Appendix III

DOE/ER/60819--T2

DE92 015055

**Budgets and Behaviors of Uranium and Thorium Series Isotopes
in the Santa Monica Basin off the California Coast**

by

Lei Yu

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

A THESIS

submitted to

Oregon State University**in partial fulfillment of
the requirements for the
degree of****Master of Science****Completed December 16, 1991
Commencement June 1992**FC06-89 ER 60819
MASTER ab**DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED**

AN ABSTRACT OF THE THESIS OF

Lei Yu for the degree of Master of Science in Oceanography presented on December 16, 1991.

Title: Budgets and Behaviors of Uranium and Thorium Series Isotopes in the Santa Monica Basin off the California Coast

Abstract approved: _____

Dr. Chih-An Huh

Samples from three time-series sediment traps deployed in the Santa Monica Basin off the California coast were analyzed to study the flux and scavenging of uranium and thorium series isotopes. Variations of uranium and thorium series isotope fluxes in the water column were obtained by integrating these time-series deployment results. Mass and radionuclide fluxes measured from bottom sediment traps compare favorably with fluxes determined from sediment core data. This agreement suggests that the near-bottom sediment traps are capable of collecting settling particles representative of the surface sediment.

The phase distributions of ^{234}Th in the water column were calculated by an inverse method using sediment trap data, which help to study the variations of ^{234}Th scavenging in the water column. Scavenging and radioactive decay of ^{234}Th are the two principal processes for balancing ^{234}Th budget in the water column. The residence times of dissolved and particulate ^{234}Th were determined by a ^{234}Th scavenging model.

Horizontal input from open ocean and vertical input from terrestrial source act as two important sources of ^{230}Th at ocean margins. The contributions of the two sources to flux of particulate ^{230}Th far exceed the water column production of ^{230}Th . In the Santa Monica Basin, the ratio between ^{230}Th horizontal input and its production keeps constant in the water column, but the ratio between ^{230}Th vertical input and its production decreases with depth.

APPROVED:

Major Professor: Associate Professor of Oceanography

Dean of College of Oceanography

Dean of Graduate School

Date thesis is presented December 16, 1991

Typed by the author Lei Yu

ACKNOWLEDGEMENTS

There are many people I would like to thank for their help and support. First of all, I would like to thank Dr. Chih-An Huh for his continuous support and academic guidance. I could not have completed my thesis without his help. Special thanks go to Dr. Mike Landry for providing sediment trap samples and data. Thanks are also due to my committee members Drs. Robert Collier, Peter Nelson and James Arthur Boucot who kindly provided helpful comments and suggestions.

I acknowledge the friendship and help provided by chemical oceanography group during the two-year study. I appreciate the help from Roald Leif, Bruce Eversmeyer, Kerstin Amthor, James McManus and Luis Pinto during my thesis writing and defence rehearsal. I also like to thank Head Student Advisor, Dr. Jefferson Gonor, and Donna Obert. They gave me much suggestions and convenience during my two-year study.

Finally, I like to express my thanks to my wife for her understanding and help in my living. I could not finish it without her emotional support.

This research was funded by U.S. Department of Energy Grant DE-FG06-89ER60819.

This thesis is dedicated to my mother who always pays high attention to my study in my country.

TABLE OF CONTENTS

1.	INTRODUCTION.....	1
2.	PREVIOUS STUDIES AND BACKGROUND.....	6
2.1	Review of ^{234}Th studies in the oceans.....	6
2.2	Review of ^{230}Th studies in the oceans.....	9
2.3	Description of geographic locations and previous studies in the area.....	12
2.3.1	Geographic locations.....	12
2.3.2	Previous studies in the area.....	14
3.	MATERIALS AND METHODS.....	17
3.1	Sediment trap sampling.....	17
3.1.1	Sediment trap.....	17
3.1.2	Trap cleaning, salt gradient and preservative.....	18
3.1.3	Sediment trap deployments.....	18
3.1.4	Sample processing.....	19
3.2	Radiochemical analysis.....	19
3.2.1	Sample digestion.....	22
3.2.2	^{210}Pb analysis.....	24
3.2.3	U and Th analyses.....	25
3.3	Radioactive counting and data reduction.....	28
3.3.1	Principle.....	28
3.3.2	Alpha-spectrometry.....	29
3.3.3	Counting.....	30
3.3.4	^{210}Pb determination.....	30
3.3.5	Determination of U and Th isotopes.....	35
4.	RESULTS AND DISCUSSION.....	37
4.1	Fluxes of U and Th-series isotopes in the Santa Monica Basin.....	37
4.1.1	Variations of U and Th-series isotope fluxes in the water column.....	37

4.1.2	Comparison of radionuclide fluxes between bottom sediment traps and surface sediments.....	43
4.2	^{234}Th scavenging from seawater and its budget in the water column.....	53
4.2.1	Model for ^{234}Th scavenging in the water column.....	53
4.2.2	Determination of $A_U\lambda_{\text{Th}}$, $A_{\text{Th}}\lambda_{\text{Th}}$ and P_{Th}	54
4.2.3	Variations of ^{234}Th scavenging rate in the water column.....	55
4.2.4	^{234}Th residence time in the water column.....	65
4.3	Horizontal versus vertical inputs of ^{230}Th as elucidated from sediment trap samples.....	70
4.3.1	^{230}Th scavenging model and budget calculation.....	70
4.3.2	Variations of horizontal and vertical inputs of ^{230}Th in the water column.....	72
5.	CONCLUSIONS.....	80
5.1	Sediment trap measured fluxes in the water column.....	80
5.2	^{234}Th scavenging and budget in the water column.....	81
5.3	Variations of horizontal and vertical inputs of ^{230}Th in the water column.....	81
6.	BIBLIOGRAPHY.....	83

LIST OF FIGURES

Figures

Page

1.1	The decay chain of uranium and thorium series isotopes and the half-lives of each isotopes. Alpha decays are shown by the vertical arrows and beta decays by the diagonal arrows.....	2
2.1	Schematic diagram of a two-particle box model.....	8
3.1.	Geographic locations of sample collection. Solid squares represent box cores, and the open square lettered with D represent sediment trap moorings deployed in station 305.....	20
3.2.	Flow chart for radiochemical analyses of U and Th isotopes.....	23
3.3.	A uranium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 200 m.....	31
3.4.	A thorium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 500 m.....	32
3.5.	A polonium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 300m.....	33
3.6.	A schematic diagram for ^{210}Pb correction.....	34
4.1.	(a) Profiles of sediment trap mass flux measured from seven different deployments at station 305 (i.e., site "D" in Fig. 3.1); (b) Profiles of sediment trap mass flux integrated from 2/8/86 to 8/28/90 at station 305.....	39
4.2.	Profiles of ^{234}Th , ^{228}Th and ^{210}Pb fluxes in the water column measured from sediment traps in 1990 at station 305 (a) fluxes from three individual trap deployments; (b) mean fluxes of three trap deployments.....	39a
4.3.	Profiles of ^{238}U , ^{232}Th and ^{230}Th fluxes in the water column measured from sediment traps in 1990 at station 305 (a) fluxes from three individual trap deployments; (b) mean fluxes of three trap	

deployments.....	41a
4.4. Excess ^{210}Pb profiles in sediment cores near station 305 Sedimentation rates are determined from slopes of the straight lines as shown (from Huh et. al., 1990).....	44
4.5. Near-bottom sediment trap-based radionuclide flux vs. sediment core-based radionuclide flux.....	50
4.6. Variations of J_{Th}/P and F_{Th}/P ratios in the water column J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. F_{Th} - the rate at which ^{234}Th is transported out of the water column by particle flux. P - the rate of ^{234}Th production by the decay of ^{238}U	59
4.7. Variations of $A_{\text{Th}}^{\text{d}}\lambda_{\text{Th}}/P$ and $A_{\text{Th}}^{\text{p}}\lambda_{\text{Th}}/J_{\text{Th}}$ ratios in the water column. $A_{\text{Th}}^{\text{d}}\lambda_{\text{Th}}$ - the rate of radioactive decay of dissolved ^{234}Th . $A_{\text{Th}}^{\text{p}}\lambda_{\text{Th}}$ - the rate of radioactive decay of particulate ^{234}Th . J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. P - the rate of ^{234}Th production by the decay of ^{238}U	60
4.8. Variations of three trap F_{Th}/P ratios in the water column. F_{Th} - the rate at which ^{234}Th is transported out of the water column by particle flux. P - the rate of ^{234}Th production by the decay of ^{238}U	63
4.9. Variations of $F_{\text{Th}}/J_{\text{Th}}$ and $A_{\text{Th}}^{\text{p}}\lambda_{\text{Th}}/J_{\text{Th}}$ ratios in the water column. J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. F_{Th} - the rate at which ^{234}Th is transported out of the water column by particle flux. $A_{\text{Th}}^{\text{p}}\lambda_{\text{Th}}$ - the rate of radioactive decay of particulate ^{234}Th	64
4.10. Profiles of dissolved ^{234}Th residence time with respect to removal onto particle and particulate ^{234}Th residence time with respect to removal from the water column.....	66
4.11. Profiles of three trap particulate ^{234}Th residence time with respect to removal from the water column.....	69

- 4.12. Variations of F_{total}/P ratios in the water column. F_{total} - represents the removal flux from the water column. P - the rate of ^{230}Th production by the decay of ^{234}U 75
- 4.13. Variations of $F_{\text{authigenic}}/P$ ratios in the water column. $F_{\text{authigenic}}$ - represents the horizontal input from the open ocean. P - the rate of ^{230}Th production by the decay of ^{234}U 77
- 4.14. Variation of $F_{\text{lithogenic}}/P$ ratios in the water column. $F_{\text{lithogenic}}$ - represents the fluvial and atmospheric input. P - the rate of ^{230}Th production by the decay of ^{234}U 78

LIST OF TABLES

<u>Tables</u>	<u>Page</u>
3.1. Dates, locations, and designs of sediment traps deployed in the Santa Monica Basin.....	21
3.2. Radionuclide activity measured from three trap deployments at station 305 (33°45'N, 118°48'W) in the Santa Monica Basin.....	36
4.1. Mass flux and radionuclide flux calculated from three trap deployments at station 305.....	38
4.2. Sediment cores near station 305.....	45
4.3. Comparison of sedimentation rate and near-bottom sediment trap flux measured from three trap deployments.....	46
4.4. Comparison of radionuclide fluxes to bottom sediment traps and surface sediments.....	49
4.5. ^{234}Th budget in the water column derived from sediment traps.....	56
4.6. Various ratios pertinent to the budget of ^{234}Th in the water column.....	58
4.7. Flux/Production ratios determined from three trap deployments.....	61
4.8. Residence time of ^{234}Th with respect to removal from the water column determined from three trap deployments.....	68
4.9. ^{230}Th budget in the water column derived from sediment traps.....	73
4.10. Flux/Production ratios of ^{230}Th in the water column.....	74

BUDGETS AND BEHAVIORS OF URANIUM AND THORIUM SERIES ISOTOPES IN THE SANTA MONICA BASIN OFF THE CALIFORNIA COAST

1. INTRODUCTION

In the marine environment, various isotopes of the uranium and thorium series can be classified into two categories based on their chemical properties and behaviors. Isotopes of the first category, including uranium (^{238}U , ^{235}U , ^{234}U) and radium isotopes (^{228}Ra , ^{226}Ra), tend to remain stably dissolved in seawater because they are non-particle reactive and are not efficiently scavenged by particles in seawater. In contrast, isotopes of the second category, such as thorium isotopes (^{234}Th , ^{230}Th , ^{228}Th), ^{210}Po and ^{210}Pb , etc., have a high affinity for particles and can be easily removed from seawater by adsorption, coprecipitation, or biological processes.

Thorium isotopes in the oceans originate from the decay of uranium isotopes (Fig. 1.1). Therefore uranium and thorium isotopes have a parent-daughter relationship in the oceans. The disparity in reactivity with particles between the parent and daughter nuclides allows radioactive disequilibria to be established in various phases of the marine system (seawater, suspended particles, bottom sediments). From these disequilibria, the natural processes and the rates at which they are operating can be deciphered because uranium and thorium isotopes contained in a closed system tend to approach a state of radioactive equilibrium through radioactive decay of the parent and growth of the daughter. Since the pioneering work of Rama et al. (1961) and Bhat et al. (1969), the

Element	U-238 Series					Th-232 Series					U-235 Series				
Neptunium															
Uranium	U-238 4.47 x 10 ⁹ yrs	U-234 2.48 x 10 ⁵ yrs									U-235 7.04 x 10 ⁸ yrs				
Protactinium		Pa-234 1.18 min										Pa-231 3.25 x 10 ⁴ yrs			
Thorium	Th-234 24.1 days	Th-230 7.52 x 10 ⁴ yrs				Th-232 1.40 x 10 ¹⁰ yrs	Th-228 1.91 yrs	Th-227 18.7 days			Th-231 25.5 hrs				
Actinium						Ac-228 6.13 hrs		Ac-227 21.8 yrs							
Radium		Ra-226 1.62 x 10 ³ yrs				Ra-228 5.75 yrs	Ra-224 3.66 days	Ra-223 11.4 days							
Francium															
Radon		Rn-222 3.82 days					Rn-220 55.6 sec	Rn-219 3.96 sec							
Astatine															
Polonium		Po-218 3.05 min	Po-214 1.64 x 10 ⁻⁴ sec		Po-210 138 days		Po-216 0.15 sec	Po-212 3.0 x 10 ⁻⁷ sec	Po-215 1.78 x 10 ⁻³ sec						
Bismuth		Bi-214 19.7 min	Bi-210 5.01 days					Bi-212 60.6 min	Bi-211 2.15 min						
Lead		Pb-214 26.8 min	Pb-210 22.3 yrs		Pb-206 stable lead (isotope)		Pb-212 10.6 hrs	Pb-208 stable lead (isotope)	Pb-211 36.1 min	Pb-207 stable lead (isotope)					
Thallium								Tl-208 3.05 min	Tl-207 4.77 min						

Fig. 1.1. The decay chain of uranium and thorium series isotopes and the half-lives of each isotopes. Alpha decays are shown by the vertical arrows and beta decays by the diagonal arrows (from Broecker and Peng, 1982).

nuclides of the uranium and thorium decay series have been extensively used by many investigators as tracers of particles and particle-reactive metals to study the rates of metal removal in the oceans.

