LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
OF COLUMBIA UNIVERSITY

PALISADES, NEW YORK

MIXING, DIFFUSION AND CIRCULATION RATES IN OCEAN WATERS

Annual Report

Physical Oceanography
Geochemistry

W.S. Broecker, Co-Principal Investigator
R.D. Gerard, Co-Principal Investigator

June 1974

PREPARED FOR THE U.S. ATOMIC ENERGY COMMISSION
UNDER CONTRACT NO. AT(11-1) 2185

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ANNUAL REPORT

Contract AT(11-1)2185

PHYSICAL OCEANOGRAPHY

SECTION

This report summarizes the research results and work in progress by the Lamont-Doherty Physical Oceanography group under this contract during the period July 1973 - June 1974.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FIELD WORK

During this period field studies on ocean circulation were carried out aboard three oceanographic ships for a total of 203 ship days (352 man days).

Studies of the thermal structure and suspended particulate material in the water column were carried out in the Western North Atlantic aboard the Research Vessel VEMA of Lamont-Doherty Geological Observatory in October - December 1973 to examine the Mediterranean outflow. The work of this cruise is summarized in Appendix A.

Three legs aboard the Lamont-Doherty Geological Observatory Research Vessel CONRAD were carried out between November 1973 and April 1974. During November 1973 on a leg across the Equatorial Atlantic between Barbados and Abidjan current measurements, STD observations and nephelometer stations were carried out in the Vema Fracture Zone. These observations in the Mid-Atlantic Ridge area were carried out to examine the circulation between the western and eastern Atlantic basins at this critical passage. This work is described in Appendix B.

Two legs (total of 90 days) of the Research Vessel CONRAD cruise 17 were devoted to intensive studies of the Antarctic circulation southeast of South Africa. On these cruises a total of 95 STD stations were accomplished on six transects across the Circumpolar region. Three successful bottom current observations were made during these cruises, the longest being a record of 72 days between Crozet Island and Kerguelen Island at about 47° south latitude. Exceptionally favorable ice conditions allowed three transects to reach within 50 - 100 miles of the Antarctic Continent.

well up on the Antarctic Continental Shelf. These cruise legs are described in Appendices C. and D.

A one month Physical Oceanographic study was carried out in the Eastern Equatorial Pacific by a Lamont-Doherty team aboard the Research Vessel MOANA WAVE (University of Hawaii ship). A dense network of STD stations and current measurements were successfully obtained in an area which is believed to be of primary interest as a site for deep ocean mining of manganese nodules. This work is summarized in Appendix E.

OTHER RESEARCH

An analysis has been completed of six years of deep ocean tide data from a Lamont-Doherty ocean bottom tide meter located in a depth of 3000 meters about 160 kilometers off the coast of northern California. These results are given in Appendix E.

Appendix F summarizes the results of our coastal circulation studies in the New York Bight. This effort which has been a relatively minor aspect of this contract has allowed Lamont-Doherty workers to develop a series of useful dye tracer techniques for observing small and medium scale circulation in shallow waters. Our present (pending) proposal for fiscal year 1975 places major emphasis on coastal circulation studies based upon these new methods.

PUBLICATIONS AND REPORTS

The following list of papers and reports on the Physical Oceanographic work of this contract were completed during this period.

Eittreim, S.L. and A.F. Amos, 1974. Bottom water characteristics of Vema Fracture Zone (abstract), Trans. AGU 55(4), p.316.

Roels, O.A., A.F. Amos, O.R. Anderson, C. Garside, K.C. Haines T.C. Malone, A.Z. Paul and G.E. Rice, 1973. The environmental impact of deep-sea mining, progress report: NOAA Tech. Report ERL 290-OD 11, May 1973, 185 pp.

Amos, A.F., 1973. The deep STD station: Techniques for making surface-to bottom STD profiles and some examples of abyssal microstructure, Proceedings, Second Plessey Environmental Systems STD Conference and Workshop, January 24-26, 1973 San Diego, California, p. 87-101.

Amos, A.F., W.B. Leaf and R.D. Gerard, 1973. A deep-ocean electronic nephelometer: Ocean 1973, IEEE International Conference on Engineering in the Ocean Environment. IEEE Publication 73-CHO 774-O-OCC, p. 24-30.

Amos, A.F. and A.L. Gordon, 1973. Continuously sampled oceanographic data: Ocean Science Committee, Ocean Affairs Board, National Academy of Sciences - National Research Council (Project Report), December 1973, 51 pp.

Baker, T.N. and A.A. Nowroozi, 1974. Analysis of six years of pelagic tidal heights from the Eastern North Pacific Ocean. (in preparation).

Appendix A

Cruise Report

Research Vessel VEMA

Cruise 30, legs 12 and 13

October - December

1973

7
Cruise Report for R/V VEMA Cruise 30, legs 12 and 13

Nephelometer and Hydrographic Measurements

Cruise Dates: Leg 12, Stavanger, Norway - Lisbon, Portugal, Oct 5-Oct 29, 1973
Leg 13, Portugal, Lisbon - Las Palmas, Canary Islands, Nov 1-Dec 1, 1973

Introduction: During legs 12 and 13 of R/V VEMA cruise 30, October 5 through December 1, 1973, nephelometer and hydrographic data were obtained in the region of the Mediterranean outflow. The primary purpose for collecting these data was to determine the magnitude and extent of the highly turbid water contained in the tongue of warm, salty water entering the Atlantic from the Mediterranean at the Strait of Gibraltar. In conjunction with this primary objective, the source and types of several clay minerals in the outflow will be determined from water samples filtered on board the ship by M. Fred Meiliers of CNRS, Paris (his own contract). The data will also provide valuable information on the nephelometry below the outflow (deeper than 1500m). The gathering of the data was a secondary part of the ship operations. For this reason, it was not always possible to obtain the best station position for the purposes of data interpretation, especially on leg 12. Nevertheless, whenever possible, station positions were chosen on the basis of (extensive) published (and unpublished) information on the outflow and by on-site use of deep XBT's (T-5's). In this manner 12 nephelometer stations were taken on leg 12 and 40 on leg 13. Figures 1 and 2 show the station positions as well as a list of all station operations. In addition to the Lamont camera-nephelometer, XBT's were used at all stations and either Nansen bottles or 30 liter Niskin bottles with reversing thermometers were used on 37 stations (denoted in legends of figures 1 and 2 either as "water sample" or WS). The collection of these data was very successful, and will lead to the completion of the goals of this project.

Station Operations: Before each station in which a Lamont camera-nephelometer was used an XBT was launched to determine the thermal structure of the water column and the optimum depth for placing the water bottles. In regions where the XBT profile showed a strong temperature inversion indicating the Mediterranean outflow all four bottles were placed through this layer. In other areas, the bottles were positioned at the depth of the clearest water (3000 - 4000 meters) as determined by previous nephelometer profiles, and as close to the bottom as sensible. These bottles were tripped by messenger before the camera-nephelometer continued down to the bottom for the camera hits. After all this gear had been returned to the deck, the nephelometer film was processed, thermometers were read and water samples were collected for both salinity measurements and filtering for particulate matter.

Data Analysis: The preliminary reduction of the nephelometer data has been completed. A sample profile is shown in figure 3. This profile is based on fairly widely spaced measurements of the nephelometer film shown here by x's. However, it does show the characteristic peaks in light scattering, or $\log (E/E_0)$, between 700 and 1500 meters. Figure 4 shows the XBT profile from the same station. Again, note the peaks in temperature between 700 and 1500 m due to the "warm" Mediterranean Outflow water. This demonstrates the connection between the high turbidity and the Mediterranean Outflow. Ultimately, the nephelometer data will be analyzed in greater detail to give more accurate profiles which will then be plotted alongside the XBT profiles. This will facilitate the interpretation of the various maxima and minima of the nephelometer profiles. Already, several interesting peaks in light scattering have been found below 2000 meters which do not bear any relation to the temperature structure. M. Fred Mellers will analyze the particulate matter collected in the filters by X-ray analysis. He will identify various clay minerals as well as determine their relative abundance by this method. The continental sources for these

minerals have been identified and their distribution in the near shore sediment has been plotted by M. Meliers. This information, together with the nephelometer and water sample data should help plot the path of these minerals from their source to the bottom of the ocean. If this method proves successful it will become a valuable tool for future oceanographic work.

We plan to publish these results in at least two papers which are now in preparation. The co-authors are Anthony Amos, Fred Meliers and Scott Daubin, Jr. In addition, this data is being used by Mr. Daubin in his Ph.D. thesis.

FIGURE 1

S 206	S 207	S 208	S 209	S 210	S 211	S 212	S 213	S 214	S 215
OCT 6	OCT 7	OCT 7	OCT 7	OCT 7	OCT 10	OCT 10	OCT 10	OCT 11	OCT 14
D 24	D 25	D 26	D 27	D 28 A	D 28	D 29 A	D 29	D 30	C 177
	K 116	K 117	K 118		K 119	K 120		K 121	K 122
		N 115			N 116			N 117	N 118
									TG 132

S 216	S 217	S 218	S 219	S 220	S 221	S 222	S 223	S 224	S 225
OCT 16	OCT 17	OCT 18	OCT 18	OCT 19	OCT 19	OCT 19	OCT 19	OCT 20	OCT 20
C 178	C 179	C 180	C 181	C 182	D 31A	D 31	D 32	C 183	WATER
K 123	K 124	K 125	---			K 126	K 127	K 128	SAMPLE
N 119	N 120	N 121	---	TG 137		N 122	N 123	N 124	
TG 133	TG 134	TG 135	TG 136					TG 138	

S 226	S 227	S 228	S 229	S 230
OCT 21	OCT 21	OCT 25	OCT 2	OCT 2
C 184	C 185	C 186	C 187	C 188
		TG 141A	TG 141B	TG 141C
TG 139	TG 140	K 129	K 130	K 131
		N 125	N 126	N 127
		WATER	SAMPLES	

TABLE 1: Sample data shown in Figure 1.

25

15

4

FIGURE 2

S231 NOV1 C189 K132 N129 WS36	S232 NOV2 C190 K133 N129 WS37	S233 NOV3 C191 K134 N130	S234 NOV4 C192 K135 N131 WS38	S235 NOV4 C193 K136 N132 WS39	S236 NOV5 C194 K137 N133 WS40	S237 NOV6 C195 K138 N134 WS41	S238 NOV6 C196 K139 N135 WS42	S239 NOV7 C197 K140 N136 W	S240 NOV7 C198 K141 N137 W
S241 NOV8 C199	S242 NOV9 C200 K142 N138 WS43	S243 NOV9 C201 K143 N139 WS44	S244 NOV10 C202 K144 N140 WS45	S245 NOV1 C203 K145 N141	S246 NOV10 C204 K146 N142 WS46	S247 NOV11 K147 N143 WS47	S248 NOV11 C205	S249 NOV11 C206 K148 N144 WS48	S250 NOV11 C207 K149 N145 WS49
S251 NOV12 C208 K150 N146 WS50	S252 NOV13 C209A K151 N147 WS51	S253 NOV13 C209 N148 WS52	S254 NOV14 C210 K152 N149 WS53	S255 NOV14 C211 K153 N150 WS54	S256 NOV14 C212, 213 K154 N151 WS55	S257 NOV15 C214K K155 N152 WS56	S258 NOV15 C215	S259 NOV15 C K156 N153 WS57	S260 NOV16 K157 N154 WS58
S261 NOV16 C216 K158 N155 WS59	S262 NOV16 C217 K159A N156 WS60	S263 NOV17 C218 K159 N151 WS61	S264 NOV18 C219 K159A N156 WS62	S265 NOV19 C220 K160 N159 WS63	S266 NOV19 D33A	S267 NOV19 D33	S268 NOV19 K161 N160	S269 NOV20 D34A	S270 NOV20 D34B
S271 NOV20 D34	S272 NOV20 K162 N161	S273 NOV20 D35	S274 NOV20 D36A	S275 NOV21 D35	S276 NOV21 D37	S277 NOV21 K163 N162	S278 NOV21 D38A	S279 NOV21 D38	S280 NOV21 K164 N163
S281 NOV22 D39A	S282 NOV23 C221	S283 NOV23 C222 K165 N164 WS64	S284 NOV23 C223	S285 NOV23 C224 K166 N165 WS65	S286 NOV25 C225	S287 NOV25 K167 N166 WS66	S288 NOV25 C226	S289 NOV25 C227	S290 NOV25 K168
S291 NOV26 C228 K169 WS67	S292 NOV28 C229	S293 NOV28 C230 K170 N167 WS68	S294 NOV29 C231 K171 N168 WS69						

TABLE 2: Sample data shown in Figure 2.

V30-13
S-245
N-141
36° 07.1'N
8° 09.6'W

FIGURE 3

FIGURE 4

XBT Trace No. 18

R/V VEMA Cruise 30 Leg 13

October 11, 1973

Station 245

Appendix B

Cruise Report

Research Vessel CONRAD

Cruise 17, leg 2

November 1973

Lamont - Doherty Geological Observatory | Palisades, N.Y. 10964
of Columbia University

Cable: LAMONT, Palisades, New York State

Telephone: Code 914, Elmwood 9-2000

TWA: 710-876-2653

CRUISE REPORT

Ship Name: ROBERT D. CONRAD

Cruise No: 17

Departure: 1 Nov. 1973 from Bridgetown, Barbados
Date Port

Arrival: 30 Nov. 1973 at Abidjan, Ivory Coast
Date Port

Days at Sea: 29 Days Foreign Port: 3
No. of days in arrival port

Area of Operation: Mid-Atlantic Ridge crestal region at approximately 11° North.

Program Description: A survey of the offset portion of Vema Fracture Zone at 11° N to study bottom water characteristics and possible circulation through the fracture zone trough. Thirteen days were spent in the survey area occupying stations for STD and light scattering profiles and water samples for particulate matter concentrations and hydrologic measurements. A bottom-mounted instrument recorded currents and light scattering for the duration of the survey period.

Participants: (All L-DGO unless otherwise specified)

Eittreim, Stephen L.
Arqueros, Jose
Bovard, William
Iltzsche, Martin
McNamee, Robert
Nicolades, Andrew
Roach, David
Stennet, Joseph
Trueworthy, Paul
Walker, Alexander
Rosselot, Fred
Wilkins, Roy

Chief Scientist
E.T.
Core Crew
Air Gun
Phototechnician
Core Describer
Heat Flow
E.T.
Core Bosun
Gravity Technician
Hydro Technician
Hydro Technician

All inquiries regarding cruise should be made to the chief scientist.

ROBERT D. CONRAD, Cruise 17, Leg 2

Barbados to Abidjan, Ivory Coast

Cruise Plan

The main objective of this 29-day long leg was a survey of the central portion of Vema Fracture Zone at 11° North. The aims of the survey were to study bottom water flow through this fracture zone, short-term temporal variations in the flow, the effects of such flow on the near-bottom thermal structure and the extent of suspended sediment transport through the fracture zone. The station work involved lowerings of STD, nephelometer (both photographic and electronic), water bottles for particulate matter, bottom camera, sediment corer and T-grad. Between stations, seismic profiling was used to delineate in detail the sediment pond of the fracture zone floor, and sonobuoy reflection/refraction measurements were made on the fracture zone walls and in the sediment pond floor. Four dredge hauls were made on the fracture zone walls. A bottom-mounted current meter/nephelometer package was deployed to record during the duration of the 12-day survey. On the leg approaching Africa, one additional station, with similar measurements, was made in the deep gap separating the Sierra Leone Rise from the continental slope off Africa. This location was thought to be, in addition to Vema Fracture Zone, a possible conduit for cold bottom waters to the Cape Verde Basin.

2.

The Vema F.Z. survey began with a 1.5 day topographic survey to determine the exact sill depth which occurs at about 41°W. The sill which forms at the intersection of the fracture zone with the western wall of the eastern rift valley was found to have a depth of 4806 m, corrected. Thus Van Andel et al's (1971) interpretation of the sill was correct in location but too shallow by about 200 m. At the completion of the topographic survey, the current meter/nephelometer package was deployed and set to record for 12 days; then the station work in the fracture zone was begun. The current meter/nephelometer package was successfully recovered after 12 days. Unfortunately, the nephelometer film drive jammed after eight hours on bottom. The current meter recorded successfully and the film is presently being processed.

Results

In the Vema Fracture Zone Trough, bottom potential temperatures of 1.25° were measured with profiles showing frequent occurrence of layers of adiabatic temperature increases adjacent to bottom (6 out the 11 temperature profiles). The near-bottom adiabatic layers ranged up to a maximum of 700 m in thickness and were most frequent at the eastern end of the flat-floored fracture zone trough which has a depth of 5000 m.

Fifty water samples were obtained and filtered for particulate matter concentrations. These samples, which were taken on the same wire as the nephelometer, will be used as further "calibration" of the nephelometer units in terms of weight concentration of particulate matter. Fifteen turbidity profiles were obtained with the photographic nephelometer in the fracture zone trough coupled with bottom photographs at each station. The stations were arranged in roughly three north-south transects of the trough spanning the region of ridge axis offset. The cold Antarctic Bottom Water comprising the bottom kilometer of the water column was consistently found to be identified with a bottom nepheloid layer of moderate scattering intensity. The 4800 m sill depth and the cold bottom water ($< 1.30^\circ \text{ t}_p$) at depths of 4000 m in the trough imply flow of this relatively high density water through the sill to mix with the warmer waters in the eastern Atlantic.

In the numerous seismic profiler transects of the trough, an east-west fault or disturbed zone was discovered offsetting the ponded well-stratified sediments of the fracture zone. The fault appears to connect the points of rift valley truncation on the west and east, i.e. it runs into the norther wall at the latter's intersection with the western rift valley and into the southern wall at the latter's intersection with the eastern rift valley. Thus it appears to be the trace of the active transform fault.

