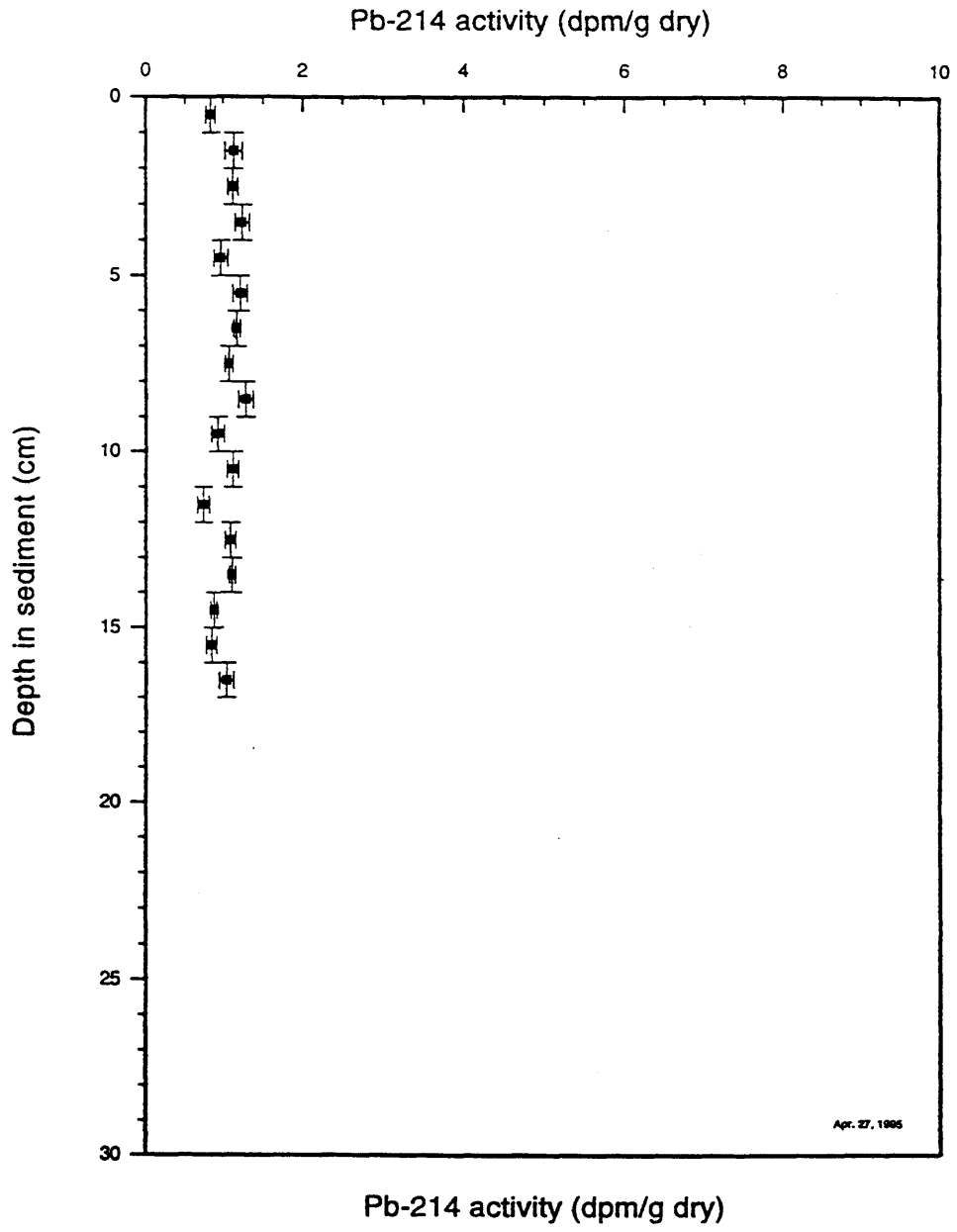


Fig. 51. Downcore Pb-214 (dpm/g) distribution in the core Ob94-13 collected in the Taz Estuary in 1994.

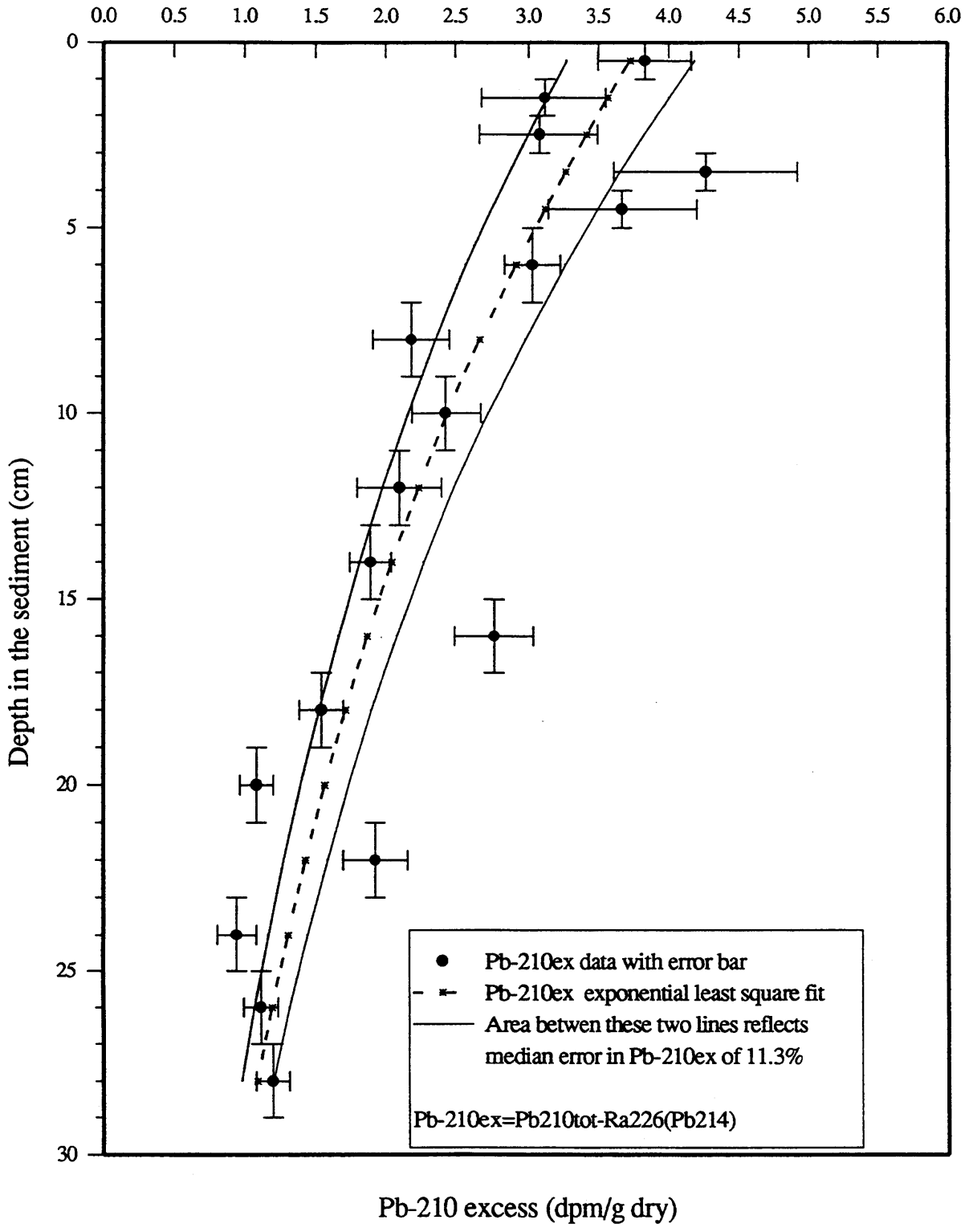


Fig. 52. Downcore excess Pb-210 (dpm/g) distribution in the core Ob94-8 collected in the Ob River Delta in 1994. Pb210 ex = Pb210tot- Ra-226 (from Pb214).

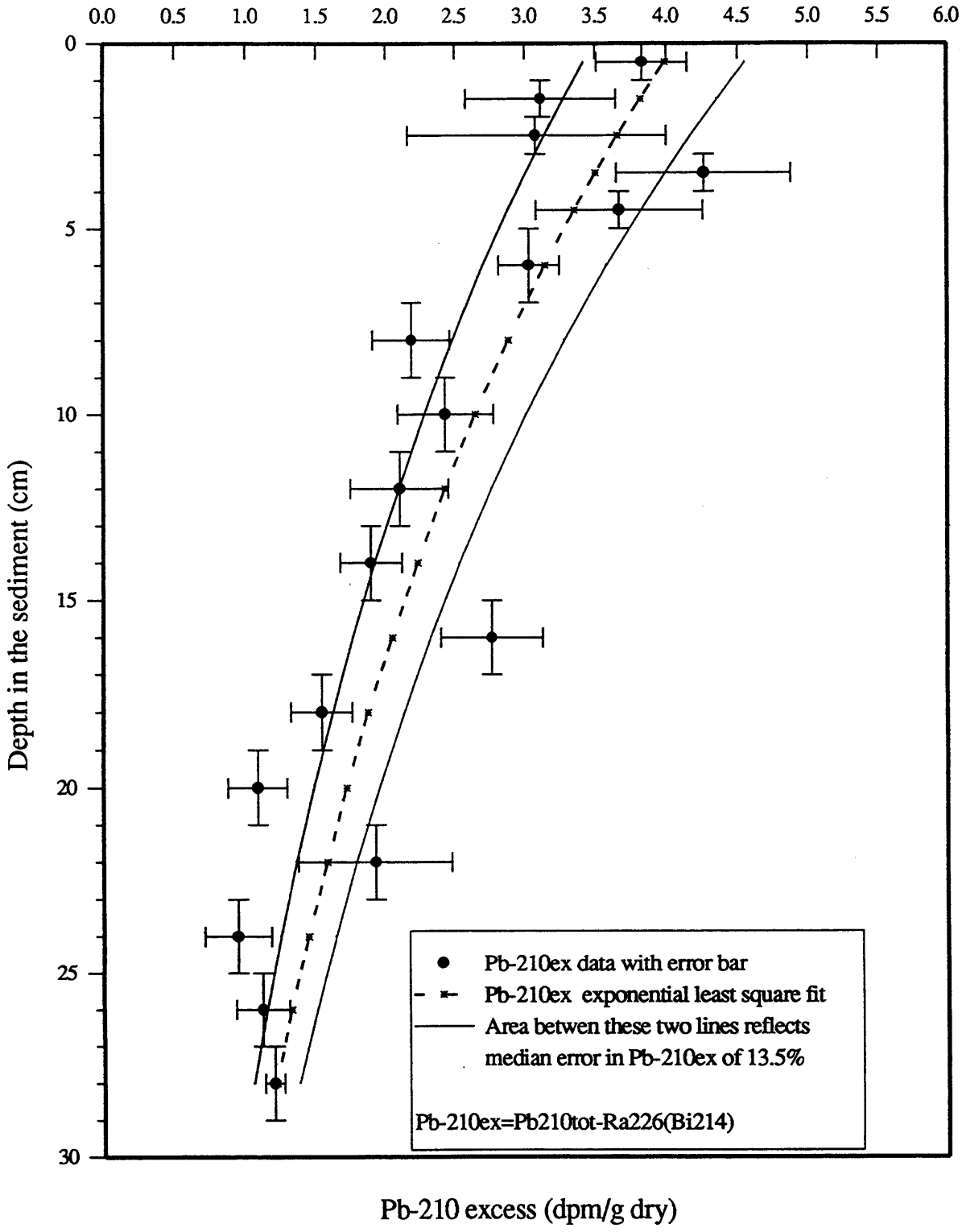


Fig. 53. Downcore excess Pb-210 (dpm/g) distribution in the core Ob94-8 collected in the Ob River Delta in 1994. Pb210 ex = Pb210tot- Ra-226 (from Bi214).

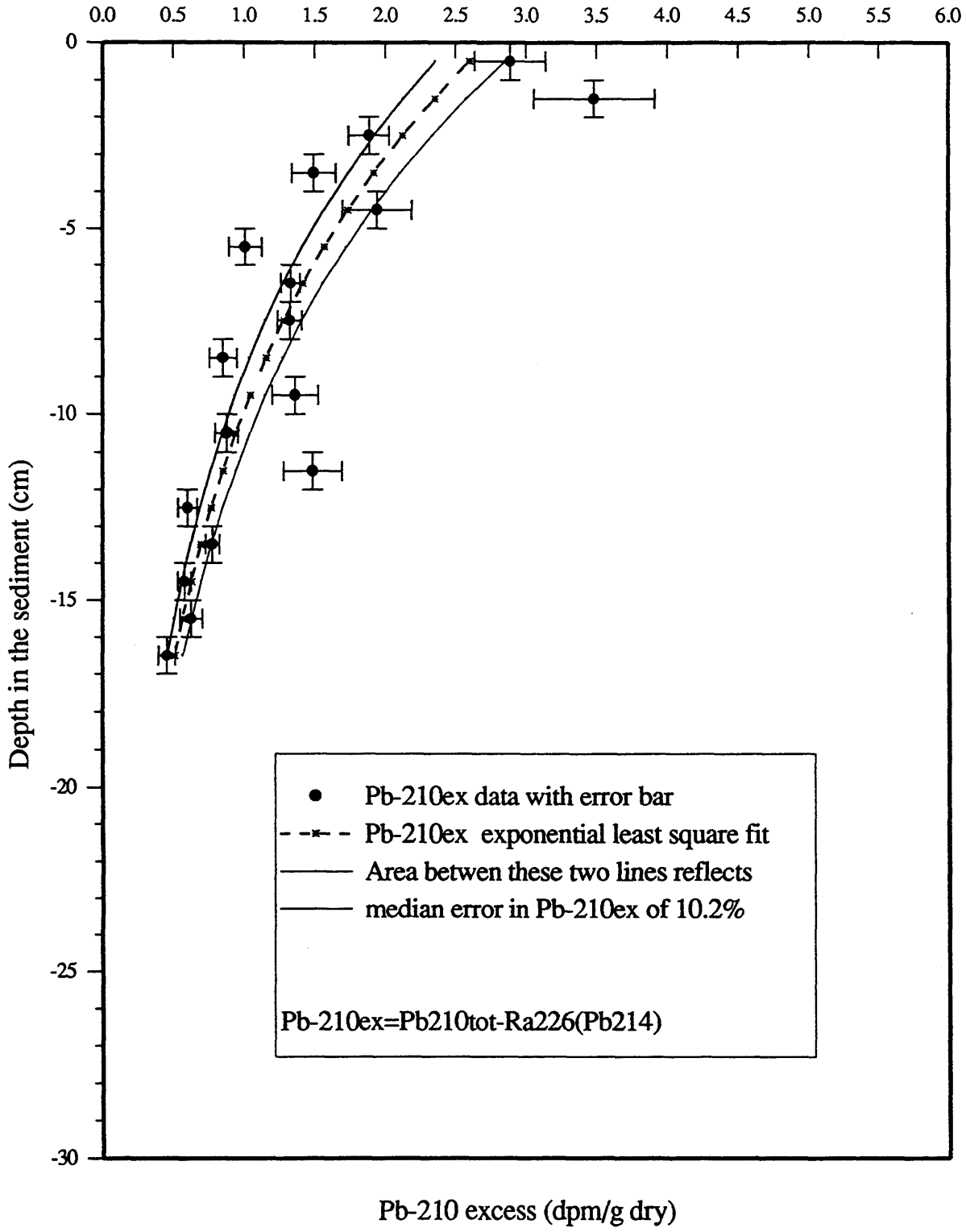


Fig. 54. Downcore excess Pb-210 (dpm/g) distribution in the core Ob94-13 collected in the Ob River Delta in 1994. Pb210 ex = Pb210tot- Ra-226 (from Pb214).