The activity of thorium isotopes in the oceans is primarily controlled by production from its soluble parent and losses through radioactive decay plus particle scavenging removal. Some thorium isotopes, such as ^{232}Th and ^{230}Th , have long half-lives, their radioactive decay is usually less important compared with removal by particle scavenging processes. Therefore, the scavenging removal of thorium isotopes is a very important process to control the budgets and behaviors of uranium and thorium series isotopes. During this process, particles and particle dynamics are especially significant for the fate of thorium isotopes in oceans.

Particles are either formed in near-surface waters by biological activity or introduced to surface waters by fluvial and atmospheric inputs of terrestrial materials. Particle cycling through the water column plays an important role in marine biogeochemistry. In general, sinking particles constitute a major transport mode to the ocean bottom. When particles pass through the water column on the way from the surface to the deep ocean, they may interact extensively with materials that are suspended or dissolved in the water column. Many biological and geochemical changes are taking place as particles sink. Consequently, some information about biogeochemical process can be obtained by studying the particles in the oceans. Due to their high particle reactivity, thorium isotopes can be used as tracers to study particle sinking processes (i.e. sedimentation processes) and address mechanisms that affect and control particles and particle-bound chemicals.

After reaching the sea floor, particles continue to be intimately involved in biological and geochemical cycles of many elements in sediments. Marine sediments serve not only as a ultimate sink for these particles, but also as a source of materials to the overlying water column by diffusion of dissolved species and suspension of fine-grained sediment particles. Comparison of sediments, especially surface sediments, with particles settling in the water column may lead to a better understanding of compositional changes and cycling of uranium and thorium isotopes during their descent to the seafloor and prior to permanent burial.

A direct method to study settling particulate matter is to collect particulate materials sinking to the ocean bottom by sediment traps, which have been widely used to measure the vertical flux of particulate matter in the oceans in many fields of marine geochemistry and biology (e.g., Soutar et al., 1977; Spencer et al., 1978; Knauer et al., 1979; Bruland et al., 1981; Gardner, 1980; Landry et al., 1991). Sediment traps can be deployed to collect sinking particles at different geographic locations and water depths. Chemical and biological properties of these particles as well as individual processes occurring in the water column can then be studied by analyzing the collected materials. Such study can help us understand the budgets and geochemical behaviors of uranium and thorium series isotopes in the oceans.

The objectives of this thesis are: (1) to study the variations of uranium and thorium isotope fluxes in the water column by analyzing the compositions of uranium and thorium isotopes of sediment trap materials; (2) to examine the changes at the sediment-water interface during early diagenesis by comparing the chemical concentrations of sediment

trap materials with those of surface sediments; (3) to estimate the phase distributions of ^{234}Th in the water column by using sediment trap data; and (4) to study the variations of ^{230}Th from different original sources by estimating the vertical and horizontal inputs of sediment trap materials. Detailed background information about ^{234}Th and ^{230}Th studies will be given in the following chapter.

The results obtained from this work is expected to increase our understanding of the fates of uranium and thorium isotopes in the oceans. This, in turn, may help quantify fluxes of uranium and thorium isotopes through the water column and determine rates of particle remineralization and recycling in the water column and surface sediments.

2. PREVIOUS STUDIES AND BACKGROUND

2.1 Review of ^{234}Th studies in the oceans

^{234}Th is produced by the radioactive decay of ^{238}U in seawater. It has a relatively short half life ($T_{1/2} = 24.1$ days). The deficiency of total ^{234}Th relative to ^{238}U has long been used as a measure of the uptake and removal of ^{234}Th through particle scavenging from oceanic surface waters (e.g., Bhat et al. 1969; Matsumoto, 1975; Knauss, 1978; Kaufman et al., 1981). These studies showed that the $^{234}\text{Th}/^{238}\text{U}$ activity ratios were low (~ 0.2) in coastal shelf waters but were closer to equilibrium (~ 0.75 -1.0) in open ocean surface waters. These ratios imply intensified scavenging at ocean margins. An important aspect of these studies is that the ^{234}Th content of unfiltered seawater was reported and that the distributions of dissolved and particulate ^{234}Th in seawater were not determined. Hence, the resulting ^{234}Th residence times represent a combination of the time required for the uptake of dissolved thorium by particles with that for the removal of particulate ^{234}Th from seawater. Following those studies, many researchers began to investigate the distribution of thorium isotopes between dissolved and particulate phases in seawater, in an effort to study the rates and mechanisms of ^{234}Th scavenging in the water column (e.g., Bacon and Anderson, 1982; Anderson et al., 1983; Nozaki et al., 1981, 1987; Coale and Bruland, 1985, 1987; Huh and Beasley, 1987).

By modeling the disequilibria between ^{234}Th and ^{238}U in the dissolved and particulate forms, Coale and Bruland (1985, 1987) obtained estimates of scavenging rates for ^{234}Th

from dissolved to particulate phases, particle residence time, and flux of ^{234}Th via particle removal. In the scavenging model, they assumed that advection and diffusion of ^{234}Th are negligible with respect to vertical transport of ^{234}Th via sinking particles, and that the activity of ^{234}Th does not change significantly over the course of their observations (i.e. assuming steady state). Thus, mass balance for ^{234}Th in the dissolved and particulate form can be obtained. The scavenging model is very useful for estimating the distribution of ^{234}Th in the water column. From the activities of dissolved and particulate ^{234}Th and the principle of mass balance, ^{234}Th residence time and removal rate from the water column can be calculated.

However, it has been difficult to define particulate ^{234}Th when applying the scavenging model because different pore-sized filters have been used to obtain particulate ^{234}Th . The vague distinction between the dissolved and particulate form resulted in different definitions of particles in the water column. At present, many thorium scavenging models have been proposed, but a two-particle box model was generally accepted by many investigators (Nozaki et al., 1985, 1987; Bacon et al., 1985, 1989; Clegg and Whitfield, 1990, 1991). Fig. 2.1 is a schematic representation of the two-particle box model. All particles can be classified into two classes: small and large. Small particles are essentially non-sinking and they comprise the bulk of the mass of particles in the water column but contribute little to the vertical flux. By contrast, large particles are rapidly sinking particles that are very rare in the water column at any point in time but are mainly responsible for the vertical flux of particles over time.

Small particles are usually obtained by *in situ* filtration. The boundary between the

Fig. 2.1. Schematic diagram of a two-particle box model.

dissolved phase and the small particle phase is often defined operationally. Usually, the "dissolved" and small particulate phases are separated by filtration using 0.4 μ m (sometimes up to 1.2 μ m) membrane filters. In previous ^{234}Th studies, particulate ^{234}Th data were usually obtained from *in situ* filtration, which may cause uncertainty due to filters having a range of pore sizes, so the activity of particulate ^{234}Th actually depends on the size of filter and this method could not measure the true phase distribution of ^{234}Th in the water column. However, large particles can be easily sampled by sediment traps and determined exactly without considering the problem of different pore-sized filters. Thus, if the activity of ^{234}Th in large particles (i.e. export out of the water column) is obtained, the total particulate ^{234}Th can be calculated by the scavenging model of Coale and Bruland (1985, 1987) rather than obtained from *in situ* filtration, which can escape the filtration problem. This method about ^{234}Th study is a focus in this thesis and will be discussed in chapter IV.

2.2 Review of ^{230}Th studies in the oceans

^{230}Th is produced in seawater by the radioactive decay of ^{234}U . Because the half-life of ^{230}Th (75,200 years) is orders of magnitude longer than its chemical residence time, virtually all of the ^{230}Th produced by uranium decay is removed by particle settling. At present, ^{230}Th has been extensively used to determine accumulation rates of deep-sea sediments and ferromanganese oxide concretions (Ku, 1976; Ivanovich and Harmon, 1982).

Because the determination of ^{230}Th in seawater has long been hampered by its

extremely low concentration, Huh and Beasley (1987) reported water column distributions of ^{230}Th in both dissolved and particulate phases in the Santa Monica Basin by using isotope dilution mass spectrometry (IDMS) method. The profile of dissolved ^{230}Th showed a deep water maximum and decreased toward the bottom, similar to the profiles observed in the Guatemala and Panama Basins (Bacon and Anderson, 1982). At the same time, they also noted the enrichment of dissolved ^{230}Th in the surface water and suggested that fluvial input is a more likely additional source of ^{230}Th to the surface Santa Monica Basin. Nozaki et al. (1987) also showed that fluvial input is an additional source of ^{230}Th to surface waters in the Japan Sea.

Fluvial and atmospheric inputs actually derive from terrestrial source. Extremely low dissolved ^{230}Th concentration in seawater leads to low scavenging of dissolved ^{230}Th from the water column. Therefore, most of particulate ^{230}Th is derived from terrestrial source. Fluvial and atmospheric inputs should be very important sources for particulate ^{230}Th . Atmospheric input is the primary source of ^{230}Th in surface waters for sites remote from land, but it is generally small compared with fluvial input at ocean margins. Thus, fluvial input is a dominant source at ocean margins. Many previously reported ^{230}Th profiles from the open ocean did not show any surface enrichment of ^{230}Th because the minor atmospheric input was the dominant source of particulate ^{230}Th in the open ocean.

Several studies have shown that certain insoluble elements are removed from seawater and deposited in sediments at ocean margins at much greater rates than they are deposited in open-ocean sediments. Spencer et al. (1981) have referred to this preferential deposition of insoluble elements at ocean margins as "boundary scavenging". Studies of

^{230}Th and ^{231}Pa have provided the most convincing evidence for the existence and importance of this phenomenon. Anderson et al. (1982, 1983) studied the removal of ^{230}Th and ^{231}Pa from the open ocean and ocean margins and found that the concentration of dissolved ^{230}Th is lower in the Panama and Guatemala Basins than in the open ocean. Because ^{230}Th is supplied by uranium decay at an essentially uniform rate throughout the oceans, the lower concentration of dissolved ^{230}Th at these margin basins implies an accelerated removal compared to the open ocean. It is also found that fluxes of particulate ^{230}Th at ocean margins are about a factor of 3 greater than fluxes at corresponding depths in the open ocean. This enhanced removal of chemical materials at ocean margins results in a horizontal concentration gradient. The horizontal concentration gradient causes horizontal input from the open ocean, drawing a net flux of dissolved ^{230}Th from the open ocean to these basins. This is also an important source of ^{230}Th to the ocean margins.

Thus, there are three sources of ^{230}Th to the ocean margins: in situ production from ^{234}U , continental input (fluvial and atmospheric) and horizontal input from the open ocean. The magnitude of ^{230}Th export out of the water column at ocean margins is actually controlled by the three sources through scavenging processes.

In fact, there are two components of ^{230}Th in sediments: authigenic and lithogenic components. The authigenic component of ^{230}Th is the fraction stripped from seawater by scavenging dissolved ^{230}Th derived from dissolved ^{234}U in seawater, while the lithogenic component is the fraction residing in detrital phase which is expected to be in equilibrium with detrital ^{234}U . Scott (1968) showed that rivers contribute an insignificant

amount of the authigenic component of particulate ^{230}Th to the oceans. Rydell and Prospero (1972) further showed that atmospheric dust is also an insignificant source of the authigenic component of particulate ^{230}Th . Thus, most of the ^{230}Th in open ocean consists of the authigenic component, while horizontal input from the open ocean could be the primary source of authigenic ^{230}Th at ocean margins, which is carried in dissolved form from the open ocean and scavenged at ocean margins. In contrast, the lithogenic component of ^{230}Th at ocean margins is mainly derived from fluvial and atmospheric inputs. Generally, authigenic and lithogenic components of particulate ^{230}Th can be distinguished by assuming that all of the ^{232}Th is detrital, that detrital ^{230}Th is in equilibrium with its uranium parent, and that the detrital $^{230}\text{Th}/^{232}\text{Th}$ activity ratio is one, a reasonably good estimate from a survey of the literature. Therefore, if the removal of particulate ^{230}Th from the water column is obtained from sediment traps, the horizontal input from the open ocean and vertical input from terrestrial sources of particulate ^{230}Th can be estimated by separating the authigenic and lithogenic components of particulate ^{230}Th and the variations of vertical and horizontal inputs at ocean margins can be further studied. This is another focus of my thesis, which hopefully will also help to understand ^{230}Th distribution and scavenging in seawater.

2.3 Description of geographic locations and previous studies in the area

2.3.1 Geographic locations

The Southern California Bight includes the 30,000 km² of ocean extending from Point Conception to Cabo Colnett, and lying between the mainland shoreline and the eastern edge of the California current. It mainly consists of the Santa Monica Basin and San Pedro Basin. Santa Monica Basin is about 70 km long, 40 km wide, 960 m deep and has a floor area of 2000 km²; it is located off the point Dume directly northwest of San Pedro Basin. San Pedro Basin, 890 m deep and 700 km² floor area, is located southwest of Palos Verdes Peninsula.

These two basins are connected above a sill depth of 740 m which controls the water flow of both basins. The sill depth is in the range of the oxygen minimum in the open ocean, where the oxygen contents are only 0.2-0.3 ml l⁻¹, in contrast to about 2.0 ml l⁻¹ for waters in deeper outer basins, or about 6 ml l⁻¹ in oxygen saturated surface water. Consequently, little life is present at these basin floors so that bioturbation of the sediment is minimal (Emery, 1960).

The Southern California Counter current is the major current system operating within the Bight. It flows in a northwesterly direction along the coast throughout the year. The deep current below 100 m flows with a steady velocity of about 25 cm sec⁻¹, while the surface current, which is better developed in late summer and fall than in spring, has an average velocity of 5-10 cm sec⁻¹ (Emery, 1960).

Sediments reaching the borderland basins are derived ultimately from coastal ranges via storm runoff, turbidity currents, river input and eolian input. Major sewage treatment plants also discharge municipal wastewater into the Southern California area with relatively high concentrations of particulate matter.

Since the sea floor of the Southern California Bight region is relatively free of disturbances by water currents and benthic organisms, this area offers several distinct advantages for study. First, the network of basins acts as an efficient receptacle for much of the natural and anthropogenic materials. Second, waters below the sill depth in the near shore basins are anoxic or nearly anoxic, so that bioturbation of sediments is minimal and sedimentation records are well preserved. Third, the movement of water is physically restricted by the basin morphology, therefore major transport and cycling processes can be studied one-dimensionally. In short, this region provides a good setting to study the short-term effects of sedimentation processes through the water column to the seafloor.