Appendix C
Cruise Report
Research Vessel CONRAD
Cruise 17 leg 4
January - February
1974

Lamont - Doherty Geological Observatory | Palisades, N.Y. 10964
of Columbia University

Cable: LAMONT, Palisades, New York State

Telephone: Code 914, Elmwood 9-2000

Twx: 710-576-2653

CRUISE REPORT

Ship Name: R/V ROBERT D. CONRAD

Cruise No: 17-04

Departure: January 5, 1974

from Cape Town

Date

Port

Arrival: February 19, 1974

at

Cape Town

Date

Port

Days at Sea: 45

Days Foreign Port: 6

No. of days in arrival port

Area of Operation: South and southwest Indian Ocean

Program Description:

Geological, geophysical, and physical oceanographic reconnaissance was carried out in the primarily unexplored region of the south Indian Ocean. The earliest history of plate movement in this region was investigated by seeking "M" (Mesozoic) series magnetic lineations adjacent to the Enderby Land margin. Major latitudinal and meridional oceanographic transects were initiated to study the physical and chemical properties of the water column. Expendable bathythermograph measurements were obtained on a routine basis and four ocean bottom current meters were deployed for recovery next leg. Four piston cores were taken and dredge hauls obtained from the upper slopes of the Kerguelen Plateau and the Enderby Land margin.

Participants (all L-DGO unless otherwise specified)

Amos, Anthony	Co-Chief Scientist
Weissel, Jeffrey	Co-Chief Scientist
Jacobs, Stanley	Hydro Program Supervisor
Bauer, Edward	Hydro STD Operator
Bruchhausen, Peter	Hydro Camera/Nephelometer
House, Leigh	Gravity
Iltzsche, Martin	Airgun/Machinist
McGoldrick, John	E.T.
Nicolades, Andrew	Core Describer
Paisley-Smith, Van	Gravity
Patlo, Susan	Hydro Chemist
Rosselot, Frederic	Hydro Technician
Stennett, Joseph	E.T.
Trueworthy, Paul	Core Bosun

All inquiries regarding cruise should be made to the chief scientist.

CRUISE REPORT RC 17-04

R/V ROBERT D CONRAD CAPE TOWN - CAPE TOWN

R/V R. D. Conrad departed from Cape Town 5 January 1974 and returned to Cape Town 19 February 1974 after sailing the track shown in the accompanying figure. About 8,000 n.m. were sailed in 45 days cruise time. While underway, continuous geophysical measurements were made (total magnetic field intensity, gravity, water depth and sediment thickness), expendable bathythermograph measurements were obtained on a routine basis, and for some parts of the leg, sea surface temperature was continuously monitored. About 36 stations were occupied en route and these comprised 51 deep and shallow STD casts, 5 piston cores, 2 rock dredges, 8 camera stations, 6 nephelometer stations and 4 ocean bottom current meters were deployed.

In general, both the geophysical equipment and the hydro equipment performed satisfactorily. On the first run down to the Antarctic margin the Mobil airguns were used together for a period of about two days. In this area of 2 sec sediment thickness the results from the two synchronized Mobil guns were deemed superior to those obtained using the Lamont airgun. Synchronization of the outgoing pulses from the airguns was achieved using a triggering delay circuit whose output appeared on a high-speed Gould brush recorder. When the ship speed varied, the guns lapsed out of synchronization due to the different towing geometries used for each. Eels performed well, although the Russian designed eel was inferior to the basic Lamont eel at high towing speeds (8 kts). Martin Iltzsche built an anti-freeze unit for use with the Lamont gun in polar waters.

This unit performed excellently throughout the leg although up to 1 gallon of mix (50% water, 50% glycol) was needed every 2 hours in extremely cold water.

In periods of excessively rough weather the gravimeter was clamped but overall, the meter performed well considering the almost constant foul weather.

The hydro winch was a major source of problem during camera/nephelometer stations. The winch controls were very poorly adjusted even though the chief engineer repeatedly worked on them. On the first few camera stations especially, near accidents occurred because of faulty hydro winch controls. It is strongly recommended that every effort be made to resolve the hydro winch control problems.

The navigational equipment suffered occasional breakdowns. For most of the leg only one satellite receiver was working at any one time. Also the PDP computer used for reduction of navigational data did not work for the first 14 days. Consequently, a backlog in navigation answers resulted and this backlog was not cleared until late in the port stay.

Some preliminary results are worth noting briefly. On the run into the western margin of Kerguelen a small fault-bounded basin of intermediate depth was crossed. Sediments contained in this basin are apparently intruded by diapiric structures. One aim of this leg was to seek "M" series magnetic lineations in the south Indian basin. On the first leg to and from the Antarctic margin, magnetic anomalies (possibly M2 and M4) were encountered south of 62°S. On the second leg to and from the margin, however, only magnetic "quiet zone" was crossed from 58°S to the lower slope. Apparently, middle to upper Cretaceous sea floor exists

in that vicinity. From the 26th to the 30th January magnetic storm activity added large amplitude noise to the magnetometer records. We are confident, however, that a simple filtering process will remove most of this noise.

Glauconitic sediment was recovered in a core from the western margin of the Agulhas plateau. This core is located at an outcrop of reflections just above acoustic basement, and the sediment recovered may therefore be old.

Approximately 250 lb of rocks were dredged from 2 sites: the upper slope of the western margin of the Kerguelen plateau and the upper slope of the Antarctic continent near 63°E long. The Kerguelen rocks consists of platy and angular basalt fragments and boulders of siliceous clays which may prove datable. The Antarctic rocks are intermediate and acid plutonics varying in metamorphic grade from unmetamorphosed to garnet gneiss. One specimen of vesicular basalt was also obtained in this dredge haul.

During this leg one physical oceanographic transect from Cape Town to Kerguelen was nearly completed. A second transect running north-south from 67°S, 63°E was left half completed. During the next leg, these transects will be finished and two more north-south transects will be added. Four ocean bottom current meters were deployed in strategic locations. A minimum recording period of two weeks will provide information on the movement of bottom waters over this time interval in the south Indian Ocean.

Leg RC 17-04 has shown that the Antarctic plate in the south Indian Ocean is at least middle Cretaceous in age as evidenced by the extensive

"quiet zone" south of 58°S and the occurrence of upper Cretaceous and Cenozoic seafloor spreading magnetic lineations further north. If the anomalies tentatively identified as M2 and M4 from this leg are confirmed by model studies then the age of the Antarctic plate southwest of the Kerguelen plateau would be somewhat older. Basement morphology obtained from seismic profiling is consistent with the assumption that the Enderby Land margin of Antarctic is a rifted continental margin. Rocks dredged from the western margin of the Kerguelen Plateau support the suggestion that the Kerguelen Plateau is an oceanic basaltic platform.

Jeffrey K. Weissel
Co-chief Scientist

Appendix D

Cruise Report

Research Vessel CONRAD

Cruise 17 leg 5

February - April

1974

Lamont-Doherty Geological Observatory | Palisades, N.Y. 10964
of Columbia University

Cable: LAMONT, Palisades, New York State

Telephone: Code 914, Elmwood 9-2900

Toll 710-876-2663

CRUISE REPORT

Ship Name: R/V ROBERT D. CONRAD

Cruise No: 17-05

Departure: 25 February 1974
Date

from Cape Town
Port

Arrival: 11 April 1974
Date

at Durban
Port

Days at Sea: 45

Days Foreign Port: 6
No. of days in arrival port

Area of Operation: Southwest Indian/Antarctic Oceans

Program Description:

This was the second of two interdependent 45-day reconnaissance cruises designed to investigate outstanding physical oceanographic, geophysical and geological problems in the South Indian Ocean. Six transects of STD stations were completed on these cruises between topographic highs in order to measure the transport and spreading patterns of the Antarctic Circumpolar Current, the Agulhas Current, Antarctic Bottom Water, North Atlantic Deep Water, Antarctic Intermediate Water and the East Wind Drift. Three of four bottom-moored current meters set on Cruise 17-04 were recovered. Continuous surface temperature measurements, 138 XBT observations, 16 camera-nephelometer stations, 13 sonobuoy refraction profiles, 14 piston cores were taken. Continuous underway topographic magnetic sediment thickness and gravity data were obtained with the primary objective of deciphering the age and history of the seafloor between the Crozet Plateaus and Antarctica.

Participants: (All L-DGO)

Jacobs, Stanley
Arqueros, Jose
Bauer, Edward
Bruchhausen, Peter
Georgi, Daniel
Hitzsche, Martin
McGoldrick, John
Nicolades, Andrew
Palsley-Smith, Van
Patla, Susan
Root, Timothy
Stennett, Joseph
Trueworthy, Paul

Chief Scientist
E.T.
STD Technician
Camera/Nephelometer/Current-Meter Technician
STD Technician
Airgun/Machinist
E.T.
Core Describer
Gravity
Chemist
STD Technician/Chemist
Head E.T.
Core Bosun

All inquiries regarding cruise operations and physical oceanography should be made to the chief scientist. Inquiries concerning geophysical data should be made to Jeffrey Weissel, L-DGO, co-chief scientist on 17-04.

R/V R. D. CONRAD departed Capetown 26 February 1974, followed the track in the accompanying figure, and arrived in Durban on 11 April 1974, 45 days and 7,613 n.m. later. Continuous underway measurements were made of water depth, sediment thickness, total magnetic field intensity, gravity and surface temperature. 138 XBT casts were made and surface samples taken every 20 miles were processed for salinity, silicate and phosphate. Stations were occupied at 41 locations and included 43 STD casts, 14 piston cores, 16 bottom camera stations, 17 nephelometer stations. Bottom-moored Savonius rotor current meters with acoustic release devices deployed on 17-04 between the Crozet and Kerguelen Islands (72 days in position 500 m above bottom; wide variation in velocity and direction) and between Crozet and Enderby Land (51 days) were recovered, while a third meter between Marion Island and Antarctica was successfully interrogated but would not rise to the surface. A vertical string of 7 inclinometer current meters between South Africa and Marion Island was also recovered. Thirteen sonobuoy runs were made along Gunnerus Bank, across the Enderby Abyssal Plain and across the Crozet Plateau.

Problems with geophysical and navigation equipment during the cruise were mostly routine and readily corrected. The Magnavox satellite navigator failed near the start of the cruise, but the back-up AN/SRN-9 navigator with PDP 8/5 computer performed well. A standard Lamont eel was used except for the last week, when an eel employing Russian-made hydrophones resulted in better low frequency records. Some increase in towing noise was observed after stations in the cold Antarctic waters, apparently due to "unkinking" of the eel after being coiled on deck. The cause of an intermittent spiking on the eel signal which left small black marks on the records had not been solved at cruise end. The casing protecting the towed sensor coil of

the magnetometer cracked at one point; replacement casings were incompatible and the entire fish had to be replaced. In cold weather current was left on in the coil while on deck to counter possible freezing. The gravity table was clamped several times during heavy weather the first two weeks and was down for 24 hours on one occasion following dry-lab flooding.

Ocean surface-to-bottom STD data were taken on analog and digital recorders with excellent results. A 9006 STD system borrowed from the ELTANIN was the primary underwater sensor. Salinity, temperature and depth corrections should be minor. Launch and retrieval of the STD/SAMS equipment was difficult and hazardous and resulted in some damage and the loss of one sample bottle and thermometers. Basic alterations are needed to the present shipboard equipment before extensive STD operations are scheduled again on the CONRAD. A prototype Innerspace Technology-Lamont rosette (SAMS III) for use with STD systems received extensive tests and usage and performed reasonably well after design changes made during the first two weeks of 17-05. The SAMS III has several advantages over existing rosettes but some further design changes will be necessary to improve reliability. The electronic nephelometer was used several times on 17-05 in conjunction with the STD, but appeared overly sensitive to vibration and gave a poor signal/noise ratio.

Water samples were collected on station with Nansen bottles attached to the STD wire and with the SAMS III system. Samples were processed for salinity to monitor STD performance and provide correction data and additionally for dissolved oxygen, silicate and phosphate. Plans to take extensive mechanical BT observations were frustrated by the loss in shipment of a Lamont BT winch. A winch borrowed from the University of Capetown for 17-05 could not be made to perform satisfactorily. Systematic observations of bird life were made by interested personnel on both cruises.

Preliminary oceanographic observations include good definition of the strong Agulhas Current and Agulhas return current by several parameters; the observed separation of the Agulhas Current from the continental slope by a narrow band of lower-salinity water; an Antarctic Intermediate Water source near the Subtropical Convergence rather than near the Polar Front and no AAIW evident at all between Marion Island and Kerguelen; a deep clockwise circulation pattern in the cul-de-sac between Africa and the Agulhas Plateau; Northward flowing Antarctic Bottom Water on the SE flanks of the Agulhas Plateau and South Mozambique Rise and on the western side of the Crozet-Kerguelen passage; silicate and phosphate maxima in the AABW and minima in the NADW, and a strong phosphate maximum associated with AAIW. AABW-type water was found up against the Antarctic continental slope on two sections, with evidence for either intermittent flow downslope or a source to the east. A down-warping of all near-surface isopleths occurs over the Antarctic continental slope.

These two back-to-back interdisciplinary 45-day legs of R/V R. D. CONRAD were extremely successful. Most all scientific objectives were realized and shipboard morale was high. With the exception of fuel-related problems, little difficulty was experienced with equipment because of cold weather. A record track length was set for CONRAD on 17-04 (7,717 n.m.) and on 17-05 the CONRAD set a record for southerly penetration (68°20'S). Average miles/day (169.2) and stations/day (.911) compared favorably with earlier cruise 17 legs.

Stanley S. Jacobs
Chief Scientist

AFRICA

RC 17-05

RC 17-04

STD SECTIONS

CURRENT METER
LOCATIONS

MURPHY IS.

CROZET IS.

ANTARCTICA

Appendix E
Preliminary Cruise Report
Research Vessel MOANA WAVE
Cruise 2
April - May
1974

by

A. F. Amos

MOANA WAVE CRUISE 2 PRELIMINARY REPORT

MOANA WAVE Cruise 2 was designed to investigate the base-line conditions on the ocean floor and in the entire water column overlying a manganese nodule province centered in the North Pacific Ocean. The cruise started on 16 April, 1974 and ended on 15 May, 1974. We occupied a network of stations centered on 8°27'N; 150°47'W in the form of a N-S/E-W cross whose arms extended 1 degree in both directions from the center. Sixteen scientists from Lamont and City College of New York participated in the cruise under the major sponsorship of NOAA.

The following areas of research were undertaken:

A. OCEAN FLOOR

(i) Topography and Sedimentology

- underway 12KHz and 3.5KHz precision depth records.

(ii) Sedimentology

- box coring (photographic documentation, shear strength, bulk properties, classification, x-radiography of biologic and lithologic structures, physical properties of substrate).
- ocean floor photographs.
- nephelometry.

(iii) Manganese Nodules

- box coring (surface and subsurface distribution).
- bottom dredging and ocean floor photographs

(number, size, morphology, degree of cover, etc.)

(iv) Benthic Ecology

- box coring (washed sample, sub-core sample left intact).
- small biological trawl (nodules, rocks examined for benthos).
- ocean floor photographs (identification of epibenthic fauna).

(v) Bottom Currents

- direct measurements (current meters)
- indirect measurements (ocean floor photographs).

(vi) Bottom Microorganisms

- cultured from box core sediments.

(vii) Trace Metals

- box core sediments.

B. WATER COLUMN

(i) Physical Oceanography

- continuous profiles of salinity and temperature (STD) surface to bottom.
- hydrographic stations (samples for salinity analysis and reversing thermometers).
- bottom and near-bottom currents (level of no motion for geostrophic determinations).
- underway temperature profiles to 750 m (XBT's).

(ii) Chemical Oceanography

- determination of pH, alkalinity and dissolved O_2 concentration at all depths.
- determination of nutrients (NH_3 , NO_3 , NO_2 , PO_4 , SiO_4) at all depths.
- determination of nutrient utilization during enrichment study.
- trace metal (Hg, Cd, As, Pb, Cu, Zn, Cr, Ni, Se, V, Be) analysis from near surface and near-bottom samples.

(iii) Biological Oceanography

- nanoplankton - net plankton productivity
- chlorophyll a determinations.
- photosynthetic capacity and photosynthesis-light intensity relationship.
- enrichment study (phytoplankton growth experiment in bottom water/surface water mixtures.
- phytoplankton taxonomy.
- Secchi disc measurements.

(iv) Suspended Particulate Material

- nephelometry (continuous profiles of light scattering: surface to bottom).
- particulate dry-weight analysis.
- organic carbon, nitrogen determinations.

C. MISCELLANEOUS EQUIPMENT AND EXPERIMENTS

- Satellite Navigation System (SATNAV)
- Acoustic Transponding Navigation System (ATNAV)

- continuous pyroheliometer measurement.
- H-P 9830 computer (system of programs devised to process hydrographic data at sea).

This cruise afforded a particularly good opportunity to do multiple near-bottom STD profiles in the North Pacific Ocean to continue work started in this area (Gordon and Gerard, 1970) and to compare time-series nephelometry and near-bottom temperature and salinity variations with conditions found in similar experiments in the Atlantic Ocean (Eittreim and Amos, 1974).

A summary of the measurements made is given in Table 1. The station locations are shown in Figures 1-4. A more detailed description of the STD/Hydrographic and ATNAV/Current Meter programs follows. Cruise Track shown in Figure 1A.

PHYSICAL OCEANOGRAPHY

I. STD/Hydro Stations

STD/Hydro stations combine the use of the continuously recording salinity/temperature/depth (STD) sensor with standard hydrographic observations using sampling bottles equipped with deep-sea reversing thermometers. During the cruise a rosette sampler (Niskin, 1968) was used to trigger the sampling bottles for the first 24 stations (until the sea cable used to trigger the sampling bottles broke down rendering the continued use of the rosette and the STD impossible). The rosette sampler held 12 x 12 liter Niskin bottles (six with thermometer frames). These bottles were tripped on a command

TABLE 1.