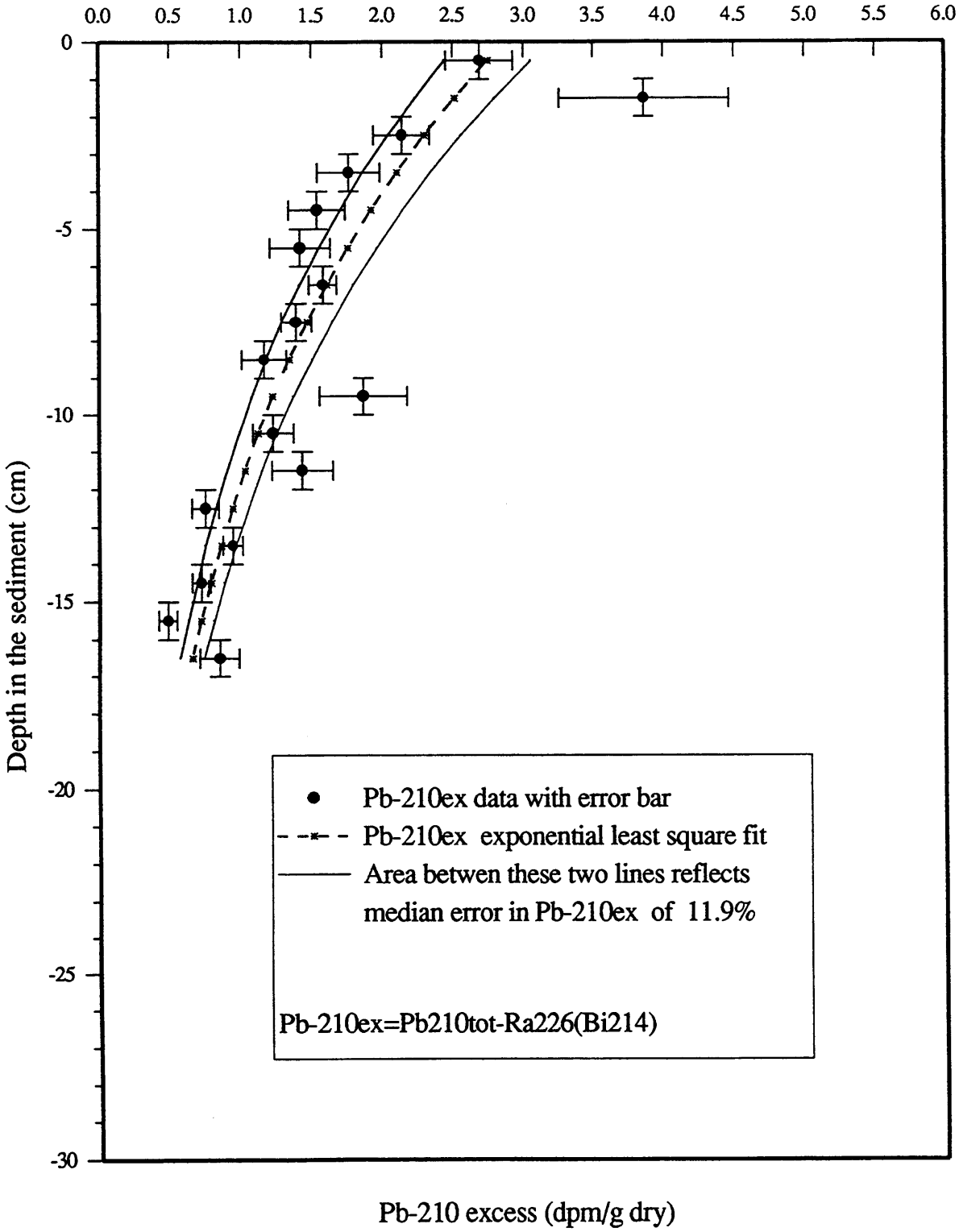


Fig. 55. Downcore excess Pb-210 (dpm/g) distribution in the core Ob94-13 collected in the Taz Estuary in 1994. Pb210 ex = Pb210tot- Ra-226 (from Bi214).

uncertainties due to the fact that the germanium detector used, has a low efficiency at Pb-214 and Bi-214 characteristic energies (352 and 609 KeV respectively). The efficiency drops by a factor of 2.5 from around 1% to 0.4%. This fact leads me to believe that Bi-214 data could be less reliable, and consequently, the Bi-214 model derived ages should be treated more with caution.

Given all the limitations described above, the constant activity -constant sedimentation model provided an independent age estimate of the Cs-137 peaks and average sedimentation rates for cores Ob94-8 and Ob94-13 (Table 10.)

Table 10. Pb-210ex derived ages of Cs-137 features in core Ob94-8 (Ob Delta) and core Ob94-13 (Taz estuary).

Core ID	Cs-137 dpth. pen		Main Cs Maxima		Subsurf Cs Maxima		Sediment Rate	
	yr.	yr.	yr.	yr.	yr.	yr.	cm/yr.	cm/yr.
	Pb-214	Bi-214	Pb-214	Bi-214	Pb-214	Bi-214	Pb-214	Bi-214
Ob94-8	1949.3	1943.5	1966.8	1963.2	1986.8	1985.8	0.607	0.534
Ob94-13	1953.9	1958.7	1963.7	1967.3	1989.8	1990.4	0.332	0.376

Several points are of importance in Table 10. There is a large discrepancy in Cs-137 penetration depth age estimates derived from the Pb-214 and Bi-214 proxies of Ra-226. Bi-214 - gives an unreasonably low age for core Ob94-8. It is a well established fact that global fallout arrival started in or around 1950. This argues strongly against the possibility that the age estimate is correct. Also, there is no sign of Cs-137 diffusion or biological mixing in the core. If these processes were to occur, then the cumulative result should have transported Cs-137 the required 6 centimeters down the core. As was described above, the Cs-137 diffusion process can not explain such a transport. Bioturbation process, indeed could easily be capable of mixing a six centimeter layer; however, if such a

process occurs in the lake, one should see it continuing, which is not the case. The Bi-214 age estimate of the Cs-137 penetration depth for core in the Taz Estuary (Ob94-13) in contrast to Ob94-8 shows an age which is too young to be true because global atmospheric fallout was well underway in 1959. Thus, in addition to analytical considerations, this is an argument that one should primarily use Pb-214 age estimates in the discussion.

The Pb-214 age estimates for both cores gives more reasonable numbers for Cs-137 penetration depth ages - 1949 and 1954 for Ob94-8 and Ob94-13, respectively. Although the Pb-214 estimate for core Ob94-8 is still too young for the fallout signal, and for core Ob94-13 is probably a bit too old, they give confidence that in general the Pb-210ex constant activity constant sedimentation rate model provides reasonable dates for the history of nuclear events. The estimated dates for the main Cs-137 maxima in cores Ob94-8 and Ob94-13 agree reasonably well with the known history of global fallout deposition. An attempt to estimate the age determination uncertainty related to the analytical error is presented graphically in Figures 52 to 55. The uncertainty was derived using a simple calculation: the maximum and minimum Pb-210ex values, using the analytical uncertainty, were fitted with an exponential decay curve. The result is that in the worse case scenario in core Ob94-8, the uncertainty of the Bi-214 estimate is no more that 1.9%. The real age determination uncertainty should be much higher. The slope uncertainty is of order 10-15% based on the regression of activity versus depth.

In all this discussion, the assumption of changing sedimentation rate has not been addressed. It is apparent, from the previous discussion of the Ob river annual sediment discharge flux variability, and from Tables 9 and 10, that sedimentation processes in a complex riverine system, like the Ob, are variable. For example, one year the lake could receive a substantial amount of old sediment free of Pb-210ex due to the sudden formation of a new branch of the river resulting in resuspension of old sediments from the floodplain. Higher Pb-210ex activity could be easily explained if there was a period of several years of low sediment delivery, but the direct atmospheric deposition was constant, thus enriching

the layer of sediment in unsupported Pb-210ex. But these hypothetical considerations cannot undermine the remarkable consistency of the sediment dating exercise. Additional support to the hypothesis of the fallout dominated composition of Cs-137 in Ob sediments comes as a result of the comparison of the average sedimentation rates obtained by the excess Pb-210 technique and by the two Cs-137 methods described above. The sedimentation rates agree extremely well for the core Ob94-8 (0.607 cm/yr. - Pb-210ex method; 0.614 cm/yr. - Cs-137 penetration depth method and 0.516 cm/yr. - Cs-137 main fallout maxima method). For core from the Taz estuary, there is excellent agreement between Cs-137 estimates (0.296 cm/yr. Cs-137 penetration depth method and 0.306 cm/yr. - Cs-137 fallout maxima method) while the Pb-210ex (0.332 cm/yr.) estimate is a only little higher then the other two.

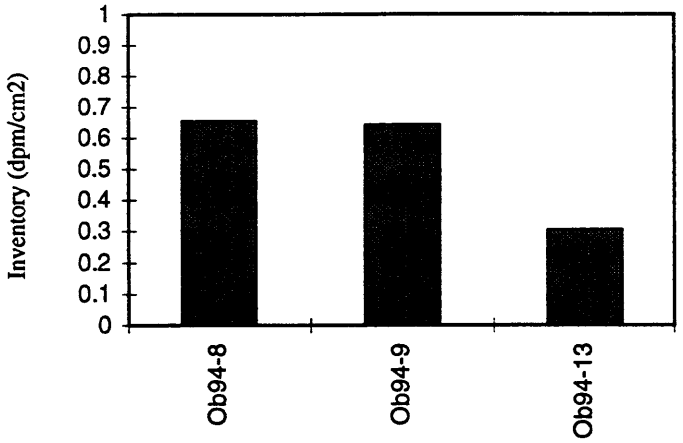
Despite the complexity of the sedimentation processes in the unstable riverine environment, and within all the limitations discussed, one can conclude that, the Pb-210ex dates are a very strong independent confirmation of the time scale of artificial radionuclide deposition pattern in the Ob River and Taz Estuary sediment cores. Smaller analytical error might improve the estimate, but the natural variability will always be greater and very difficult to account for, unless sophisticated modeling techniques are used.

6-D. Plutonium Data and Isotopic Ratios

Plutonium isotope analyses were completed for two cores from the Ob Delta (Ob94-8; Ob94-9) and for the Taz Estuary core (Ob94-13). Also, Pu data for some samples for cores Ob94-3; Ob94-7B and Ob94-10A are presented in Appendix 1. Surface Pu-239,240 activities are between 6.13 dpm/kg for core Ob94-7B and 29.36 dpm/kg for core Ob94-9. I believe that surface sample of core Ob94-3 (58.2 dpm/kg) does not represent a true contemporary surface sediment sample, but an exposed buried fallout peak, as a result of an erosion process as was described earlier.

Downcore Pu-239,240 distributions are presented in Figures 56-58. Pu-239,240 in cores Ob94-8, Ob94-9 and Ob94-13, show two distinct maxima, a small one close to the surface and another, the deeper main maximum. The shape of the sediment Pu-239,240 profiles are practically identical to those of Cs-137 in the same cores. I believe that this finding strongly suggests that the source of Pu-239,240 in the sediment is the same as for Cs-137. Figure 59 shows the Pu-239,240 inventories for the sediment cores. The inventories are almost identical for cores Ob94-8 and Ob94-9 from the Ob Delta and about 2.1 times higher than that of the Taz Estuary core. This fact confirms, the conclusion based on Cs-137 inventories: that the Ob Delta sediments receive a higher proportion of radionuclides from imported wash-in material than from global fallout flux compared with the sediments from the Taz Estuary.

Fig. 59. Pu-239,240 Inventories in the Ob Delta and Taz estuary sediments



Pu-238 isotopes were also analyzed at many locations. However, the analytical uncertainties in the measurements are too big to make any reliable conclusions. These data will need to be revised at a later stage.

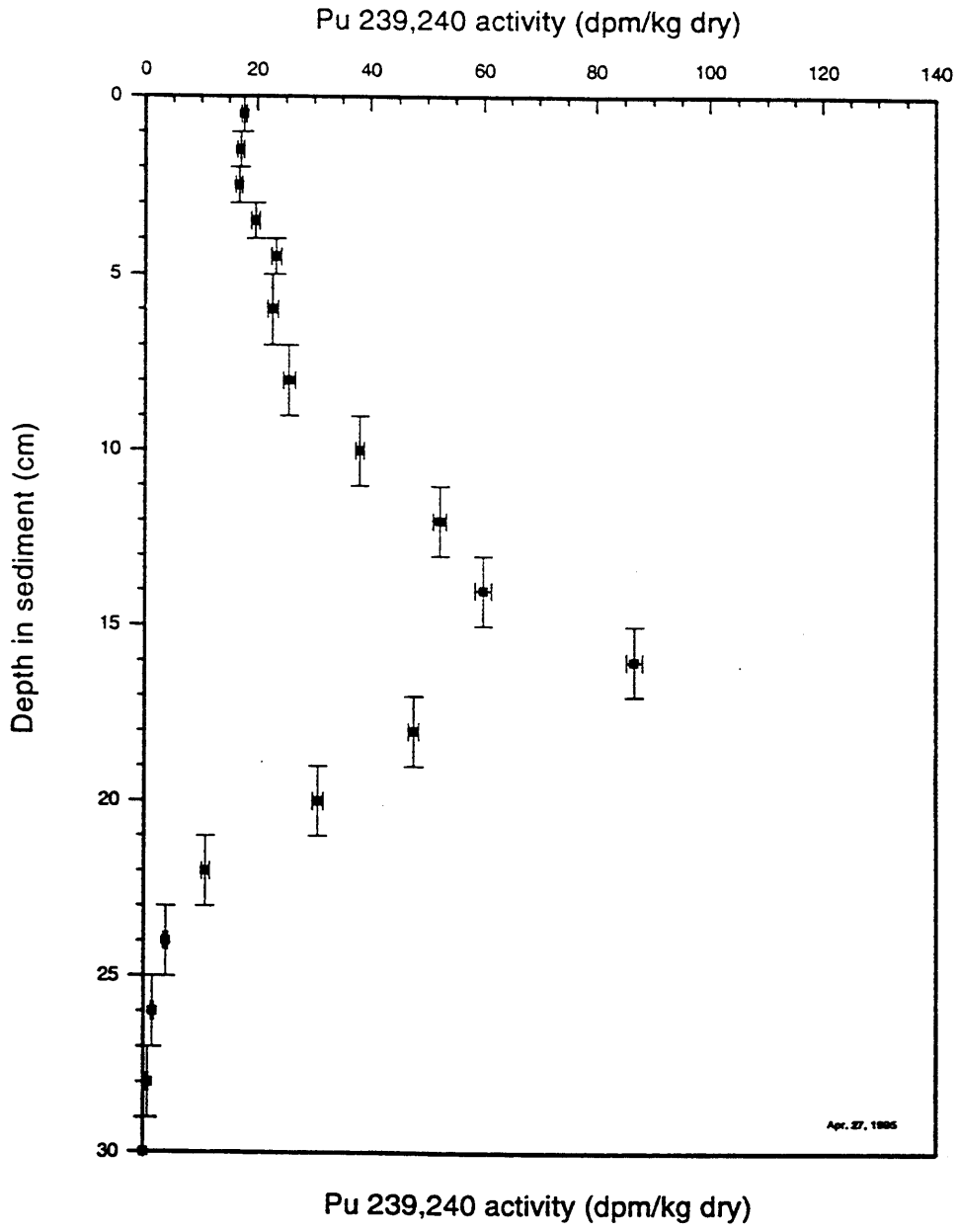


Fig. 56. Downcore Pu-239,240 (dpm/kg) distribution. Station Ob94-8 collected in the Ob River Delta.