2.3.2 Previous studies in the area

In 1985, a multidisciplinary program was established to study processes that control the cycling and transport of energy-related materials in the waters of the Southern California coastal region. This program is known as the CaBS (California Basin Study) program. It mainly focused on the Santa Monica (SM) and San Pedro (SP) Basins. As a component of the CaBS program, our laboratory has the primary goals of determining sources, mass balance, removal rates and transport pathways for selected radionuclides such as U and Th isotopes in this region.

Previously, Bruland et al. (1981) deployed sediment traps at 892 m depth in the central Santa Monica Basin and reported that ^{210}Pb flux of sediment trap materials is fairly consistent with the flux derived from sediments. A similar conclusion was drawn recently

by Huh et al. (1990) that concentrations and fluxes of ^{210}Pb and ^{228}Th measured from sediment trap materials were in agreement with those of surface sediments. Wong et al. (1991) also found that radionuclide fluxes measured from sediment traps in 1986-1988 were consistent with the average fluxes determined from the sediment core samples. However, other radionuclide fluxes from sediment trap have not been compared with those of sediment yet. So, it is necessary to study U-series isotope fluxes in the water column and to compare their fluxes with those of sediment cores systematically. From radiochemical studies of sediment cores and sediment trap samples, the sedimentation processes in the SM-SP Basins may be addressed, sediment chronologies may be established, and the sources and transport pathways of sedimentary material may be examined.

In the CaBS program, a large number of sediment cores, sediment traps and water samples were collected. Profiles of dissolved Th isotopes in the water column were obtained. In addition, sedimentation rates based on sediment cores and mass fluxes based on sediment traps have been obtained. This thesis intends to use these uranium and thorium series isotope data to further elucidate the budgets and behaviors of these radionuclides in the Santa Monica Basin.

A major part of my study is based upon analyses of a time-series of sediment trap deployments. The traps were deployed in the Santa Monica Basin during the period from January to August 1990. From the data, the following three aspects will be discussed: (1) variations of U and Th isotope fluxes in the water column and comparison of these fluxes with those of sediments; (2) variations of distributions and residence times of

dissolved and particulate ^{234}Th in the water column; and (3) variations of open ocean and continental inputs of ^{230}Th at ocean margins.

3. MATERIALS AND METHODS

3.1 Sediment trap sampling

The rapid increase over the past decade in the use of sediment traps to measure downward transport of particulate matter in the oceans has sparked considerable discussion on the efficiency of trap sampling systems and protocols. There is strong theoretical and experimental evidence that the quantity of material collected by traps in a flow field can be biased by trap size, shape, aspect ratio, etc. (Hargrave and Burns, 1979; Gardner, 1980; Butman, 1986; Baker, Milburn and Tennant, 1988). During the CaBS program, Landry et al. (1991) conducted field tests for potential sources of sediment trap bias. They found no significant or consistent bias in rate estimates for different traps by analyzing fluxes of particulate carbon, nitrogen, etc.

Below is a brief account of the trap design and operational protocols. Detailed descriptions can be found in Landry et al. (1991).

3.1.1 Sediment trap

All traps used in the three deployments are VERTEX multiple traps. These are specially designed for longer deployments, as they are less complicated, less expensive and more durable.

Because the basic design of the sediment trap is to reduce turbulence and the rate

of seawater exchange within the trap, VERTEX multitraps are constructed of acrylic roundstock, and have a mouth area of 45 cm^2 , an aspect ratio of 10:1 and a volume of 3.4 liters. Although these traps lack a closure mechanism, a removable baffle system, which is constructed of 16 smaller and bevelled tubes of 7.6 cm length, combined with the high aspect ratio and salt gradient, minimizes washout of trap materials during recovery.

3.1.2 Trap cleaning, salt gradient and preservative

All traps were cleaned with micro solution and rinsed with distilled water. Subsequently, they were completely filled and soaked for at least one day with 10% HCl, and then rinsed with a copious volume of Milli-Q water. Finally, they were filled in the laboratory with a premixed and filtered solution of 40 g l^{-1} analytical grade NaCl and 2% acetate buffered formalin in Milli-Q water, capped and transported full to the ship. In addition, 40 g of dry NaCl was added to each trap before deployment to provide a stronger density gradient near the bottom. Formalin was used as the standard preservative since mercuric chloride did not keep zooplankton bodies firm enough for efficient removal of those "swimmers" prior to subsampling trap materials.

3.1.3 Sediment trap deployments

Sediment traps were placed at 50 m (or 75 m), 100 m, 150 m, 200 m, 300 m, 500 m, 700 m, and 850 m depths at CalCOFI station 305, which is located at $33^{\circ}45'N$,

118°48'W above the deepest (905 m) part of the Santa Monica Basin (Fig. 3.1). Samples were collected during three different time intervals in 1990: from February 5 to April 18; April 18 to July 8; and July 15 to August 28. All the information about dates, locations, and duration of deployment is given in Table 3.1.

3.1.4 Sample processing

Traps were placed in dark crates on shipboard immediately after recovery to protect pigments from photodegradation. The process was always on board and began as soon as the last trap was on board. The whole process was generally completed within 24 hours.

For deep-moored arrays, the deepest traps were processed first because they contained fewer swimmers and the sediments were finer and consequently could be handled more rapidly than traps from shallower depths.

In the laboratory, samples were centrifuged to remove excess seawater and examined under a microscope to pick out "swimmers". Subsequently samples were washed with artificial seawater, oven dried at 55° C, and weighed.

3.2 Radiochemical analysis

All U and Th isotopes, except for ^{234}Th , were measured by the α -spectrometry method in this work. Samples must be brought into solution to allow isotopic

Fig. 3.1. Geographic locations of sample collection. Solid squares represent box cores, and the open square lettered with D represent sediment trap moorings deployed in the station 305.

Table 3.1. Dates, locations and designs of sediment traps deployed in the Santa Monica Basin.

<i>Dates</i>	2/5-4/18/90	4/18-7/8/90	7/15-8/28/90
<i>Days</i>	72	81	46
<i>Station</i>	305	305	305
<i>Trap Type</i>	VERTEX	VERTEX	VERTEX
<i>Array</i>	Morred	Moored	Morred
<i>Depth (m)</i>	75, 100, 150, 200 300, 500, 700, 850	50, 100, 150, 200 300, 500, 700, 850	50, 100, 150, 200 300, 500, 700, 850
<i>Preservative</i>	Formalin	Formalin	Formalin

equilibration of the natural isotopes with isotopes added as yield monitors. Elements of interest are separated from the major elements constituting the bulk of the sample as well as from each other to allow counting without interferences. Each purified isotope is then plated as a thin source suitable for α -spectrometry. A detailed description of the procedures for U and Th isotopes is given in the following section (Fig. 3.2).

Samples for ^{234}Th analysis were different from other radionuclides. ^{234}Th activities were determined by γ -spectrometry at the University of Southern California. Due to its short half-life, the activity of ^{234}Th must be corrected to the time of the sample collection.

3.2.1 Sample digestion

The following procedures were followed to carry out sample digestion.

1. Before chemical treatment, one gram of dried sediment trap material was weighed and placed in a polyethylene beaker. Distilled water was added to dampen the sample.
2. Appropriate amounts of ^{236}U , ^{229}Th , and ^{208}Po spikes were added into the sample prior to sample digestion as the yield monitors for uranium, thorium and polonium isotopes, respectively.
3. Inorganic material (primarily alumino-silicates) was decomposed by adding a mixture of concentrated HCl (12N) and HF (~50%) to the beaker. Then the beaker was placed under an infrared heat lamp to evaporate the sample slurry to dryness. The time of the drying process depended on the lamp power and the amount of solution, and it usually took 5-8 hours. In most cases, the samples were left unattended overnight.

Fig. 3.2. Flow chart for radiochemical analyses of U and Th isotopes.

4. Organic matter digestion was completed by the following steps. After drying the sample, a small amount of concentrated HNO_3 (16N) was added to dampen the dry sample and the mixture was washed out to a pyrex beaker with a little amount of concentrated HNO_3 . Meanwhile, an equal amount of concentrated HClO_4 (70%) was added to the sample, and the beaker was covered with a watch glass. The sample was heated on a hot plate until orange fume (NO) ceased. Then the cover was removed and the liquid in the beaker was evaporated to decrease the volume to below approximately 5ml.

3.2.2 ^{210}Pb analysis

The activity of ^{210}Pb was indexed by ^{210}Po , which is much easier to measure. The ^{210}Po chemical procedure was completed by the following steps.

1. The sample was diluted with distilled water after the above steps, and then NH_4OH was added to form a $\text{Fe}(\text{OH})_3$ precipitate. Po, U and Th isotopes were co-precipitated with iron hydroxide. This step separated Po and other radionuclides from the bulk of major elements.

2. The mixture was poured into a 50 ml plastic centrifuge tube and centrifuged. The supernatant liquid was removed from the centrifuge tube.

3. The spun-down precipitates were dissolved in an equal volume of 6N HCl after washing with distilled water.

4. The solution was diluted with distilled water to a concentration of 1.5N HCl .

5. Ascorbic acid ($C_6H_8O_6$) was added to the sample solution to serve as a masking agent to complex Fe, but leave Po free in the solution. The sample solution turned from brown to colorless or slightly bluish.

6. A polished silver disc was placed into the beaker and then the beaker was placed on a hot plate for about 2 hours at 70 - 90°C. Finally, Po was deposited on the silver disc from the sample solution.

7. The disc was picked up from the solution and rinsed with distilled water and dried.

8. The disc was counted by α -spectrometry. The ^{210}Po activity, and hence that of ^{210}Pb , was determined (this will be described in the next section).

3.2.3 Th and U analyses

After Po plating, the sample solution was evaporated to dryness and the residue was digested with $\text{HNO}_3 + \text{HClO}_4$ to decompose the ascorbic acid. Similar to Po, Th and U isotopes were separated from the bulk samples by co-precipitating with iron hydroxide. The washed precipitate was dissolved in concentrated HCl (12N) to make a solution of 8N HCl. The solution was passed through an anion exchange column (column dimension: 10 mm i.d. and 10 cm length). The resin (Biorad AG 1x8 100-200 mesh, chloride form) was conditioned with 8N HCl beforehand. At 8N HCl condition, thorium was removed in the eluate while uranium was adsorbed by the resin. Thorium and uranium were separated with three column volumes of 8N HCl. Subsequently, uranium was removed

from the column by eluting with three column volumes of 0.1N HCl.

Purification of the U and Th fractions

After the above operation, both U and Th fractions from the column effluent were evaporated until dry and picked up with 8N HNO₃. Subsequently two separate but identical anion exchange columns were conditioned with 8N HNO₃, and a clean-up step was performed on the column with three column volumes of 8N HNO₃. U and Th were loaded on the anion exchange column in the form of nitrate salt to remove Fe from U, and Al from Th because U and Th were strongly adsorbed onto the resin in the nitrate form. After adequately rinsing with 8N HNO₃, Th was eluted with 8N HCl and U with 0.1N HCl. The purified U and Th fractions were evaporated to dryness on a hot plate. If copious amounts of residue were obtained, the same column procedure was repeated. Upon dryness, U and Th fractions were completely prepared for the next step.

Extraction of Th and U

Purified Th sample was dissolved by adding approximately 2 ml of 0.1N HNO₃ and transferred to a centrifuge tube. An equal volume of 0.25M TTA/benzene solution was then added to the centrifuge tube. TTA (4,4,4-Trifluoro-1-(2-thienyl)-1,3-butanedione) is a β -diketone and forms a stable chelate complex with Th, which is easily extracted by benzene at a pH greater than zero (Ryabchikov and Golbraikh, 1963). By mixing and

centrifugation, Th can be extracted into the TTA benzene solution from 0.1N HNO₃ aqueous phase solution. This was the final step of purifying small quantities of Th from a complex mixture of elements such as the alkaline earth and rare earth elements, actinium and several other metal cations. Under our experimental conditions (pH=1), the extractions were repeated twice to ensure a near quantitative transfer of Th from the aqueous phase to the organic phase.

The purified U fraction was also dissolved in the same way as that with thorium. Further purification was needed before U extraction since a low level Th contamination may significantly disturb determination of U. U purification was obtained through Th pre-extraction. After the exclusion of traces of Th from U, the purified U was extracted. Once the U aqueous solution was regulated by 0.1N NaOH to pH=3-4, U was extracted from the aqueous phase to the TTA/benzene phase. The same extraction was repeated twice to ensure that most of the U was extracted from the aqueous phase to the organic phase. The extracted U and Th were ready for deposition onto stainless steel discs.

Deposition of thorium and uranium onto discs

After a stainless-steel disc was placed on a hot plate, the extracted U or Th was deposited onto a hot disc by stippling the organic phase containing U or Th. While plating, the organic solvent was removed by evaporation. Finally, U or Th was left on the disc which was flamed to remove the organic residue. The discs were then ready for α -spectrometry.

3.3 Radioactive counting and data reduction

3.3.1 Principle

The activity of a radionuclide (A) is proportional to the number of atoms (N) in the sample at time t , defined by the law of radioactive decay, $A = -dN/dt = \lambda N$, where λ is the decay constant, which is characteristic of each radionuclide.

The activity of a radionuclide can be determined by means of an analytical technique called isotope dilution. This method is based on the determination of the isotopic composition of an element in a mixture of a known quantity of a "spike" with an unknown quantity of the "normal element" in the sample. The spike is a solution containing a known concentration of a particular element whose isotopic composition has been changed by enrichment of one of its naturally occurring or artificial isotopes. The sample to be analyzed contains an unknown quantity of the element and an unknown isotopic composition. Therefore, when a sample with an unknown amount of isotope is mixed with a known amount of spike, the isotopic composition of the mixture can be used to calculate activities of isotopes in the sample.

From the activity ratios of the nuclide of interest to the spike determined from the counting results of α -spectrometry, the specific activity (dpm/g) of the radionuclide in the sample can be calculated by the equation:

$$A_{\text{interest}}(\text{dpm/g}) = A_{\text{spike}} \times (\text{counts})_{\text{interest}}/(\text{counts})_{\text{spike}}/\text{sample wt(g)}$$

Where A_{interest} is the activity of an unknown isotope in the sample, A_{spike} is the activity of

a known isotope in the spike, $\text{counts}_{\text{interest}}/\text{counts}_{\text{spike}}$ represents isotopic activity ratios between the nuclide of interest and the spike, which is derived from the counting results of α -spectrometry.

3.3.2 Alpha-spectrometry

Alpha-emitting isotopes were counted by α -spectrometry, which measures and distinguishes isotopes with different α -decay energies. An α -spectrometer is composed of a number of components as follows:

1. Detector - silicon surface barrier detectors were used to count α -emitting nuclides.
2. Amplifier - amplifies and shapes the pulses to the required degree.
3. Pulse height analyser - sort the pulses according to their amplitudes, and then form the required spectra.