DATE	TIME Z START END		ACTIVITY	CAMERA STN #	STD + HYDRO STN	TRACE METAL HYDRO	BOX CORE	NEPH. METER	SHALLOW CAST	SUB- BOTTOM TRAWL	DEEP HYDRO	MINI LUB	CURRENT METER	OTHER
Apr. 16 21	0802	0255	Steam Honolulu to Stn. #1	-	-	-	-	-	-	-	-	-	-	-
21	0255	1400	Occupy Stn. #1	-	1	-	-	-	-	-	TV	-	-	TV
21 22	1400	1830	Steam between Stn. #1 & 2	-	-	-	-	-	-	-	-	-	-	-
22 26	1830	2022	Occupy Stn. #2	1	2,3,4, 5,6,7, 8,9	1	1,2	1	1,2	1	1	1	Deploy 1,2,3	-
26	2022	2358	Steam between Stn. #2 & 3	-	-	-	-	-	-	-	-	-	-	-
26 27	2358	1817	Occupy Stn. #3	-	10	-	3,4	-	-	-	2	-	-	-
27	1817	2325	Steam between Stn. #3 & 2	-	-	-	-	-	-	-	-	-	-	-
27 28	2325	0415	Occupy Stn. #2	-	11	-	-	-	-	-	-	-	Deploy 4	-
28	0415	0712	Steam between Stn. #2 & 4	-	-	-	-	-	-	-	-	-	-	-
28 29	0712	1622	Occupy Stn. #4	1	12,13 14,15	2	5,6	2	3	-	3	-	-	SES 2
29	1622	2132	Steam between Stn. #4 & 11	-	-	-	-	-	-	-	-	-	-	-
29 May 1	2132	0600	Occupy Stn. #11	2	16,17 18	3	7	3	4	2	4	-	-	-

DATE	TIME START	Z END	ACTIVITY	CAMERA STN #	STD + HYDRO STN	TRACE METAL HYDRO	BOX CORE	NEPH. METER	SHALLOW CAST	SUB- BOTTOM TRAWL	DEEP HYDRO	MINI LUB	CURRENT METER	OTHER
May 1	0600	1950	Steam between Stn.#11 & 13	-	-	-	-	-	-	-	-	-	-	-
1 2	1950	2100	Occupy Stn.#13	3	19,20 21	4	-	4	5	-	5	-	-	-
2 3	2100	0356	Steam between Stn.#13 & 10	-	-	-	-	-	-	-	-	-	-	-
3 4	0356	0830	Occupy Stn.#10	-	22,23 24	5	9,10	5	6	-	6	-	-	-
3 4	0830	1601	Steam between Stn.#10 & 2	-	-	-	-	-	-	-	-	-	-	-
4 5	1601	0400	Occupy Stn.#2	4	-	-	-	-	-	4	4	-	-	Atnav 1 & 2
5	0400	0732	Steam between Stn.#2 & 6	-	-	-	-	-	-	-	-	-	-	-
5 6	0732	1318	Occupy Stn.#6	5	-	6	11	6	7	5	7	-	-	-
6	1318	1835	Steam between Stn.#6 & 16	-	-	-	-	-	-	-	-	-	-	-
6 7	1835	1600	Occupy Stn.#16	6	-	7	12	7	8	-	-	-	-	-
7	1600	2314	Steam between Stn.#16 & 8	-	-	-	-	-	-	-	-	-	-	-
7 9	2314	0433	Occupy Stn.#8	7	-	8	14	8	9	-	9	-	-	-

DATE	TIME START	Z END	ACTIVITY	CAMERA STN #	STD + HYDRO STN	TRACE METAL HYDRO	BOX CORE	NEPH. METER	SHALLOW CAST	SUB- BOTTOM TRAWL	DEEP HYDRO	MINI LUB	CURRENT METER	OTHER
May 9	0433	0837	Steam between Stn.#8 & 2	-	-	-	-	-	-	-	-	-	-	-
9 10	0837	2203	Occupy Stn.#2	8	-	9	15	-	-	-	10	-	Recover 2,3,1	Atnav 3,4,5
10 11	2203	1146	Steam between Stn.#2 & 1	-	-	-	-	-	-	-	-	-	-	-
11 12	1146	0300	Occupy Stn.#1	9	-	10,11	17	-	10	-	11	-	-	-
12 15	0300	1648	Steam between Stn.#1 & Honolulu	-	-	-	-	-	-	-	-	-	-	-

Figure 4

signal from the deck control unit, obviating the need for attaching the bottles individually to the cable and waiting for a messenger to descend and trip them. As each bottle was tripped, the exact output from all three STD parameters was noted giving us a more accurate measurement of the depth at which each one was tripped than is normally possible with a standard hydrographic cast. Both the STD and a bottom-finding pinger were attached directly to the large frame of the rosette sampler which allowed for (a) close proximity of STD-rosette for good calibration; (b) accurate determination of how far above the ocean floor our samples were collected and some measure of protection from mechanical shock during launching and recovery procedures. Despite the large size of this STD-rosette-pinger package, and the lack of a 'hero' platform, safe launchings and recoveries were made by using the hydraulic 'A' frame, the large opening in the rail and snubbing lines on the underwater package. A detailed description of the techniques we used in taking the STD stations is given in Amos (1973). The salinity and thermometer data from the rosette samples were used to (a) describe the physical oceanography of the water column and augment the STD data (b) provide in situ calibration data for the STD sensors. Sample spacing in the water column was determined largely by the needs of other programs (trace metals, particulates, primary productivity, etc.) whose samples came from the same Niskin bottles. An attempt was made, however, to cover the entire water column with samples to adequately describe its dissolved oxygen and nutrient content.

When the sea cable conductor shorted out, it was decided

not to replace it with the spare as its length of 5400 meters was marginally adequate to reach the ocean bottom. The STD-rosette was abandoned and the 12-liter bottles were put directly onto the sea cable after this. Fifteen additional hydro stations were occupied in this way.

II. Data Reduction, Storage and Display System

A series of programs were written during MOANA WAVE 2 to reduce, store and display the hydrographic data.

A Hewlett-Packard Model 9830 with high speed page printer was available on board and was found to be a most versatile computer to perform these tasks.

Programs written to date:

- THERM 1 - computes temperature, thermometric depth, for hydro stations
- THERM 2 - computes temperature, thermometric depth for rosette stations and compares these data with STD temperatures and depths
- SALIN 1 - computes corrected salinity from conductivity ratio of samples run on an inductive salinometer
- SALIN 2 - computes salinity as above for rosette samples and compares with STD derived salinities
- TSTORE - stores thermometer calibration data on cassette
- ILIST - lists thermometer calibration data stored on cassette

- DSTORE - stores hydrographic data on cassette
- HLIST - lists hydrographic data on cassette
- SIGMA - computes sigma-T from temperature and salinity
- SDVEL - computes sound velocity from temperature, salinity and depth.

III. ATNAV/Current Meter Program

(a) ATNAV System

At Station 2, in the center of our survey grid, an Acoustically Transponding Navigation (ATNAV) system was deployed. This system made by AMF Inc., consists of 3 bottom-mounted acoustic transponders, deployed in a triangle whose sides are approximately 5 km in length. Precise navigation of both the surface vessel and a fourth, submerged transponder (attached to the dredge or camera wire, for example) with respect to the fixed beacon locations on the ocean floor is obtained using the ATNAV system. The purpose of the ATNAV system was three-fold in this study:

1. To provide an accurate location system for our main central station so that we could reoccupy it at any time throughout the survey.
2. Precisely locate the position of a camera (for example) so that the effects of dredging on the ocean floor may be photographed after the dredging has occurred.
3. Provide recoverable anchorages for 3 of the 4 strings of current meters that were deployed at Station 2.

The shipboard end of the ATNAV system consists of a transducer, deck command unit, PDP-11 computer, teletypewriter and a flat-bed plotter. A towable transducer was provided with the system, but as MOANA WAVE did not have a suitable winch to handle the towing body and faired cable, a non-towed transducer was used, necessitating stopping the ship before the transducer could be lowered.

The ATNAV program can also be regarded as an evaluation of the whole system, used here for the first time in the deep ocean, as a tool to aid in research on manganese nodule areas (Figure 5 shows an example of an ATNAV plot).

(b) Current Meters

Nine Geodyne film-recording current meters (three Model 101, six Model 102) were deployed on four separate arrays: three on the ATNAV beacons at the apices of the ATNAV triangle (designated sites A, B and C) and one in the center of the triangle (designated site D). The distances between these arrays was considered to be insignificant (as far as horizontal variability of currents in this deep ocean basin is concerned) although there were some small seamounts within our study area.

The heights of the current meters above bottom were 10, 20, 30, 50, 100, 210, 410, 1010, 2010 meters. They were deployed in three strings of 2 meters each and one string of 3 meters (Table 2).

129-13-18-6

ATNAV PLOT OF HYDRO #34

KEY
 O = SHIP'S POSITION
 + = SUBMERGED XPONDER POSITION
 X = ATNAV BEACON LOCATION

Y-AXIS (meters)

-1852. -926.0 0.0000 926.0 1852. 2878. 3704. 4630.

X-axis (meters)

END STATION

STEAMING ON WIRE

START STATION
(SHIP DRIFTING)

TABLE 2

CM #	SITE	# OF CM's IN ARRAY	HEIGHT ABOVE BOTTOM (m)	REMARKS
2	A	3	30, 50, 100	Acoustic release failed to respond to release command*
3	B	2	210, 410	Recovered intact
1	C	2	1010, 2010	Recovered intact
4	D	2	10, 20	Left for recovery in Oct. 1974

*A further attempt to recover these will be made in October 1974.

A typical array is shown in Figure 6.

Deployment

Each array was deployed by first lifting the main flotation and the current meter immediately below that clear of the deck and into the water using the coring winch and 'A' frame on the ship's stern. When these were in the water they were released and allowed to float away from the ship by putting a few turns on the engines (if necessary), while paying out the polypropylene wire from storage reels. Each subsequent meter and the acoustic beacon were made slightly positively bouyant by adding a single 16" diameter glass sphere immediately above them. When all the line of each section was payed out, it was stoppered-off around a cleat while the next current meter or beacon was attached to the

Figure 6.

Details of (top and bottom) connections to current meters.

end (with its section of line already attached to it). This was then lifted over the stern manually and cast off and the process repeated until only the anchor weight remained on deck. This was then manually pushed over the stern to complete the deployment (it had already been placed close to the edge of the ship, but tied off to prevent a premature launch).

The descent rate was approximately 70 m/min except for CM #4 which used a main flotation package of two 16" spheres. This descended at approximately 120 m/min.

Recovery

This was accomplished at night because we have found that the flashing surface beacon is the best way to visually locate the flotation package once it has surfaced. Unfortunately one of the flashers failed due to a faulty pressure switch, but we were able to spot the yellow polypropylene line even though the visibility was extremely poor due to heavy squalls. The long lengths of line were hauled aboard using a capstain on the hydrographic winch. The meters and beacons were hauled aboard manually. The ascent rate was approximately 100 m/min.

General Notes

(i) The AMF flotation package (3 x 17" diameter Benthos spheres in a vertical frame did not ride well on the sea surface when ballasted only by a single current meter (or acoustic beacon). A triangular package with the flag in the

center would be preferable for better visibility.

(ii) Although the acoustic beacon provides continuous slant-range data (displayed on Nixie tube readout) while the package is ascending and when it is on the surface, a submersible radio direction finder beacon would be a useful addition to aid in recovery.

BIBLIOGRAPHY

- AMOS, A.F., 1973. The Deep STD Station: Techniques for making surface-to-bottom STD Profiles and some examples of Abyssal Microstructure: Jan. 1973 Proceedings, Second Plessey Environmental Systems' STD Conf. and Workshop, San Diego, Calif., pp 87-101.
- EITTREIM, S. and A. F. AMOS, 1974. Bottom water characteristics of Vema Fracture Zone (Abstract): Trans. AGU 55(4), 316.
- GORDON, A.L. and R. D. GERARD. North Pacific Bottom Potential Temperature. Geo. Soc. of America, Memoir 126, 1970.
- NISKIN, S., 1968. A deck command multiple water sampler. Mar. Sci. Instrument. 4, 19-24, Plenum Press.

APPENDIX F

ANALYSIS OF SIX YEARS OF PELAGIC
TIDAL HEIGHTS FROM THE EASTERN
NORTH PACIFIC OCEAN

by

TED N. BAKER AND ALI A. NOWROOZI

ANALYSIS OF SIX YEARS OF PELAGIC
TIDAL HEIGHTS FROM THE EASTERN
NORTH PACIFIC OCEAN ¹

TED N. BAKER and ALI A. NOWROOZI ²

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
of COLUMBIA UNIVERSITY
PALISADES, NEW YORK 10964

and

DEPT. of GEOLOGY, COLUMBIA UNIVERSITY
NEW YORK, NEW YORK 10027

Abstract

An ocean bottom geophysical station, OBS III, was implanted on the floor of the Pacific Ocean in May, 1966, at a depth of 3903 meters about 160 km off the coast of Northern California. This station was in continuous operation until September 10, 1972. Nearly six years of tidal height are analyzed for a number of components. Amplitudes and Greenwich epochs for the M2, S2, K1 and O1 components are compared with theoretical and empirical cotidal charts for the area. Reasonable agreement exists for each component with at least some of the respective charts. However, the uncertain position of the amphidromic point for each component is not resolved.

---

1. Lamont-Doherty Geological Observatory Contribution No. 0000

2.
Present Address: Dept. of Geology, Pahlavi University,
Shiraz, Iran

INTRODUCTION

In May, 1966, an ocean bottom geophysical station, OBS III, was implanted on the floor of the Pacific Ocean at $38^{\circ} 9.2'N$ and $124^{\circ} 54.4'W$. This location is about 160 km west of San Francisco, California. The package contains short and long period seismometers, current speed and direction sensor, temperature sensor, hydrophones and a vibrotron pressure sensor for measurement of oceanic tidal height. Recorded data, operating power and remote commands are transmitted to the Point Arena, California, shore station by means of a submarine cable. Details of instrumentation, power supply and transmission of data are given by Sutton et al (1965) and Latham and Nowroozi (1968). OBS III operated continuously until September, 1972, when the cable failed. This paper is an analysis of the ocean tide data collected over a period of nearly six years prior to the cable failure. Shorter lengths of this data have been analyzed previously by Nowroozi et al (1969), Nowroozi (1970) and Nowroozi (1972).

DATA

Output from the vibrotron pressure sensor was recorded on both strip chart and magnetic tape. For this analysis, a total of 52,128 consecutive hourly heights from 0000 hours October 1, 1966 GMT through 2300 hours September 10, 1972 GMT were read and punched on cards. Theoretical or equilibrium tidal height was calculated for the same period as the observed data by a method following Longman (1959) except that the fourth power of the sun's parallax was included.

METHODS of ANALYSIS

Any record of observed tides will contain non-periodic fluctuations in sea level in addition to the periodic fluctuations due to tides. Possible sources of non-periodic fluctuations are meteorological variations, changes in the mean density of the water column above OBS III and instrumental drift.

HARMONIC ANALYSIS

In this method, the record is analyzed without regard to particular frequencies, so that the continuum of background noise may be determined as well as tidal contributions. Let N equal the number of hourly readings. Then the frequencies (in cycles/hour) are given by

$$\omega_j = j/N, \quad j = 1, N/2$$

In this analysis, $N=52,128$. This corresponds to periods from 2 hours to 52,128 hours. A considerable saving in time was achieved by using a version of the fast Fourier transform algorithm given by Cooley and Tukey (1965). This algorithm does not limit the number of input points to 2^M (where M is an integer) but allows an arbitrary number of input points. Computing time to transform 52,128 points (producing 26,064 harmonics) was about 55 seconds on an IBM 360/91. Before

4.
transforming, the mean and linear trend were removed by a linear least squares technique.

CONVOLUTION

In this method, the record is analyzed only for those frequencies which are of interest. We used 63 tidal frequencies, taken from Table 2 of Schureman (1958). Computing time for convolution and elimination of 63 components was about 4 minutes on an IBM 360/91.

ELIMINATION

In a limited series of observations, the amplitude and phase of each component are contaminated by the effects of the other components. The only components not affected are those that have an integral number of cycles in the length of data analyzed. Clearly, it would take an extremely long series of observations for this to be the case for each component. It would not be practical to analyze such a length of data even if it were available. Alternatively, one may correct the amplitudes and phases obtained from a limited series of data. We used a method similar to that given by Schureman (1958). Tidal constants obtained by convolution were corrected by this method in 4 iterations.

TIDAL CONSTANTS

Table 1 gives the amplitudes, local epochs and Greenwich epochs of major diurnal and semi-diurnal components. The local epoch $K(\omega_j)$ is the phase lag behind the local equilibrium tides. It is related to the Greenwich epoch $G(\omega_j)$ and the local longitude L (where L is taken positive for west longitude and negative for east longitude) by

$$G(\omega_j) = K(\omega_j) + P \cdot L$$

where P is 1 for diurnal and 2 for semi-diurnal components.

Only those components whose amplitude is greater than 1 cm. by at least one of the two methods of analysis are given. Amplitudes and phases of constants obtained by convolution are corrected for contamination, while those obtained by harmonic analysis are not. Therefore, constants obtained by convolution are believed to be more reliable than those obtained by harmonic analysis. The amplitudes for most components agree quite well for both methods. However, the phases of the smaller components generally do not agree very well. The amplitudes and phases of the larger components agree quite well with an earlier analysis of shorter lengths of this data (see Nowroozi (1972)).

Table 2 gives the constants for the long period components. These are not to be taken as particularly reliable, since the continuum of background noise is significant at these periods. The constants for Mf, MSf and Mm are probably more reliable than those for Ssa and Sa for two reasons: (1) the noise in the vicinity of the former has less amplitude, and (2) there are many more cycles of the former in 6 years than there are of the latter. There is poor agreement between these constants and those obtained by Nowroozi (1970) and Nowroozi (1972).

In an attempt to improve these estimates, the hourly readings were low pass filtered and then re-sampled at 24 hour intervals. The decimated record was broken into 8 twenty-six week segments which represented the least noisy part of the record. After being transformed, the 8 resulting amplitude spectra were averaged, resulting in an increase in the signal/noise ratio of a factor of $\sqrt{8}$. Unfortunately, there was still too much long period noise to see any spectral peaks at tidal frequencies. In principle, however, it should be possible to resolve these components if a long enough record is available. One should thus

beware of tidal constants given for long period components based on analysis of short lengths of data, even up to a year.

SPECTRA

Amplitude spectra obtained from nearly 6 years of hourly observed tidal height and hourly calculated theoretical (or equilibrium) tidal height are given in figures 1, 2, 3 and 4. Figure 1 gives the spectra for those components that have significant amplitude. As one would expect with tidal measurements in deep water, there are no significant compound tides or overtides in the spectrum. Therefore, the spectrum is not shown for periods shorter than 9.65 hours. Appropriate portions of figure 1 are expanded and shown in figures 2, 3 and 4.