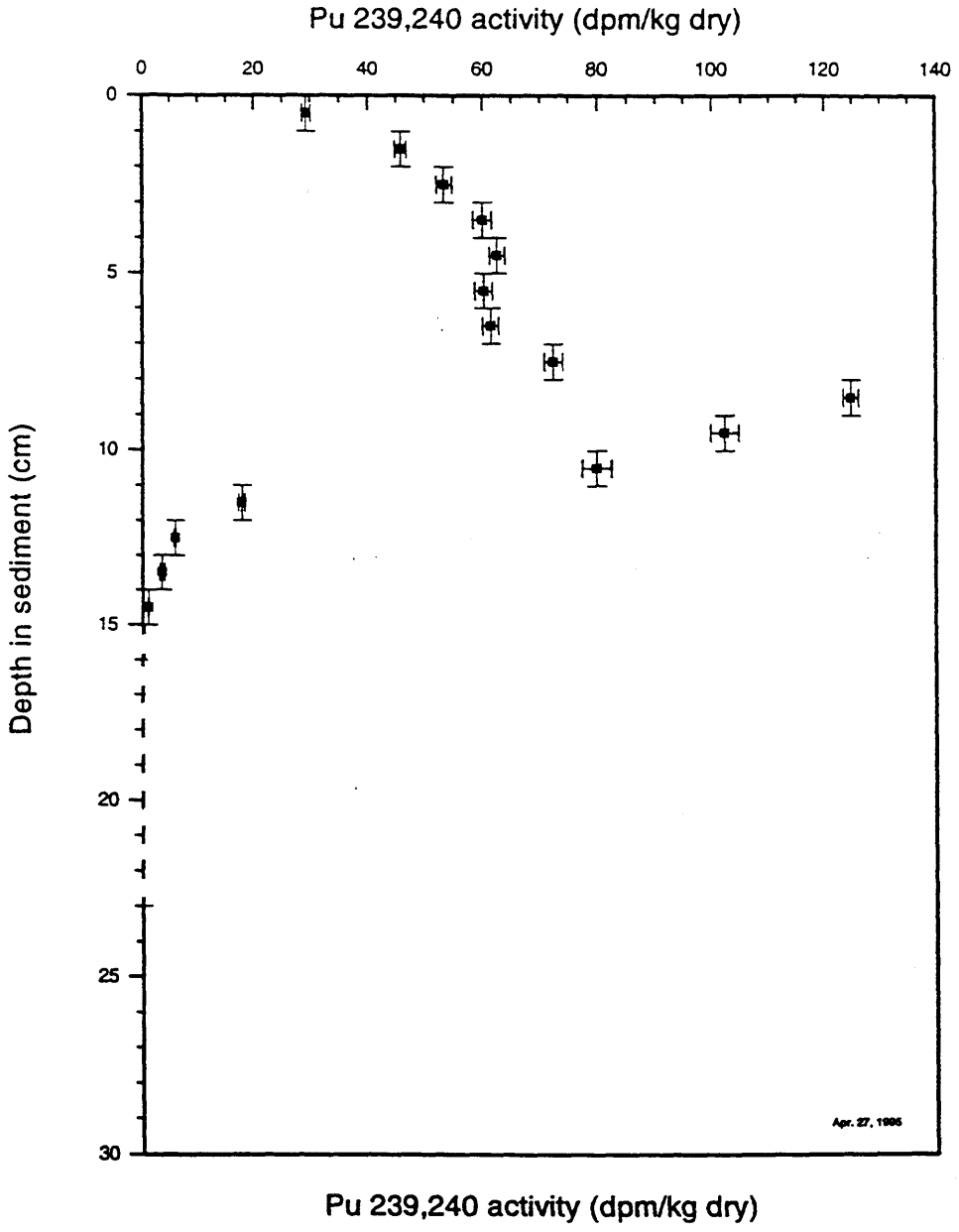


Fig. 57. Downcore Pu-239,240 (dpm/kg) distribution. Station Ob94-9 collected in the Ob River Delta.

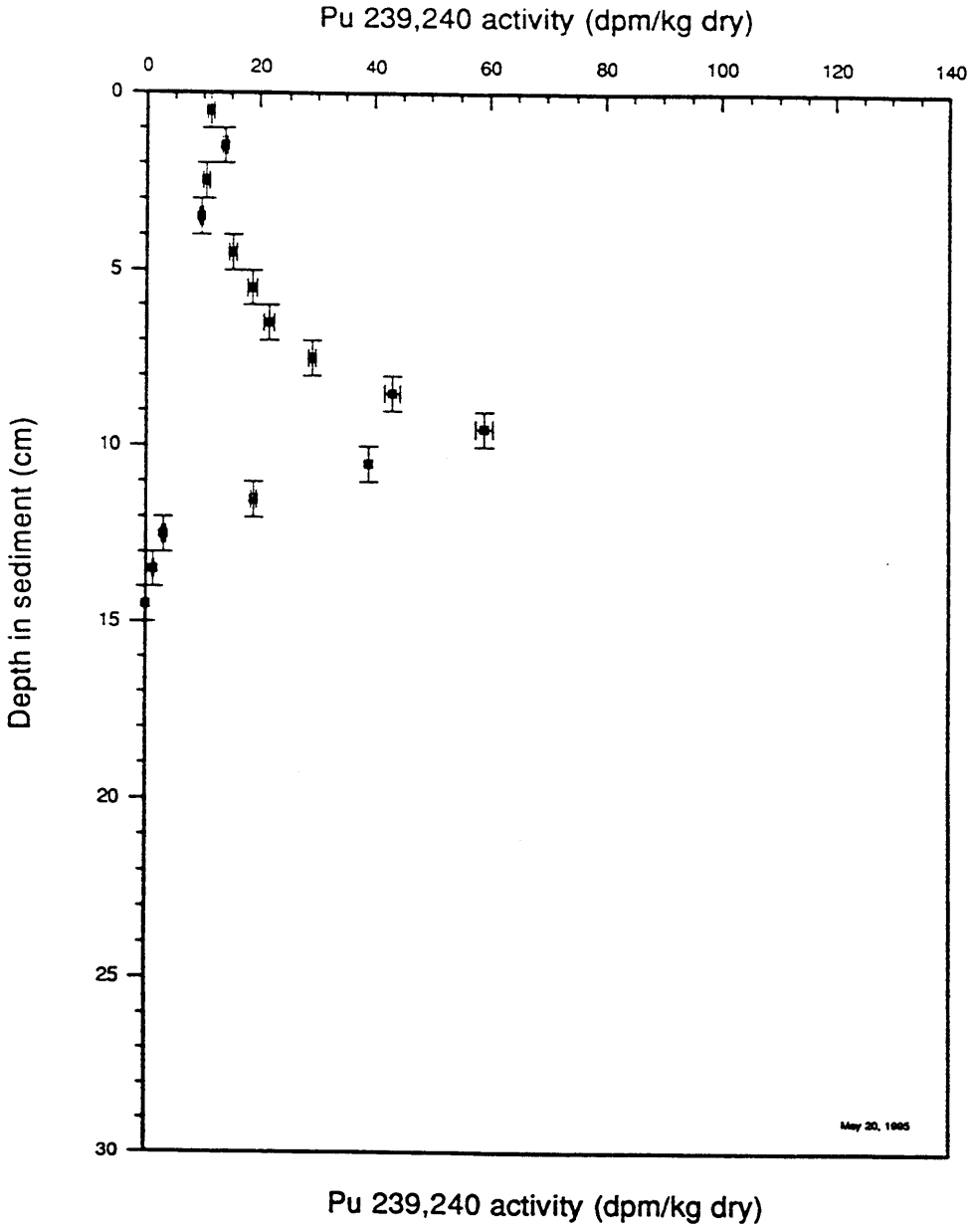


Fig. 58. Downcore Pu-239,240 (dpm/kg) distribution. Station Ob94-13 collected in the Taz Estuary.

6-E. The Pu-239,240/Cs-137 isotope ratios in the Ob Delta and Taz Estuary sediments

The goal of this study is to address the question of potential delivery of radioactivity from the nuclear production facilities which are located upstream from Salekhard in the headwaters of the Ob river. Radioactive releases from the "Mayak" nuclear facilities are the main concern. The fact that this release is quantatively large is also important. Table 11 shows Pu-239,240/Cs-137 ratios observed in the Ob Delta and Taz Estuary cores. The Pu-239,240/Cs-137 isotope ratio estimates from different literature sources are also summarized in this table.

Table 11. Pu-239,240/Cs-137 averaged ratios for the Ob Delta and Taz Estuary cores and compilation of available literature data on the ratio.

Pu-239,240/Cs-137 ratios						
	Pb-239,240/Cs-137 activity ratios					
Core ID (N)	1994			1962	1962	1962
		err	err	calculated	low end	high end
			%	decay corr.		
Ob94-3 (6)	0.0281	0.0035	12.6	0.0135	0.0118	0.0152
Ob94-7B (6)	0.0218	0.0059	27.2	0.0105	0.0076	0.0133
Ob94-8 (16)	0.0272	0.0049	17.9	0.0130	0.0107	0.0154
Ob94-9 (13)	0.0264	0.0050	18.9	0.0127	0.0103	0.0151
Ob94-10A (6)	0.0285	0.0034	11.9	0.0137	0.0120	0.0153
Ob94-13 (11)	0.0355	0.0086	24.1	0.0171	0.0129	0.0212
Literature Data Estimates Corrected for 1994 and 1962 levels.						
Global Fallout Estimates.						
Air Stratospheric (EML - 1962)	0.0251			0.0120		
Ice, Antarctica, (Koide et al., 1979)	0.0272			0.0130		
Soils, Germany. (Bunzl & Kracke, 1988)	0.0248			0.0119		
Russian Tests (Koide et al. 1979)	0.0303			0.0145		
Great Lakes (Alberts & Wahlgren, 1981)	0.0321	Great lakes (1981) data reported for 1976				
Lake, Switzerland (Wan et al., 1987)	0.0369			0.0177		
Rain, Mediterannean Sea Thein et al. (1980)	0.0291			0.0136		
Global fallout. Aarkrog et al. (1992)	0.0230			0.0111		
Nuclear Production Facility, "Mayak".						
Techa R. (Trapeznikov et al. 1993a) Water.	0.00133	0.00070		0.00064	0.00030	0.00098
Techa R. (Trapeznikov et al. 1993a) Sediment Silt+Sand	0.00341	0.00459		0.00164	-0.00056	0.00384
Techa R. (Trapeznikov et al. 1993a) Silt	0.00161	0.00058		0.00077	0.00049	0.00105
Techa R. (Trapeznikov et al. 1993b) Sediments	0.00400	0.00100		0.00192	0.00144	0.00240

The mean value of all Pu-239,240/Cs-137 in Ob Delta cores samples is 0.0264±0.0045 in 1994. This value is in perfect agreement with the mean Pu239,240/Cs-137 value of 0.0258±0.0024 for atmospheric fallout measured in soils, air, wet and dry precipitation around the globe and decay corrected for 1994 (Table 11). The Ob Delta value is a little lower than the one observed in the Great Lakes - 0.0321 and 0.0369 for a lake in Switzerland. It is very interesting to see that mean Pu-239,240/Cs-137 for the Taz Estuary core is also a little higher - 0.0355±0.0086, and is in perfect agreement with the other lake measurements. It is important to mention, that the uncertainties in the Ob Delta and Taz Estuary core ratios overlap.

Despite the fact that the values are not significantly different, and that they all support the global fallout origin of particle reactive radioactivity in the Ob Delta and Taz Estuary cores, one can attempt the following exercise, assuming that there is no variation in the fallout ratio and no error in the determination of the Pu-239,240/Cs-137 ratios.

Assuming that Taz Estuary core ratio of 0.0355 represents the pure global fallout signature in this region, and having approximate numbers for the Techa river Pu-239,240/Cs-137 ratio, one can calculate the fraction of Cs-137 of the Techa radioactivity (Pb-239,240/Cs-137 = 0.0030$\pm$0.0012) which should be added to the sediment in order to bring the ratio to the mean Ob Delta value. The possible contribution from the upstream source component could vary between 22 and 42% for the cores, being 28 percent on average. This exercise outlines the possibility of a significant contribution of upstream derived radioactivity to the Ob Delta sediments. However, the calculation was based on the assumption that the Taz Estuary ratio is representative of mean cumulative global fallout. The Taz estimate was derived using only eleven samples and has an uncertainty of 24.1 % in itself. This uncertainty introduces a big error into the radioactivity contribution estimate. The estimated average percentage of the upstream contribution varies between 2.1 and 43% - due only to the uncertainty in the Taz Estuary ratio. The range is huge, and calls for much more careful treatment of the Taz Estuary number as a global fallout proxy. Alternatively, based on the global fallout estimates of the Pu-239,240/Cs-137 ratio made around the world (Table 11), excluding the ratios measured in the large lakes, it can be seen that the average upstream radioactivity contribution varies between -17 % and + 2%. This argument suggests that there is little upstream derived radioactivity detectable in the Ob Delta sediments.