Two α -spectrometer systems were used during this work. The old system has four silicon surface barrier detectors (Tennelec PD-300-100-19) mounted inside four separate vacuum chambers. The vacuum was provided by a Sargent Welch Scientific Co. model 1400 Dual-seal vacuum pump. The detectors have an active surface area of 300 mm² and a minimum depletion thickness of 100 micrometer. Detector bias was supplied by ORTEC model 428 detector bias supply.

The new system is composed of four Tennelec model TC 256 α -spectrometers, a TC 356 router/multiplexer, a TB 3/TC 911 NIM bin and power supply, a Nucleus Inc. model Quantum-8 multichannel pulse height analyzer and an OKI Data Industry Co. model 93

microline printer.

3.3.3 Counting

To perform a background correction, we always counted blank discs before sample discs. During counting, all chambers were under vacuum. Spectra were printed out by a computer terminal printer and then the counting results were obtained.

Typical sample spectra of U, Th and Po isotopes are shown in Figures 3.3, 3.4 and 3.5. The spectra give the following activity ratios:

$^{238}\text{U}/^{236}\text{U}$ and $^{234}\text{U}/^{236}\text{U}$ from the uranium spectrum; $^{232}\text{Th}/^{229}\text{Th}$, $^{230}\text{Th}/^{229}\text{Th}$ and $^{228}\text{Th}/^{229}\text{Th}$ from the thorium spectrum; and $^{210}\text{Po}/^{208}\text{Po}$ from the polonium spectrum.

A back correction against decay from the time of counting to the time of mounting is required for ^{210}Po .

3.3.4 ^{210}Pb determination

To determine ^{210}Pb via ^{210}Po , three time points should be recorded for decay correction (Fig. 3.6). They are designated as T_0 , T_1 and T_2 .

T_0 = time of sample collection; i.e., the time when the supply of ^{210}Pb (from seawater) to sediment traps ceased.

T_1 = time of ^{210}Po plating; i.e., the time when ^{210}Po was isolated from the sample and no longer supported by its parent, ^{210}Pb .

T_2 = time of counting; taking the mid-point of the counting interval.

From T_0 to T_1 , ^{210}Pb decayed from A_0 to A_1 . During this period, ^{210}Po was in

Fig. 3.3. A uranium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 200 m.

Fig. 3.4. A thorium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 500 m.

Fig. 3.5. A polonium spectrum for sediment trap sample from station 305, 7/15-8/28/90, 300m.

Fig. 3.6. A schematic diagram for ^{210}Pb correction.

equilibrium with ^{210}Pb ; i.e., $^{210}\text{Pb} = ^{210}\text{Po}$.

From T_1 to T_2 , ^{210}Po was separated from and no longer supported by ^{210}Pb . It decayed at its own rate ($T_{1/2} = 138$ days), from A_1 to A_2 .

From counting results, A_2 can be obtained:

A_2 (dpm/g) = (^{210}Po cumulative counts) / (^{208}Po cumulative counts) $\times$ ^{208}Po activity (dpm)/sample weight (g).

A_0 (the activity of ^{210}Pb at T_0) can be calculated from the equation:

$$A_0 = A_2 e^{\lambda_2 \Delta t_2} e^{\lambda_1 \Delta t_1} = A_2 e^{(\lambda_2 \Delta t_2 + \lambda_1 \Delta t_1)}$$

Where λ_1 is the decay constant of $^{210}\text{Pb} = 8.514 \times 10^{-5} \text{ day}^{-1}$

λ_2 is the decay constant of $^{210}\text{Po} = 5.022 \times 10^{-3} \text{ day}^{-1}$

Δt_1 is the time span from T_0 to T_1

Δt_2 is the time span from T_1 to T_2

3.3.5 Determination of U and Th isotopes

From the counting results, ^{238}U activity can be determined by the equation:

$$A_{^{238}\text{U}}(\text{dpm/g}) = A_{^{236}\text{U}}(\text{dpm}) \times (^{238}\text{U counts}) / (^{236}\text{U counts}) / \text{sample wt(g)}.$$

^{232}Th , ^{230}Th and ^{228}Th activities can be determined by the equation:

$$A_{\text{Th}}(\text{dpm/g}) = A_{^{229}\text{Th}}(\text{dpm}) \times (\text{Th counts}) / (^{229}\text{Th counts}) / \text{sample weight (g)}.$$

Table 3-2 shows all data of radionuclide activities measured from the time-series sediment trap samples.

Table 3.2. Radionuclide activity measured from three trap deployments at station 305 (33°45'N, 118°48'W) in the Santa Monica Basin.

Depth (m)	Radionuclide activity (dpm/g)						
	U-238	Th-234	Th-232	Th-230	Th-228	Pb-210	Po-210
Duration: 2/5/90-4/18/90							
75	1.56	4242	0.85	1.06	3.57	86.8	85.4
100	2.23	4793	0.87	0.97	4.88	126	92.1
150	2.46	5602	0.98	1.24	6.51	136	110
200	2.11	5633	0.99	1.58	7.73	134	113
300	2.19	6198	1.22	1.87	8.49	162	122
500	2.13	5953	1.50	2.13	8.32	151	133
700	2.63	6059	1.82	2.62	10.6	158	141
850	2.25	6618	1.68	2.63	13.5	176	144
Duration: 4/18/90-7/8/90							
50	4.45	4062	0.34	0.48	2.28	43.7	56.4
100	3.16	4557	0.75	0.85	4.24	89.6	65.2
150	2.92	5019	0.76	1.04	5.06	91.9	81.8
200	2.79	5274	0.88	1.34	6.06	103	78.4
300	2.52	5656	1.07	1.21	5.82	97.5	85.2
500	2.66	5370	1.28	1.85	6.17	110	116
700	2.45	5870	1.68	2.61	7.85	128	137
850	2.38	7313	1.36	2.44	13.2	151	151
Duration: 7/15/90-8/28/90							
50	0.97	3367	0.51	0.50	4.19	40.5	155
100	1.91	5357	1.11	1.33	3.97	98.0	91.0
150	1.87	5184	1.45	1.82	5.22	114	75.5
200	1.78	4674	1.62	2.22	4.90	102	79.7
300	2.03	4553	1.65	2.22	6.18	116	83.2
500	2.33	4970	1.62	2.30	6.42	102	116
700	3.80	5992	1.97	2.60	7.28	97.2	132
850	9.42	5804	1.75	2.63	10.1	59.2	105

4. RESULTS AND DISCUSSION

4.1 Fluxes of U and Th-series isotopes in the Santa Monica Basin

4.1.1 Variations of U and Th-series isotope fluxes in the water column

The amount of particles travelling through the water column per unit of time and area can be expressed by mass flux ($\text{mg m}^{-2} \text{d}^{-1}$), which can be calculated by dividing the dry weight of trapped sediment sample by sediment trap area and deployment time period. Fluxes of radionuclides ($\text{dpm m}^{-2} \text{d}^{-1}$) can be calculated by multiplying the mass flux and measured activities of radionuclides (dpm/g). All mass fluxes and U and Th-series isotope fluxes from the CaBS work are given in Table 4.1.

Fig. 4.1 shows vertical profiles of mass fluxes from three trap deployments at CalCOFI station 305. Vertical profiles of mass flux by previous investigators (Huh et al., 1989) are also presented in this figure for comparison. All these profiles show that, in general, mass fluxes at this station increase with depth regardless of the time period of trap deployments. In the deep basin, the increase of mass flux with depth suggests lateral input of particles from the shelf edge or the basin slope.

Although mass flux increases with depth, profiles of radionuclide fluxes in the water column at station 305 show no correlation with that of mass fluxes. Fig. 4.2 shows clearly that ^{234}Th , ^{228}Th and ^{210}Pb fluxes increase with depth and exhibit large variability. This is because these isotopes are highly particle reactive and are mostly scavenged from

Table 4.1. Mass flux and radionuclide flux calculated from three trap deployments at station 305.

Depth	Mass Flux	Radionuclide flux (dpm/m^2/d)						
(m)	(mg/m^2/d)	U-238	Th-234	Th-232	Th-230	Th-228	Pb-210	Po-210
Duration: 2/5/90-4/18/90								
75	340.4	0.53	1444	0.29	0.36	1.22	29.5	29.1
100	314.6	0.70	1508	0.27	0.31	1.54	39.5	29.0
150	284.8	0.70	1595	0.28	0.35	1.85	38.7	31.3
200	288.2	0.61	1623	0.28	0.46	2.23	38.6	32.6
300	292.5	0.64	1813	0.36	0.55	2.48	47.3	35.7
500	328.3	0.70	1954	0.49	0.70	2.73	49.6	43.8
700	412.8	1.09	2501	0.75	1.08	4.36	65.4	58.2
850	397.4	0.89	2630	0.67	1.05	5.36	69.8	57.3
Duration: 4/18/90-7/8/90								
50	610.2	2.72	2479	0.21	0.29	1.39	26.7	34.4
100	397.7	1.26	1812	0.30	0.34	1.69	35.6	25.9
150	430.8	1.26	2162	0.33	0.45	2.18	39.6	35.2
200	449.7	1.25	2372	0.40	0.60	2.73	46.2	35.3
300	465.9	1.18	2635	0.50	0.56	2.71	45.4	39.7
500	434.8	1.16	2335	0.55	0.80	2.68	47.8	50.3
700	473.3	1.16	2778	0.80	1.23	3.72	60.8	65.0
850	449.9	1.07	3290	0.61	1.10	5.95	67.8	67.9
Duration: 7/15/90-8/28/90								
50	383.9	0.37	1293	0.20	0.19	1.61	15.5	59.5
100	306.8	0.59	1644	0.34	0.41	1.22	30.1	27.9
150	408.5	0.76	2118	0.59	0.74	2.13	46.6	30.8
200	512.5	0.91	2395	0.83	1.14	2.51	52.3	40.8
300	578.0	1.17	2632	0.95	1.28	3.57	67.0	48.1
500	434.3	1.01	2158	0.70	1.00	2.79	44.3	50.4
700	432.9	1.65	2594	0.85	1.13	3.15	42.1	57.1
850	410.5	3.87	2383	0.72	1.08	4.13	24.3	43.1

Fig. 4.1. (a) Profiles of sediment trap mass flux measured from seven different deployments at station 305 (i.e., site "D" in Fig. 3.1); (b) Profiles of sediment trap mass flux integrated from 2/8/86 to 8/28/90 at station 305.

Fig. 4.2. Profiles of ^{234}Th , ^{228}Th and ^{210}Pb fluxes in the water column measured from sediment traps in 1990 at station 305 (a) fluxes from three individual trap deployments; (b) mean fluxes of three trap deployments.

(a)

(b)

the water column by particles. The increase with depth in fluxes is consistent with continuous scavenging of dissolved isotopes through the water column by settling particles. In addition, ^{234}Th , ^{228}Th and ^{210}Pb fluxes increase quickly near the surface, indicating that a high scavenging rate occurs in the euphotic zone.

The naturally occurring isotope ^{234}Th is produced at a constant rate throughout the water column by α -decay of its conservative parent ^{238}U . Dissolved ^{234}Th is present at a high activity (1 dpm/kg) in the oceans. ^{210}Pb ($T_{1/2}=22.3$ years, <100 dpm/kg) and ^{228}Th ($T_{1/2}=1.91$ years, <0.1 dpm/kg) have longer half-lives and lower activities in the oceans than that of ^{234}Th ($T_{1/2}=24$ days) (Broecker and Peng, 1982), so that more ^{234}Th is scavenged from seawater and the ^{234}Th flux is much higher than that of ^{228}Th and ^{210}Pb in the water column (Fig. 4.2).

^{232}Th and ^{230}Th fluxes show relatively little variation with depth compared with the above three isotopes (Fig. 4.3). This is because ^{232}Th and ^{230}Th isotopes in the water column come primarily from detrital sources and their fluxes from water column scavenging processes are small compared with terrestrial input. Fig. 4.3 also shows that the ^{238}U flux remains constant in the water column. In fact, the ^{238}U flux only represents detrital ^{238}U that remains constant in the water column, because ^{238}U is a conservative isotope and little scavenging occurs in the water column.

Fig. 4.3. Profiles of ^{238}U , ^{232}Th and ^{230}Th fluxes in the water column measured from sediment traps in 1990 at station 305 (a) fluxes from three individual trap deployments; (b) mean fluxes of three trap deployments.

(a)

(b)

4.1.2 Comparison of radionuclide fluxes between bottom sediment traps and surface sediments

Five sediment cores near station 305 were analyzed for U and Th isotopes and their sedimentation rates were determined by the excess ^{210}Pb method in the previous studies and this research (Fig. 4.4). Table 4.2 shows that the sedimentation rate of sediment core BC-1 of cruise CaBS-XI is $421.9 \text{ mg m}^{-2} \text{ d}^{-1}$, is very close to those of four other sediment cores previously measured. This indicates small variability of sedimentation rate with time in this region. Previous studies have also shown that sedimentation rates are very stable in this region (Bruland et al., 1981; Huh et al., 1987, 1989). All this proves that the central SM basin is characterized by a low and stable sedimentation rate and a well-preserved sediment record. Thus, it is appropriate to compare sediment trap flux with sedimentation rate at the basin floor.

Table 4.3 lists comparisons of bottom sediment trap fluxes with sedimentation rate. Mean sedimentation rate ($430.1 \text{ mg m}^{-2} \text{ d}^{-1}$) determined from five sediment cores is used to represent the sedimentation rate at station 305. The ratio of SR/STF (0.97) (SR: sedimentation rate; STR: sediment trap flux) shows that mass fluxes of the near bottom sediment trap in our study agree favorably with sedimentation rates at the bottom. Bruland et al. (1981) deployed sediment traps at 892m depth in the central SM basin and found that the ratio of sediment trap flux to the sedimentation rate was approximately 0.89. From the sediment trap data measured by Huh et al. (1989), the ratio of SR/STF is approximately 1.29. These results indicate that near-bottom sediment trap mass flux

Fig. 4.4. Excess ²¹⁰Pb profiles in sediment cores near station 305. Sedimentation rates are determined from slopes of the straight lines as shown (from Huh et. al., 1990).

Table 4.2. Sediment cores near station 305.