The long period part of the spectrum is shown in figure 2. The component having a period of 219.15 hours is labeled Mm + Mf after Nowroozi (1972). ^{This component is given by Schureman (1958) as A7.} The noise appearing in the spectrum of theoretical tides is entirely digital. The noise in the spectrum of observed tides is quite large, particularly for periods greater than about a week. Since the long period components have small amplitudes (probably 1 to 2 cm.), they are lost in the continuum.

Diurnal components are shown in figure 3. Most components occurring in the noise-free equilibrium spectrum are seen in the observed spectrum. Only the smallest components are lost in the background noise. Figure 4 displays the semi-diurnal components. Again, there is excellent agreement between the observed and noise-free spectra. A notable feature of the K1, O1, N2 and M2 components is the presence of tidal cusps in the spectra, even in the noise-free equilibrium spectra.

COTIDAL CHARTS

The tidal constants obtained for OBS III will now be compared with cotidal charts of the eastern North Pacific. These are either empirical charts, based on shore and island tide gauges, or theoretical charts, based on numerical integration of Laplace's tidal equations. Empirical charts are taken from Harris (1904), Dietrich (1944) and Villain (1952). Theoretical charts are taken from Bogdanov et al (1964), Hendershott (1966), Tiron et al (1967), Pekeris and Accad (1969) and Munk et al (1970). Charts are given for the M2, S2, K1 and O1 components.

The M2 cotidal charts are given in figure 5. The amplitude and Greenwich epoch for M2 are 54.25 cm. and 199.6° by convolution, and 53.89 cm. and 218.8° by harmonic analysis. These values agree fairly well with charts given by Villain (1952), Bogdanov et al (1964) and Tiron et al (1967). Amplitudes are in fairly good agreement with those charts for which amplitudes are given. Phases agree reasonably in most cases except for Pekeris and Accad (1969). Their chart has the wrong sense of rotation around the amphidromic point.

Figure 6 gives the cotidal charts for the S2 component given by Dietrich (1944), Bogdanov et al (1964) and Tiron et al (1967). The amplitude and Greenwich epoch for S2 are 13.02 cm. and 211.4° by convolution, and 13.18 cm. and 210.9° by harmonic analysis. Amplitudes do not agree well with Bogdanov et al (1964) or Tiron et al (1967). However, phases agree well with Dietrich (1944) and Bogdanov et al (1964).

Cotidal charts for the K1 component are given in figure 7. The amplitude and Greenwich epoch for K1 are 43.23 cm. and 219.1° by convolution, and 43.86 cm. and 228.5° by harmonic analysis. Amplitudes are not in good agreement with any of the charts given. Phases agree fairly well with all of the charts.

The O1 cotidal charts are given in figure 8. The amplitude and Greenwich epoch for O1 are 28.37 cm. and 219.8° by convolution, and 28.22 cm. and 228.3° by harmonic analysis. These amplitudes are larger than those given by Bogdanov et al (1964) and Tiron et al (1967). However, phases agree quite well with all of the charts given.

CONCLUSIONS

We have analyzed nearly six years of continuous tidal heights, revealing the amplitudes and Greenwich epochs for several constituents. At present, this is the longest series of tidal heights which has been measured in the deep ocean. This data is free from compound tides and overtides caused by shallow water.

The M2, S2, K1 and O1 components are compared with cotidal charts for the eastern North Pacific Ocean. The constants for each component agree reasonably well for at least some of the respective charts. A conspicuous feature of the charts for a given component is the uncertainty of the position of the amphidromic point. Although these constants must be considered for the construction of any new cotidal charts for the North Pacific, they are too far from the amphidromic point to resolve its position more accurately. Hopefully, more deep ocean tidal measurements will be done to settle this question.

ACKNOWLEDGMENTS

Drs. A. Gordon, K. Hunkins and J. Kuo kindly reviewed this manuscript.
This research was supported by Atomic Energy Commission contract
no. AT(11-1)2185 and National Science Foundation contract no. GA 21473.

REFERENCES

- Bogdanov, K.T., K.V. Kim, and V.A. Magarik, Numerical solution of tide hydrodynamic equations by means of BESM-2 electronic computer for the Pacific area, Tr. Inst. Okeanol. Akad. Nauk SSSR, 75, 73-98, 1964.
- Cooley, J.W. and J.W. Tukey, An algorithm for the machine calculation of complex Fourier series, Math. Computation, 19, 297-301, 1965.
- Dietrich, G., Die Schwingungssysteme der halbund eintägigen Tiden in den Ozeanen, Veroff. Inst. Meersk., Univ. Berlin, A41, 1-68, 1944.
- Doodson, A.T., The harmonic development of the tide generating potential, Proc. Roy. Soc. Ser. A., 100, 305-329, 1921.
- Harris, R.A., Manual of Tides, part 1 to 5, appendices to reports, U.S. Coast and Geodetic Survey, Washington D.C., 1894-1907.
- Hendershott, M.C., The numerical integration of Laplace's tidal equations in idealized ocean basins, Proc. Symp. on Math-Hydrodynamical Investigations of Physical Processes in the Sea, Moscow, 1966.
- Latham, G.V., and A.A. Nowroozi, Wave, weather, and ocean bottom microseisms, J. Geophys. Res., 73, 3945-3956, 1968.
- Longman, I.M., Formulas for computing the tidal accelerations due to the moon and sun, J. Geophys. Res., 64, 2351-2360, 1959.
- Munk, W., F. Snodgrass, and M. Wimbush, Tides off-shore: Transition from California coastal to deep-sea waters, Geophys. Fluid Dyn., 1, 161-235, 1970.
- Nowroozi, A.A., G. Sutton, and B. Auld, Oceanic Tides Recorded on the Sea Floor, Ann. de Geophys., 22, 512-517, 1966.
- Nowroozi, A.A., M. Ewing, J.E. Nafe, and M. Fleigel, Deep Ocean Current and Its Correlation with the Ocean Tide off the Coast of Northern California, J. Geophys. Res., 73, 1921-1932, 1968.

- Nowroozi, A.A., J. Kuo, and M. Ewing, Solid Earth and Oceanic Tides Recorded on the Ocean Floor off the Coast of Northern California, J. Geophys. Res., 74, 605-614, 1969.
- Nowroozi, A.A., Spectrum and prediction of tides off the coast of California, Ann. Geophys., 26, 259-271, 1970.
- Nowroozi, A.A., Long-term measurements of pelagic tidal height off the coast of Northern California, J. Geophys. Res., 77, 434-443, 1972.
- Pekeris, C.L., and Y. Accad, Solution of Laplace's equations for the M2 tide in the world oceans, Phil. Tran. Roy. Soc. London, A265, 413-436, 1969.
- Schureman, P., Manual of harmonic analysis and prediction of tides, U.S. Coast and Geod. Surv. Publ., 98, 1958.
- Sutton, G.H., W.G. McDonald, D.D. Prentiss, and S.N. Thanos, Ocean-bottom seismic observatories, Proc. IEEE, 53, 12, 1909-1921, 1965.
- Tiron, K.D., Y.N. Sergeev, and A.N. Michurin, Tidal charts of the Pacific, Atlantic, and Indian oceans, Vestnik of Leningrad University 24, 122-135, 1967.
- Villain, C., Cartes des lignes cotidales dans les oceans, Ann. Hydrogr. (Paris) 1, 4(3), 269-388, 1952.

TABLE 1
Tidal Constants for Major Diurnal and Semidiurnal Components

Component	Period (hr)	Amplitude (cm)	By Convolution		By Harmonic Analysis		
			Greenwich Epoch (deg)	Local Epoch (deg)	Amplitude (cm)	Greenwich Epoch (deg)	Local Epoch (deg)
K2	11.9672						
S2	12.0000	4.55	181.9	292.1			
L2	12.1916	13.02	211.4	321.6	4.51	205.5	315.7
M2	12.4206	1.41	220.6	330.8	13.18	210.9	321.1
N2	12.6260	54.25	199.6	309.8	1.03	307.8	58.0
M2	12.6534	1.31	122.7	232.9	53.89	218.8	329.0
M2	12.8718	11.39	152.2	262.4	1.81	244.5	354.7
M2	12.9054	1.02	121.5	231.7	11.76	160.1	270.3
		1.01	160.7	270.9	1.09	160.5	270.7
OO1	22.3061				1.02	89.5	199.7
J1	23.0985	2.02	225.8	100.9			
K1	23.9345	2.44	230.6	105.7	2.07	236.2	111.3
S1	24.0000	43.23	219.1	94.2	2.49	271.2	146.3
P1	24.0659	0.27	287.3	162.4	43.86	228.5	103.6
M1	24.8332	11.46	218.8	93.9	1.39	304.1	179.2
O1	25.8193	1.15	224.7	99.8	12.57	213.0	88.1
Q1	26.8684	28.37	219.8	94.9	2.18	220.0	95.1
		4.89	210.9	86.0	28.22	228.3	103.4
					4.99	183.1	63.2

TABLE 2

Tidal Constants for Long Period Components

Component	Period (hr)	<u>By Convolution</u>		<u>By Harmonic Analysis</u>	
		Amplitude (cm)	Greenwich Epoch (deg)	Amplitude (cm)	Greenwich Epoch (deg)
Hf	327.86	1.59	106.7	1.60	104.5
MSf	354.37	0.80	108.6	0.58	105.5
Mm	661.31	3.16	353.7	1.96	7.1
Ssa	4382.90	18.10	163.9	12.04	170.2
Sa	8765.82	12.01	319.4	7.41	301.3

OBS. III, OBSERVED OCEAN TIDES
5400 HARMONICS

FIGURE 1a

OBS III, THEORETICAL OCEAN TIDES
5400 HARMONICS

FIGURE 1b

OBS III, OBSERVED OCEAN TIDES
998 HARMONICS

FIGURE 2a

OBS III, THEORETICAL OCEAN TIDES
999 HARMONICS

FIGURE 2b

OBS III, OBSERVED OCEAN TIDES
689 HARMONICS

FIGURE 3a

FIGURE 3b

OBS III, OBSERVED OCEAN TIDES
648 HARMONICS

FIGURE 4a:

OBS III, THEORETICAL OCEAN TIDES
648 HARMONICS

FIGURE: 4b

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE CAPTIONS

- FIGURE 1a. Spectrum of observed tides calculated from nearly six years of hourly heights.
- FIGURE 1b. Same as fig. 1a for equilibrium tides.
- FIGURE 2a. Spectrum of long period components calculated from nearly years of observed tides.
- FIGURE 2b. Same as fig. 2a for equilibrium tides.
- FIGURE 3a. Spectrum of diurnal components calculated from nearly six years of observed tides.
- FIGURE 3b. Same as fig. 3a for equilibrium tides.
- FIGURE 4a. Spectrum of semi-diurnal components calculated from nearly six years of observed tides.
- FIGURE 4b. Same as fig. 4a for equilibrium tides.
- FIGURE 5. M2 cotidal charts for the eastern North Pacific Ocean. Dashed lines are co-range lines in cm. Solid lines are co-phase lines in degrees relative to Greenwich.
- FIGURE 6. Same as fig. 5 for S2 component.
- FIGURE 7. Same as fig. 5 for K1 component.
- FIGURE 8. Same as fig. 5 for O1 component.

Appendix G

Small and Medium Scale
Features in the Circulation
Off the New Jersey Coast

Abstract of presentation given
at

Shelf Dynamics Program

Annapolis, April 1974

by

Arnold L. Gordon

Annual Report on Contract AT(11-1)2185

to

Division of Biomedical and Environmental Research
U.S. Atomic Energy Commission

TRANSPORT AND TRANSFER RATES IN THE WATERS OF THE
CONTINENTAL SHELF

by

Geochemical Section

Lamont-Doherty Geological Observatory
Palisades, New York 10964

Principal Investigators:

Wallace S. Broecker

Herbert W. Feely

June 30, 1974

ABSTRACT

The main effort under this contract during the past few years has been directed towards the determination of the distribution of radium-228 and thorium-228 in the oceans of the world. During the past year this study has been focused primarily on the shallow waters over the continental shelves. The radium-228 data should be of value in the estimation of mechanisms and rates of diffusion and transport across the shelf, while the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios should provide information on the rate of removal of reactive heavy metals from solution in seawater by interaction with suspended particulates and by biological processes. During the past year we have begun the collection of samples of shelf sediment and suspended particulate matter which we believe must be studied along with the water samples to permit the delineation of the source functions of radium-228 in shelf waters, and the determination of removal mechanisms of thorium-228 and other heavy metals from solution.

TABLE OF CONTENTS

Chapter I.	Introduction.
Chapter II.	Sampling and Analytical Procedures.
Chapter III.	The Distribution of Radium-228 in the Oceans.
Chapter IV.	The Variations in the Concentration of Thorium-228 and in the Activity Ratio, $^{228}\text{Th}/^{228}\text{Ra}$, in the Oceans.
Chapter V.	The Study of the Geochemistry of Radium and Thorium in the Area of the New York Bight.
Chapter VI.	Additional Geochemical Studies.
References	
Appendix A.	Radium-228 Profile at the Second GEOSECS Inter-calibration Station, 1970, in the North Atlantic. Earth Planet. Sci. Lett. <u>16</u> (1972) 141-145.
Appendix B.	The Residence Time of Thorium in Surface Sea Water and its Implications Regarding the Rate of Reactive Pollutants. Earth Planet. Sci. Lett. <u>20</u> (1973) 35-44.
Appendix C.	Distribution of ^{228}Ra in the World Ocean. J. Geophys. Res. <u>78</u> (1973) 8827-8848.

CHAPTER I - INTRODUCTION

During the past several years an investigation of the distribution of radium-228 and thorium-228 in the world oceans has been underway at this laboratory with financial support from the Atomic Energy Commission. Our primary purpose in this investigation has been to obtain enough information concerning the distribution of radium-228 in the oceans to be able to use this radionuclide as a tracer for the estimation of mechanisms and rates of diffusion of ocean water. A secondary purpose has been the attempt to use the measured variations in the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios in the oceans to provide information on the rate of removal of chemically active elements from seawater by interaction with suspended particulates and by biological processes. Reprints of three articles which summarize previous results of this investigation (Trier et al., 1972; Broecker et al., 1973; Kaufman et al., 1973) are included as appendices to this report.

Radium-228 ($t_{1/2} = 6.7 \text{ yr}$) is produced by the radioactive decay of long-lived thorium-232 ($t_{1/2} = 1.41 \times 10^{10} \text{ yr}$). The thorium-232 concentration in solution in seawater is negligible, but the thorium content of seafloor sediments provides a constant source of radium-228. Because radium is relatively soluble in seawater in comparison to thorium, radium-228 which is produced within the seafloor sediments crosses the sediment-water interface and diffuses into the seawater, and away from that interface. The sediments on some continental shelves

2

appear to be especially good sources of radium-228, and the highest concentrations of this nuclide in seawater have been found in coastal surface waters (Moore, 1969b; Kaufman et al., 1973). As these coastal waters mix with the surface waters of the open ocean, they provide the surface mixed layer with measurable concentrations of radium-228. The waters of the thermocline layer and of the deep water masses receive no comparable supply of this radionuclide via horizontal advection or eddy diffusion. Consequently, the concentrations of radium-228 in these waters are generally near or below the limits of detection. The downward movement of radium-228 from the mixed surface layer into the thermocline layer produces a concentration gradient, the steepness of which is a function of the effective constant of vertical eddy diffusion within the thermocline layer. The sediments of the deep seafloor also serve as a source of radium-228, and the upward diffusion of this radionuclide through the bottom waters and into the overlying deep water masses, which contain negligible concentrations of radium-228, produces a concentration gradient. The steepness of this gradient is a function of the rate of vertical eddy diffusion within these bottom waters. These vertical concentration gradients were first suggested by the work of Moore (1969a, 1969b), and were more firmly established by early work performed as part of this investigation (Trier et al., 1972; Kaufman et al., 1973). They are now being intensively studied as part of the IDOE program, Geochemical Ocean Sections

(GEOSECS) (Craig, 1972). In this investigation our attention is now centered on the distribution of radium-228 within the near-surface waters of the ocean, and especially in shelf waters, with the view of using this radionuclide for the study of mechanisms and rates of horizontal transport of water.

It has long been known that thorium has a relatively short residence time in seawater (Moore and Sackett, 1964; Somayalulu and Goldberg, 1966; Bhat et al., 1969; Kaufman, 1969; Broecker et al., 1973). The thorium-228 ($t_{1/2} = 1.91$ yr) which is produced by the radioactive decay of radium-228 in seawater is removed too quickly, from surface waters at least, to achieve radioactive equilibrium with its parent. The activity ratio $^{228}\text{Th}/^{228}\text{Ra}$ in surface waters is generally well below a value of 1.0 (Moore, 1969b; Broecker et al., 1973). This situation has created interest in the possibility of using thorium-228 as a tracer for studying mechanisms and rates of removal of heavy, chemically active metals from seawater by natural processes. Such metals have become potentially serious pollutants of the marine environment, and there is a great need for a more thorough understanding of their marine geochemistry.

Past Studies Within This Research Project

The investigation of radium-228 and thorium-228 in seawater was begun originally under Contract AT(30-1)3139, which was later redesignated AT(11-1)3180. In 1973 this work was shifted to Contract AT(11-1)2185. The original concept was to perform a reconnaissance study of the distribution of these radio-

nuclides in the ocean, following the original investigation performed by Moore (1969a, 1969b). Large samples of seawater, in excess of 600 liters, were needed for this work, and it soon became evident that sampling of deep water was generally impractical, especially since most sampling had to be performed aboard ships of opportunity. Therefore most of the work performed in this investigation has involved measurement of surface samples. This tendency has been reinforced by the determination that the deep waters of the ocean generally contain rather low concentrations of these radioisotopes, and thus are not easily measured with good precision.

Most samples have been collected during cruises by the research vessels of Lamont-Doherty Geological Observatory: R/V VEMA and R/V CONRAD. These have provided coverage of the surface waters of some regions of the North Atlantic Ocean, Indian Ocean and Pacific Ocean. Since these cruises were primarily designed to permit geophysical study of the seafloor, they did not give as broad a coverage of the oceans as we might desire. Sampling has also been performed, especially in the North Atlantic, aboard vessels belonging to other institutions or to the U.S. Coast Guard. Some of these shorter cruises have more nearly provided the type of coverage which we wished to obtain, but in regions of only limited area. Results of measurements of most samples collected during 1966 to 1970 were reported by Broecker et al. (1973) and Kaufman et al. (1973). Reprints of these papers are attached to this report as Appendices A and B.