The high Pu-239,240/Cs-137 ratio in the Taz estuary needs an explanation. There are at least two reasons which can explain the higher ratio: Cs - Pu fractionation in large water bodies and close in fallout from the Novaya Zemlya Testing site. As is shown in Table 11, Great Lake sediments as well as those in Swiss lakes, both showed higher Pu-239,240/Cs-137 ratios. The explanation of this fact was attributed to the possibility of Cs

and Pu fractionation in the large water bodies. The second possibility is that the Taz Estuary sediment coring site is located nearer to the Novaya Zemlya Testing site. There is no information on the Pu-239,240/Cs-137 ratio of these atmospheric tests, however it was suggested that, on average, Russian tests had a greater Pu-239,240/Cs-137 ratio that the ones conducted in the West. Koide et al. (1979) reported that the average Russian test ratio was about 0.0145 in 1962, which if decay corrected for 1994, would be 0.0303. This value is closer to the one observed in the Taz core. Another fact which could explain the even higher ratio in the Taz core is that close in fallout is characterized, on average, by higher Pu-239,240/Cs-137 ratios. Such close in fallout could easily explain the Taz Estuary value.

From the discussion above, it may be concluded that the analytical errors in the Taz Estuary Pu-239,240/Cs-137 ratio raise questions regarding its use as the sole global fallout reference. The sediment core Pu/Cs ratio from the Ob Delta is impossible to distinguish from published global fallout values. Thus I believe that the amounts of non-global fallout, from upstream in the Ob river watershed, in the Ob delta sediments, even if present, are small and at this point impossible to quantify reliably.

CHAPTER 7

CONCLUSIONS

The objectives of this work were to assess the potential transfer of sediment borne nuclear contamination to the Arctic Ocean from sources in the nuclear weapons complex of sites along the Ob River and its tributaries. The approach was to use the record of downstream sediment transport laid down in delta sediments to reconstruct a chronology of nuclear contamination at the mouth of the Ob River.

The primary conclusion from this work is that the annually flooded Sor lakes connected to the main channel of the river are indeed excellent places to sample accumulating sediments. Although the delta and the myriad of connected small lakes are complex environments, it seems that it is often possible to collect sediment cores there in which recent deposition is preserved without significant post-depositional disturbance of the accumulated sediment layers. Bioturbation, if present, does not appear to be a dominant process and the observed downcore distributions of deposited artificial radionuclides appear to mostly reflect the history of their delivery.

Attempts to date the accumulation of delta sediments using the down core distribution of excess (unsupported) Pb-210 ended with mixed success. In some cores, the excess Pb-210 record indeed was able to be used to develop a deposition timescale consistent with time-markers in the artificial radionuclide profiles. However, in others, the complexity of the depositional environment created as yet unexplained perturbations in the record, which made dating uncertain. Nevertheless, the general trend did not negate depositional timescales which made sense for Pu and Cs-137.

The Pb-210 chronologies dated the large maxima of Pu and Cs-137 at depth in all the cores at a timeframe in the mid-60's consistent with the conclusion that they derived from global fallout of atmospheric nuclear weapons' tests. This conclusion was confirmed by the observation that the sediment Pu/Cs-137 ratios were essentially identical to those

found in samples containing only global fallout. These comparisons suggested that the Ob delta cores contained little or no nuclear contaminants from upstream sources. If present, these sources are unlikely to contribute more than 10% of the total amount of the observed levels.

The implication of the failure to observe significant amounts of radioactivity from upstream sources in the Ob delta sediments is that correspondingly minimal amounts of this signal have been transferred to the Ob Estuary and Arctic Ocean. This excepts radioactivity with low particle absorption characteristics eg, Sr-90, which is likely to have been transferred to the estuary and Arctic with minimal retention in the riverine sediment system.

These conclusions give rise to the hypothesis that the Ob River system acts effectively to delay the transfer of sediment borne contamination from the upper part of the watershed to the delta region - at least over multi-decadal timescales. Perhaps the flood plain component of the system acts as storage of such contamination as part of the annual cycle of melting ice, overbank flooding and deposition in the flood plain catchment area.

These conclusions not only address the fate of nuclear contamination released to the Ob system over the past five decades and in the environment at present, but also provide an indication of the behavior of future contamination released as a result of some catastrophic event. This information will serve to test models of the transport of such releases downriver.

REFERENCE LIST

Aarkrog A. (1988) The radiological impact of the Chernobyl debris compared with that from nuclear weapons fallout. *Journal of Environmental Radioactivity,* **6**, 151-162.

Aarkrog A., H. Dahlgaard, M. Frissel, L. Foulquier, N. V. Kulikov, I. V. Molchanova, C. Myttenaere, S. P. Nielsen. G. G. Polikarpov, P. I. Yushkov (1992) Sources of Antropogenic Radionuclides in the Southern Urals. *Journal of Environmental Radioactivity*, **15**, 69-80.

Aarkrog A., Y. Tsaturov, G. G . Polikarpov (1993) Sources to environmental radioactive contamination in the former USSR. October 1993 Report.

Aarkrog, A., L. Botter-Jensen, Q-J. Chen, H. Dahlagaard, H. Hansen, E. Holm, B. Lauridsen, S. P. Nielsen, J. Sogaard-Hansen (1989) Environmental Radioactivity in Denmark in 1987. Riso-R-563, Riso National Laboratory, Roskilde.

Alberts J. J., M. A. Wahlgren (1981) Concentrations of Pu-239,240, Cs-137, and Sr-90 in the waters of the Laurentian Great lakes. Comparison of 1973 and 1976 values. *Environmental Science and Technology* **15**, 95-98.

Anonymous (1992) Nuclear Explosions in the USSR. Part 1. Northern Test Site. Reference Information. Moscow. 194pp.

Beasley, T. M. (1987). Transuranic radionuclides in the Columbia River: Sources, Inventories and Geochemical Behavior. Environmental research on actinide elements. *United States Department of Energy.*

Beasley, T. M. and C. D. Jennings (1984) Inventories of 239,240 Pu, 241 Am, 137 Cs, and 60 Co in Columbia River Sediments from Hanford to the Columbia River Estuary. *Environmental Science and Technology.* **18**, 207-212.

Bjurman, B. et al. (1990) The Detection of Radioactive Material from a Venting Underground Nuclear Explosion. *Journal of Environmental Radioactivity* **11**, 1-14.

Bopp R. F., H. J. Simpson, C. R. Olsen, R. M. Trier, N. Kostyk (1982) Chlorinated hydrocarbons and radionuclide chronologies in sediments of the Hudson River and Estuary, New York. *Environmental Science and Technology*, **16**, 666-675.

Bowen V. T., V. E. Noshkin, H. L. Volchok, H. D. Livingston, K M. Wong (1974) Cesium -137 to Strontium-90 ratios in the Atlantic ocean 1966 through 1972. *Limnology and Oceanography*,**19, No 4**, 670-681.

Bowen V. Y., K. M. Wong, V. E. Noshkin (1971) Plutonium 239 in and over the Atlantic *Ocean. Journal of Marine Research* **29**, 1.

Breteler R. J., V. T. Bowen, D. L. Schneider, R. Henderson (1984) Sedimentological reconstruction of the recent pattern of mercury pollution in the Niagara river. *Environmental Science and Technology,* **18**, 404-409.

Brunskill G. J., S. D. Ludlam, T. -H. Peng (1984) Fayetteville Green Lake, New Yourk, U.S.A. VIII. Mass balance for Cs-137 in water, varved and non-varved sediments. *Chemical Geology*, **44**, 101-117.

Buesseler K. O. (1987) Chernobyl: Oceanographic studies in the Black sea. *OCEANUS,* **30,** 23-30.

Bunzl K., W. Kracke (1988) Cumulative deposition of Cs-137, Pu-238, Pu-239,240 and Am-241 from global fallout in soils from forest grassland and arable land in Bavaria (FRG). *Journal of Environmental Radioactivity*, **8**, 1-14.

Bjurman, B.et al. (1990) The Detection of Radioactive Material from a Venting Underground Nuclear Explosion. *Journal of Environmental Radioactivity*, **11**, 1-14.

Cawse P. A. (1983) The accumulation of Cs-137 and Pu-239,240 in soils of Great Britain, and transfer to vegetation. In: Ecological Aspects of Radionuclide Release. (Ed. P. J. Coughtrey), pp. 47-62. *Blackwell Scientific Publications*, Oxford.

Conclusion of the commission on the estimation of the ecological situation in the region of production association "MAYAK", organized by the direction of the Presidium of Academy of Sciences. Academy of Sciences. (1991). *Zhurnal Radiobiologii* (Russian Journal of Radiobiology) **31**, 436-452 (in Russian).

Cutshall N. H., I. L. Larsen, M. M. Nichols (1981) Man-made radionuclides confirm rapid burial of kepone in James River sediments. *Science*, **213**, 440-442.

Cutshall, N. H., M. R. Guerin (1987) Global and site specific multimedia (Field) studies. A symposium Proceedings Multimedia approaches to pollution control. pp. 78-88.

Doronin, Yu. P., V. V. Ivanov, A. Z. Svyatsky (1990) Mathematical modeling of sea-river water interaction processes in river mouths of the Arctic zone. *Transactions of the 5th All Union Hydrological Conference* (In Russian), **9**, River mouth L. Hydrometeoizdat, pp. 163-170.

Doronina, N. A.,V. V. Ivanov, Yu. V. Nalimov (1976) River mouth ice regime investigation results. Transactions of 6 All-Union Hydrological Conference (In Russian) **6**, pp. 289-291.

Durham, R. W., S. R. Joshi (1980) Recent sedimentation rates, Pb-210 fluxes, and particle settling velosities in Lake Huron, Laurentian Great lakes. *Chemical Geology*, **31**, 53-66.

Edgington, D. N., J. A. Robins (1975) The behavior of plutonium and other long-lived radionuclides in Lake Michigan. Impacts of nuclear releases into aquatic environment. *International Atomic Energy Agency*.pp 245-260.

Farmer, J. L., V. T. Bowen, V. E. Noshkin (1980) Long-lived artificial radionuclides in Lake Ontario, II. Plutonium, americium, strontium-90 and cesium-137 in sediment cores. *Limnology and Oceanography.*

Faure, G. (1986) Principles of isotope geology. New York, John Wylie and Sons.

Foster, R. F. (1972) The history of Hanford and its contribution of radionuclides to the Columbia River. The Columbia River Estuary and Adjacent Ocean Waters. Seattle, University of Washington Press.

Francis, C. W., F. S. Brinkley (1976) Preferential adsorption of Cs-137 to micaceous minerals in contaminated freshwater sediment. *Nature*, **260**, 511-513.

Gavini, M. B. (1978) Radionuclide ratios in wet and dry deposition samples from June 1976 through December 1977. *Earth and Planetary Science Letters.*, **41**, 228-232.

Geology of the USSR. West Siberian lowland. (1964) **44**, part 1. (In Russian) M. "Nedra", 550 pp.

Hardy, E. P. (1971) Fallout program quarterly summary report. USDOE Report HASL-245.

Hardy, E. P. (1974) Worldwide distribution of plutonium. Part of the AEC presentation at the EPA Plutonium Standards Hearings. Washington, D. C., December 10-11, 1974.

Hardy, E. P., (1977) Environmental Quarterly: Final Tabulation of Monthly Sr-90 Fallout Data: 1954-1976. USAED Report HASL-329.

Hardy, E. P., P. W. Krey, H. L. Volchok (1973) Global inventory and distribution of fallout plutonium. *Nature* **241**, 444-445.

Hardy, R. P. (1973) The Ratio of Cs-137 to Sr-90 in the Global Fallout. USAEC, HASL-273.

Hardy, E. P., H. L. Volchok, H. D. Livingston and J. C. Burke (1980) The time pattern of off-site plutonium deposition from Rocky Flats plant by lake sediment analysis. *Environment International.* **4**, 21-30.

Harley, J. H. (1975) Transuranium elements on land. US DOE HASL Report -291 I-104.

Harley, N., I. Fisenne, L. D. Y. Ong, J. Harley (1965) Fission Yield and Fission Product Decay. *USAEC Report HASL*,**164**, 251-261.

Health and Safety Laboratory (HASL) (1975) Transuranic Data. *HASL Tech. Mem.*, TM **75**, 9-22.

Heit, M., K. M. Miller (1987) Cesium-137 sediment depth profiles and inventories in Adirondack Lake sediments. *Biogeochemistry*, **3** ,243-265.

Hohenemser, C., M. Deicher, A. Ernst, H. Hofsass, G. Lindner, E. Recknagel (1986) Cherbobyl: an early report. *Environment.* **28** ,6-13; 30-43.

Ivanov,V. V. (1980) Hydrologic regime of lower reaches and mouths of West Siberian rivers, and estimates of its variations from territorial redistribution of water resources. (In Russian), *Problems of the Arctic and Antarctic*, **55**, 20-43.

Ivanov, V. V. (1974) Basic concepts for hydrologic-morphologic zoning of river mouth areas in the Arctic. (In Russian) In: Factors and philosophy of physical-geographic zoning of global Polar regions. L., 102-120.

Ivanov, V. V., V. M. Makeyev (1990) Importance of hydrological and ther natural parameters for long-term formations of mouth river areas in the Arctic zone (In Russian). Transactions of 5 All-Union Hydrological Conference, **9**., River mouth, pp. 65-74.

Ivanov, V. V., Yu. V. Nalimov Results aerial survey in downstream and mouth areas of Arctic rivers (In Russian). *Problems of the Arctic and Antarctic*, **57**, 71-90.

Ivanov, V. V. (1968) Calculation procedure for runoff component of level fluctuation in river mouths. (In Russian). *Transactions of the Arctic and Antarctic Research Institute*, **283**, 12- 29.

Ivanov, V. V., O. N. Medkova, V. M. Makeyev (1995) Characteristic features of sedimentation process in lower reaches and mouth of the Ob river. In press. Work performed on the request by Woods Hole Oceanographic Institution on behalf of "Ob River Project".

Joseph, A. B., P. F. Gustafson, F. A Schuert, H. L. Volchok and A Tamplin. (1979) Sources of radioactivity and their characteristics. In: Radioactivity in the Marine Environment, 6-41, National Academy of Sciences, Washington, D. C.

Khotuleva, M. V., V. A. Chechetkin, N. A. Melnichenko (1993) Radioactive contamination of Russia's Techa River. *Environmental Science and Technology.* **27,** 606-607.

Koide, M., R. Michel, E. D. Goldberg, M. M. Herron, C. C. Langway (1979), Depositional history of artificial radionuclides in the Ross ice shelf, *Antarctica. Earth and Planetary Science Letters*, **44**, 205-223.

Krey, P. W., L. E. Toonkel, M. Schonberg (1975) Project Airstream. US DOE HASL Report -291 II-7.

Krey, P. W. (1976) Remote plutonium contamination and total inventories from Rocky Flats. *Health Physics*. **30**, 209-214.

Krishnaswami, S, D. Lal (1978) Radionuclide limnochronology, In: Lakes: chemistry, geology and physics. (Ed. Alenman).