<i>Cruise Name</i>	CaBS-I	CaBS-III	CaBS-III	CaBS-V	CaBS-XI
<i>Box Core No.</i>	BC-102	BC-31	BC-1	BC-3	BC-1
<i>Depth (m)</i>	910	910	906	910	904
<i>Dates</i>	10/14/85	5/18/86	5/19/86	4/8/87	1/26/90
<i>Sedimentation Rate (mg/m²/d)</i>	454.8	408.9	432.9	432.9	421.9

Mean = 430.1 mg/m²/d

Table 4.3. Comparison of sedimentation rate and near-bottom sediment trap flux measured from three trap deployments.

<i>Bottom Trap</i>	I	II	III
<i>Dates</i>	9/6/77-10/30/77	2/8/86-10/1/88	2/5/90-8/28/90
<i>Trap Type</i>	Soutar	Soutar	VERTEX
<i>Depth (m)</i>	892	850	850
<i>Preservative</i>	HgCl ₂	HgCl ₂	Formalin
<i>Sediment Trap Flux (STF) (mg/m²/d)</i>	463	557	419.3
<i>Sedimentation Rate (SR) (mg/m²/d)</i>	520.5	430.1	430.1
<i>SR/STF</i>	0.89	1.29	0.97

I Bruland et al. (1981)

II Huh et al. (1989)

is close to sedimentation rate and can be used for estimating sedimentation rate.

Although there were some flux changes in the three deployment periods, I do not think it justifies to say that there is no agreement between sediment trap flux and sedimentation rate. Differences in experimental conditions, as summarized in Table 4.3, could be responsible for this seemingly apparent disagreement. Besides deployment period, VERTEX type traps and formalin were used in this work, while Soutar type traps and HgCl_2 were used in other studies. At present, there appears to be no significant difference among different deployment periods or trap types (Landry et al., 1991). However, the effect of different preservatives could be an important factor. Many studies have found formalin to be superior for longer-term deployments (Powell and Fisher, 1982; Lee et al., 1988, 1989) since it hardens tissue and allows one to remove swimmers easily. In contrast, dissolution of tissue in mercury-poisoned traps leaves some organic matter remains in the sediment traps and thus imposes a bias in the flux measurement. Thus, it seemed that the difference in the three fluxes may be caused by using different preservatives. It is necessary to evaluate effectiveness of formalin and HgCl_2 for long term sediment trap deployment in the future by deploying a twin trap that preserves one set of samples in mercuric chloride and another set in formalin.

The greatly favorable comparison between sediment trap flux and sedimentation rate suggests that sediment traps are a very useful tool to study sedimentation rate. In fact, the most powerful application of sediment traps as collection and monitoring devices is the ability to extend their use to areas which are not amenable to sediment studies. The outer regions of the Southern California Bight may provide a case in point. Low

sedimentation rates ($\sim 10 \text{ mg cm}^{-2} \text{ yr}^{-1}$) and extensive bioturbation lead to mixing of the near-surface sediments. This makes it difficult to determine sedimentation rates by the excess ^{210}Pb method. If sediment traps are deployed above the seafloor of such a region, they can collect freshly settling particles during the deployment period and sedimentation rates can be estimated.

Fluxes of six radionuclides to bottom traps and surface sediments are also compared as given in Table 4.4. For long-lived isotopes, such as ^{238}U ($T_{1/2}=4.47 \times 10^9$ years), ^{232}Th ($T_{1/2}=1.4 \times 10^{10}$ years) and ^{230}Th ($T_{1/2}=75200$ years), their fluxes to sediment traps agree very well with those of surface sediments as shown in Fig. 4.5. However, short-lived isotopes are different from long-lived isotopes. ^{234}Th and ^{228}Th fluxes to bottom sediment traps do not agree well with those of surface sediments.

Previous studies showed that the activities of ^{228}Th and ^{210}Pb in near-bottom traps and surface sediments were very similar in the central SM basin (Bruland et al., 1981; Huh et al., 1989; Wong et al., 1991). But other isotopes of the U and Th series have not been studied for comparison. In this study, a comparison of five radionuclides provides a evidence that fluxes of U and Th series isotopes to bottom sediment traps are consistent with those to surface sediments, except for ^{234}Th . It is well known that these isotopes can be used as tracers to study the behavior of some other trace metals during sedimentation processes. Thus, if radionuclide compositions in sediments, especially surface sediments, are affected and changed, some information can be obtained from a study of bottom sediment traps. It is further hoped that this comparison could be extended to other chemical constituents in sediments, such as trace metals and organic compounds. Most

Table 4.4. Comparison of radioisotope fluxes to bottom sediment trap and surface sediments.

<i>Radioisotope</i>	^{238}U	^{232}Th	^{230}Th	^{228}Th	^{210}Pb	^{234}Th
<i>Half-life (years)</i>	4.47×10^9	1.4×10^{10}	75200	1.91	22.3	24.1 (days)
<i>Sediment Trap*</i> <i>ST (850 m)</i>	0.98	0.67	1.08	5.15	53.97	2767.7
<i>Sediment*</i> <i>S-1 (0-0.25 cm)</i>	0.904	0.568	0.632	2.939	46.47	129.36
<i>S-2 (0.25-0.5 cm)</i>	0.971	0.666	0.833	3.128	50.32	45.21
<i>S-1/ST</i>	0.922	0.848	0.585	0.571	0.861	0.047
<i>S-2/ST</i>	0.991	0.994	0.771	0.607	0.932	0.016

* (dpm/m²/d)

0-0.25 cm ~ 0.8 years

0.25-0.5 cm ~ 2.4 years

Fig. 4.5. Near-bottom sediment trap-based radionuclide flux vs. sediment core-based radionuclide flux.

toxic trace metals in the oceans are like thorium isotopes in that they are also particle-reactive. However, to directly calculate the residence times of reactive pollutants is usually difficult. With the aid of thorium isotopes, the fates of other reactive metals can be more easily studied. Because thorium isotopes are produced and decay at known rates, they can be used as process and time tracers to postulate the rate at which relevant pollutants are removed.

From the above results, it was concluded that ^{234}Th and ^{228}Th fluxes to bottom sediment traps do not compare well with those of surface sediments. The inconsistency may be caused by: radioactive decay, diffusion of the parent nuclides, and/or sediment mixing. First, radioactive decay is a dominant factor for ^{234}Th and ^{228}Th deficiencies in sediments because their half lives are far shorter than those of the other four nuclides. In most cases, the average sampling time of sediment trap measurement is far less than a year and the collected materials are fairly fresh. However, sediments usually represent hundreds or thousands of years of deposition, at least several years for surface sediments. Thus, once particles are deposited on the seafloor, the activities of the short-lived nuclides in sediments will diminish rapidly with time. Accordingly, calculated fluxes to sediments will be less than those to sediment traps. This factor is a most important for the short-lived isotope ^{234}Th .

Secondly, ^{228}Ra , the parent of ^{228}Th , easily diffuses into the overlying water column from sediments. The loss of most ^{228}Ra from sediments by diffusion will affect the activity of ^{228}Th in sediments. Thus, the ^{228}Th flux to sediment traps will not match that to the sediments. Because more ^{228}Ra diffuses into the overlying water from surface

sediments than from subsurface sediments, a better agreement with trap flux can be observed in the 0.25-0.5cm layer rather than in the 0.0-0.25cm layer. Although ^{226}Ra has the same chemical property as ^{228}Ra , which diffuses into the water column from sediments, the activity of ^{226}Ra is far less than that of ^{210}Pb in sediments, and nearly all of the ^{210}Pb comes from sea water. Diffusion of ^{226}Ra does not have a significant influence on ^{210}Pb distribution in sediments than ^{228}Ra on ^{228}Th .

Thirdly, sediment mixing can dilute observable effects of deposition of "young" particulate and anthropogenic materials in the surface layer. After fresh sediment particles reach the sea floor, sediment mixing reduces high radionuclide activities in surface sediments by dilution with older, less radioactive material from below. Sediment mixing is a very significant factor for short-lived nuclides, but long-lived nuclides are less susceptible to this effect because there are low activities of short-lived nuclides in deep sediments due to rapid decay but little change for long-lived nuclide activities with depth. Therefore, the time-integrated ^{210}Pb flux measured from mixed sediments is essentially the same as that of bottom sediment traps, but calculated fluxes of ^{228}Th and ^{234}Th to sediments are not consistent with those of bottom sediment traps. Even if the activities of ^{228}Th and ^{234}Th of a very fresh sediment layer (at depth $Z \rightarrow 0$) have been measured, fluxes to sediment based on these activities are still less than fluxes to bottom sediment traps .

4.2 ^{234}Th scavenging from seawater and its budget in the water column

4.2.1 Model for ^{234}Th scavenging in the water column

^{234}Th has a relatively short half-life ($T_{1/2}=24.1$ days) and high particle reactivity. It is produced ubiquitously in the water column by its parent ^{238}U . If advection and diffusion of ^{234}Th are assumed to be negligible with respect to its vertical transport, and if the activity of ^{234}Th does not change significantly over the course of long-term observations (i.e. steady state), then the rate of change of dissolved ^{234}Th activity in the water column (Coale and Bruland, 1985, 1987) can be expressed as:

$$\partial A_{\text{Th}}^{\text{d}} / \partial t = A_{\text{U}} \lambda_{\text{Th}} - A_{\text{Th}}^{\text{d}} \lambda_{\text{Th}} - J_{\text{Th}} = 0 \quad (1)$$

Where A_{U} (dpm/m³) is the activity of parent ^{238}U in the water column, λ_{Th} (d⁻¹) is the decay constant of ^{234}Th , A_{Th}^{d} (dpm/m³) is the activity of dissolved ^{234}Th in seawater, and J_{Th} (dpm/m³/d) is the removal rate of ^{234}Th from the dissolved to the particulate phase, representing all particulate ^{234}Th . The product of A_{U} and λ_{Th} is the production rate of ^{234}Th by the decay of ^{238}U . The product of A_{Th}^{d} and λ_{Th} is the radioactive decay rate of dissolved ^{234}Th .

Similarly, the rate of change of particulate ^{234}Th activity can be expressed as:

$$\partial A_{\text{Th}}^{\text{p}} / \partial t = J_{\text{Th}} - A_{\text{Th}}^{\text{p}} \lambda_{\text{Th}} - P_{\text{Th}} = 0 \quad (2)$$

Where A_{Th}^p (dpm/m³) is the activity of particulate ²³⁴Th, J_{Th} (dpm/m³/d) is the source of particulate ²³⁴Th, $A_{Th}^p \lambda_{Th}$ is the rate at which particulate ²³⁴Th is lost due to radioactive decay, and P_{Th} (dpm/m³/d) is the rate at which ²³⁴Th is transported out of the water column by large, settling particle, represented by sediment trap-measured flux of ²³⁴Th.

J_{Th} and P_{Th} represent the non-radioactive removal rates for dissolved (A_{Th}^d) and particulate (A_{Th}^p) ²³⁴Th respectively. Under steady state conditions the mean residence time (τ_d) of dissolved ²³⁴Th in the water column with respect to removal onto particles can be defined as:

$$\tau_d = A_{Th}^d / J_{Th}$$

and that of particulate ²³⁴Th with respect to removal from the water column can be defined as:

$$\tau_p = A_{Th}^p / P_{Th}$$

4.2.2 Determination of $A_U \lambda_{Th}$, $A_{Th}^d \lambda_{Th}$ and P_{Th}

Because sediment traps were deployed at different depths in the basin, it is convenient to consider the water column over the sediment trap depth as an integral body. Thus, each term in the scavenging model is the cumulative result integrated from the surface to the depth of interest.

As ²³⁸U is conservative in seawater, the activity of ²³⁸U varies little with depth. From the activity of uranium in seawater, which follows salinity by the empirical relationship: ²³⁸U (dpm/l) = 0.07081 x salinity (Ku et al., 1977), the production of ²³⁴Th in the water

column, $A_U \lambda_{Th}$, can be calculated.

The concentration of dissolved ^{234}Th in the water column in general changes more obviously in the surface euphotic zone, whereas below the surface layer, it remains nearly constant. In the Santa Monica Basin, dissolved ^{234}Th usually increases with depth from ~1.0 dpm/kg near the surface to slightly over 2.0 dpm/kg at 100 m. Below 100 m, dissolved ^{234}Th remains fairly constant down to 300 m and presumably throughout the rest of the water column. If temporal variation of dissolved ^{234}Th is assumed to be negligible, profiles of dissolved ^{234}Th activity can be obtained from available data, and the integrated activity of dissolved ^{234}Th from the surface to the depth of interest can be calculated.

Based upon the variables determined from chemical analyses of sediment trap materials and the activities of uranium and dissolved ^{234}Th , the terms $A_U \lambda_{Th}$, $A_{Th}^d \lambda_{Th}$ and P_{Th} can be determined. Then J_{Th} and $A_{Th}^p \lambda_{Th}$ can be calculated from equations (1) and (2). The calculated results and the budget of ^{234}Th in the water column are listed in Table 4.5.

4.2.3 Variations of ^{234}Th scavenging rate in the water column

As defined earlier, J_{Th} is the removal rate of ^{234}Th from dissolved to particulate phases, which can be considered as the source of particulate ^{234}Th . P_{Th} is the rate at which ^{234}Th is transported out of the water column by particle flux. Therefore, the ratios of $J_{Th}/\text{Production}$ and $P_{Th}/\text{Production}$ represent the fractions of ^{234}Th adsorbed from the dissolved form onto particles and ^{234}Th removed from the water column over the total production of ^{234}Th , respectively. Larger ratios represent higher scavenging rates. These

Table 4.5. ^{234}Th budget in the water column derived from sediment traps.