When the IDOE GEOSECS Program was conceived to provide coordinated measurement of many properties in a series of profiles across the oceans of the world, it was decided that measurements of radium-228 and thorium-228 should be included. Since the preliminary testing and intercalibration had to be performed before IDOE funds became available, the preliminary studies of radium-228 and some of the work with radium-226 was performed as part of this investigation. These results have been published by Broecker et al. (1970) and Trier et al. (1972). Thus far during Project GEOSECS numerous vertical profiles of near-surface samples and some vertical profiles of near-bottom samples have been obtained for analysis of radium-228 and thorium-228. These will complement the many surface samples collected as part of the present investigation.

Most samples collected during 1966 to 1968 were analyzed for thorium-228 as well as for radium-228, but during 1969 and 1970 only radium-228 was measured. Reevaluation of the early results during 1971 led to the reinclusion of thorium-228 in the analytical scheme for samples collected during that and later years.

The data which have been obtained thus far for surface water of the oceans have indicated that the concentration gradients of radium-228 are steepest in the water of the coastal zone. It appears, therefore, that radium-228 should serve as a good tracer for studies of the mixing of coastal waters with waters of the open ocean. It has also been found that

thorium-228 is more depleted in seawater, relative to its radium-228 parent, in coastal waters than in waters of the open ocean. Evidently those chemical and biological processes which remove thorium from seawater are most active in the shallow waters over the continental shelf. Of course, it is within the coastal zones of the ocean that the greatest number and most serious problems of pollution of the marine environment occur, and it is here that radioactive tracers such as radium-228 and thorium-228 have their greatest potential usefulness. Consequently, during the past year our main efforts within this research project have been shifted to the study of these radionuclides in the shelf environment.

Other studies, including the measurement of concentrations of lead-210 and polonium-210 in seawater, and some aspects of a study of the extraction of reactive metals from fresh waters by natural processes (in the Canadian Government's Experimental Lakes Area) were performed as part of this research project.

Present and Future Studies Within This Research Project

The current principal aims of this research project are to obtain enough information about the marine geochemistry of radium and thorium isotopes to permit the use of radium-228 to trace the mixing of shelf water with the waters of the open ocean, and to obtain enough information about the distribution of various heavy reactive metals between the water, sediment, and dispersed particulate phases to be able to predict the

fate of such metals when they are introduced into the marine environment.

The results of the early reconnaissance studies begun under this project showed that radium-228 concentrations were generally higher in coastal zone surface waters than in the waters of the open ocean, but that the magnitude of this effect varied from one coast to another. It was decided, therefore, that as many different coastal zones should be sampled as was possible. What amounts to a reconnaissance study of coastal zones has been undertaken primarily by taking advantage of vessels of opportunity. This effort has been fairly successful during the Atlantic and Pacific GEOSECS cruises, with samples being collected for this project as the R/V KNORR in the Atlantic and R/V MELVILLE in the Pacific entered or left ports at the completion or beginning of legs of the cruises. We were also invited to accompany Dr. Stuart Kupferman of the College of Marine Sciences of the University of Delaware aboard the R/V EASTWARD on two cruises, one in 1972 and one in 1974, and to collect samples as this vessel crossed the continental shelf, the slope water, and the Gulf Stream on its way to and from the Sargasso Sea on cruises between Lewes, Delaware and Beaufort, North Carolina. Vessels chartered by the City University of New York, formerly the R/V ATLANTIC TWIN and more recently the R/V COMMONWEALTH, have been used for sampling in the region of the New York Bight. During the past year additional 250 gallon polyethylene tanks have been acquired to permit the

processing of up to four samples at once, and a submersible pump has been put into use, so that vertical profiles of water samples can be taken at individual stations over the continental shelf. It is expected that the differences between the various coasts with respect to the concentrations and distributions of radium and thorium isotopes in the coastal waters will be related to the currents along those coasts and to the mineralogical composition of sediments on the shelves. Hopefully these measurements will indicate the extent to which the radium and thorium distributions vary with variations in these hydrologic and geologic factors.

It is anticipated that a major effort to delineate the source functions of radium-228 in shelf waters of the New York Bight will be begun during the coming year as a main aspect of this research project. Our greatest efforts at delineating this source function will be directed at estimating the rate of release of radium-228 into the seawater from shelf sediments, since this seems to be the only important source of this nuclide. One approach to this study will involve the collection of cores of sediment where this is feasible, and the measurement of radium-228 concentrations within the pore water as a function of depth within the core. A diffusion model will then be used to estimate the rate of flux of radium-228 out of the sediment based on the observed gradients in the pore water. It is anticipated that other nuclides will also be measured in these pore waters, as

described below. During May 1974 a few cores were collected in the New York Bight to test the feasibility of such measurements of pore water.

It is anticipated that the contribution of radium-228 and thorium-228 to the shelf water by rivers is negligible when considering the entire shelf water mass, but to verify this it is planned to undertake a limited amount of sampling of the streams which discharge into the New York Bight area. During the past year a few samples were collected in Lake Ontario, in conjunction with other studies being performed in that lake, to see what levels of radium-228 and thorium-228 might be expected in a large fresh water system, and a few samples were collected in the Hudson estuary.

A second aspect of our investigation which we expect to increasingly emphasize is the study of the removal of reactive heavy metals from seawater by natural processes. Most importantly we will undertake to determine the effectiveness of removal of radium-228 and thorium-228 from seawater by reaction with inorganic and organic particulates suspended in the water. During May 1974 we succeeded in separating the particulates from one 800 liter sample of water using a continuous flow centrifuge. The sample appeared to consist largely of phytoplankton. It is anticipated that numerous such samples of particulate matter will be separated and analyzed radiochemically for radium and thorium isotopes and for other radionuclides, as described below, during the coming year.

It is anticipated that the samples of sediment, pore water, seawater and suspended particulates which are to be analyzed for radium-228 and thorium-228 will be analyzed as well for other reactive heavy metal radionuclides of interest. These will include lead-210 and polonium-210, which have previously been measured in seawater as part of our research project. It is expected that plutonium and some gamma emitting fission products will also be included because of their potential environmental significance. The analysis of plutonium in seawater samples was planned and was begun during the past year, but was then suspended. We hope to be able to undertake these analyses during the coming year to enable our studies to provide as many environmentally significant data as is possible.

CHAPTER II - SAMPLING AND ANALYTICAL PROCEDURES

Analysis of Radium-228 and Thorium-228 in Seawater

Sampling and analytical procedures have been modified from time to time during our investigation, but the procedures described here have been used for the great majority of our samples. Seawater samples of 600 to 1700 liters have been collected either by means of a permanently mounted pump for surface samples, a submersible pump for near-surface samples to a depth of about 350 meters, or by multiple lowerings of 200 liter Gerard-Ewing samplers for samples of deep water. The water is placed in one or more polyethylene tanks of 760 liters (200 gallons) or 860 liters (225 gallons) capacity. The seawater solution is acidified with hydrochloric acid and is stirred. A solution containing iron chloride and barium chloride carriers and thorium-230 spike solution (usually 14.8 dpm per tank) is added, and the sample is again stirred. Enough ammonium hydroxide is then added to raise the pH to about 7, producing a mixed precipitate of iron hydroxide, with coprecipitated thorium, and barium sulfate with coprecipitated radium and thorium. This mixed precipitate is allowed to settle to the bottom of the polyethylene tanks, is separated from the supernatant solution, and is returned to the laboratory for analysis.

The iron hydroxide, with its coprecipitated thorium, is dissolved in hydrochloric acid, is separated from the insoluble barium sulfate residue, which contains the radium, by

centrifugation, and is analyzed for thorium-228 using the procedures described by Moore (1969a) and by Broecker et al. (1973). Iron is removed from the thorium fraction by isopropyl ether and the solution is passed through an anion exchange column to remove the uranium present. The eluate is evaporated to a smaller volume (~150 ml), and NH_4OH is added to reprecipitate hydroxides. These are then separated from the solution, dissolved with HCl , and passed through a cation exchange column. The thorium fraction, which remains on the column, is eluted with oxalic acid and evaporated to dryness in the presence of nitric and perchloric acids. The thorium is then taken up in HNO_3 and extracted into TTA (thenoyltrifluoroacetone) at a pH of about 2. The TTA is evaporated from a stainless steel disk creating a thin source of thorium suitable for α counting.

The BaSO_4 fraction of the precipitate is fused with Na_2CO_3 - K_2CO_3 . The carbonate formed is converted to chloride with HCl , rinsed, and dissolved in distilled water. The radium solution is freed of all thorium by means of repeated $\text{Fe}(\text{OH})_3$ precipitations. A thorium-230 spike is then added and the solution stored for a known period of time during which thorium-228 grows toward equilibrium with its parent radium-228. The thorium is then separated by several $\text{Fe}(\text{OH})_3$ precipitations, processed as described above, and mounted for α spectrometric measurement.

During the period of thorium-228 growth in the radium solution, the radium-226 content of the solution is determined by sweeping radon gas, accumulated for a known period of time, out of the solution with helium carrier. The radon is frozen out in liquid air cooled traps and quantitatively transferred to an α scintillation counter.

The thorium-228 content of the sample is calculated from the $^{228}\text{Th}/^{230}\text{Th}$ ratio measured on the thorium fraction and a knowledge of the amount of thorium-230 spike added per unit of seawater. Corrections are made for the extent of thorium-228 growth during storage in the precipitate and for decay after laboratory separation. The radium-228 content is obtained by measuring the $^{228}\text{Ra}/^{226}\text{Ra}$ ratio in the radium fraction and the measured concentration of radium-226 in water samples collected at the station. From the $^{228}\text{Th}/^{230}\text{Th}$ ratio measured on the stored radium fraction and a knowledge of the amount of thorium-230 spike added to the solution, the amount of thorium-228 generated during the growth period can be calculated. From this the amount of radium-228 in the radium fraction can be determined. The radium-226 in the radium fraction is calculated from the amount of radon-222 generated in the solution during the known growth period.

Measurements of reagent blanks have indicated that radium-228 and thorium-228 are introduced into the samples by the reagents, and particularly by the barium chloride which is used to coprecipitate radium from seawater. Our best estimate

at the present time is that 0.5 ± 0.1 dpm of both radium-228 and thorium-228 are introduced into each 850 liter tank during sample processing. During the first few years of the project less carrier was used, and only 0.2 ± 0.04 dpm of both radionuclides was introduced into each tank. Current data are corrected for these blank values, and older data are in the process of being corrected. The accuracy of this blank correction is verified by the calculation of essentially zero thorium-228 concentrations in samples of deep water from the Southern Atlantic collected during the Atlantic GEOSECS cruise. This blank correction represents a significant fraction of the radium-228 and thorium-228 activity in some samples. It has represented 50% to 100% of the activities of thorium-228 and radium-228 in samples collected south of the Antarctic Convergence, and 10% to 20% of the activities of these radionuclides in samples of deep water collected in the North Atlantic. For typical seawater samples collected over the continental shelf of North America it has represented 10% to 30% of the activity of thorium-228, but only 0.5% to 1% of the activity of radium-228.

Our thorium-230 spike solutions were obtained from the Amersham/Searle Corporation. Alpha spectra of pure spike solution show no discernible activity attributable to other thorium isotopes. These spike solutions are calibrated against a thorium-228 standard solution and against thorium nitrate powder, processed in 1906, and presumably now having radium-228

and thorium-228 grown into equilibrium with the thorium-232 which makes up the bulk of the sample. Both the thorium-228 standard solution and the thorium nitrate powder were also obtained from Amersham/Searle Corporation. No activity attributable to other isotopes of thorium was found in alpha spectra of the thorium-228 standard. Alpha spectra of the thorium nitrate powder indicate that it does contain thorium-228 (and presumably, therefore, also radium-228) in radioactive equilibrium with thorium-232. Unfortunately, this powder also contains thorium-230 amounting to about 17% of the activity of thorium-232 (or thorium-228) in the powder. Calibrations of our thorium-230 spikes against these two standards have given results consistent with each other, and also consistent with an earlier calibration against a uranium-232-thorium-228 standard solution.

Some duplicate samples of seawater have been collected and analyzed separately to permit estimation of the precision of the analysis. Available results are tabulated in Table 1. Generally the duplicates agree to within the estimated error in the analysis. The worst set of duplicates involved two samples, Ra 1332 and Ra 1333, collected in shallow water in the New York Bight. Both of these contained large amounts of sediment, and this appears to have interfered with the analysis. This indicates that caution will have to be exercised in the measurement of radium and thorium in shelf waters, and in the interpretation of the results, since the concentration of particles in this water is often high.

TABLE 1. Duplicate analyses of seawater for
radium-228 and thorium-228

Sample Number	Location	$\frac{\text{dpm } ^{228}\text{Ra}}{100 \text{ kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100 \text{ kg}}$
Ra 1108	Sargasso Sea surface water,	2.7 ± 0.6	1.01 ± 0.08
Ra 1109	R/V SPENCER, 23 Aug 1971.	3.1 ± 0.6	0.94 ± 0.07
Ra 1332	New York Bight surface water	18.6 ± 6.0	0.19 ± 0.01
Ra 1333	(containing sediment), R/V ATLANTIC TWIN, 18 Jul 1972.	29.8 ± 9.4	< 0.1
Ra 1338	GEOSECS Atlantic Test Cruise,	4.7 ± 0.6	0.55 ± 0.05
Ra 1339	5 meters, R/V KNORR, 5 Jul 1972.	(lost)	0.57 ± 0.05
Ra 1345	GEOSECS Atlantic Test Cruise,	2.0 ± 0.3	1.10 ± 0.08
Ra 1346	350 meters, R/V KNORR, 11 Jul 1972.	2.3 ± 0.4	1.11 ± 0.09
Ra 1384	Slope water, east of Cape	5.9 ± 1.2	0.55 ± 0.05
Ra 1385	Hatteras, 5 meters, R/V EAST- WARD, 31 Oct 1972.	5.6 ± 1.1	0.52 ± 0.05
Ra 1883	New York Bight surface water,	-	0.67 ± 0.06
Ra 1884	R/V COMMONWEALTH, 15 Jan 1974.	-	0.54 ± 0.05
Ra 1910	New York Bight surface water,	-	0.32 ± 0.03
Ra 1911	R/V COMMONWEALTH, 13 May 1974.	-	0.34 ± 0.04
Ra 1848	North Pacific surface water,	-	0.15 ± 0.02
Ra 1849	R/V MELVILLE, 30 Sep 1973.	-	0.11 ± 0.02

Analysis of Lead-210 and Polonium-210 in Seawater

The experimental procedures for the determination of lead-210 and polonium-210 have undergone slight modifications from one group of samples to another as simplifications and improvements have been developed. The procedure described here is the one most recently used. Seawater samples of 30 liters to 200 liters have been collected using submersible pumps, surface mounted pumps and 30 liter Niskin bottles. Several 20 liter samples have also been collected for determination of radium-226. Biological samples consist of fish and plankton.

The seawater samples are acidified with HCl spike solutions containing iron carrier, 20-40 mg of stable lead and, if polonium-210 is to be measured, 1-2 dpm of polonium-208 or polonium-209 are added and the sample is thoroughly mixed. Enough ammonia is added to make the solution basic and precipitate iron hydroxide. Lead precipitates as sulfate and is scavenged by the hydroxide, and polonium is coprecipitated as the hydroxide or oxide. The precipitate is allowed to settle, is separated from the supernatant seawater-ammonia solution, and is transferred to a small polyethylene container for return to the laboratory for analysis.

The precipitate is further separated from the supernatant by centrifuging and by washing with distilled water. The precipitate is dissolved in enough HCl so that the solution is at least 8N in acid. Most of the iron is removed by extraction of the iron-chloride complex into isopropyl ether. The

lead and polonium remain in the aqueous portion, which is evaporated to a small volume and then diluted with distilled water and HCl so that 200 ml to 300 ml of 0.5N HCl solution results. A copper disk 2-3 cm in diameter is placed in the solution and the solution is heated at 80-90°C for 2 hours. The polonium-210 and polonium spike deposit on the copper as a thin layer. The large excess of stable lead assures that only an insignificant fraction of the lead-210 will plate out. The disk is placed in an alpha spectrometer and the polonium-210 content determined by the ratio of net counts registered under the polonium-210 and polonium spike peaks. The results are corrected for decay of polonium-210 between collection and processing.

The solution containing lead is made 1.2N in HCl and passed through an anion exchange column containing AG1-X8 resin. Lead is retained at this normality. The lead is eluted with distilled water. Bismuth and polonium, which would interfere with the subsequent analysis, remain on the resin. The chemical yield of the lead procedure is determined by analyzing a small portion of the eluted lead by atomic absorption spectroscopy. The purified lead fraction is set aside for several months and the lead-210 content determined by extracting and measuring the polonium-210 which grows in.

The biological samples are destroyed in a mixture of nitric and perchloric acids. The siliceous residue from the plankton is dissolved with HF and added to the remainder of

the solution. Iron carrier, lead and polonium spikes are added and the above procedure is followed.

Radium-226 is determined by purging the seawater sample of initial radon with helium, and allowing radon-222 to grow back. The radon-222 is swept from the sample and measured in an alpha scintillation counter.

Analysis of Uranium and Thorium Series Radionuclides in Sediment

A procedure has been developed to determine several of the uranium and thorium series isotopes in sediment. The procedure involves the sequential use of well known isotope purification steps.

The sediment sample is dried at 110°C and split into three or four aliquots of 1-2 grams each. If there is a high percentage of organic material present, the aliquots are heated at 400°C for one hour. It has been found that excess organic material interferes with several of the procedures. One aliquot is analyzed for radium-226 and radium-228, and to obtain ratios of the thorium isotopes. The sample is leached with hot 1.5N HCl for one hour, and then is centrifuged and the leachate is transferred to a 500 ml bottle. The sample is flushed with helium, and radium-226 is determined by subsequent growth and measurement of its daughter radon-222. The sample is then transferred to a beaker, iron carrier is added, and iron hydroxide is precipitated by the addition of ammonia. Thorium, which is coprecipitated by the iron hydroxide, is

determined by standard methods. Radium remains in solution. Dilute sulfuric acid is added and radium is precipitated as the sulfate by addition of barium chloride. Radium-228 is determined by measuring the growth of its daughter, thorium-228.