Krishnaswamy, S., D. Lal, J. M. Martin, M. Meybeck (1971) Geochronology of lake sediments. *Earth and Planetary Science Letters*, **11**, 407-414.

Larsen, R. J. (1984) Graphic presentation of quarterly Sr-90 fallout data 1954-1982. U.S. DOE Rep. EML 424.

Larsen, R. J. (1985) Worldwide Deposition of Sr-90 Through 1983. USDOE Report EML-444.

Latsis, A. (1992) Eto ozero-zavtrashniy Chernobyl (This lake is tomorrow's Chernobyl). *Moscow News* **18**.

Laverov, N. P. (1995) On basic sources of radioactive contamination of the Russian Arctic Region. (Presentation at ONR Arctic Nuclear Waste Assessment Program Workshop. Woods Hole Oceanographic Institution. May 1-5,1995, Woods Hole MA, USA).

Lazukov, G. I. (1970) Anthropogenic effects in the northern half of West Siberia (Stratigraphy) (In Russian), *Moscow University Publishing House*, pp. 322.

Levi, B. G. (1986) Cause and impact of Chernobyl accident still hazy. *Physics Today,* **39 No. 7**, 17-21.

Linsalata, P., M. E. Wrenn, N. Cohen, N. P. Singh (1980) Pu-239,240 and Pu-238 in sediments of the Hudson River Estuary. *Environmental Science and Technology*, **14**, 1519-1523.

Linsalata, P., H. J. Simpson, C. R. Olsen, N. Cohen and R. M. Trier (1985) Plutonium and Radiocesium in the water column of the Hudson River Estuary. *Environmental Geological Water Science*, **7**, 193-204.

Livingston, H. D., D. R. Mann and V. T. Bowen (1975) Analytical procedures for transuranic elements in seawater and marine sediments. Anaytical Methods in Oceanography (Gibb, T.R.P. Jr. Ed.), *Advances in Chemistry Series,* **147**, ACS, New York, 124.

Livingston, H. D., V. T. Bowen (1979) Pu and Cs-137 in coastal sediments. *Earth and Planetary Science Letters*, **43**, 29-45.

Longmore, M. E., B. M. O'Leary, C. W. Rose (1983) Cesium-137 profiles in the sediments of a partial-meromictic lake of Great Sandy Island (Fraser Island), Queensland, Australia. *Hydrobiologia,* **103**, 21-27.

Lystsov, B. N., A. B. Ivanov, A. E. Kolyshkin (1993) Radioecological aspects of the Tomsk accident. *Atomnaya Energiya* (in Russian) **74**, 364-367.

Makeyev, V. M. (1988) Ob bay level fluctuations in Holocene. Geographic and glaciologic research in Polar countries (In Russian), *Hydrometeoizdat,* **L**, 137-146.

Makeyev, V. M., D. Yu. Bolshiyanov, O. N. Medkova, V. B. Savin, B. G. Fyodorov (1988) Characteristic morphological features of the Ob mouth valley zone, contemporary delta formation history (In Russian). Geographic and glaciologic research in Polar countries. *Hydrometeoizdat,* **L**, 125-137.

McCall, P. L., J. A. Robbins, G. Matisoff (1984) Cs-137 and Pb-210 transport and geochronologies in urbanized reservoirs with rapidly increasing sedimentation rates. *Chemical Geology*, **44**, 33-65.

Miller, K. M., M. Heit (1986) A time resolution methodology for assessing the quality of lake sediment cores that are dated by Cs-137. *Limnology and Oceanography* **31**, 1292-1300.

Monetti, M. A., R. J. Larsen (1991) Worldwide deposition of Strontium-90 through 1986. USDOE Report EML-533.

Morozov, N. P., G. N. Baturin, V. V. Gordeev and Y. G. Gurvich (1976) Composition of Suspension and Sediments in the Estuaries of the Northern Dvina, Mezen', Pechora, and Ob' Rivers. *Soviet Hydrology*, **15(3)**,235-243.

Nesterova, I. L. (1960) Chemical composition of suspensions and dissolved matters of the river Ob. 4: 355-361.

Nikipelov, B. V., E. G. Drozko (1990) The explosion in Southern Urals. *Priroda* (in Russian) **897**, 48-49.

Nikipelov, B. V., G. N. Romanov, L. A. Buldakov, N. S. Babayev, Yu. B. Kholina, E. I. Mikerin, (1989) The radiation accident in the Southern Urals in 1957. *Atomnaya Energiya* (in Russian), **67** ,74-80.

Nosov, A. B., M. V. Ashanin, A. B. Ivanov, A. M. Martynova (1993) radioactive contamination of the Yenisey river as a result of waste disposal of Krasnoyarsk Mining-Chemical Plant. *Atomnaya Energiya*, **74**, 144-150.

Olsen, C. R., H. J. Simpson, R. M. Trier (1981) Plutonium, radiocesium and radiocobalt in sediments of the Hudson River estuary. *Earth and Planetary Science Letters*, **55**, 377-392.

Olsen, C. R., H. J. Simpson, T. -H. Peng, R. F. Bopp, R. M. Trier (1981) Sediment mixing and accumulation rate effects on radionuclide depth profiles in Hudson Estuary sediments. *Journal of Geophysical Research*, **86,** 11020-11028.

Olsen, C. R., P. E. Biscaye, H. J. Simpson, R. M. Trier, N. Kostyk, R. F. Bopp, Y. -H. Li (1980) Reactor-released radionuclides and fine-grained sediment transport and accumulation patterns in Barnegat Bay, New Jersey and adjacent shelf waters. *Estuarine and Coastal Marine Science*, **10**, 119-142.

Olsen, C. R., H. J. Simpson and R. M. Tier (1981) Plutonium, radiocesium and radiocobalt in the sediments of the Hudson River estuary. *Earth and Planetary Sciences Letters* **55**, 377-392.

Olsen, C. R., H. J. Simpson, R. F. Bopp, S. C. Williams, T. H. Peng and B. L. Dech (1978) A geochemical analysis of the sediments and sedimentation in the Hudson estuary. *Journal of Sedimentary Petrology,* **48(2)**, 401-418.

Patel, B. S., S. Patel and S. Pavar (1978) Desorption of radioactivity from nearshore sediment. *Estuarine and Coastal Marine Science,* **7**, 49-58.

Pavlotskaya, F. I., T. A. Goryachenkova, V. V. Emelanov, Z. M. Fedorova, B. F. Myasoedov (1992) Pu-239,240 behavior in soils of the forest steppe zone after the southern Ural's accident in 1957. *Atomnaya Energiya* **73**, 32-37.

Perkins, R. W., J. L. Nelson and W. L. Haushild (1966) Behavior and transport of radionuclides in the Columbia River between Hanford and Vancouver, Washington. *Limnology and Oceanography*. **11**, 235-248.

Popov, B. A., Z. A. Zhigarev, V. N. Novikov, V. A. Sovershaev, V. Yu Biryukov, V V. E. Zemchikhin, E. V. Fyodorova, O. N. Medkova (1987) Bank and bottom dynamics of mouth coastline of the Ob (In Russian). *Water Resources*, **4**, 129-132.

Raymer, S. (1992) Tests leave rivers radioactive. We. 1, 14.

Razumikhina, K. V. (1984) Contemporary sediment runoff regime in the Ob mouth area (In Russian). *Transactions of the Leningrad University, Geology, Geography*, **N24**, 65-73.

Ritchie, J. C., J. R. McHenry (1990) Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *Journal of Environmental Quality*, **19**, 215-233.

Robbins, J. A., D. N. Edginton (1975) Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. *Geochimica et Cosmochimica Acta*, **39**, 285-304.

Robbins, J. A., J. R. Krezoski, S. C. Mozley (1977) Radioactivity in sediments of the Great Lakes: Post-depositional redistribution by deposit-feeding organisms. *Earth and Planetary Science Letters*, **36**, 325-333.

Robbins, J. A., P. L. McCall, J. B. Fisher, J. R. Krezorski (1979) Effect of deposit feeders on migration of Cs-137 in lake sediments. *Earth and Planetary Science Letters*, **42** 277-287.

Romanov, G. N., A. S. Voronov (1990) The post-accident radiation situation. *Priroda*, **897**, 50-52.

Romanov, G. N., B. V. Nikipelov, E. G. Drozko (1990) The Kyshtym accident: causes, scale and radiation characteristics. In: Proceedings of "Seminar on Comparative Assessment of the Environmental Impact of radionuclides Released during Three major Nuclear Accidents: Kyshtym, Windscale, Chernobyl". Luxemburg, 1-5 October 1990. EUR 13574. pp. 26-40.

Romanov, G. N., D. A. Spirin, R. M. Aleksakhin (1990) Behavior of radioactive substances in the environment. *Priroda*, **5** ,53-58.

Sanders, S. M. and A. L. Boni. (1980) The detection study of plutonium-bearing particles following the reprocessing of reactor fuels. Transuranic elements in the environment. *U. S. Department of Energy.*

Shen, G. T., E. R. Sholkovitz and D. R. Mann (1983) The coagulation of dissolved 239,240-Pu in the estuaries as determined from a mixing experiment. *Earth and Planetary Sciences Letters*, **64**, 437-444.

Simpson, H. J, P. Linsalata, C. R. Olsen, N. Cohen, R. M. Trier (1987) Transport of fallout and reactor radionuclides in the drainage basin of the Hudson River estuary. Environmental Research on Actinide Elements, Proceedings of a symposium held at Hilton Head, South Carolina, November 7-11, 1983, (Editor: J. E. Pinder). Pp. 273-297.

Smith, J. N. C. T. Schafer (1987) A 20th-century record of climatologically modulated sediment accumulation rates in a Canadian Fjord. *Quaternary Research*, **27**, 232-247.

Smith, J. N., K. M. Ellis, D. M. Nelson (1987) Time-dependent modelling of fallout radionuclide transport in a drainage basin: Significance of "slow" erosional and "fast" hydrological components. *Chemical Geology,* **63**, 157-180.

Smith, J. N. and K. M. Ellis (1982) Transport mechanism for Pb-210, Cs-137 and Pu fallout radionuclides through fluvial-marine systems. *Geochimica et Cosmochimica Acta*, **46**, 941-954.

Strakhov, N. M., N. G. Brodskaya, L. M. Razzhivina, A. N. Rateev, M. A. Sapozhnikov, D. G. Shitova and E. S. Shitova (1954) Obrazovanie osadkov v sovremennikh vodoemakh. (Formation of Sediments in Modern Aquatoria). Moscow, Izdatelstvo Akademii Nauk SSSR (Publishing House Akademii Nauk SSSR).

Tcherkezian, V. O. (1993) Personal communication. V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences.

Thein, M., S. Ballestra, A. Yamato, R. Fukai (1980) Delivery of Transuranic elements by rain to the Mediterranean Sea. *Geochimica et Cosmochimica Acta*, **44**, 1091-1097.

Thomas, C. W., R. W. Perkins (1974) Transuranic elements in the atmosphere. Batelle Pacific Northwest Laboratory. Report BNWL-1881, UC-48.

Torgersen, T., M. E. Longmore (1984) Cs-137 diffusion in the highly organic sediment of Hidden Lake, Fraser Island, Queensland. *Australian Journal of Freshwater Research*, **35** ,537-548.

Trabalka, J. R., S. I. Auerbach (1990) One western prospective of the 1957 Soviet nuclear accident. In: Proceedings of "Seminar on Comparative Assessment of the Environmental Impact of Radionuclides Released during Three major Nuclear Accidents: Kyshtym, Windscale, Chernobyl". Luxemburg, 1-5 October 1990. EUR 13574. pp. 41-69.

Trapeznikov, A. V., A. Aarkrog, N. V. Kulikov, S. P. Nielsen, V. N. Pozolotina, G. Polikarpov, V. N. Trapeznikova, M. Ya. Chebotina, V. N. Chukanov, P. Yushkov (1993b). Radioactive Contamination of the Ob River system from the Nuclear Enterprise "Mayak" in the Urals. Proceeding of the International Conference on Environmental Radioactivity in the Arctic and Antarctic. 23rd-27th August 1993. Kirkenes, Norway.

Trapeznikov, A. V., V. N. Pozolotina, M. Ya. Chebotina, V. N. Chukanov, V. N. Trapeznikova, N. V. Kulikov, S. P. Nielsen, A. Aarkrog. (1993a) Radioactive contamination of the Techa River, the Urals. *Health Physics*, **65**, 481-488.

Voskresenskiy, K. P. (1963) Normal Annual Runoff of the Rivers of the Soviet Union and Its Variations. Leningrad, Gidrometeoizda.

Wahlgren, M. A., D. M. Nelson (1975) Verh. Internat. Verein. *Limnology and Oceanography*, **19**, 317-322.

Wan, G. J., P. H. Santschi, M. Sturm, K. Farrenkothen, A. Lueck, E. Werth, Ch. Schuler (1987). Natural (Pb-210, Be-7) and fallout (Cs-137, Pu-239,240, Sr-90) radionuclides as geochemical tracers of sedimentation in Greifensee, Switzerland. *Chemical Geology*, **63**, 181-196.

Yokoyama, Y, H-V. Nguyen (1980) Direct and non-destructive dating of marine sediments, manganese nodules, and corals by high resolution gamma-ray spectrometry. In: Isotope Marine Chemistry, (Eds. Goldberg, Horibe) pp. 259-289.

Zander, I., R. Araskog (1973) Nuclear Explosions 1945-1972 Basic Data. FOA 4 Report A 4505-A1, Research Institute of National Defense, Department 4, S-104 50 Stockholm 80, SWEDEN.