Depth (m)	$A_U \lambda_{Th}$ (dpm/M ² /d)	P_{Th} (dpm/M ² /d)	$A_{Th}^d \lambda_{Th}$ (dpm/M ² /d)	J_{Th} (dpm/M ² /d)	$A_{Th}^p \lambda_{Th}$ (dpm/M ² /d)	A_{Th}^d (dpm/m ²)	A_{Th}^p (dpm/m ²)	τ_d (days)	τ_p (days)
50	3508	1293	1603	1905	612	55746	21283	29	16
100	7016	1644	3519	3497	1853	122378	64441	35	39
150	10524	2118	6574	3950	1832	228620	63710	58	30
200	14033	2395	9716	4317	1922	337887	66840	78	28
300	21049	2632	16071	4978	2346	558890	81585	112	31
500	35081	2158	28631	6450	4292	995681	149260	154	69
700	49114	2594	41191	7923	5329	1432472	185323	181	71
850	59638	2383	50611	9027	6644	1760065	231054	195	97

 $A_U \lambda_{Th}$ - production of ^{234}Th . P_{Th} - sediment trap flux of ^{234}Th . $A_{Th}^d \lambda_{Th}$ - decay rate of dissolved ^{234}Th . J_{Th} - removal rate of ^{234}Th from dissolved to particulate phase. $A_{Th}^p \lambda_{Th}$ - decay rate of particulate ^{234}Th . A_{Th}^d - activity of dissolved ^{234}Th . A_{Th}^p - activity of particulate ^{234}Th . τ_d - residence time of dissolved ^{234}Th . τ_p - residence time of particulate ^{234}Th .

ratios can reflect the variations of ^{234}Th budget in the water column. Table 4.6 lists the ratios of $J_{\text{Th}}/\text{Production}$, $P_{\text{Th}}/\text{Production}$, $P_{\text{Th}}/J_{\text{Th}}$, $A_{\text{Th}}^d \lambda_{\text{Th}}/\text{Production}$ and $A_{\text{Th}}^p \lambda_{\text{Th}}/\text{Production}$ in the water column. Fig. 4.6 shows that the ratios of $J_{\text{Th}}/\text{Production}$ and $P_{\text{Th}}/\text{Production}$ are obviously higher in surface water than in deep water, reflecting the variation of ^{234}Th scavenging rate with depth. $J_{\text{Th}}/\text{Production}$ and $P_{\text{Th}}/\text{Production}$ ratios are the highest in the top 50 m of the water column (54% and 37%) (Table 4.6). This ratio indicates that half of the ^{234}Th produced by ^{238}U decay is scavenged and transported out of the surface water. A similar result was found by Coale and Bruland (1987) in surface waters off central California. They estimated that the ^{234}Th particle flux out of the surface layer is usually 40%-60% of the dissolved ^{234}Th production rate from ^{238}U decay in the surface layer.

It is reasonable that dissolved ^{234}Th and ^{238}U are close to equilibrium in deep water, where the total ^{234}Th available for scavenging is unlimited. However, particulate ^{234}Th is an insignificant part of the total ^{234}Th and little ^{234}Th is scavenged in the deep water compared with the total ^{234}Th . In contrast to the high rates of desorption and decay (implied by an equilibrium condition) the amount of scavenged ^{234}Th is comparatively small. Fig. 4.7 shows that the majority of ^{234}Th in the deep water (850 m) is lost through radioactive decay both in dissolved form (85%) and particulate form (74%) and that only a minor fraction of ^{234}Th is removed out of the water column by scavenging. Table 4.7 shows that the $J_{\text{Th}}/\text{Production}$ ratios of three time-series trap results decrease with depth, reaching only 4~6 % at 850 m. Huh and Beasley (1987) also determined that the flux of ^{234}Th scavenged over the collection period at the base of the basin was only about 5% of the water column production of ^{234}Th . Thus, radioactive decay is the most important

Table 4.6. Various ratios relevant to the budget of ^{234}Th in the water column.

Depth	$A_{\text{Th}}^d \lambda_{\text{Th}} / A_U \lambda_{\text{Th}}$	$A_{\text{Th}}^p \lambda_{\text{Th}} / J_{\text{Th}}$	$J_{\text{Th}} / A_U \lambda_{\text{Th}}$	$P_{\text{Th}} / A_U \lambda_{\text{Th}}$	$P_{\text{Th}} / J_{\text{Th}}$
(m)	(%)	(%)	(%)	(%)	(%)
50	45.70	32.13	54.30	36.86	67.87
100	50.16	52.99	49.84	23.43	47.01
150	62.47	46.38	37.53	20.13	53.62
200	69.24	44.52	30.76	17.07	55.48
300	76.35	47.13	23.65	12.50	52.87
500	81.61	66.54	18.39	6.15	33.46
700	83.87	67.26	16.13	5.28	32.74
850	84.86	73.60	15.14	4.00	26.40

$A_U \lambda_{\text{Th}}$ - production of ^{234}Th .

P_{Th} - sediment trap flux of ^{234}Th .

$A_{\text{Th}}^d \lambda_{\text{Th}}$ - decay rate of dissolved ^{234}Th .

J_{Th} - removal rate of ^{234}Th from dissolved to particulate phase.

$A_{\text{Th}}^p \lambda_{\text{Th}}$ - decay rate of particulate ^{234}Th .

Fig. 4.6. Variations of J_{Th}/P and F_{Th}/P ratios in the water column. J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. F_{Th} - the rate at which ^{234}Th is transported out of the water column by particle flux. P - the rate of ^{234}Th production by the decay of ^{238}U .

Fig. 4.7. Variations of $A_{Th}^4 \lambda_{Th} / P$ and $A_{Th}^P \lambda_{Th} / J_{Th}$ ratios in the water column. $A_{Th}^4 \lambda_{Th}$ - the rate of radioactive decay of dissolved ^{234}Th . $A_{Th}^P \lambda_{Th}$ - the rate of radioactive decay of particulate ^{234}Th . J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. P - the rate of ^{234}Th production by the decay of ^{238}U .

Table 4.7. Variations of Flux/Production ratio from three trap deployments.

Depth (m)	Flux/production 2/5-4/18/90	Flux/production 4/18-7/8/90	Flux/production 7/15-8/28/90
50 (75)	41.16	70.7	36.9
100	21.5	25.8	23.4
150	15.2	20.5	20.1
200	11.6	16.9	17.1
300	8.6	12.5	12.5
500	5.6	6.67	6.15
700	5.1	5.66	5.28
850	4.4	5.52	4

factor controlling the budget of particulate ^{234}Th in the deep water.

Fig. 4.8 shows a higher $P_{\text{Th}}/\text{Production}$ ratio in the surface water during a biological bloom from April 18 to July 8, 1990. Seasonal changes in the ratio in the surface water suggest that scavenging is more intense in late spring to early summer than in other seasons. Because terrestrial particulate input and biological processes are the dominant sources of particulate materials in the surface water at ocean margins, they should be the determining factor for ^{234}Th scavenging in the upper layer. Many studies (e.g. Bacon et al., 1985; Eppley, 1989) imply that biological uptake is the governing process for scavenging in the upper ocean. Fisher et al. (1987) suggested that marine phytoplankton could be an important sequestering agent for thorium in surface water. Honeyman et al. (1988) found a strong correlation between the scavenging rate constants and the suspended particle concentrations. Therefore, phytoplankton bloom in surface seawater should be responsible for intense scavenging of ^{234}Th .

Most particulate ^{234}Th can be transported out of the surface water by particle fluxes, expressed by a high $F_{\text{Th}}/J_{\text{Th}}$ ratio in the upper 50 m (Fig. 4.9). It appears that the vertical particle transport can be studied by ^{234}Th scavenging. The increase of the $A_{\text{Th}}^{\text{P}}\lambda_{\text{Th}}/J_{\text{Th}}$ ratio with depth below 300 m indicates that most particulate ^{234}Th is lost through decay below 300 m, and that ^{234}Th scavenging is less significant in deep water. Thus, ^{234}Th can be used to study scavenging in the euphotic zone, and to trace vertical particle transport. In contrast, it is not suitable to use ^{234}Th study the vertical particle transport to the deep sea due to loss through decay. It has been proposed that the depletion of ^{234}Th by scavenging and removal from the euphotic zone via the particle flux can be used to provide an

Fig. 4.8. Variations of three trap F_T/P ratios in the water column. F_T - the rate at which ^{234}Th is transported out of the water column by particle flux. P - the rate of ^{234}Th production by the decay of ^{238}U .

Fig. 4.9. Variations of F_{Th}/J_{Th} and $A_{Th}\lambda_{Th}/J_{Th}$ ratios in the water column. J_{Th} - the rate of removal of ^{234}Th from dissolved to particulate phase. F_{Th} - the rate at which ^{234}Th is transported out of the water column by particle flux. $A_{Th}\lambda_{Th}$ - the rate of radioactive decay of particulate ^{234}Th .

independent check of new production estimated by other means (e.g., Eppley, 1989; Murray et al., 1989; Jackson et al., 1989).

4.2.4 ^{234}Th residence time in the water column

The residence times of dissolved and particulate ^{234}Th can be obtained from the scavenging model; both increase with depth (Fig. 4.10). For dissolved ^{234}Th , its residence time with respect to adsorption onto and removal by particles corresponds with previous reports; it increases with depth, from 3-4 weeks at the surface to >5 months below the euphotic zone. However, the residence time of particulate ^{234}Th in this study is longer than that in previous reports (Huh and Beasley, 1987; Coale and Bruland, 1985).

The activity of total particulate ^{234}Th was usually determined in previous studies by using filters of different pore sizes, whereas it was calculated from the scavenging model in this study. Since small particles contribute greatly to the bulk of the mass of particles in the water column and large, rapidly sinking particles are mainly responsible for the vertical flux of particles, small particles mainly control the activity of total particulate ^{234}Th . If part of the small particles are lost through *in situ* filtration due to the vague distinction between dissolved and particulate phases, the activity of total particulate ^{234}Th determined from *in situ* filtration may be underestimated. In deed, the total particulate ^{234}Th calculated from scavenging model is more than that from *in situ* filtration. This may explain the disparity in residence times of particulate ^{234}Th between this and other studies.

Fig. 4.10. Profiles of dissolved ^{234}Th residence time with respect to removal onto particle and particulate ^{234}Th residence time with respect to removal from the water column.

The reciprocals of the residence times of dissolved and particulate ^{234}Th are generally used to represent the scavenging rate of ^{234}Th from dissolved to particulate form, and the removal rate of particulate ^{234}Th , respectively. Therefore, the increase of residence times of dissolved and particulate ^{234}Th with depth represents the decrease of ^{234}Th scavenging and removal rate in the water column. As mentioned in the discussion of the ^{234}Th budget, the majority of dissolved and particulate ^{234}Th is removed by scavenging in the upper layer of the water column, while the majority of dissolved and particulate ^{234}Th is lost by decay in the deep water column. ^{234}Th scavenging and removal rates decrease with depth, corresponding to the increase of ^{234}Th residence times. Thus, ^{234}Th residence times indicate variation of the ^{234}Th scavenging rate from the dissolved to the particulate phase and removal rate from the water column.

Table 4.8 and Fig. 4.11 clearly show that residence times in later spring to early summer are shorter than in other seasons in the water column due to high scavenging in the spring. This suggests that residence time of ^{234}Th is very useful indicator for scavenging processes. Many studies have made use of the residence time of ^{234}Th for studying new production because the residence time of ^{234}Th has been found to be closely related to new production (Coale and Bruland, 1987; Murray et al., 1989).

Table 4.8. Residence time of ^{234}Th with respect to removal from the water column determined from three trap deployments.

Depth (m)	2/5-4/18/90 (days)	4/18-7/8/90 (days)	7/15-8/28/90 (days)
50	11	-8	16
100	46	32	39
150	51	29	30
200	58	29	28
300	61	31	31
500	80	61	69
700	75	64	71
850	85	61	97

Fig. 4.11. Profiles of three trap particulate ^{234}Th residence time with respect to removal from the water column.

4.3 Horizontal versus vertical inputs of ^{230}Th as elucidated from sediment trap data

4.3.1 ^{230}Th scavenging model and budget calculation

In general, ^{230}Th is used as a tracer to study scavenging in the deep open ocean, for which advection and diffusion can be neglected. In that case, the rate of change of the total amount of ^{230}Th can be expressed as: $\partial A_{\text{Th}}^T / \partial t = A_U \lambda_{\text{Th}} - A_{\text{Th}}^T \lambda_{\text{Th}} - J$. At ocean margins, however, horizontal input from the open ocean (Anderson et al., 1982, 1983) and fluvial and atmospheric inputs from the continental source (Nozaki et al., 1980; Huh and Beasley, 1987) will lead to intensified scavenging flux of ^{230}Th , so in this case these additional transport processes should be considered in the ^{230}Th budget calculation, and the steady state distribution of the total ^{230}Th can be represented as:

$$\partial A_{\text{Th}}^T / \partial t = A_U \lambda_{\text{Th}} - A_{\text{Th}}^T \lambda_{\text{Th}} - J + F_H + F_V = 0 \quad (3)$$

Where A_U (dpm/m³) is the activity of the parent nuclide ^{234}U , A_{Th}^T (dpm/m³) is the activity of the total ^{230}Th , and λ_{Th} (d⁻¹) is the radioactive decay constant of ^{230}Th . J , F_H and F_V (dpm/m³/d) respectively represent the removal rate by scavenging, the horizontal input, and the vertical input.

The term $A_{\text{Th}}^T \lambda_{\text{Th}}$ is generally neglected due to the long half-life of ^{230}Th ($T_{1/2}=75,200$ years). Thus, the equation can be rewritten as:

$$A_U \lambda_{Th} + F_H + F_V = J \text{ ----- (4)}$$

In fact, the particulate ^{230}Th flux (J) from sediment traps consists of two components: authigenic and lithogenic. Authigenic ^{230}Th is produced by uranium derived from seawater, while lithogenic ^{230}Th comes from detrital uranium in terrestrially-derived mineral phases. No direct method has been found yet to estimate the lithogenic ^{230}Th component from sediment trap flux. It is generally assumed that all of the ^{232}Th is detrital, that detrital ^{230}Th is in equilibrium with its parent, and that the detrital $^{230}\text{Th}/^{232}\text{Th}$ activity ratio is one (Anderson et al., 1983). Thus, the lithogenic ^{230}Th can be calculated as below:

$$^{230}\text{Th}_L = ^{230}\text{Th}_T - (^{230}\text{Th}/^{232}\text{Th})_D * (^{232}\text{Th})_L \text{ ----- (5)}$$

Where the subscripts T, L and D refer to total, lithogenic and detrital component, respectively.

The horizontal input from the open ocean contributes mainly to the authigenic component of ^{230}Th because there is a low concentration of particles in the open ocean and hence the lithogenic component of ^{230}Th from the open ocean is negligibly small. The lithogenic ^{230}Th comes mainly from the terrestrial source such as the fluvial and atmospheric inputs in the detrital phase (Scott, 1968; Rydell and Prospero, 1972). As will be shown later, the lithogenic and authigenic ^{230}Th components from sediment trap fluxes may reflect vertical input from the terrestrial source and horizontal input from the open ocean, respectively. Horizontal and vertical inputs of ^{230}Th can be determined by the

^{230}Th scavenging model by resolving the authigenic and lithogenic components of ^{230}Th from sediment trap fluxes.