A second aliquot is analyzed for polonium-210, lead-210, thorium-232, and uranium. The sediment is leached with hot 1.5N HCl. Spikes of polonium-208, uranium-232, thorium-228, and stable lead are added. The leachate is evaporated to a small volume and diluted with water and HCl to give 100 ml of 1N HCl solution. A 2-3 cm copper disk is placed at the bottom of the beaker and the solution heated to 80-90°C for 2 hours. Polonium is deposited on the copper. The solution is evaporated to near dryness and is made 8N in HCl. The solution is passed through an anion exchange column. Lead and thorium are eluted, while uranium and polonium are retained. The uranium is eluted with 0.1N HCl. The solution containing thorium and lead is evaporated to a small volume and made 1.5N in HCl. The solution is again passed through an anion exchange column. Lead is retained and thorium eluted. The lead is eluted with distilled water and precipitated as the chromate by addition of sodium chromate. Lead-210 is determined by growth of its daughter polonium-210.

The solution containing thorium is loaded onto a cation exchange column. Impurities are eluted with washes of 4N and 8N HCl. Thorium is eluted with 0.75N oxalic acid. The eluate

is evaporated to dryness with concentrated HNO_3 and HClO_4 . The residue is dissolved in a few ml. of dilute HNO_3 , and thorium is extracted into a few drops of a benzene solution of TTA. The TTA solution is evaporated onto a stainless steel disk, and the TTA is burned off. The thorium is then measured using an alpha spectrometer.

CHAPTER III - THE DISTRIBUTION OF RADIUM-228 IN THE OCEANS

The first systematic measurements of radium-228 and thorium-228 in the oceans were made by Moore (1969a, 1969b). He concluded that radium-228 is primarily supplied to the ocean by diffusion from sediments containing thorium-232. The highest $^{228}\text{Ra}/^{226}\text{Ra}$ activity ratios occur in coastal waters that are in contact with terrigenous sediments and have a restricted circulation with the open ocean. Moore noted that large variations occur in the $^{228}\text{Ra}/^{226}\text{Ra}$ activity ratio from place to place within surface waters and that this ratio appears to be generally higher in Atlantic surface waters than in Pacific surface waters. He observed that samples collected at depths greater than a few hundred meters contain very low concentrations of radium-228, generally below the lower limit of detection. Evidently the rate of downward mixing of the radium-228 into the intermediate and deep water is slow in comparison with its rate of radioactive decay. He did find, however, that samples collected within 100 meters of the ocean floor contained significant amounts of radium-228, evidently derived from the deep sea sediments. Moore concluded that radium-228 should be applicable as a tracer in studies of processes occurring with a 3- to 30-year time scale.

Our investigation of the distribution of radium-228 in the oceans was begun to extend Moore's reconnaissance study and to determine in which particular areas of oceanographic research the use of radium-228 as a tracer might be most

beneficial. The early results of this investigation have been reported by Kaufman et al. (1973). These results agreed with those obtained by Moore, and showed that near-shore surface waters normally contain much higher radium-228 concentrations than surface waters collected in the open sea, that surface waters normally contain much higher radium-228 concentrations than intermediate and deep waters, but that near-bottom waters are somewhat enriched in radium-228. Surface waters of the North Atlantic and Indian Oceans were found to contain significantly higher concentrations of radium-228 than those of the Pacific and Antarctic Oceans. Vertical profiles of radium-228 concentrations were used to calculate values of the constant for vertical eddy diffusion in the surface and bottom layers of the ocean at several locations. The meridional gradient of radium-228 in the surface waters south of Australia and New Zealand was used to calculate a value of the constant for horizontal eddy diffusion perpendicular to the wind-driven circulation.

This reconnaissance study was continued sporadically into 1972 with collections of samples of surface water being performed aboard Lamont-Doherty ships during cruises in the Atlantic, Pacific, and Indian Oceans. We report below the unpublished results from two of these cruises, R/V VEMA cruise 28 and R/V CONRAD cruise 14. We also report below the results of measurements from two cruises related to Project GEOSECS. One of these, performed aboard the Woods Hole Oceanographic

Institution's vessel, R/V KNORR, involved the testing of a 780 liter Gerard-Ewing sampler built for that program. The second, performed aboard the German vessel, R/V METEOR, was a geochemical investigation of the North Atlantic designed to complement data obtained from GEOSECS.

Radium-228 in the Norwegian Sea and Greenland Sea

Samples of surface water were collected for analysis of radium-228 during two legs of R/V VEMA cruise number 28 in the Norwegian Sea and Greenland Sea during July to September 1970. The results of the analysis of these samples are presented in Table 2, and they are plotted on maps of this region in Figures 1 and 2. In Figure 1 arrows are drawn to represent the surface currents in the surface waters of these seas, as described by Sverdrup et al. (1942). In Figure 2 the temperature of the surface waters, as measured during the sampling, is shown by a series of isotherms.

These surface water concentrations of radium-228 will be of value in the interpretation of data for North Atlantic Deep Water which will be obtained during GEOSECS, since much of this deep water originates by wintertime cooling and sinking of water in the Norwegian Sea-Greenland Sea area. Preliminary results from measurements of GEOSECS samples, as well as results of measurements of deep samples collected aboard the R/V METEOR and reported below, indicate that the circulation of this deep water is rapid enough that detectable radium-228 concentrations persist in it even where it is sampled far from its source areas.

The distributions of radium-228 shown in Figures 1 and 2 indicate that in the Norwegian Sea and Greenland Sea, as is true elsewhere in the oceans, samples collected along the coasts of bordering lands contain higher concentrations than samples collected far from such coasts. The eastern half of the Norwegian Sea and the western half of the Greenland Sea generally display higher concentrations of radium-228 than are found in the waters of the northeastern North Atlantic which flow into this bordering sea (Kaufman et al., 1973). This suggests that the Greenland and Norwegian continental shelves, and probably the shelves of the British Isles and the North Sea, contribute important amounts of radium-228 to the surface waters of the Norwegian and Greenland Seas. If this were not so, these seas should contain very low concentrations of radium-228, at least below 0.5 dpm/100 kg. The deep mixing of this water during the winter must dilute the radium-228 which enters these seas in the surface water by redistributing it through the underlying water mass.

Table 2. Samples collected in the Norwegian Sea and Greenland Sea in July-September 1970 aboard R/V VEMA and analyzed for radium-228.

Sample Number	Collection Date	Latitude	Longitude	dpm ^{228}Ra	dpm ^{226}Ra	dpm ^{228}Ra 100 kg
Ra 1008	19 Jul 1970	65°15'N	30°08'W	0.12		1.0±0.2
Ra 1010	21 Jul 1970	67°10'N	25°18'W	0.52		4.4±0.7
Ra 1011	23 Jul 1970	68°56'N	17°43'W	0.15		1.3±0.2
Ra 1012	24 Jul 1970	71°08'N	18°14'W	0.47		4.0±0.6
Ra 1013	24 Jul 1970	72°00'N	14°15'W	0.36		3.1±0.5
Ra 1014	25 Jul 1970	73°20'N	11°40'W	0.21		1.8±0.3
Ra 1015	26 Jul 1970	75°25'N	09°15'W	0.19		1.6±0.2
Ra 1017	28 Jul 1970	74°25'N	02°34'W	0.07		0.6±0.1
Ra 1018	29 Jul 1970	72°38'N	02°59'E	0.14		1.2±0.2
Ra 1019	30 Jul 1970	71°10'N	07°57'E	0.20		1.7±0.3
Ra 1020	1 Aug 1970	66°26'N	02°05'E	0.17		1.4±0.2
Ra 1021	7 Aug 1970	61°51'N	04°03'E	1.29		11.0±1.6
Ra 1022	8 Aug 1970	62°54'N	0°35'E	0.26		2.2±0.3
Ra 1023	9 Aug 1970	65°14'N	04°33'W	0.12		1.1±0.2
Ra 1024	10 Aug 1970	66°58'N	09°03'W	0.09		0.7±0.1
Ra 1025	11 Aug 1970	67°33'N	19°45'W	0.18		1.5±0.2
Ra 1026	13 Aug 1970	69°23'N	08°40'W	0.09		0.8±0.1
Ra 1027	14 Aug 1970	71°17'N	08°20'W	0.14		1.2±0.2
Ra 1028	16 Aug 1970	68°56'N	01°53'W	0.12		1.0±0.2
Ra 1029	17 Aug 1970	67°30'N	0°01'E	0.09		0.7±0.1
Ra 1030	17 Aug 1970	67°40'N	0°15'E	0.10		0.8±0.1
Ra 1031	18 Aug 1970	66°40'N	02°53'E	0.16		1.4±0.2
Ra 1032	18 Aug 1970	68°34'N	02°55'E	0.29		2.4±0.4
Ra 1033	19 Aug 1970	66°34'N	06°17'E	0.10		0.9±0.1
Ra 1034	20 Aug 1970	66°34'N	08°05'E	0.72		6.2±0.9
Ra 1035	21 Aug 1970	68°40'N	06°37'E	0.22		1.9±0.3

Table 2 (cont'd.)

Ra 1036	23 Aug 1970	68°35'N	13°12'E	1.17	9.9±1.5
Ra 1037	24 Aug 1970	69°40'N	13°39'E	0.49	4.2±0.6
Ra 1038	24 Aug 1970	70°22'N	16°00'E	0.52	4.5±0.7
Ra 1039	26 Aug 1970	73°20'N	14°15'E	0.29	2.4±0.4
Ra 1040	26 Aug 1970	73°51'N	12°05'E	0.22	1.9±0.3
Ra 1041	27 Aug 1970	74°26'N	04°27'E	0.11	1.0±0.1
Ra 1042	28 Aug 1970	74°00'N	04°14'E	0.13	1.1±0.2
Ra 1043	29 Aug 1970	73°03'N	05°49'E	0.16	1.3±0.2
Ra 1044	30 Aug 1970	71°45'N	0°03'E	0.23	2.0±0.3
Ra 1045	2 Sep 1970	68°01'N	05°42'E	0.16	1.4±0.2

Figure 1. The distribution of radium-228 (dpm/100 kg)
in the surface waters of the Norwegian Sea and
Greenland Sea. Arrows indicate the general pattern
of surface currents in these seas.

Figure 2. Relation of the radium-228 distribution
(concentrations in dpm/100 kg) to temperature
(isotherms in °C) in the surface waters of the
Norwegian Sea and Greenland Sea.

Radium-228 in the Indian Ocean and Pacific Ocean

Samples of surface water were collected for analysis of radium-228 during much of R/V CONRAD cruises numbers 14 and 15 in the Indian Ocean, the Indonesian Seas, the Pacific Ocean and the South Atlantic Ocean during January 1971 to June 1972. Numerous samples from these cruises are still in process of analysis, but results from the early part of the cruises are presented in Table 3. Results from measurements of samples collected in the Indian Ocean during CONRAD 14 are plotted in Figure 3, together with results of earlier sampling reported by Kaufman et al. (1973). Results for samples collected in the Indonesian Seas during this cruise are plotted in Figure 4, together with earlier results and some results from samples collected during a cruise of the R/V MELVILLE, which are discussed later in this report. Results for samples collected in the western Pacific and Bering Sea during this cruise are plotted in Figure 5, together with earlier results and results from the R/V MELVILLE cruise. Arrows drawn on each of these figures to represent the wintertime circulation of the surface waters are based on maps in Sverdrup et al. (1942).

The results for the Indian Ocean (Fig. 3) show a steep concentration gradient across this ocean from very high radium-228 concentrations near the coasts of Indonesia and Australia and in the North Equatorial Current to very low concentrations south of the Antarctic Convergence. This indicates that radium-228 could serve as an excellent tracer for studies of

the circulation of surface waters within the Indian Ocean. The finding of very low concentrations and very high concentrations in close proximity to each other (samples Ra 1074 and Ra 1075; samples Ra 1089 and Ra 1090) suggests that intricate patterns of eddy diffusion might be revealed by detailed studies of the distribution of this nuclide in the surface waters of that ocean.

The results for the Indonesian Seas (Fig. 4) show that an intricate mixing of surface water from the Pacific Ocean, containing relatively low concentrations of radium-228, with water from some of the shallow seas in the region, containing very high concentrations, occurs within these seas. Here also radium-228 should serve as an excellent tracer of mixing processes. The presence of such high concentrations of radium-228 in some of these seas may offer clues for the description of the source function of this nuclide in the oceans.

The results for the western Pacific (Fig. 5) suggest that the Japanese islands and Siberian coast are relatively poor contributors of radium-228 to the oceans when compared to the lands bordering the Indian Ocean. The Bering Sea contains relatively low concentrations when compared, for example, to the Norwegian and Greenland Seas, so it seems likely that the low concentrations found within the western half of the Pacific are in part at least due to a relatively poor source area and not just to dilution throughout a larger ocean. A study of what is known of the mineralogy of the shelf sediments along these coasts should contribute to our better understanding of this source function.

Table 3. Samples collected aboard R/V CONRAD during CONRAD
Cruise No. 14, and analyzed for radium-228.

Sample Number	Collection Date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100 \text{ kg}}$
<u>Within the Indian Ocean</u>					
Ra 1071	31 Jan 1971	39°14'S	24°45'E	0.35	3.0±0.4
Ra 1073	2 Feb 1971	37°40'S	26°52'E	0.37	3.2±0.5
Ra 1074	3 Feb 1971	34°40'S	29°30'E	1.20	10.2±1.5
Ra 1075	4 Feb 1971	32°41'S	31°06'E	0.07	0.6±0.1
Ra 1076	7 Feb 1971	33°37'S	39°40'E	0.15	1.2±0.2
Ra 1078	10 Feb 1971	35°57'S	44°40'E	0.28	2.4±0.4
Ra 1079	11 Feb 1971	36°51'S	44°48'E	0.30	2.5±0.4
Ra 1080	22 Feb 1971	28°27'S	52°56'E	0.36	3.1±0.5
Ra 1084	26 Feb 1971	22°11'S	51°38'E	0.08	0.6±1.2
Ra 1085	3 Mar 1971	19°42'S	58°56'E	0.33	2.8±0.4
Ra 1086	4 Mar 1971	19°01'S	61°21'E	0.61	5.2±0.9
Ra 1087	5 Mar 1971	17°20'S	63°57'E	0.73	6.2±1.1
Ra 1088	6 Mar 1971	17°26'S	63°47'E	0.49	4.2±0.8
Ra 1089	7 Mar 1971	13°30'S	70°10'E	0.08	0.7±0.1
Ra 1090	8 Mar 1971	12°03'S	73°10'E	0.65	5.5±1.0
Ra 1091	9 Mar 1971	11°10'S	75°59'E	0.91	7.7±1.2
Ra 1092	11 Mar 1971	06°26'S	79°42'E	1.00	8.5±1.3
Ra 1095	18 Mar 1971	11°10'S	88°32'E	0.68	5.8±0.9
Ra 1097	21 Mar 1971	04°01'S	88°34'E	0.63	5.4±0.8
Ra 1100	25 Mar 1971	01°34'N	90°04'E	0.64	5.5±0.8
Ra 1101	27 Mar 1971	04°21'N	92°59'E	0.86	7.3±1.1
Ra 1102	29 Mar 1971	06°16'N	94°26'E	0.81	6.9±1.0
Ra 1124	9 Apr 1971	07°48'S	103°17'E	1.10	9.3±1.6
Ra 1126	12 Apr 1971	06°34'S	102°12'E	0.86	7.3±1.3
Ra 1127	13 Apr 1971	06°04'S	102°19'E	1.04	8.8±1.6
Ra 1128	17 Apr 1971	09°54'S	100°05'E	0.96	8.2±1.2
Ra 1131	22 Apr 1971	14°06'S	103°49'E	1.06	9.0±1.3
Ra 1133	26 Apr 1971	21°36'S	101°23'E	0.61	5.2±0.8

Table 3 (cont'd.)

Ra 1135	28 Apr 1971	19°51'S	107°46'E	1.08	9.2±1.4
Ra 1137	30 Apr 1971	17°26'S	114°34'E	0.88	7.5±1.1
Ra 1138	1 May 1971	15°58'S	117°49'E	1.25	10.6±1.6
Ra 1139	2 May 1971	14°34'S	120°52'E	0.49	4.2±0.6
Ra 1140	3 May 1971	13°54'S	124°03'E	1.13	9.6±1.4
Ra 1141	9 May 1971	11°27'S	129°03'E	2.06	17.5±2.6

Within the Indonesian Seas and the South China Sea

Ra 1142	10 May 1971	09°55'S	125°31'E	1.49	12.7±1.9
Ra 1143	11 May 1971	10°22'S	123°20'E	1.98	16.9±2.5
Ra 1144	12 May 1971	08°52'S	123°00'E	2.03	17.3±2.6
Ra 1145	13 May 1971	08°38'S	125°03'E	3.14	26.7±4.0
Ra 1146	14 May 1971	06°52'S	124°07'E	1.81	15.4±2.3
Ra 1147	15 May 1971	05°24'S	125°49'E	2.31	19.6±2.9
Ra 1148	16 May 1971	02°59'S	125°06'E	1.14	9.7±1.5
Ra 1149	18 May 1971	0°22'N	125°46'E	0.99	8.4±1.3
Ra 1150	20 May 1971	01°53'N	122°05'E	0.41	3.5±0.5
Ra 1151	22 May 1971	06°16'N	119°36'E	0.68	5.8±0.9
Ra 1152	24 May 1971	08°49'N	116°19'E	1.23	10.5±1.6
Ra 1153	28 May 1971	14°35'N	116°01'E	1.61	13.7±2.1
Ra 1154	30 May 1971	17°52'N	115°12'E	1.58	13.4±2.0

Within the Philippine Sea, Western Pacific and Bering Sea

Ra 1172	18 Jun 1971	36°02'N	143°35'E	0.33	2.3±0.7
Ra 1173	21 Jun 1971	40°13'N	152°52'E	0.27	1.9±0.3
Ra 1174	23 Jun 1971	45°02'N	150°45'E	0.63	4.4±0.6
Ra 1176	27 Jun 1971	43°40'N	156°43'E	0.18	1.2±0.2
Ra 1177	28 Jun 1971	48°45'N	154°27'E	0.10	0.7±0.1
Ra 1178	1 Jul 1971	47°40'N	163°27'E	0.10	0.7±0.1
Ra 1180	5 Jul 1971	50°17'N	165°05'E	0.18	1.3±0.2
Ra 1181	8 Jul 1971	51°46'N	160°49'E	0.13	0.9±0.1
Ra 1183	10 Jul 1971	53°02'N	163°46'E	0.06	0.4±0.1
Ra 1186	13 Jul 1971	53°48'N	171°58'E	0.08	0.6±0.1
Ra 1187	14 Jul 1971	53°26'N	175°19'E	0.05	0.4±0.1

Table 3 (cont'd.)