APPENDIX 1

Sample Data Tables

File: OB94-3.fln dat

Table A1.1

Ob Estuary 1994 Station OB94-3 Data

Sample ID	Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226) dpm/g	Pb-214 (Ra-226) err dpm/g	Bi-214 (Ra-226) dpm/g	Bi-214 (Ra-226) err dpm/g	Pb-210t (Total) dpm/g	Pb-210t (Total) err dpm/g	Pb-210 excess (1) dpm/g Pb210ex=Pb210t-Ra226(Pb214)	Pb-210 excess (1) err dpm/g	Pb-210 excess (2) dpm/g Pb210ex=Pb210t-Ra226(Bi214)	Pb-210 excess (2) err dpm/g
ZG3001	0.0-0.5	65.73	1.26	0.43	1.13	0.16	0.61	0.10	7.78	0.56	6.65	1.08	7.17	1.28
ZG3002	0.5-1.5	54.49	1.38	0.63	1.29	0.12	1.07	0.13	6.97	0.36	5.68	0.61	5.89	0.77
ZG3003	1.5-2.5	42.44	1.53	0.88	1.07	0.12	0.70	0.11	3.98	0.30	2.91	0.39	3.28	0.56
ZG3004	2.5-3.5	35.39	1.63	1.06										
ZG3005	3.5-4.5	34.84	1.64	1.07	1.14	0.06	1.34	0.07	2.53	0.14	1.40	0.11	1.20	0.09
ZG3006	4.5-5.5	33.42	1.67	1.11	0.98	0.08	0.94	0.08	2.19	0.17	1.21	0.14	1.25	0.15
ZG3007	5.5-6.5	34.58	1.65	1.08	1.23	0.11	0.50	0.07	2.29	0.24	1.06	0.15	1.79	0.32
ZG3008	6.5-7.5	33.43	1.67	1.11	1.32	0.13	1.27	0.15	2.91	0.29	1.59	0.22	1.64	0.25
ZG3009	7.5-8.5	33.72	1.66	1.10	1.04	0.11	0.66	0.09	2.57	0.26	1.54	0.23	1.91	0.33
ZG3010	8.5-9.5	33.25	1.67	1.11	1.28	0.12	0.74	0.10	2.54	0.25	1.26	0.17	1.79	0.30

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226) dpm/cm2	Pb-214 (Ra-226) err dpm/cm2	Bi-214 (Ra-226) dpm/cm2	Bi-214 (Ra-226) err dpm/cm2	Pb-210t (Total) dpm/cm2	Pb-210t (Total) err dpm/cm2	Pb-210excess (1) dpm/cm2	Pb-210excess (1) err dpm/cm2	Pb-210excess (2) dpm/cm2	Pb-210excess (2) err dpm/cm2
Inventory	9.5	0.32	7.3	0.30	25.7	0.75	16.2	0.84	18.4	1.12

File: OB94-3.fin dat

Table A1.1

Ob Estuary 1994 Station OB94-3 Data

Data In Bold measured by R. Bojanowski (Institute of Oceanology, Poland)

Sample ID	Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age year Pb214=Ra226	Pb-210ex age year Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG3001	0.0-0.5	2.02	0.11	1991.3	1990.0	**58.20**	**3.60**	**1.86**	**0.582**	0.032	31.86	0.029	6.50
ZG3002	0.5-1.5	2.93	0.07	1983.0	1978.2	**73.20**	**2.40**	**2.56**	**0.366**	0.035	14.66	0.025	3.34
ZG3003	1.5-2.5	3.21	0.07	1972.0	1962.3	95.36	1.55	4.05	0.061	0.043	2.22	0.030	1.68
ZG3004	2.5-3.5	1.54	0.04	1961.0	1946.5	40.41	0.97	2.39	0.068	0.059	3.74	0.026	2.48
ZG3005	3.5-4.5	0.87	0.05	1950.0	1930.7	22.44	0.96	1.22	?	0.055	?	0.026	4.58
ZG3006	4.5-5.5	0.63	0.04	1939.0	1914.8								
ZG3007	5.5-6.5	0.52	0.04	1928.0	1899.0	**13.20**	**1.20**	**0.26**	**0.092**	0.020	36.16	0.026	9.72
ZG3008	6.5-7.5	0.49	0.04	1917.0	1883.1						?		
ZG3009	7.5-8.5	0.25	0.04	1906.0	1867.3	8.76	0.53	0.67	0.849	0.077	126.39	0.035	8.30
ZG3010	8.5-9.5	0.21	0.04	1895.0	1851.5								

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2	Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2
Inventory	10.0	0.15				

File: OB94-4.fln dat

Table A1.2

Ob Estuary 1994 Station OB94-4 Data

Sample ID	sed.Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226) dpm/g	Pb-214 (Ra-226) err dpm/g	Bi-214 (Ra-226) dpm/g	Bi-214 (Ra-226) err dpm/g	Pb-210t (Total) dpm/g	Pb-210t (Total) err dpm/g	Pb-210 excess (1) dpm/g Pb210ex=Pb210t-Ra226(Pb214)	Pb-210 excess (1) err dpm/g	Pb-210 excess (2) dpm/g Pb210ex=Pb210t-Ra226(Bi214)	Pb-210 excess (2) err dom/g
ZG4001	0-1	77.76	1.15	0.26	1.25	0.25	0.85	0.18	8.99	0.91	7.74	1.72	8.14	1.87
ZG4002	1-2	76.89	1.16	0.27	1.09	0.17	1.10	0.16	7.54	0.57	6.44	1.10	6.43	1.08
ZG4003	2-3	72.55	1.20	0.33	1.55	0.17	0.84	0.12	6.74	0.46	5.19	0.67	5.90	0.92
ZG4004	3-4	69.22	1.23	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZG4005	4-5	66.45	1.25	0.42	0.50	0.11	0.32	0.06	6.11	0.59	5.60	1.31	5.78	1.24
ZG4006	5-6	65.92	1.26	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZG4007	6-7	65.35	1.26	0.44	1.52	0.12	1.21	0.11	4.93	0.27	3.41	0.32	3.73	0.40
ZG4008	7-8	62.63	1.29	0.48	0.98	0.16	1.25	0.20	2.59	0.37	1.61	0.34	1.34	0.28
ZG4009	8-9	62.48	1.29	0.48	1.54	0.18	2.52	0.27	4.03	0.40	2.49	0.39	1.51	0.22
ZG4010	9-10	60.39	1.31	0.52	1.05	0.08	1.00	0.08	2.92	0.17	1.87	0.18	1.92	0.19
ZG4011	10-11	57.37	1.34	0.57	1.20	0.08	1.25	0.09	3.35	0.18	2.16	0.18	2.11	0.19
ZG4012	11-12	55.13	1.37	0.61	0.64	0.26	0.71	0.29	2.43	0.69	1.79	0.88	1.72	0.85
ZG4013	12-13	55.67	1.36	0.60	1.22	0.07	1.11	0.08	2.53	0.15	1.31	0.11	1.42	0.13
ZG4014	13-14	54.31	1.38	0.63	1.29	0.06	1.12	0.06	2.13	0.11	0.85	0.06	1.01	0.08

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226) dpm/cm2	Pb-214 (Ra-226) err dpm/cm2	Bi-214 (Ra-226) dpm/cm2	Bi-214 (Ra-226) err dpm/cm2	Pb-210t (Total) dpm/cm2	Pb-210t (Total) err dpm/cm2	Pb-210excess (1) dpm/cm2	Pb-210excess (1) err dpm/cm2	Pb-210excess (2) dpm/cm2	Pb-210excess (2) err dpm/cm2
Inventory	6.3	0.24	6.3	0.27	21.9	0.67	15.5	1.02	15.6	1.02

File: OB94-4.fin dat

Table A1.2

Ob Estuary 1994 Station OB94-4 Data

Sample ID	sed.Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age y Pb214=Ra226	Pb-210ex age y Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137 err %
ZG4001	0-1	3.30	0.20	1991.6	1991.5						
ZG4002	1-2	3.03	0.08	1986.7	1986.6						
ZG4003	2-3	2.87	0.13	1981.8	1981.6						
ZG4004	3-4	3.03	0.13	1976.9	1976.7						
ZG4005	4-5	3.35	0.19	1972.0	1971.7						
ZG4006	5-6	4.08	0.14	1967.1	1966.8						
ZG4007	6-7	3.18	0.20	1962.3	1961.8						
ZG4008	7-8	1.62	0.10	1957.4	1956.9						
ZG4009	8-9	1.07	0.04	1952.5	1951.9						
ZG4010	9-10	0.55	0.04	1947.6	1947.0						
ZG4011	10-11	0.34	0.03	1942.7	1942.0						
ZG4012	11-12	0.24	0.02	1937.8	1937.1						
ZG4013	12-13	0.23	0.04	1932.9	1932.1						
ZG4014	13-14	0.11	0.02	1928.1	1927.2						

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2		Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2	
Inventory	10.0	0.17						

Table A1.3

Ob Estuary 1994 Station OB94-7A data

Sample ID	sed.Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226)		Bi-214 (Ra-226)		Pb-210t (Total)		Pb-210 excess (1)		Pb-210 excess (2)	
					dpm/g	err dpm/g	dpm/g	err dpm/g	dpm/g	err dpm/g	dpm/g	err dpm/g	dpm/g	err dom/g
											Pb210ex=Pb210t-Ra226(Pb214)		Pb210ex=Pb210t-Ra226(Bi214)	
ZG7A01	0-1	50.43	1.42	0.71	1.34	0.05	1.33	0.07	3.28	0.18	1.94	0.13	1.95	0.15
ZG7A02	1-2	47.68	1.46	0.76	1.35	0.04	1.37	0.05	3.31	0.11	1.96	0.09	1.94	0.10
ZG7A03	2-3	46.13	1.48	0.80	1.54	0.06	1.52	0.08	2.78	0.17	1.24	0.09	1.26	0.10
ZG7A04	3-4	39.63	1.57	0.95	1.45	0.06	1.92	0.10	5.81	0.32	4.36	0.30	3.88	0.29
ZG7A05	4-5	42.68	1.52	0.87	1.49	0.06	1.58	0.08	2.65	0.17	1.16	0.09	1.07	0.09
ZG7A06	5-6	41.03	1.55	0.91	1.42	0.07	1.85	0.12	5.02	0.39	3.60	0.34	3.17	0.32
ZG7A07	6-7	42.89	1.52	0.87	1.26	0.05	1.80	0.08	4.72	0.26	3.46	0.24	2.92	0.21
ZG7A08	7-8	36.15	1.62	1.03	1.46	0.08	1.28	0.10	2.45	0.23	0.99	0.11	1.16	0.14
ZG7A09	8-9	35.98	1.62	1.04	1.25	0.05	1.56	0.08	4.00	0.25	2.76	0.20	2.44	0.20
ZG7A10	9-10	40.76	1.55	0.92	1.26	0.05	1.60	0.08	4.82	0.25	3.56	0.23	3.22	0.23
ZG7A11	10-11	42.45	1.53	0.88	1.47	0.08	1.44	0.10	2.61	0.21	1.14	0.11	1.18	0.13
ZG7A12	11-12	41.93	1.53	0.89	1.48	0.05	1.37	0.07	2.31	0.15	0.83	0.06	0.94	0.08
ZG7A13	12-13	44.07	1.51	0.84	1.41	0.06	1.63	0.08	2.73	0.17	1.32	0.10	1.10	0.09
ZG7A14	13-14	43.20	1.52	0.86	1.44	0.06	1.44	0.08	2.08	0.19	0.65	0.06	0.64	0.07
ZG7A15	14-15	41.04	1.55	0.91	1.42	0.04	1.55	0.03	2.39	0.03	0.98	0.07	0.85	0.07

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226)		Bi-214 (Ra-226)		Pb-210t (Total)		Pb-210 excess (1)		Pb-210 excess (2)	
	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2
Inventory	21.8	0.20	22.8	0.29	50.9	0.78	29.0	0.60	28.1	0.60

Table A1.3

Ob Estuary 1994 Station OB94-7A data

Sample ID	sed.Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age y Pb214=Ra226	Pb-210ex age y Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137 err %
ZG7A01	0-1	0.47	0.05	1993.7	1993.6						
ZG7A02	1-2	0.67	0.04	1991.6	1991.5						
ZG7A03	2-3	0.68	0.06	1989.5	1989.3						
ZG7A04	3-4	0.71	0.06	1987.5	1987.2						
ZG7A05	4-5	0.84	0.06	1985.4	1985.0						
ZG7A06	5-6	1.31	0.08	1983.3	1982.9						
ZG7A07	6-7	2.47	0.06	1981.3	1980.7						
ZG7A08	7-8	1.01	0.08	1979.2	1978.6						
ZG7A09	8-9	1.12	0.05	1977.1	1976.4						
ZG7A10	9-10	2.49	0.06	1975.1	1974.3						
ZG7A11	10-11	4.12	0.11	1973.0	1972.1						
ZG7A12	11-12	1.74	0.06	1970.9	1970.0						
ZG7A13	12-13	1.69	0.07	1968.9	1967.8						
ZG7A14	13-14	0.33	0.05	1966.8	1965.7						
ZG7A15	14-15	0.07	0.02	1964.7	1963.6						

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2		Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2	
Inventory	17.6	0.22						

File: OB94-7B.fln dat

Table A1.4

Ob Estuary 1994 Station OB94-7B Data

Sample ID	sed.Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226)		Bi-214 (Ra-226)		Pb-210t (Total)		Pb-210 excess (1)		Pb-210 excess (2)	
					dpm/g	err dpm/g	dpm/g	err dpm/g	dpm/g	err dpm/g	dpm/g Pb210ex=Pb210t-Ra226(Pb214)	err dpm/g	dpm/g Pb210ex=Pb210t-Ra226(Bi214)	err dom/g
ZG7B01	0-1	63.12	1.28	0.47	1.32	0.07	1.40	0.10	3.38	0.19	2.07	0.16	1.99	0.18
ZG7B02	1-2	55.74	1.36	0.60	1.49	0.11	1.41	0.10	3.43	0.19	1.94	0.18	2.02	0.18
ZG7B03	2-3	53.37	1.39	0.65	1.34	0.04	1.47	0.05	2.72	0.10	1.38	0.06	1.26	0.07
ZG7B04	3-4	52.42	1.40	0.67	1.43	0.07	1.52	0.09	3.36	0.19	1.93	0.14	1.84	0.15
ZG7B05	4-5	49.70	1.43	0.72	1.50	0.07	1.48	0.09	2.95	0.18	1.44	0.11	1.46	0.13
ZG7B06	5-6	48.18	1.45	0.75	1.43	0.04	1.48	0.05	2.84	0.11	1.41	0.07	1.36	0.07
ZG7B07	6-7	48.79	1.44	0.74	1.41	0.03	1.45	0.04	2.81	0.09	1.40	0.06	1.36	0.06
ZG7B08	7-8	48.56	1.45	0.74	1.40	0.07	1.58	0.10	3.04	0.21	1.64	0.14	1.46	0.13
ZG7B09	8-9	47.94	1.45	0.76	1.31	0.08	1.63	0.10	3.00	0.19	1.69	0.15	1.36	0.12
ZG7B10	9-10	45.97	1.48	0.80	1.45	0.03	1.49	0.04	2.36	0.08	0.91	0.04	0.87	0.04
ZG7B11	10-11	43.63	1.51	0.85	1.33	0.03	1.32	0.04	2.13	0.09	0.80	0.04	0.81	0.04
ZG7B12	11-12	45.95	1.48	0.80	1.26	0.08	1.47	0.11	2.49	0.20	1.23	0.12	1.03	0.11
ZG7B13	12-13	11.30	2.14	1.90	1.16	0.02	1.16	0.03	2.12	0.06	0.96	0.03	0.96	0.04
ZG7B14	13-14	56.61	1.35	0.59	1.39	0.07	1.46	0.09	2.41	0.18	1.01	0.09	0.95	0.09
ZG7B15	14-15	38.10	1.59	0.98	1.43	0.04	1.54	0.03	2.54	0.04	1.11	0.10	1.00	0.09
ZG7B16	15-16	51.04	1.42	0.69	1.37	0.01	1.39	0.01	2.40	0.01	1.02	0.03	1.01	0.03
ZG7B17	16-17	38.85	1.58	0.97	1.41	0.04	1.26	0.03	2.36	0.04	0.95	0.08	1.09	0.10
ZG7B18	17-18	38.63	1.58	0.97	1.33	0.01	1.40	0.01	2.37	0.01	1.04	0.02	0.97	0.02
ZG7B19	18-19	36.91	1.61	1.02	1.65	0.05	1.61	0.04	1.76	0.04	0.10	0.01	0.15	0.02
ZG7B20	19-20	36.56	1.61	1.02	1.48	0.04	1.55	0.03	2.05	0.04	0.57	0.05	0.50	0.05
ZG7B21	20-21	35.25	1.64	1.06	1.43	0.04	1.70	0.03	1.90	0.03	0.47	0.04	0.20	0.02
ZG7B22	21-22	35.72	1.63	1.05	1.50	0.03	1.49	0.02	2.20	0.03	0.69	0.04	0.71	0.04
ZG7B23	22-23	40.01	1.56	0.94	1.65	0.02	1.67	0.02	2.02	0.02	0.37	0.02	0.35	0.02