In the ^{230}Th budget calculation, the term $A_U\lambda_{\text{Th}}$ was determined from the integrated production of ^{230}Th by decay of ^{234}U from the surface to the depth of interest. ^{234}U activity in seawater can be derived from ^{238}U activity because the seawater ratio of $^{234}\text{U}/^{238}\text{U}$ is equal to 1.14. J is equal to the sediment trap flux of ^{230}Th , and the vertical input (F_V) was determined by the lithogenic component of ^{230}Th . Then, the authigenic component of ^{230}Th from sediment traps was obtained by the difference between ^{230}Th flux (J) and the vertical input (F_V), i.e. it equals to $F_H + A_U\lambda_{\text{Th}}$. The rate of supply of ^{230}Th by horizontal input (F_H) could simply be computed by the difference between the authigenic component of ^{230}Th from sediment trap flux and ^{230}Th in situ production rate.

The ^{230}Th budget given in Table 4.9 shows that the ^{230}Th sediment trap flux greatly exceeds in situ production, indicating that the ^{230}Th flux (J) is mainly supplied by the horizontal (F_H) and the vertical (F_V) inputs, and that the authigenic component of ^{230}Th from sediment trap flux is approximately equal to the horizontal input (F_H).

4.3.2 Variations of horizontal and vertical inputs of ^{230}Th in the water column

The ratios $J/\text{Production}$, $F_H/\text{Production}$ and $F_V/\text{Production}$ represent the sediment trap flux, the horizontal input and the vertical input of ^{230}Th , respectively. Table 4.10 shows that there is a remarkable difference between the ratios $J/\text{Production}$ and $F_H/\text{Production}$. The $J/\text{Production}$ ratio decreases with depth (Fig. 4.12). If the contribution of the

Table 4.9. ^{230}Th budget in the water column derived from sediment traps.

73

<hr/>					
2/5-4/18/90		(dpm/m ² /d)			
Depth (m)	P	F _{total}	F _{lithogenic}	F _{authigenic}	H _z
50	0.004	0.36	0.29	0.07	0.066
100	0.007	0.31	0.27	0.04	0.033
150	0.011	0.35	0.28	0.07	0.059
200	0.014	0.46	0.28	0.18	0.166
300	0.021	0.55	0.36	0.19	0.169
500	0.035	0.7	0.49	0.21	0.175
700	0.049	1.08	0.75	0.33	0.281
850	0.06	1.05	0.67	0.38	0.32
4/18-7/8/90					
Depth (m)					
50	0.004	0.29	0.21	0.08	0.076
100	0.007	0.34	0.3	0.04	0.033
150	0.011	0.45	0.33	0.12	0.109
200	0.014	0.6	0.4	0.2	0.186
300	0.021	0.56	0.5	0.06	0.039
500	0.035	0.8	0.55	0.25	0.215
700	0.049	1.23	0.8	0.43	0.381
850	0.06	1.1	0.61	0.49	0.43
7/15-8/28/90					
Depth (m)					
50	0.004	0.19	0.2	-0.01	-0.014
100	0.007	0.41	0.34	0.07	0.063
150	0.011	0.74	0.59	0.15	0.139
200	0.014	1.14	0.83	0.31	0.296
300	0.021	1.28	0.95	0.33	0.309
500	0.035	1	0.7	0.3	0.265
700	0.049	1.13	0.85	0.28	0.231
850	0.06	1.08	0.72	0.36	0.3

P - the rate of ^{230}Th production by the decay of ^{234}U .

F_{total} - the removal flux from the water column.

F_{lithogenic} - lithogenic source, i.e. the fluvial and atmospheric input.

F_{authigenic} - authigenic source, i.e. horizontal input from open ocean and in-situ production.

H_z - the horizontal input from open ocean.

Table 4.10. Flux/Production ratios of ^{230}Th in the water column.

2/5-4/18/90 Depth (m)	F_{total}/P	$F_{\text{authigenic}}/P$	$F_{\text{lithogenic}}/P$	H_z/P
50	90	17.5	72.5	16.50
100	44.29	5.71	38.57	4.71
150	31.82	6.36	25.45	5.36
200	32.86	12.86	20.00	11.86
300	26.19	9.05	17.14	8.05
500	20.00	6.00	14.00	5.00
700	22.04	6.73	15.31	5.73
850	17.50	6.33	11.17	5.33
4/18-7/8/90				
Depth (m)				
50	72.50	20.00	52.50	19.00
100	48.57	5.71	42.86	4.71
150	40.91	10.91	30.00	9.91
200	42.86	14.29	28.57	13.29
300	26.67	2.86	23.81	1.86
500	22.86	7.14	15.71	6.14
700	25.10	8.78	16.33	7.78
850	18.33	8.17	10.17	7.17
7/15-8/28/90				
Depth (m)				
50	47.50	-2.50	50.00	-3.50
100	58.57	10.00	48.57	9.00
150	67.27	13.64	53.64	12.64
200	81.43	22.14	59.29	21.14
300	60.95	15.71	45.24	14.71
500	28.57	8.57	20.00	7.57
700	23.06	5.71	17.35	4.71
850	18.00	6.00	12.00	5.00

P - the rate of ^{230}Th production by the decay of ^{234}U .

F_{total} - the removal flux from the water column.

$F_{\text{lithogenic}}$ - lithogenic source, i.e. the fluvial and atmospheric input.

$F_{\text{authigenic}}$ - authigenic source, i.e. horizontal input from open ocean and in-situ production.

H_z - the horizontal input from open ocean.

Fig. 4.12. Variations of F_{tot}/P ratios in the water column. F_{tot} - represents the removal flux from the water column. P - the rate of ^{230}Th production by the decay of ^{234}U .

horizontal input ($F_H/\text{Production}$) from the open ocean did not change greatly in the water column, variation of $J/\text{Production}$ ratio would reflect variation of the vertical input because of $J = F_H + F_V$. It is clear from the $F_H/\text{Production}$ ratios (~ 10) in Table 4.10 that the horizontal input from the open ocean does not change significantly with depth (Fig. 4.13). On the other hand, from Fig. 4.14, it is clear that the vertical input ($F_V/\text{Production}$) decreases with depth. These data are consistent with the following: the lithogenic component of ^{230}Th from sediment trap flux comes mostly from the surface ocean through fluvial and atmospheric inputs.

Anderson et al. (1983) used a different particulate $^{230}\text{Th}/^{231}\text{Pa}$ ratio in sediment trap material collected in the Panama and Guatemala Basins to estimate horizontal flux by setting up a two-box model. They concluded that the horizontal input acts as a source of ^{230}Th at ocean margins. They estimated that $F_H/\text{Production}$ measured by sediment traps was 1.85, much smaller than the value of 10 used in this study.

It is necessary to point out that the Panama and Guatemala Basins are far from land compared with the Santa Monica Basin. The horizontal input was a dominant source in the Anderson et al. model. The ^{230}Th flux from sediment traps comes mainly from the authigenic component of ^{230}Th , i.e. the horizontal input and in situ production. Only a minor lithogenic component of ^{230}Th is contributed by the vertical input. Thus, particulate ^{230}Th from the sediment trap flux is contributed mainly by the horizontal input and in situ production and the $F_H/\text{Production}$ is not very big. In contrast, the Santa Monica Basin is the inner basin of the Southern California Borderlands and lies directly offshore of Los Angeles, circulation in this deep basin is restricted due to topographic controls. Both the

Fig. 4.13. Variations of $F_{\text{authentic}}/P$ ratios in the water column. $F_{\text{authentic}}$ - represents the horizontal input from the open ocean. P - the rate of ^{230}Th production by the decay of ^{234}U .

Fig. 4.14. Variation of $F_{\text{lithogenic}}/P$ ratios in the water column. $F_{\text{lithogenic}}$ - represents the fluvial and atmospheric input. P - the rate of ^{230}Th production by the decay of ^{234}U .

vertical input and the horizontal input are important sources for particulate ^{230}Th from the sediment trap flux, which greatly exceeds in situ production of ^{230}Th contribution to the sediment trap flux. Thus, the $F_H/\text{Production}$ ratios are much higher in this area.

Other reasons that the $F_H/\text{Production}$ ratios in the Santa Monica Basin greatly exceed those of the Panama and Guatemala Basins should be considered. First, a slight deviation of J and F_v would have a significant effect on ratios because the difference between them are far greater than in situ production of ^{230}Th . Second, the ratio of $^{230}\text{Th}/^{232}\text{Th}$ was assumed to be one in the calculation of the lithogenic component of ^{230}Th , which would underestimate the lithogenic component of ^{230}Th , leading to a higher $F_H/\text{Production}$ ratio. Third, strong upwelling occurs in the Santa Monica Basin, causing a change in the horizontal input from the open ocean. Finally, coastal sewage treatment plants and other anthropogenic material input contribute considerably to sources of ^{230}Th along their pathways, which make sources of ^{230}Th flux more complex.

5. CONCLUSIONS

5.1 Sediment trap measured fluxes in the water column

Mass and radionuclide fluxes measured from near-bottom sediment traps in the Santa Monica Basin, if integrated over a longer period, compare favorably with fluxes determined from sediment core data. The near-bottom sediment traps are capable of collecting settling particles representative of the surface sediment. In areas of low sediment accumulation rates and extensive bioturbation, it is usually difficult to determine their sedimentation rates by ^{210}Pb method because the mixing process of near-surface sediments dilutes the observable effects of deposition of "young" particulates and anthropogenic materials and reduces surface sediment radionuclide activity. However, sediment traps can be used to collect fresh particles, unaffected by bioturbation and mixing, some information about sediments can be obtained to study sediments. Therefore, sediment traps can be applied as collection and monitoring devices to extend to areas not amenable to sediment studies.

Sediment trap data are very useful for the calculation of the radionuclide budget in the water column. With the help of the scavenging model, the distribution of ^{234}Th in dissolved and particulate phase can be determined and the variations of vertical and horizontal inputs of particulate ^{230}Th in the water column can also be estimated. These results contribute to the understanding of the behaviors of uranium and thorium isotopes in the water column.

5.2 ^{234}Th scavenging and budget in the water column

By using a ^{234}Th scavenging model, the budget of ^{234}Th in the water column can be determined. The variations of ^{234}Th budget in dissolved and particulate phase can be also obtained, which helps to study the ^{234}Th scavenging process in the water column.

From the ^{234}Th budget in the water column, it can be concluded that the vertical transport of ^{234}Th is primarily controlled by the particulate ^{234}Th scavenged from the water column. The scavenging process occurs mainly in the surface layer and particulate ^{234}Th scavenged from the water column decreases with depth. Scavenging and radioactive decay of ^{234}Th are the two principal processes that control the ^{234}Th budget in the water column. Sediment trap results also show that the terrestrial particulate matter and biological processes are the two main factors controlling scavenging process.

The residence time of dissolved ^{234}Th is the same as that found in previous studies, but the residence time of particulate ^{234}Th is different from previous studies. The discrepancy may be caused by different operational definitions of particle size during the determination of particulate ^{234}Th . It is suggested that total particulate ^{234}Th may be calculated by using sediment trap data rather than using in situ filtration.

5.3 Variations of horizontal and vertical inputs of ^{230}Th in the water column

Horizontal input from the open ocean and vertical input from terrestrial sources act as two important sources of particulate ^{230}Th at ocean margins, such as the Santa Monica

Basin. The two source contributions to flux of particulate ^{230}Th greatly exceed the water column production of ^{230}Th . Therefore, these transport processes should be considered in the calculation of ^{230}Th budget.

From the ^{230}Th scavenging model, the horizontal and vertical inputs could be obtained. These results demonstrate that the horizontal input remains constant in the water column and the vertical input decreases with depth. $F_H/\text{Production}$ ratio of particulate ^{230}Th measured in this study is much larger than that of the ratio measured by Anderson et al., which may be caused by different basin conditions.

6. BIBLIOGRAPHY

1. Anderson, R. F., Bacon, M. P. and Brewer, P. G. (1983a). Removal of ^{230}Th and ^{231}Pa from the open ocean. *Earth planet. Sci. Lett.* 62, 7-23.
2. Anderson, R. F., Bacon, M. P. and Brewer, P. G. (1983b). Removal of ^{230}Th and ^{231}Pa at ocean margins. *Earth planet. Sci. Lett.* 66, 73-90.
3. Bacon, M. P. and Anderson, R. F. (1982). Distribution of thorium isotopes between dissolved and particulate forms in the deep sea. *J. Geophys. Res.* 83, 2045-2056.
4. Bacon, M. P., C.-A. Huh, A. P. Fleer and W. G. Deuser (1985). Seasonality in the flux of natural radionuclides and plutonium in the deep Sargasso Sea. *Deep Sea Res.* 32, 277-299.
5. Bacon, M. P., C.-A. Huh and R. M. Moore (1989). Vertical profiles of some natural radionuclides over the Alpha Ridge, Arctic Ocean. *Earth Planet. Sci. Lett.* 95, 15-22.
6. Baker, E. T., H. B. Milburn and D. A. Tennant (1988). Field assessment of sediment trap efficiency under varying flow conditions. *Journal of Marine Research*, 46, 573-592.
7. Bhat, S. G., Krishnaswami, S., Lal, D., Rama, M. and Moore, W. S. (1969). $^{234}\text{Th}/^{238}\text{U}$ ratios in the ocean. *Earth Planet. Sci. Lett.* 5, 483-491.
8. Brewer, P. G. and W. M. Hao (1979). Ocean elemental scavenging. In: Chemical Modeling in Aqueous System - Speciation, sorption, solubility, and kinetics. Am. Chem. Soc. Symposium Series 93. E. A. Jenne (eds.). Am. Chem. Soc. pp 26-274.
9. Bowen, V. T., Noshkin, V. E., Livingston, H. D. and Volchok, H. L. (1980). Fallout radionuclides in the Pacific Ocean: vertical and horizontal distributions, largely from GEOSECS stations. *Earth Planet. Sci. Lett.* 48, 411-434.
10. Brewer, P. G., Y. Nozaki, D. W. Spencer and A. P. Fleer (1980). A sediment trap experiment in the deep sub-tropical Atlantic: isotopic and elemental fluxes.