Ra 1188	15 Jul 1971	52°23'N	178°50'E	0.04	0.3±0.1
Ra 1189	19 Jul 1971	53°53'N	171°25'W	0.07	0.5±0.1
Ra 1191	24 Jul 1971	56°42'N	178°46'W	0.09	0.6±0.1
Ra 1193	28 Jul 1971	60°28'N	175°54'E	0.18	1.8±0.7
Ra 1197	30 Jul 1971	58°47'N	171°40'E	0.05	0.4±0.1
Ra 1199	1 Aug 1971	58°40'N	166°55'E	0.20	1.4±0.4
Ra 1203	6 Aug 1971	56°44'N	166°59'E	0.07	0.5±0.1
Ra 1204	7 Aug 1971	55°49'N	172°02'E	0.03	0.2±0.1

Figure 3. The distribution of radium-228 (dpm/100 kg)
in the surface waters of the Indian Ocean. Arrows
indicate the general pattern of surface currents
during the Northern Hemisphere winter.

Figure 4. The distribution of radium-228 (dpm/100 kg)
in the surface waters of the Indonesian Seas.
Arrows indicate the general pattern of surface
currents during the Northern Hemisphere winter.

Figure 5. The distribution of radium-228 in the surface waters of the Pacific Ocean. Arrows indicate the general pattern of surface currents during the Northern Hemisphere winter.

A Vertical Profile of Radium-228 Concentrations
Near Puerto Rico

A vertical profile of radium-228 samples was collected near Puerto Rico in February 1972 as part of a test of a large Gerard-Ewing sampler (780 liter capacity) built for GEOSECS. The results of measurement of these samples are presented in Table 4, together with results of measurements of samples collected in the same area in 1970 and reported by Kaufman et al. (1973). The agreement between these two sets of data in characterizing the vertical distribution of radium-228 in these waters is excellent.

Table 4. Samples collected near Española and Cuba in 1970 and near Puerto Rico in 1972, and analyzed for radium-228.

Sample Number	Collection Date	Latitude (°N)	Longitude (°W)	Depth (m)	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100 \text{ kg}}$
<u>Collected near Española and Cuba in 1970:</u>						
Ra 0996	22 Feb 1970	20°32'	72°44'	40	0.44	3.7 ±0.6
Ra 0995	19 Feb 1970	19°28'	74°52'	50	0.46	3.9 ±0.6
Ra 0998	24 Feb 1970	20°38'	72°46'	250	0.16	1.4 ±0.2
Ra 0999	24 Feb 1970	20°37'	72°56'	750	0.020	0.20±0.05
Ra 0994	19 Feb 1970	19°33'	74°44'	1500	0.13	1.7 ±0.3
<u>Collected near Puerto Rico in 1972:</u>						
Ra 1268	19 Feb 1972	19°00'	66°10'	5	0.50	4.2 ±0.6
Ra 1269	20 Feb 1972	19°00'	66°10'	200	0.18	1.5 ±0.2
Ra 1270	20 Feb 1972	19°00'	66°10'	400	0.13	1.1 ±0.2
Ra 1271	20 Feb 1972	19°00'	66°10'	600	0.037	0.32±0.05
Ra 1272	20 Feb 1972	19°00'	66°10'	800	0.009	0.09±0.01

Radium-228 Measurements of Samples Collected by
the R/V METEOR

During June 1971 the German vessel R/V METEOR undertook a sampling cruise in the North Atlantic to study the marine geochemistry of the region in a project coordinated with GEOSECS. Samples of water for radium-228 and thorium-228 analysis as part of our research project were collected during this cruise. The results of these analyses are given in Table 5.

Three samples of subsurface water were collected during this cruise. They agree in showing that even the deep water appears to contain measurable concentrations of radium-228. Preliminary results of measurements of a few deep water samples from the North Atlantic collected during GEOSECS appear to confirm this. These samples also show that even in deep water, thorium-228 does not appear to reach radioactive equilibrium with radium-228, an observation which will be alluded to again later in this report.

The results of the measurements of the surface samples are in agreement with the earlier results reported by Kaufman et al. (1970) in showing concentrations of 1 to 2 dpm ^{228}Ra /100 kg in the surface waters of the eastern North Atlantic. They also agree with our other results in showing higher concentrations in the waters over the continental shelf of Europe.

Table 5. Samples collected aboard R/V METEOR in the North Atlantic in June 1971
and analyzed for radium-228 and thorium-228.

Sample Number	Collection Date	Latitude	Longitude	Depth (m)	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100 \text{ kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100 \text{ kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
Ra 1160	9 Jun 1971	38°30'N	11°30'W	5	0.16	1.12±0.18	0.32±0.05	0.29
Ra 1164	15 Jun 1971	42°48'N	34°23'W	5	0.22	1.53±0.20	0.34±0.03	0.22
Ra 1165	17 Jun 1971	43°48'N	42°56'W	5	0.30	2.10±0.26	0.56±0.05	0.27
Ra 1166	19 Jun 1971	45°48'N	37°18'W	5	0.28	1.95±0.25	0.48±0.04	0.25
Ra 1167	21 Jun 1971	48°30'N	25°12'W	5	0.21	1.45±0.19	0.41±0.04	0.28
Ra 1168	22 Jun 1971	49°14'N	18°26'W	5	0.19	1.32±0.17	0.31±0.05	0.24
Ra 1169	23 Jun 1971	49°35'N	11°57'W	5	0.14	1.00±0.14	0.24±0.02	0.24
Ra 1170	25 Jun 1971	50°22'N	0°02'W	5	1.27	8.86±1.16	0.61±0.06	0.07
Ra 1171	26 Jun 1971	52°08'N	03°06'E	5	0.92	6.44±0.83	0.96±0.08	0.15
Ra 1162	13 Jun 1971	41°12'N	25°59'W	490	0.14	0.95±0.18	0.41±0.04	0.43
Ra 1161	13 Jun 1971	41°12'N	25°59'W	2490	0.02	0.21±0.08	0.13±0.04	0.62
Ra 1163	15 Jun 1971	42°48'N	34°23'W	2550	0.03	0.36±0.10	0.19±0.04	0.53

THE VARIATIONS IN THE CONCENTRATION OF
THORIUM-228 AND IN THE ACTIVITY RATIO,
 $^{228}\text{Th}/^{228}\text{Ra}$, IN THE OCEANS

Moore (1969A, 1969B) was originally motivated to analyze seawater for radium-228 when Moore and Sackett (1964) found that marine concentrations of thorium-228 far exceeded those of the thorium-232 from which it should presumably have been derived. The initial results of the thorium-228 analysis of seawater published by Moore (1969A) indicated that the activity ratio $^{228}\text{Th}/^{228}\text{Ra}$ was less than 1.0 in surface waters, probably exceeded 1.0 at depths of a few hundred meters, and might approximate 1.0 in the deep water. When our investigation of the distribution of radium-228 in the oceans was undertaken, most samples were analyzed for thorium-228 as well in an effort to provide a more firm understanding of the distribution of this nuclide in the seas.

The results of the analysis of thorium-228 in the samples collected during the early years of our investigation have been discussed by Broecker et al. (1973). They conclude that the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio in the surface water of the open ocean averages 0.21, and that this suggests that thorium has a mean chemical removal time of 0.7 year in this environment. The activity ratio is lower in surface waters closer to the continental shelf, and mean chemical removal times of less than 0.5 year are indicated for thorium-228 in such waters. These mean times include both the uptake of the thorium-228 by particulate matter and its removal from the surface layer, presumably by settling or with migrating organisms. Broecker et al. (1973) estimate that the cycling time

of phosphorus atoms and of other critical nutrients in surface seawater from one generation of plants to the next is on the order of 0.5 year, but that a typical phosphorus atom resides in the surface water for about 5 years before being returned to the deep water by settling of particles to which it is attached or by sinking of the water which contains it. Hence, they conclude that each phosphorus atom is reused by organisms within the surface ocean about ten times before being fixed into a particle which falls to the deep sea. On the other hand, the 0.7 year mean chemical removal time of thorium-228 suggests that the thorium produced within the surface ocean is efficiently removed by each generation of plant matter. Unlike phosphorus atoms which are reused efficiently, thorium is not transferred from one generation of plants to the next. Instead it is carried below the base of the mixed layer after its first incorporation into plant matter.

If the marine geochemistry of some other heavy metals with environmental importance is similar to that of thorium, a thorough understanding of the mechanisms by which thorium is removed from solution in seawater could be valuable in the study of some pollution problems. It was decided, therefore, to obtain as much information as possible on the variation of concentrations of thorium-228 and variations in the activity ratio $^{228}\text{Th}/^{228}\text{Ra}$ within the oceans. It has been left mainly to GEOSECS to establish the distribution of thorium-228 concentrations and of the activity ratio $^{228}\text{Th}/^{228}\text{Ra}$ as a function of depth in the open oceans, although three subsurface samples collected aboard the R/V METEOR were analyzed for these as part of this investigation (Table 5). We have concentrated on measuring the variations of thorium-228

concentrations and $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios within surface waters, and in a variety of oceanographic environments in hopes of discerning which factors most strongly influence these variations.

We will discuss first the vertical distribution of thorium-228 in the oceans, primarily as indicated by preliminary results from GEOSECS. Then we will discuss the results of our measurements of surface water since 1971, and particularly of our attempts to survey the effects of local coastline conditions on the concentrations of radium-228 and thorium-228 in the continental shelf environment.

The Vertical Distribution of Thorium-228 in the Oceans

The data presented in Table 5 for samples collected aboard the R/V METEOR agree with the results of Moore (1969A) and Broecker et al (1973) in showing depletion of thorium-228 with respect to radium-228 in surface water, with a $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio of about 0.25 in the open ocean. The sample collected at 490m depth (Ra 1162) does not show as high a thorium-228 concentration as might have been predicted from Moore's early results, and neither do the samples of deep water (Ra 1161 and Ra 1163) show $^{228}\text{Th}/^{228}\text{Ra}$ ratios close to 1.0.

Some preliminary results of profiles of radium-228 and thorium-228 measured on GEOSECS samples are plotted in Figures 6 through 12. Other patterns of vertical distributions have been observed, but these illustrate the most common pattern plus some of the variability.

Stations KNORR 29-248 and -249 (Figures 6 and 7) were made during a trial leg which preceded the Atlantic GEOSECS cruise.

Station 248 was made in the slope water south of New England, while station 249 was made closer to Bermuda in the Sargasso Sea at a location used for an intercalibration test cruise in 1970. Samples collected in the upper 100 meters of water at these two stations gave similar results, with high radium-228 concentrations and $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios of about 0.12 to 0.30. At greater depths, however, the distributions of radium-228 and thorium-228 at the two stations differed markedly. At the Sargasso Sea station the concentrations continued to be high down to at least 350 m (and presumably to the top of the permanent thermocline at about 630 m), and the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio was about 0.5. At the slope water station the concentrations were relatively low at depths below 100 meters, and the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio was about 1.0.

The data for GEOSECS stations 5 and 11 (Figures 8 and 9), which are located south and southeast of Greenland, are typical of those obtained from stations over much of the oceans. At these stations the radium-228 concentrations decreased with depth in the upper few hundred meters, while the thorium-228 concentration increased with depth below the surface mixed layer, and approached or exceeded 1.0 at a depth of a few hundred meters. These patterns are in agreement with some of the early results of Moore (1969A).

The data for GEOSECS stations 17 and 19 (Figures 10 and 11) in the Greenland Sea and Norwegian Sea show typical vertical distributions of thorium-228, but peculiarly erratic distributions of radium-228. At these stations, as at those shown in Figures 8 and 9, the near-surface depletion of thorium-228 parallels a

similar near-surface depletion of phosphate. Since the latter is attributed to consumption of phosphate by organisms and its subsequent removal to deeper water in particulate matter, it is tempting to attribute the near-surface depletion of thorium-228 to the same processes, as was done by Broecker et al. (1973).

The data for the near-bottom profile of radium-228 and thorium-228 concentrations at GEOSECS station 32, shown in Figure 12, indicates that even in deep water where biological removal of thorium from solution would not be expected, the $^{228}\text{Th}/^{228}\text{Ra}$ ratio does not approach 1.0. Neither does this activity ratio appear to increase with increasing distance from the bottom. This suggests that non-biological processes are capable of removing thorium from seawater, and at rates that are significant when compared to the rate of transport of radium-228 through the water by eddy diffusion. This demonstrates that in our study of surface waters we cannot expect to find biological activity to be uniquely important in the removal of thorium and similar metals from the seawater, but must consider the inorganic processes involving the interaction of such metals with suspended organic and inorganic particulates.

The Distribution of Thorium-228 in Surface Waters

Broecker et al. (1973) found that $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios are lower in nearshore waters than they are in the surface waters of the open ocean. This probably results from the combination of two factors: biological productivity is higher and concentrations of suspended particulates, both organic and inorganic, are higher in the waters over the continental shelf than in the waters

FIGURE 6: The vertical distribution of salinity and
of concentrations of radium-228 and thorium-228
at Atlantic GEOSecs Trial Leg Station KNORR
29-248

FIGURE 7: The vertical distribution of temperature, salinity, density and concentration of phosphate, radium-228, and thorium-228 at Atlantic GEOSECS Trial Leg Station KNORR 29-249

Atlantic GEOSECS Trial Leg, Station 248 (38° 49' N, 70° 02' W)

FIGURE 8: The vertical distribution of temperature, salinity, density and concentrations of phosphate, radium-228 and thorium-228 at Atlantic GEOSECS Station 5

Atlantic GEOSECS, Trial Leg, Station 249 (35° 56' N, 67° 56' W)

Atlantic GEOSECS, Leg I, Station 5 (56°54'N, 42°47'W)

FIGURE 9: The vertical distribution of temperature, salinity, density and concentrations of phosphate, radium-228 and thorium-228 at Atlantic GEOSECS Station 11

Atlantic GEOSECS, Leg I, Station 11 (63°30'N, 35°14'W)

Figure 10: The vertical distribution of temperature, salinity, density and concentrations of phosphate, radium-228 and thorium-228 at Atlantic GEOSecs Station 17

Atlantic GEOSECS, Leg II, Station 17 (74° 56'N, 01° 07'W)

FIGURE 11: The vertical distribution of temperature, salinity, density and concentrations of phosphate, radium-228 and thorium-228 at Atlantic GEOSECS Station 19

Atlantic GEOSecs, Leg II, Station 19 (64°10'N, 05°36'W)

FIGURE 12: The vertical distribution of radium-228 and
thorium-228 in near-bottom water at Atlantic
GEOSECS Station 32

of the open ocean. As a beginning step toward determining the relative importance of these two factors in controlling the rate of removal of thorium-228 from seawater, thorium-228 as well as radium-228 is being measured in the series of samples of surface seawater collected by vessels as they cross continental shelves in various parts of the oceans. In Chapter 3 we referred to our expectation that these samples will yield information on the dependence of the concentration of radium-228 in shelf waters upon local hydrologic conditions and local sediment composition. They should also yield information upon the dependence of rates of thorium removal from seawater upon local conditions. The analysis of three of these series of samples has been completed, and the results are summarized in Tables 6 through 8.

The first series of samples was collected aboard the R/V MELVILLE of Scripps Institution of Oceanography on a cruise from Singapore to Samoa during June to August 1971. Preliminary results of the analysis of these samples are given in Table 6. Very high concentrations of radium-228 were found in the South China Sea, but much lower concentrations were encountered once the vessel passed through the Balabac Strait and into the Sulu Sea, the Celebes Sea and into the Philippine Sea and the Western Pacific. Concentrations of radium-228 were found to be very low in the southern tropical Pacific. The $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios were lower than 0.2 in all but one of these samples, and the data for the single exception appear suspect. Thus the rate of removal of thorium appears to be significantly higher in these warm waters of the tropical Pacific and Indonesian seas than it is in the oceans in general, as characterized by Broecker et al. (1973),

and it appears to be much higher here than in the other oceanic region for which we have good data: the Sargasso Sea. 7.

Data for the Sargasso Sea are included in the results of measurements of a series of samples collected aboard the R/V SPENCER of the U.S. Coast Guard on a cruise from Bermuda to Norfolk to New York City during August 1971. These results are presented in Table 7. In the Sargasso Sea, radium-228 concentrations of 2.2 to 3.3 dpm/100 kg were found. The $^{228}\text{Th}/^{230}\text{Th}$ ratio ranged from 0.26 to 0.52 with a mean of 0.35. This is significantly higher than the value of 0.21 reported by Broecker et al (1973) for the open ocean in general. This indicates that the removal of thorium from the surface waters of the Sargasso Sea is relatively slow.

Data for the continental shelf off the eastern coast of the United States are included in the SPENCER results in Table 7. Radium-228 concentrations were high, as expected, and the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios were low: 0.02 to 0.06. These ratios are even lower than those observed in the tropical western Pacific, and indicate rapid removal of thorium from the shelf water.