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226)		Bi-214 (Ra-226)		Pb-210t (Total)		Pb-210 excess (1)		Pb-210 excess (2)	
	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2	dpm/cm2	err dpm/cm2
Inventory	22.7	0.19	25.5	0.23	43.8	0.43	19.5	0.32	18.3	0.33

File: OB94-7B.fin dat

Table A1.4

Ob Estuary 1994 Station OB94-7B Data

Sample ID	sed.Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age y Pb214=Ra226	Pb-210ex age y Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG7B01	0-1	0.22	0.07	1993.5	1993.5	6.13	0.28	1.36	0.092	0.222	8.09	0.028	13.17
ZG7B02	1-2	0.27	0.07	1991.2	1991.0	4.71	0.31	0.21	?	0.044	?	0.017	13.56
ZG7B03	2-3	0.27	0.04	1988.9	1988.5	5.97	0.27	0.47	0.023	0.080	6.73	0.022	6.58
ZG7B04	3-4	0.45	0.06	1986.5	1986.0								
ZG7B05	4-5	0.41	0.06	1984.2	1983.5	7.46	0.31	3.86	0.187	0.517	6.34	0.018	6.43
ZG7B06	5-6	0.25	0.04	1981.8	1981.1								
ZG7B07	6-7	0.27	0.03	1979.5	1978.6								
ZG7B08	7-8	0.33	0.07	1977.2	1976.1	9.97	0.37	0.32	0.023	0.032	8.11	0.030	7.80
ZG7B09	8-9	0.65	0.08	1974.8	1973.6								
ZG7B10	9-10	0.56	0.03	1972.5	1971.1								
ZG7B11	10-11	0.47	0.03	1970.2	1968.6	7.37	0.31	0.40	?	0.054	?	0.016	4.55
ZG7B12	11-12	0.58	0.08	1967.8	1966.2								
ZG7B13	12-13	0.57	0.02	1965.5	1963.7								
ZG7B14	13-14	1.60	0.07	1963.2	1961.2								
ZG7B15	14-15	1.26	0.04	1960.8	1958.7								
ZG7B16	15-16	0.69	0.01	1958.5	1956.2								
ZG7B17	16-17	0.70	0.03	1956.1	1953.8								
ZG7B18	17-18	0.66	0.01	1953.8	1951.3								
ZG7B19	18-19	0.45	0.03	1951.5	1948.8								
ZG7B20	19-20	0.16	0.03	1949.1	1946.3								
ZG7B21	20-21	0.04	0.03	1946.8	1943.8								
ZG7B22	21-22			1944.5	1941.4								
ZG7B23	22-23			1942.1	1938.9								

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2	Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2
Inventory	9.2	0.17				

Table A1.5

Ob Estuary 1994 Station OB94-8 data

Sample ID	sed.Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226) dpm/g	Pb-214 (Ra-226) err dpm/g	Bi-214 (Ra-226) dpm/g	Bi-214 (Ra-226) err dpm/g	Pb-210t (Total) dpm/g	Pb-210t (Total) err dpm/g	Pb-210 excess (1) dpm/g Pb210ex=Pb210t-Ra226(Pb214)	Pb-210 excess (1) err dpm/g	Pb-210 excess (2) dpm/g Pb210ex=Pb210t-Ra226(Bi214)	Pb-210 excess (2) err dom/g
ZG8001	0-1	73.66	1.19	0.31	1.17	0.09	1.36	0.10	5.00	0.23	3.83	0.33	3.64	0.32
ZG8002	1-2	66.62	1.25	0.42	1.29	0.14	1.16	0.16	4.40	0.37	3.11	0.44	3.24	0.54
ZG8003	2-3	65.53	1.26	0.43	1.38	0.15	0.13	0.03	4.46	0.36	3.08	0.41	4.33	0.92
ZG8004	3-4	63.00	1.29	0.48	0.95	0.13	1.29	0.18	5.22	0.39	4.26	0.66	3.93	0.61
ZG8005	4-5	61.57	1.30	0.50	1.09	0.13	1.08	0.15	4.77	0.37	3.67	0.53	3.69	0.59
ZG8006	5-7	53.97	1.38	0.64	1.09	0.06	1.16	0.07	4.12	0.15	3.03	0.20	2.96	0.22
ZG8007	7-9	53.14	1.39	0.65	0.96	0.09	1.08	0.12	3.14	0.25	2.18	0.27	2.06	0.28
ZG8008	9-11	49.58	1.43	0.72	1.24	0.10	0.90	0.10	3.67	0.23	2.43	0.24	2.77	0.35
ZG8009	11-13	53.89	1.38	0.64	1.03	0.11	1.00	0.14	3.13	0.29	2.10	0.30	2.13	0.35
ZG8010	13-15	54.93	1.37	0.62	1.37	0.08	1.01	0.08	3.26	0.18	1.89	0.15	2.25	0.22
ZG8011	15-17	55.10	1.37	0.61	1.42	0.11	1.22	0.13	4.19	0.26	2.76	0.27	2.97	0.36
ZG8012	17-19	52.89	1.39	0.66	1.42	0.10	1.16	0.11	2.96	0.21	1.54	0.16	1.80	0.22
ZG8013	19-21	51.05	1.42	0.69	1.42	0.10	0.95	0.10	2.51	0.21	1.08	0.12	1.56	0.21
ZG8014	21-23	51.53	1.41	0.68	1.52	0.13	0.53	0.09	3.45	0.28	1.92	0.23	2.92	0.55
ZG8015	23-25	49.53	1.43	0.72	1.38	0.13	1.02	0.14	2.33	0.26	0.95	0.14	1.31	0.23
ZG8016	25-27	51.60	1.41	0.68	1.28	0.09	0.95	0.10	2.40	0.19	1.12	0.12	1.45	0.19
ZG8017	27-29	47.41	1.46	0.77	1.01	0.07	1.48	0.10	2.21	0.15	1.20	0.12	0.74	0.07

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226) dpm/cm2	Pb-214 (Ra-226) err dpm/cm2	Bi-214 (Ra-226) dpm/cm2	Bi-214 (Ra-226) err dpm/cm2	Pb-210t (Total) dpm/cm2	Pb-210t (Total) err dpm/cm2	Pb-210 excess (1) dpm/cm2	Pb-210 excess (1) err dpm/cm2	Pb-210 excess (2) dpm/cm2	Pb-210 excess (2) err dpm/cm2
Inventory	22.9	0.27	18.9	0.29	60.1	0.63	37.2	0.68	41.2	0.93

File: OB94-8.fin dat

Table A1.5

Ob Estuary 1994 Station OB94-8 data

Sample ID	sed.Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age y Pb214=Ra226	Pb-210ex age y Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG8001	0-1	0.68	0.07	1993.8	1993.7	17.64	0.47	0.42	0.005	0.024	2.87	0.026	10.11
ZG8002	1-2	0.58	0.06	1992.1	1991.7	16.90	0.63	0.87	0.009	0.052	3.85	0.029	10.27
ZG8003	2-3	0.56	0.07	1990.3	1989.8	16.77	0.57	0.28	0.006	0.017	4.02	0.030	12.48
ZG8004	3-4	0.81	0.09	1988.6	1987.8	19.81	0.74	0.46	?	0.023	?	0.024	11.54
ZG8005	4-5	1.04	0.05	1986.8	1985.8	23.35	0.81	0.97	0.034	0.041	4.92	0.022	5.59
ZG8006	5-7	0.92	0.05	1984.2	1982.9	22.75	0.93	1.07	0.062	0.047	7.08	0.025	6.54
ZG8007	7-9	1.04	0.05	1980.7	1978.9	25.66	1.05	1.22	0.050	0.048	5.80	0.025	6.19
ZG8008	9-11	1.59	0.05	1977.2	1975.0	38.19	0.75	1.49	?	0.039	?	0.024	3.87
ZG8009	11-13	2.07	0.07	1973.8	1971.1	52.27	1.18	1.90	?	0.036	?	0.025	4.13
ZG8010	13-15	2.44	0.08	1970.3	1967.1	60.00	1.45	2.74	?	0.046	?	0.025	4.18
ZG8011	15-17	3.08	0.04	1966.8	1963.2	86.79	1.43	3.58	?	0.041	?	0.028	2.09
ZG8012	17-19	1.94	0.07	1963.3	1959.2	47.71	0.92	1.11	0.092	0.023	8.51	0.025	4.07
ZG8013	19-21	1.12	0.07	1959.8	1955.3	30.84	0.94	1.48	0.055	0.048	4.83	0.028	7.08
ZG8014	21-23	0.35	0.04	1956.3	1951.4	10.99	0.72	0.90	0.069	0.082	10.05	0.031	12.42
ZG8015	23-25	0.16	0.01	1952.8	1947.4	3.93	0.37	0.95	?	0.025	?	0.025	13.55
ZG8016	25-27	0.04	0.01	1949.3	1943.5	1.53	0.27	0.11	0.025	0.043	28.98	0.043	44.14
ZG8017	27-29			1945.8	1939.5	0.74	0.12						

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2		Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2		
Inventory	20.7	0.13		0.524	0.002	0.023	0.000		

Table A1.6

Ob Estuary 1994 Station OB94-9 Data

Sample ID	Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226) dpm/g	Pb-214 (Ra-226) err dpm/g	Bi-214 (Ra-226) dpm/g	Bi-214 (Ra-226) err dpm/g	Pb-210t (Total) dpm/g	Pb-210t (Total) err dpm/g	Pb-210 excess (1) dpm/g Pb210ex=Pb210t-Ra226(Pb214)	Pb-210 excess (1) err dpm/g	Pb-210 excess (2) dpm/g Pb210ex=Pb210t-Ra226(Bi214)	Pb-210 excess (2) err dpm/g
ZG9001	0-1	70.07	1.22	0.36	1.27	0.12	0.23	0.03	5.90	0.32	4.63	0.49	5.67	0.85
ZG9002	1-2	60.65	1.31	0.52	0.95	0.11	0.55	0.08	6.44	0.41	5.49	0.75	5.89	0.91
ZG9003	2-3	56.40	1.35	0.59	0.57	0.06	1.27	0.11	4.69	0.23	4.11	0.50	3.42	0.33
ZG9004	3-4	54.22	1.38	0.63	1.20	0.09	1.59	0.12	4.38	0.23	3.17	0.29	2.79	0.26
ZG9005	4-5	55.21	1.37	0.61	1.32	0.09	1.03	0.09	4.11	0.21	2.79	0.23	3.09	0.30
ZG9006	5-6	53.44	1.39	0.65										
ZG9007	6-7	53.19	1.39	0.65										
ZG9008	7-8	54.18	1.38	0.63	1.36	0.08	1.40	0.10	4.15	0.20	2.79	0.22	2.75	0.24
ZG9009	8-9	49.63	1.43	0.72	1.32	0.09	1.03	0.09	3.32	0.20	2.00	0.18	2.29	0.23
ZG9010	9-10	46.90	1.47	0.78	1.60	0.09	1.33	0.10	3.67	0.19	2.07	0.16	2.34	0.22
ZG9011	10-11	45.36	1.49	0.81	1.31	0.14	1.39	0.16	2.40	0.27	1.10	0.17	1.01	0.16
ZG9012	11-12	42.64	1.52	0.87	1.33	0.11	0.94	0.11	2.96	0.25	1.63	0.19	2.02	0.29
ZG9013	12-13	45.32	1.49	0.81	1.44	0.09	1.35	0.10	2.26	0.16	0.82	0.08	0.91	0.09
ZG9014	13-14	41.16	1.55	0.91	1.43	0.12	1.18	0.13	2.86	0.24	1.43	0.17	1.68	0.23
ZG9015	14-15	42.63	1.52	0.87	1.40	0.09	1.02	0.09	1.93	0.15	0.53	0.05	0.91	0.11
ZG9016	15-16	42.88	1.52	0.87										
ZG9017	16-17	40.54	1.55	0.92	1.20	0.10	0.88	0.10	1.51	0.16	0.31	0.04	0.63	0.10
ZG9018	17-18	38.81	1.58	0.97										
ZG9019	18-19	36.45	1.62	1.03										
ZG9020	19-20	36.85	1.61	1.02	1.31	0.05	0.97	0.05	1.53	0.08	0.22	0.01	0.56	0.04
ZG9021	20-21	33.85	1.66	1.10										
ZG9022	21-22	36.51	1.62	1.03	1.18	0.10	0.48	0.06	1.87	0.17	0.68	0.08	1.39	0.21
ZG9023	22-23	36.88	1.61	1.02	0.88	0.08	0.76	0.09	2.19	0.18	1.31	0.16	1.42	0.20
ZG9024	23-24	39.77	1.57	0.94	1.34	0.07	1.03	0.08	1.67	0.12	0.34	0.03	0.64	0.07

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226) dpm/cm2	Pb-214 (Ra-226) err dpm/cm2	Bi-214 (Ra-226) dpm/cm2	Bi-214 (Ra-226) err dpm/cm2	Pb-210t (Total) dpm/cm2	Pb-210t (Total) err dpm/cm2	Pb-210 excess (1) dpm/cm2	Pb-210 excess (1) err dpm/cm2	Pb-210 excess (2) dpm/cm2	Pb-210 excess (2) err dpm/cm2
Inventory	11.8	0.32	10.4	0.33	32.0	0.68	20.2	0.70	21.6	0.86