- J. Mar. Res.* 38, 703-728.
11. Broecker, W. S., Kaufman, A. & Trier, R. M. (1973). The residence time of thorium in the surface sea water and its implications regarding the rate of reactive pollutants. *Earth Planet. Sci. Lett.* 20, 35-44.
 12. Broecker, W. S. and T.-H. Peng (1982). *Tracers in the Sea*. Lamont-Doherty Geological Observatory, Columbia University, Palisades.
 13. Bruland, K. W., Franks, R. P., Landing, W. M. and Soutar, A. (1981). Southern California inner basin sediment trap calibration. *Earth Planet. Sci. Lett.* 53, 400-408.
 14. Bruland, K. W. (1983). Trace metals in sea-water. In; *Chemical Oceanography*, Vol.18, 157-220 (Editors: J. P. Reley and R. Chester) Academic Press.
 15. Bruland, K. W. and K. H. Coale (1986). Surface water $^{234}\text{Th}/^{238}\text{U}$ disequilibria: spatial and temporal variations of scavenging rates within the Pacific ocean. pp. 159-172. In, J. D. Burton, P. G. Brewer, and R. Chesselet (eds.). *Dynamic processes in the chemistry of the upper ocean*. Plenum Pub. Co.
 16. Butman, C. A. (1986). Sediment trap biases in turbulent flows: results from a laborboratory flume study. *Journal of Marine Research* 44, 645-693.
 17. Byung C. Cho & Farooq Azam (1988). Major role of bacteria in biogegeochemical fluxes in the ocean's interior. *Nature* 332, 31.
 18. Chen, J.-H, Edwards, R. L., Wasserburg, G. J. (1986b). ^{238}U , ^{234}U and ^{232}Th in seawater. *Earth planet. Sci. Lett.* 80, 241-252.
 19. Chun, Y. (1989). Geochemistry of thorium in natural water systems. M.S. thesis, Oregon state University.
 20. Clegg, S. L. and M. Whitfield (1990a). A generalized model for the scavenging of trace metals in the open ocean--I. Particle cycling. *Deep-Sea Res.* 37, 809-832.
 21. Clegg, S. L. and M. Whitfield (1990b). A generalized model for the scavenging of trace metals in the open ocean--II. Thorium scavenging. *Deep-Sea res.* (in press).
 22. Coale, K. H. & Bruland, K. W. (1985). $^{234}\text{Th}:$ ^{238}U disequilibrium within the

- California Current. *Limnol. Oceanogr.* 30, 22-33.
23. Coale, K. H. & Bruland, K. W. (1987). Oceanic stratified euphotic zone as elucidated by ^{234}Th : ^{238}U disequilibria. *Limnol. Oceanogr.* 30(1), 189-200.
 24. Cochran, J. K. (1982). The oceanic chemistry of the U- and Th-series nuclides. In: *Uranium series disequilibrium: Applications to environmental problems*. M. Ivanovich and R.S. Marmon (eds.) Clarendon Press.
 25. Cochran, J. K., Livingston, H. D., Hirschberg, D. J. and Surprenant, L. D. (1987). Natural and anthropogenic radionuclide distributions in the Northwest Atlantic Ocean. *Earth Planet. Sci. Lett.* 84, 135-152.
 26. Eppley, R. W. and B. J. Peterson (1979). Particulate organic matter flux and planktonic new production in the deep ocean. *Nature* 282-282.
 27. Eppley, R. W. (1989). New production: history, methods and problems. In: *Dahlem workshops in "productivity of the ocean: present and past"*. W. H. Berger, V. Smetacek, and O. Weffer (eds). pp. 85-97, Wiley, New York.
 28. Fisher, N. S., J.-L. Teyssie, S. Krishnaswami, and M. Baskaran (1987). Accumulation of Th, Pb, U, and Ra in marine phytoplankton and its geochemical significance. *Limnol. Oceanogr.* 32, 131-142.
 29. Gardner, W. D. (1980a). Sediment trap dynamics and calibration: a laboratory evaluation. *Journal of Marine Research* 38, 17-39.
 30. Gardner, W. D. (1980b). Field assessment of sediment traps. *Journal of Marine Research* 38, 41-52.
 31. Goldberg, E. D. (1954). Marine Chemistry 1. Chemical scavengers of the sea. *J. Geol.* 62, 249-265.
 32. Honeyman, B. D., L. S. Balistrieri and J.W. Murray (1988). Oceanic trace metal scavenging, the importance of particle concentration. *Deep-Sea Res.* 35, 227-246.
 33. Huh, C.-A. (1982). Radiochemical and chemical studies of manganese nodules from three sedimentary regimes in the North Pacific. Ph.D. Thesis, University of Southern California, Los Angeles.
 34. Huh, C.-A. and Bacon, M. P. (1985a). Determination of thorium concentration

- in seawater by neutron activation analysis. *Anal. Chem.* 57, 2138-2142
35. Huh, C.-A. and Bacon, M. P. (1985b). ^{232}Th in the eastern Caribbean Sea. *Nature* 316(22), 718-721.
 36. Huh, C.-A. and Beasley, T. M. (1987). Profiles of Dissolved and particulate thorium isotopes in the water column of coastal Southern California. *Earth Planet. Sci. Lett.* 85, 1-10.
 37. Huh, C.-A., Zahnle, D. L., Small, I. F. and Noshkin, V. E. (1987). Budgets and behaviors of uranium and thorium series isotopes in Santa Monica Basin sediments. *Geochim. Cosmochim. Acta* 51, 1743-1754.
 38. Huh, C.-A., (1988). Determination of thorium in seawater by neutron activation analysis and mass spectrometry. In: radionuclides: A tool for Oceanography (Eds. J. C. Guary, P. Guegueniat and R.J. Pentreath), *Elsevier Applied Science*, 83-91.
 39. Huh, C.-A., L. F. Small, S. Niemi, B. P. Finney, B. M. Hickey, N. B. Kachel, D. S. Gorsline and P. M. Williams, 1990. Sedimentation dynamics in the Santa Monica-San Pedro Basin off Los Angeles: radiochemical, sediment trap and transmissometer studies. *Continental Shelf Research* 10, 137-164.
 41. Huh, C.-A. and D. C. Kadko, 1991. *Uranium series disequilibrium in marine sediments*. Chapter 13 in *Uranium Series Disequilibrium: Applications to Environmental Problems*, 2nd edition, (eds. M. Ivanovich and R. S. Harmon), Oxford University Press (in print).
 42. Huh, C.-A., B. P. Finney, J. K. Stull, 1991. Anthropogenic inputs of several heavy metals to nearshore basins off Los Angeles. *Progress in Oceanography* (in print).
 43. Ivanovich, M. and Harmon, R. S. (Editor). *Uranium Series Disequilibrium: Applications to Environmental Problems* (1982).
 44. Kaufman, A. (1969). The ^{232}Th concentration of surface ocean water. *Geochim. Cosmochim. Acta* 33, 717-724.
 46. Knauer, G. A., J. H. Martin and K. W. Bruland (1979). Fluxes of particulate

- carbon, nitrogen, and phosphorus in the upper water column of the northeast Pacific. *Deep-sea Research* 26, 97-108.
47. Knauer, G. A. and J. H. Martin (1981). Primary production and carbon nitrogen fluxes in the upper 1,500m of the northeast Pacific. *Limnology and Oceanography* 26, 181-186.
 48. Knauer, G. A., D. M. Karl, J. H. Martin and C. N. Hunter (1984). In-situ effects of selected preservatives on the total carbon, nitrogen and metals collected in sediment traps. *Journal of Marine Research* 42, 445-462.
 49. Knauer, G. A., D. G. Redalje, W. G. Harrison and D. M. Karl (1990). New production at the VERTEX time-series site. *Deep-sea Research* 37 (7), 1121-1134.
 50. Knauss, K. G., T. L. Ku and W. S. Moore (1978). Radium and thorium isotopes in the surface waters of the East Pacific and coastal Southern California. *Earth Planet. Sci. Lett.* 24 39, 235-249.
 51. Koide, M., Bruland, K. W. and Goldberg, E. D. (1973). $^{228}\text{Th}/^{232}\text{Th}$ and ^{210}Pb geochronologies in marine and lake sediments. *Geochim. cosmochim. Acta* 37, 1171-1181.
 52. Ku, T. L. (1976). The uranium-series methods of age determination. Annual review of Earth and planetary Sciences 4, 347-379.
 53. Ku, T. L., K. G. Knauss, and G. G. Mathiew (1977). Uranium in open ocean, concentration and isotopic composition. *Deep Sea Res.* 24, 1005-1017.
 54. Ku, T. L. and Broecker, W. S. (1969). Radiochemical studies on manganese nodules of deep sea origin. *Deep Sea Res.* 16, 625-637.
 55. Kuznetsov, Y., Simonyak, Z., Elizarova, A. and Lisitsyn, A. (1966). Content of Pa and Th isotopes in ocean water. *Radiokhimiya* 8, 455-458.
 56. Langmuir, D. (1978). Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits. *Geochim. cosmochim. Acta* 42, 547-569.
 57. Landry, M. R., W. K. Peterson, and C. C. Andrews (1991). Particulate flux in the

water column overlying Santa monica Basin: Adventures in sediment trapology (in print).

58. Lazarev, K. F., Nikolazv, D. S. and Grashchenko, S. M. (1961). Concentration of thorium istopes in sea water. *Radiokhimiya* (III) (5), 623-635.
59. Lee, C., S. G. Wakeham and J. I. Hedges (1988). The measurement of oceanic particle flux- Are "swimmers" a problem ? *Oceanography* 1: 34-36.
60. Lee, C., J. I. Hedges, S. G. Wakeham, and N. L. Zhu (1990). Effectiveness of poisons and preservatives in retarding bacterial activity in sediment trap material and their effect on the collection of swimmers (in print).
61. Li, Y.-H., Feely, H. W. and Santschi, P. H. (1979). ^{228}Th - ^{228}Ra radioactive disequilibrium in the New York Bight and its implications for coastal pollution. *Earth Planet. Sci. Lett.* 42, 13-26.
62. Mangini, A. and Key, R. M. (1983). A ^{230}Th profile in the Atlantic Ocean. *Earth Planet. Sci. Lett.* 62, 377-384.
63. Matsumoto, E. (1975). ^{234}Th - ^{238}U radioactive disequilibrium in the surface layer of the ocean. *Geochim. Cosmochim. Acta* 39, 205-212.
64. Mckee, B. A., DeMaster, D. J. and Nittrouer, C. A. (1984). The use of $^{234}\text{Th}/^{238}\text{U}$ disequilibrium to examine the fate of paticle-reactive species on the Yangtze continental shelf. *Earth Planet. Sci. Lett.* 68, 431-442.
65. Miyake, Y., Sugimura, Y. and Yasujima, T. (1970). Thorium concentration and the activity ratios $^{230}\text{Th}/^{232}\text{Th}$ and $^{228}\text{Th}/^{232}\text{Th}$ in the sea water in the western North Pacific. *J. Oceangr. Soc. Japan* 26(3), 130-136.
66. Moore, W. S. and W. M. Sackett (1964). Uranium and thorium series inequilibrium in seawater. *J. Geophys. Res.* 69, 5401-5405.
67. Moore, W. S. (1969). Measurement of ^{228}Ra and ^{228}Th in sea water. *J. Geophys. Res.* 74, 694-704.
68. Murray, J. W., J. N. Downs, S. Strom, C.-L. Wei, and H. W. Jannasch (1989). Nutrient assimilation, export production and ^{234}Th scavenging in the Eastern Equatorial Pacific. *Deep sea Res.* 36, 1471-1489.

69. Nozaki, Y., K. K. Turekian and K. von Damm (1980). ^{210}Pb in GEOSECS water profiles from the North Pacific. *Earth Planet. Sci. Lett.* 49, 393-400.
70. Nozaki, Y. Yang, A.-S. and Yamada, M. (1987). Scavenging of thorium in the ocean. *J. Geop. Res.* 92, 772-778.
71. Nozaki, Y., Y. Horibe and H. Tsubota (1981). The water column distributions of thorium isotopes in the western North Pacific, *Earth Planet. Sci. Lett.* 54, 203-216.
72. Nozaki, Y. and Y. Horibe (1983). Alpha-emitting thorium isotopes in northwest Pacific deep waters, *Earth Planet. Sci. Lett.* 65, 39-50.
73. Nozaki, Y. and T. Nakanishi (1985). ^{231}Pa and ^{230}Th profiles in the open ocean water column. *Deep-sea Res.* 32, 1209-1220.
74. Powell, H., and K. Fischer (1982). Comparison study of bactericides for sediment traps. *EOS* 63 (45): 1016.
75. Rama, M. K. and E. D. Goldberg (1961). Lead-210 in natural waters, *Science* 134, 98-99.
76. Ryabchikov, D. I., Gol'braikh, E. K. (1969). The analytical chemistry of Thorium. The MacMillan Company, New York.
77. Spencer, D. W., P. G. Brewer, A. Bleer, S. Honjo, S. Krishnaswami and Y. Nozaki (1978). Chemical fluxes from a sediment trap experiment in the deep Sargasso Sea. *J. Mar. Res.* 36, 493-523.
78. Spencer, D. W., M. P. Bacon and P. G. Brewer (1981). Models of the distribution of ^{210}Pb in a section across the north equatorial Atlantic Ocean. *J. Mar. Res.* 39, 119-138.
79. Soutar, A., S. A. Kling, P. A. Crill, E. Duffrin, and K. W. Bruland (1977). Monitoring the marine environment through sedimentation. *Nature* 266, 136-139.
80. Somayajulu, B. L. K. and Goldberg, E. D. (1966). Thorium and uranium isotopes in seawater and sediments. *Earth Planet. Sci. Lett.* 1, 102-106.
81. Taguchi, K., K. Harada and S. Tsunogai (1989). Particulate removal of ^{230}Th and ^{231}Pa in the biologically productive North Pacific. *Earth Planet. Sci. Lett* 93, 223-232.

82. Tsunogai, S., K. Taguchi, and K. Harada (1986). Seasonal variation in the difference between observed and calculated particulate fluxes of ^{234}Th in Funka Bay, Japan. *J. Oceanogr. Soc. Japan.* 42, 91-98.
83. Wei, C. L. (1990). Studies of marine scavenging by naturally occurring radionuclides. Ph.D. thesis, Univ. Washington.
84. Wong, K. M., T. A. Jokela, R. J. Eagle, J. L. Brunk and V. E. Noshkin (1991). Radionuclide concentrations, fluxes and residence times at Santa Monica and San Pedro Basins (in print).
85. Yang, Y.-L., H. Elderfield and M. Ivanovich (1991). ^{230}Th and ^{231}Pa in equatorial Pacific and Panama Basin sediments (in preparation).

END

**DATE
FILMED**

8 / 5 / 92