Table A1.6

Ob Estuary 1994 Station OB94-9 Data

Sample ID	Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age year Pb214=Ra226	Pb-210ex age year Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG9001	0-1	1.62	0.09	1992.2	1992.7	29.36	0.74	1.61	?	0.055	?	0.018	2.83
ZG9002	1-2	1.92	0.11	1988.5	1990.0	45.83	0.99	1.43	0.015	0.031	2.40	0.024	2.51
ZG9003	2-3	2.07	0.09	1984.8	1987.4	53.45	1.36	2.31	?	0.043	?	0.026	2.73
ZG9004	3-4	2.44	0.09	1981.1	1984.7	59.31	1.57	3.43	0.086	0.058	3.65	0.024	2.78
ZG9005	4-5	2.61	0.10	1977.4	1982.1	62.53	1.30	3.29	?	0.053	3.22	0.024	2.22
ZG9006	5-6	2.15	0.11	1973.8	1979.4	60.25	1.51	2.30	?	0.038	?	0.028	2.76
ZG9007	6-7	2.32	0.06	1970.1	1976.8	61.45	1.36	1.83	?	0.030	?	0.026	2.28
ZG9008	7-8	3.36	0.07	1966.4	1974.2	72.46	1.58	2.94	0.079	0.041	3.46	0.022	2.22
ZG9009	8-9	4.32	0.06	1962.7	1971.5	124.79	1.38	4.79	0.058	0.038	1.64	0.029	1.13
ZG9010	9-10	4.03	0.14	1959.0	1968.9	102.23	2.42	3.18	0.069	0.031	3.21	0.025	2.50
ZG9011	10-11	2.54	0.10	1955.4	1966.2	78.86	2.42	10.12	?	0.128	?	0.031	3.22
ZG9012	11-12	0.66	0.04	1951.7	1963.6	17.80	0.58	1.18	0.040	0.066	4.67	0.027	3.71
ZG9013	12-13	0.15	0.03	1948.0	1960.9	5.88	0.21	0.73	0.027	0.123	5.16	0.039	7.83
ZG9014	13-14	0.06	0.04	1944.3	1958.3	3.54	0.43	0.01	?	0.003	?	0.064	54.84
ZG9015	14-15			1940.6	1955.6	1.03	0.11	1.23	0.177	1.194	17.99	?	?
ZG9016	15-16			1937.0	1953.0	0.38	0.08	0.26	?	0.676	?	?	?
ZG9017	16-17			1933.3	1950.3								
ZG9018	17-18			1929.6	1947.7								
ZG9019	18-19			1925.9	1945.0								
ZG9020	19-20			1922.2	1942.4								
ZG9021	20-21			1918.5	1939.7								
ZG9022	21-22			1914.9	1937.1								
ZG9023	22-23			1911.2	1934.5								
ZG9024	23-24			1907.5	1931.8								

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2	Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2
Inventory	20.1	0.22	0.526	0.004	0.029	0.000

Ob Estuary 1994 Station OB94-10A Data

Sample ID	Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Cs-137		Pu-239,240		Pu-238		Pu-238/Pu-239,240		Pu-239,240/Cs-137	
					dpm/g	err dpm/g	dpm/kg	err dpm/kg	dpm/kg	err dpm/kg		err %		err %
ZG10A01	0-1	73.73	1.19	0.31	0.34	0.08	11.09	0.41					0.033	9.49
ZG10A02	1-2	66.36	1.25	0.42	0.39	0.04								
ZG10A03	2-3	53.51	1.39	0.64	0.32	0.06								
ZG10A04	3-4	60.14	1.31	0.52	0.33	0.06								
ZG10A05	4-5	53.10	1.39	0.65	0.58	0.09								
ZG10A06	5-6	59.60	1.32	0.53	0.39	0.05								
ZG10A07	6-7	57.15	1.35	0.58	0.43	0.05								
ZG10A08	7-8	48.25	1.45	0.75	0.47	0.06								
ZG10A09	8-9	57.19	1.35	0.58	0.56	0.07								
ZG10A10	9-10	58.77	1.33	0.55	0.64	0.08	15.09	0.46	1.17	?	7.741	?	0.024	4.81
ZG10A11	10-11	58.17	1.34	0.56	0.42	0.05								
ZG10A12	11-12	53.72	1.38	0.64	0.40	0.05								
ZG10A13	12-13	53.69	1.38	0.64	0.38	0.03								
ZG10A14	13-14	48.81	1.44	0.74	0.49	0.05								
ZG10A15	14-15	58.74	1.33	0.55	0.67	0.08								
ZG10A16	15-16	57.86	1.34	0.56	0.64	0.08								
ZG10A17	16-17	56.80	1.35	0.58	0.75	0.03								
ZG10A18	17-18	55.17	1.37	0.61	0.50	0.07								
ZG10A19	18-19	53.27	1.39	0.65	0.47	0.08	14.10	0.46	1.17	?	8.324	?	0.030	5.92
ZG10A20	19-20	52.17	1.40	0.67	0.58	0.05								
ZG10A21	20-21	51.35	1.41	0.69	0.53	0.05								
ZG10A22	21-22	51.99	1.40	0.67	0.60	0.07								
ZG10A23	22-23	50.64	1.42	0.70	0.48	0.07								
ZG10A24	23-24	49.61	1.43	0.72	0.57	0.03								
ZG10A25	24-25	52.26	1.40	0.67	0.64	0.06								
ZG10A26	25-26	51.95	1.41	0.68	0.78	0.07								
ZG10A27	26-27	53.25	1.39	0.65	0.95	0.06								
ZG10A28	27-28	52.99	1.39	0.65	0.69	0.05								
ZG10A29	28-29	52.25	1.40	0.67	0.63	0.04								
ZG10A30	29-30	51.88	1.41	0.68	0.69	0.05	17.66	0.53	4.81	?	27.263	?	0.026	3.52

File: OB94-10A.fin dat

Table A1.7

Sample ID	Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Cs-137 dpm/g	Cs-137 err dpm/g	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG10A31	30-31	49.89	1.43	0.72	0.60	0.05								
ZG10A32	31-32	50.21	1.43	0.71	0.65	0.05								
ZG10A33	32-33	49.10	1.44	0.73	0.63	0.03								
ZG10A34	33-34	48.91	1.44	0.74	0.58	0.05								
ZG10A35	34-35	49.14	1.44	0.73	0.66	0.04								
ZG10A36	35-36	48.85	1.44	0.74	0.65	0.04								
ZG10A37	36-37	52.09	1.40	0.67	0.64	0.05								
ZG10A38	37-38	50.12	1.43	0.71	0.68	0.04								
ZG10A39	38-39	47.52	1.46	0.77	0.58	0.05	18.04	0.54	1.31	?	7.243	?	0.031	3.66
ZG10A40	39-40	44.77	1.50	0.83	0.60	0.04								
ZG10A41	40-41	47.81	1.46	0.76	0.86	0.04								
ZG10A42	41-42	47.70	1.46	0.76	0.84	0.03								
ZG10A43	42-43	46.95	1.47	0.78	0.83	0.04								
ZG10A44	43-44	45.49	1.49	0.81	0.79	0.03								
ZG10A45	44-45	45.66	1.48	0.81	0.85	0.03	22.59	0.61	0.48	?	2.132	?	0.027	2.88
ZG10A46	45-46	44.62	1.50	0.83	0.88	0.05								
ZG10A47	46-47	42.95	1.52	0.87	0.83	0.04								
ZG10A48	47-48	42.94	1.52	0.87	0.97	0.06								
ZG10A49	48-49	45.75	1.48	0.80	1.44	0.05								
ZG10A50	49-50	46.12	1.48	0.80	1.64	0.06								
ZG10A51	50-51	41.15	1.55	0.91	2.19	0.06								
ZG10A52	51-52	40.61	1.55	0.92	2.21	0.06								
ZG10A53	52-53	38.80	1.58	0.97	1.54	0.02								
ZG10A54	53-54	37.61	1.60	1.00	1.34	0.07								
ZG10A55	54-55	35.89	1.63	1.04	1.02	0.03								
ZG10A56	55-56	32.75	1.68	1.13	0.59	0.02								
ZG10A57	56-57	31.12	1.70	1.17	0.46	0.04								
ZG10A58	57-58	22.00	1.88	1.47	0.18	0.01								
ZG10A59	58-59	20.01	1.92	1.54	0.06	0.02								
ZG10A60	59-60	20.04	1.92	1.54	0.00	0.01								

Inventories Calculated for Cs-137 penetration depth	Cs-137 dpm/cm2	Cs-137 err dpm/cm2	Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2
Inventory	32.00	0.28				

Table A1.8

Ob Estuary 1994 Station OB94-13 Data

Sample ID	Depth cm	Water %	Density g/cm3 wet	gdry/cm3	Pb-214 (Ra-226) dpm/g	Pb-214 (Ra-226) err dpm/g	Bi-214 (Ra-226) dpm/g	Bi-214 (Ra-226) err dpm/g	Pb-210t (Total) dpm/g	Pb-210t (Total) err dpm/g	Pb-210 excess (1) dpm/g Pb210ex=Pb210t-Ra226(Pb214)	Pb-210 excess (1) err dpm/g	Pb-210 excess (2) dpm/g Pb210ex=Pb210t-Ra226(Bi214)	Pb-210 excess (2) err dpm/g
ZG1301	0-1	70.12	1.22	0.36	0.84	0.06	1.04	0.08	3.73	0.18	2.89	0.25	2.69	0.24
ZG1302	1-2	56.65	1.35	0.59	1.13	0.11	0.75	0.10	4.61	0.33	3.48	0.43	3.87	0.60
ZG1303	2-3	45.78	1.48	0.80	1.12	0.06	0.86	0.07	3.00	0.16	1.88	0.15	2.14	0.20
ZG1304	3-4	44.19	1.50	0.84	1.24	0.09	0.97	0.10	2.73	0.20	1.49	0.15	1.76	0.22
ZG1305	4-5	46.56	1.47	0.79	0.97	0.09	1.36	0.13	2.91	0.24	1.94	0.25	1.54	0.20
ZG1306	5-6	43.14	1.52	0.86	1.21	0.09	0.79	0.09	2.22	0.19	1.01	0.12	1.42	0.21
ZG1307	6-7	43.71	1.51	0.85	1.17	0.04	0.92	0.04	2.50	0.09	1.33	0.07	1.58	0.10
ZG1308	7-8	41.97	1.53	0.89	1.07	0.05	1.00	0.06	2.39	0.11	1.32	0.09	1.39	0.10
ZG1309	8-9	42.22	1.53	0.88	1.28	0.09	0.96	0.10	2.13	0.19	0.85	0.10	1.17	0.16
ZG1310	9-10	44.55	1.50	0.83	0.93	0.08	0.42	0.06	2.29	0.19	1.36	0.16	1.86	0.31
ZG1311	10-11	40.06	1.56	0.94	1.12	0.07	0.77	0.07	2.00	0.14	0.88	0.08	1.23	0.14
ZG1312	11-12	34.57	1.65	1.08	0.74	0.08	0.79	0.09	2.23	0.20	1.48	0.20	1.43	0.21
ZG1313	12-13	28.64	1.75	1.25	1.09	0.07	0.95	0.08	1.69	0.15	0.60	0.07	0.75	0.09
ZG1314	13-14	33.42	1.67	1.11	1.11	0.04	0.95	0.05	1.89	0.09	0.78	0.05	0.94	0.07
ZG1315	14-15	30.26	1.72	1.20	0.88	0.04	0.74	0.05	1.46	0.09	0.58	0.05	0.72	0.06
ZG1316	15-16	31.72	1.69	1.16	0.85	0.07	0.99	0.09	1.47	0.14	0.63	0.08	0.48	0.06
ZG1317	16-17	44.27	1.50	0.84	1.04	0.09	0.65	0.08	1.50	0.15	0.46	0.06	0.85	0.14

Inventories Calculated for Cs-137 penetration depth	Pb-214 (Ra-226) dpm/cm2	Pb-214 (Ra-226) err dpm/cm2	Bi-214 (Ra-226) dpm/cm2	Bi-214 (Ra-226) err dpm/cm2	Pb-210t (Total) dpm/cm2	Pb-210t (Total) err dpm/cm2	Pb-210 excess (1) dpm/cm2	Pb-210 excess (1) err dpm/cm2	Pb-210 excess (2) dpm/cm2	Pb-210 excess (2) err dpm/cm2
Inventory	12.9	0.27	10.7	0.31	29.3	0.62	16.4	0.51	18.6	0.68

Table A1.8

Ob Estuary 1994 Station OB94-13 Data

Sample ID	Depth cm	Cs-137 dpm/g	Cs-137 err dpm/g	Pb-210ex age year Pb214=Ra226	Pb-210ex age year Bi214=Ra226	Pu-239,240 dpm/kg	Pu-239,240 err dpm/kg	Pu-238 dpm/kg	Pu-238 err dpm/kg	Pu-238/Pu-239,240	Pu-238/Pu-239,240 err %	Pu-239,240/Cs-137	Pu-239,240/Cs-137 err %
ZG1301	0-1	0.28	0.06	1993.1	1993.3	11.32	0.61	?	?	?	?	0.041	9.46
ZG1302	1-2	0.43	0.05	1989.8	1990.4	13.85	0.47	0.22	0.010	0.016	5.52	0.032	4.71
ZG1303	2-3	0.33	0.04	1986.5	1987.5	10.52	0.61	?	?	?	?	0.032	6.97
ZG1304	3-4	0.31	0.02	1983.3	1984.6	9.65	0.35	0.08	0.001	0.008	3.79	0.031	4.03
ZG1305	4-5	0.58	0.04	1980.0	1981.7	15.32	0.71	0.25	0.003	0.016	4.79	0.027	5.11
ZG1306	5-6	0.54	0.03	1976.7	1978.9	18.74	0.79	1.48	0.090	0.079	7.37	0.035	4.55
ZG1307	6-7	0.75	0.02	1973.5	1976.0	21.62	0.87	0.80	?	0.037	?	0.029	4.12
ZG1308	7-8	1.03	0.03	1970.2	1973.1	29.04	0.64	1.24	0.034	0.043	3.52	0.028	2.29
ZG1309	8-9	1.25	0.05	1966.9	1970.2	43.21	1.34	1.65	?	0.038	?	0.035	3.28
ZG1310	9-10	1.30	0.05	1963.7	1967.3	59.15	1.47	1.93	0.044	0.033	3.37	0.046	2.61
ZG1311	10-11	0.74	0.05	1960.4	1964.5	39.10	?	?	?	?	?	0.053	?
ZG1312	11-12	0.35	0.02	1957.1	1961.6	19.06	0.53	1.31	0.046	0.069	4.51	0.055	3.02
ZG1313	12-13	0.05	0.03	1953.9	1958.7	3.03	0.41	?	?	?	?	0.060	42.18
ZG1314	13-14			1950.6	1955.8	1.31	0.19	?	?	?	?	1.204	114.77
ZG1315	14-15			1947.3	1952.9								
ZG1316	15-16			1944.1	1950.0								
ZG1317	16-17			1940.8	1947.2								

Inventories	Cs-137 dpm/cm2	Cs-137 err dpm/cm2	Pu-239,240 dpm/cm2	Pu-239,240 err dpm/cm2	Pu-238 dpm/cm2	Pu-238 err dpm/cm2
Inventory	6.7	0.11	0.251	0.002	0.008	0.000