The third series of samples was collected aboard the R/V EASTWARD of Duke University on a cruise from Lewes, Delaware to Beaufort, North Carolina during October-November 1972. Results of measurements of these samples are given in Table 8, and are plotted on a map of this coastal region in Figure 13. The concentrations of radium-228 found on this cruise appear to be higher than those found in comparable locations in the ocean during the SPENCER cruise a year earlier. The thorium-228 concentrations found were similar to those found during the SPENCER cruise, and the

$^{228}\text{Th}/^{228}\text{Ra}$ concentrations found were consequently lower. Of course, the one sample of Sargasso Sea water collected aboard the EASTWARD may have had a quite different origin than the several samples of Sargasso Sea water collected further southward and eastward aboard the SPENCER, and no samples of slope water and perhaps none of Gulf Stream water were collected during the SPENCER cruise. The EASTWARD data appear to show a systematic increase in $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio from the shelf water, to the slope water, to the Gulf Stream water and to the Sargasso Sea water.

The data from these three cruises are consistent with the concept that the biological productivity of water is the primary factor in limiting the accumulation of thorium-228 in surface water. The shelf water, which has the highest productivity of the regions samples, has the shortest mean chemical removal time of thorium and lowest $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios. The water of the tropical Pacific has intermediate values, and the Sargasso Sea water, where biological productivity is lowest, has the longest mean chemical removal time and the highest $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios.

Several series of samples have been collected aboard the vessels utilized for the GEOSECS sampling: the R/V KNORR of Woods Hole Oceanographic Institution on the Atlantic GEOSECS cruise, and the R/V MELVILLE on the Pacific GEOSECS cruise. Preliminary data for some of the series, including only results of thorium-228 analyses, are given in Tables 9 through 13. Two series of samples of surface water were collected for radium-228 and thorium-228 analysis during Leg V of the Atlantic GEOSECS cruise. Figure 14

TABLE 6

Samples Collected Aboard the R/V MELVILLE on a Cruise from Singapore to Samoa
and Analyzed for Radium-228 and Thorium-228

Sample Number	Collection Date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
<u>Collected in the South China Sea:</u>							
Ral205	27 June '71	05°18'N	111°23'E	1.68	14.3±2.2	1.40±0.07	0.10
Ral206	28 June '71	06°50'N	114°23'E	1.77	15.7±2.3	-	-
<u>Collected in the Balabac Strait:</u>							
Ral207	29 June '71	07°50'N	117°07'E	1.69	14.3±2.2	0.54±0.03	0.04
<u>Collected in the Sulu Sea:</u>							
Ral208	30 June '71	07°00'N	120°00'E	0.13	1.1±0.3	-	-
Ral209	1 July '71	06°14'N	120°24'E	0.23	2.0±0.3	0.14±0.01	0.07
<u>Collected in the Celbes Sea:</u>							
Ral210	2 July '71	03°59'N	122°20'E	0.14	1.2±0.2	0.14±0.01	0.12
<u>Collected in the Philippine Sea:</u>							
Ral211	5 July '71	07°22'N	127°10'E	0.16	1.3±0.2	0.12±0.01	0.09
Ral212	7 July '71	11°00'N	129°34'E	0.26	2.2±0.3	-	-
Ral213	8 July '71	13°25'N	131°40'E	0.12	1.1±0.2	0.15±0.02	0.14
Ral214	10 July '71	16°33'N	133°14'E	0.16	1.3±0.2	0.15±0.01	0.12
Ral215	11 July '71	17°04'N	135°13'E	0.22	1.9±0.3	0.15±0.01	0.08
Ral216	15 July '71	14°54'N	143°36'E	0.14	1.2±0.2	0.16±0.01	0.14
<u>Collected in the Western Tropical Pacific:</u>							
Ral217	27 July '71	12°40'N	145°25'E	0.13	1.1±0.2	0.13±0.01	0.12
Ral218	28 July '71	11°07'N	147°32'E	0.04	0.3±0.1	0.14±0.01	0.41
Ral219	29 July '71	08°59'N	150°30'E	0.36	3.1±0.5	0.14±0.03	0.05
Ral220	30 July '71	06°26'N	154°34'E	0.30	2.3±0.3	-	-
Ral221	31 July '71	03°43'N	159°01'E	0.21	1.8±0.3	0.13±0.02	0.07
Ral222	1 Aug. '71	01°34'N	162°26'E	0.06	0.5±0.1	0.10±0.01	0.19
Ral223	3 Aug. '71	02°48'S	169°25'E	0.13	1.1±0.2	0.13±0.02	0.06
Ral224	5 Aug. '71	07°16'S	176°19'E	0.06	0.5±0.1	0.03±0.01	0.06
Ral225	6 Aug. '71	11°12'S	177°29'W	0.06	0.5±0.1	0.06±0.01	0.12
Ral226	7 Aug. '71	13°44'S	172°38'W	0.06	0.5±0.1	0.06±0.01	0.13
Ral227	17 Aug. '71	15°20'S	172°28'W	0.10	0.8±0.1	0.07±0.01	0.09

Table 7

Samples Collected Aboard the R/V SPENCER on a Cruise from Bermuda to Norfolk to New York City, and Analyzed for Radium-228 and Thorium-228

Sample Number	Collection date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
Collected between Bermuda and the edge of the continental shelf:							
Ra1103	22 Aug. '71	31°55'N	65°12'W	0.31	2.2±0.5	0.95±0.07	0.44
Ra1104	22 Aug. '71	31°54'N	65°55'W	0.46	3.2±0.6	0.92±0.07	0.29
Ra1105	22 Aug. '71	31°55'N	66°46'W	0.48	3.3±0.6	1.11±0.09	0.33
Ra1106	23 Aug. '71	31°55'N	68°55'W	0.34	2.4±0.7	0.93±0.07	0.39
Ra1107	23 Aug. '71	31°55'N	69°42'W	0.29	2.0±0.8	1.05±0.07	0.52
Ra1108	23 Aug. '71	32°08'N	70°20'W	0.38	2.7±0.6	1.01±0.08	0.38
Ra1109	23 Aug. '71	32°08'N	70°20'W	0.44	3.1±0.6	0.94±0.07	0.31
Ra1110	23 Aug. '71	32°24'N	70°44'W	0.38	2.7±0.5	0.97±0.08	0.36
Ra1111	24 Aug. '71	33°11'N	72°05'W	0.44	3.0±0.6	1.02±0.08	0.33
Ra1112	24 Aug. '71	33°34'N	72°40'W	0.42	3.0±0.6	0.90±0.07	0.31
Ra1113	24 Aug. '71	33°54'N	73°14'W	0.41	2.9±0.5	0.88±0.07	0.31
Ra1114	24 Aug. '71	34°15'N	73°46'W	-	-	0.99±0.08	-
Ra1115	25 Aug. '71	34°52'N	74°38'W	0.51	3.6±0.6	0.93±0.08	0.26
Collected over the continental shelf between Cape Hatteras and New York City:							
Ra1116	25 Aug. '71	35°16'N	75°02'W	1.12	8.9±1.5	0.33±0.04	0.04
Ra1117	25 Aug. '71	36°04'N	75°19'W	1.46	11.7±2.0	0.34±0.03	0.03
Ra1118	26 Aug. '71	37°00'N	76°18'W	-	-	0.49±0.05	-
Ra1119	26 Aug. '71	37°28'N	75°16'W	1.13	9.0±1.6	0.22±0.13	0.02
Ra1120	26 Aug. '71	38°10'N	74°32'W	1.00	8.0±1.5	0.48±0.04	0.06
Ra1121	26 Aug. '71	39°01'N	74°00'W	1.12	9.0±1.6	0.44±0.04	0.05

Table 8

Samples Collected Aboard the R/V EASTWARD on a Cruise from Lewes, Delaware to Beaufort, North Carolina and analyzed for Radium-228 and Thorium-228

Sample Number	Collection date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
Collected in the Sargasso Sea:							
Ra1387	1 Nov. '72	36°00'N	72°48'W	0.79	5.6±1.0	0.93±0.07	0.17
Collected in the Gulf Stream:							
Ra1386	1 Nov. '72	36°28'N	72°48'W	0.94	6.6±1.2	0.74±0.06	0.11
Ra1388	2 Nov. '72	36°01'N	74°06'W	0.90	6.3±1.2	0.68±0.07	0.11
Collected in the Slope Water:							
Ra1385	31 Oct. '72	37°01'N	73°00'W	0.85	5.9±1.2	0.55±0.05	0.09
Ra1384	31 Oct. '72	37°01'N	73°00'W	0.80	5.6±1.1	0.52±0.05	0.09
Ra1383	31 Oct. '72	37°26'N	73°29'W	1.10	8.8±1.6	0.55±0.04	0.06
Ra1389	3 Nov. '72	36°14'N	74°30'W	1.26	8.8±1.6	0.53±0.05	0.06
Collected in the Shelf Water:							
Ra1382	30 Oct. '72	38°13'N	74°24'W	1.79	14.3±2.6	0.23±0.03	0.02
Ra1381	30 Oct. '72	38°41'N	74°56'W	2.23	17.8±3.1	0.36±0.04	0.02
Ra1390	4 Nov. '72	36°25'N	74°56'W	1.67	13.3±2.5	0.25±0.03	0.02
Ra1391	5 Nov. '72	36°42'N	75°26'W	2.94	23.6±4.1	0.16±0.04	0.01

FIGURE 13: Concentrations of radium-228 and thorium-228 measured in samples of surface water collected aboard the R/V EASTWARD during a cruise from Lewes, Delaware to Beaufort, North Carolina

shows the locations of sample collections (and the locations of GEOSECS radon stations) as the KNORR left Recife and headed for its first regular station, station 53. Thorium-228 results for these samples are presented in Table 9. Figure 15 shows the locations of sample collections (and the locations of GEOSECS radon stations) as the KNORR headed toward Buenos Aires from its last regular station, station 61, of Leg V. Thorium-228 results for these samples are presented in Table 10. A comparable set of thorium-228 data, which is given in Table 11, was obtained as the KNORR headed back out to sea to begin Leg VI. It is noteworthy that both of these tracks detected a zone of high thorium-228 concentrations at about 54°W longitude with lower concentrations encountered farther landward and farther seaward. All of these samples are currently undergoing analysis for radium-228.

Table 12 lists thorium-228 data for a series of GEOSECS stations made progressively farther north, and closer to Africa, and then for three surface samples collected for radium-228 and thorium-228 analysis as the KNORR headed for Capetown at the end of Leg VII of the GEOSECS Atlantic cruise. It is evident that the most southerly stations contained too low a concentration of thorium-228 (and probably also of radium-228) for precise analysis by our technique. As the KNORR proceeded northward, however, the thorium-228 concentration (and presumably also the radium-228 concentration) rose considerably. The northward increases in thorium-228 concentration were probably more the result of the KNORR crossing the Antarctic Convergence than the approach to the African coast, but when the radium-228 data are available it will be more evident whether that coast itself was a controlling factor.

Results of measurements of thorium-228 in samples collected at the beginnings of Legs I and II of the Pacific GEOSECS cruise, as the R/V MELVILLE departed first from San Diego and later from Honolulu, are given in Table 13. Similar samples collected on subsequent legs of the Pacific GEOSECS cruise have not yet been analyzed for thorium-228, and of course, no analyses of radium-228 in such samples are yet available. Almost all the ports visited by the MELVILLE during the Pacific GEOSECS cruise are located on volcanic islands which lack the type of sediment-covered, broad shelf typical of the coasts bordering the Atlantic. The objective of these measurements in the Pacific is to determine whether these volcanic islands modify the local marine concentrations of radium-228 and thorium-228.

When all of these near shore samples have been analyzed, and the data are compared with those for samples collected in the open oceans, we hope to have some indication of just how much variation exists between different types of coasts with respect to concentrations of radium-228 and thorium-228. This will provide important clues to both the source function of radium-228 and to the relative importance of various biological, chemical and physical factors on the rate of removal of thorium from seawater.

Table 9

Samples Collected Aboard R/V KNORR (Atlantic GEOSECS, Leg V)
Leaving Recife, Brazil, and analyzed for Thorium-228

Sample Number	Collection date	Latitude (°S)	Longitude (°W)	dpm ²²⁸ Th 100kg
Ra1547	4 Nov. '72	08°12'	34°38'	0.45±0.05
Ra1548	4 Nov. '72	08°17'	34°30'	0.45±0.04
Ra1549	4 Nov. '72	08°21'	34°22'	-
Ra1550	5 Nov. '72	08°26'	34°12'	0.40±0.05
Ra1551	5 Nov. '72	08°36'	33°47'	0.53±0.05
Ra1552	5 Nov. '72	08°44'	33°34'	0.43±0.05
Ra1553	5 Nov. '72	08°49'	33°27'	0.40±0.04
Ra1554	5 Nov. '72	08°58'	33°12'	0.25±0.08
Ra1555	5 Nov. '72	09°21'	32°32'	0.46±0.07
Ra1556	6 Nov. '72	09°41'	31°57'	0.40±0.05
Ra1557	6 Nov. '72	10°03'	31°22'	0.41±0.04
Ra1558	6 Nov. '72	10°23'	30°46'	0.44±0.04
Ra1559	6 Nov. '72	10°42'	30°43'	-
Ra1560	6 Nov. '72	11°04'	29°34'	0.41±0.06
Ra1561	6 Nov. '72	11°27'	28°58'	0.52±0.05
Ra1562	6 Nov. '72	11°48'	28°22'	0.97±0.23

Table 10

Samples Collected Aboard R/V KNORR (Atlantic GEOSECS, Leg V)
approaching Buenos Aires, and analyzed for Thorium-228

Sample Number	Collection date	Latitude (°S)	Longitude (°W)	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$
Ra1603	24 Nov. '72	36°00'	45°00'	-
Ra1610	25 Nov. '72	35°58'	46°03'	0.72±0.06
Ra1611	26 Nov. '72	35°55'	47°47'	0.62±0.05
Ra1612	26 Nov. '72	35°43'	49°06'	-
Ra1613	26 Nov. '72	35°35'	50°26'	0.79±0.06
Ra1614	26 Nov. '72	35°29'	51°16'	0.79±0.06
Ra1615	26 Nov. '72	35°30'	52°00'	0.91±0.08
Ra1616	26 Nov. '72	35°24'	52°37'	0.41±0.12
Ra1617	26 Nov. '72	35°16'	53°04'	0.25±0.04
Ra1618	26 Nov. '72	35°11'	53°32'	0.80±0.07
Ra1619	26 Nov. '72	35°08'	53°54'	1.76±0.14
Ra1620	26 Nov. '72	35°08'	54°19'	2.31±0.18
Ra1621	26 Nov. '72	35°06'	54°38'	0.15±0.03
Ra1622	26 Nov. '72	35°06'	54°55'	0.47±0.07

Table 11

Samples Collected Aboard R/V KNORR (Atlantic GEOSECS, Leg VI)
Leaving Buenos Aires, and Analyzed for Thorium-228

Sample Number	Collection date	Latitude (°S)	Longitude (°W)	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$
Ra1648	3 Dec. '72	35°25'	55°09'	-
Ra1649	3 Dec. '72	35°39'	54°58'	0.41±0.05
Ra1650	3 Dec. '72	35°55'	54°29'	4.58±0.34
Ra1651	3 Dec. '72	36°00'	54°19'	1.29±0.11
Ra1652	3 Dec. '72	36°10'	53°58'	0.34±0.04
Ra1653	3 Dec. '72	36°22'	53°37'	0.58±0.07
Ra1654	3 Dec. '72	36°43'	52°50'	0.89±0.10
Ra1655	3 Dec. '72	37°36'	51°24'	0.54±0.08
Ra1656	8 Dec. '72	40°21'	49°42'	0.73±0.06

Table 12

Samples Collected Aboard R/V KNORR (Atlantic GESECS, Leg VII)
 Southwest of Africa and approaching Capetown, South Africa, and analyzed for Thorium-228

Sample Number	Latitude (°S)	Longitude (°E)	Depth (m)	dpm ^{228}Th 100kg
<u>Atlantic GESECS Station 91 (29 Jan. '73)</u>				
Ra1696	49°35'	11°31'	1	0.04±0.02
Ra1697	49°35'	11°31'	50	0.01±0.02
Ra1698	49°35'	11°31'	105	0.03±0.02
Ra1699	49°35'	11°31'	140	0.04±0.02
Ra1700	49°35'	11°31'	175	0.07±0.02
<u>Atlantic GESECS Station 92 (31 Jan. '73)</u>				
Ra1701	46°13'	14°36'	1	0.01±0.02
Ra1702	46°13'	14°36'	55	0.02±0.02
Ra1703	46°13'	14°36'	110	0.07±0.02
Ra1704	46°13'	14°36'	176	0.06±0.02
<u>Atlantic GESECS Station 93 (2 Feb. '73)</u>				
Ra1705	41°46'	18°27'	1	-0.01±0.02
Ra1706	41°46'	18°27'	30	0.30±0.04
Ra1707	41°46'	18°27'	91	0.12±0.02
Ra1708	41°46'	18°27'	176	0.56±0.05
<u>Atlantic GESECS Station 94 (3 Feb. '73)</u>				
Ra1709	38°24'	19°22'	3	0.92±0.07
Ra1710	38°24'	19°22'	70	0.86±0.07
Ra1711	38°24'	19°22'	140	1.09±0.07
Ra1712	38°24'	19°22'	175	1.28±0.09
<u>Approaching African Coast (4 Feb. '73)</u>				
Ra1713	37°36'	19°04'	3	1.08±0.12
Ra1714	35°50'	18°35'	3	1.01±0.07
Ra1715	34°39'	18°18'	3	0.71±0.06

Table 13

Samples Collected Aboard R/V MELVILLE (Pacific GEOSECS, Legs I and II)
Leaving San Diego and Leaving Honolulu, and analyzed for Thorium-228

Sample Number	Collection date	Latitude (°N)	Longitude (°W)	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$
Ra1890	23 Aug. '73	32°38'	117°32'	0.14±0.04
Ra1891	23 Aug. '73	32°39'	117°45'	0.13±0.02
Ra1814	15 Sept. '73	21°15'	157°45'	0.10±0.02
Ra1815	15 Sept. '73	21°48'	157°00'	0.13±0.03
Ra1816	16 Sept. '73	23°07'	158°02'	0.07±0.03
Ra1817	16 Sept. '73	23°34'	158°08'	0.16±0.03
Ra1813	17 Sept. '73	26°42'	158°56'	0.13±0.03

FIGURE 14: The locations sampled for radium-228 and thorium-228 and the locations of GEOSECS stations during the beginning of Leg V of the Atlantic GEOSECS cruise

FIGURE 15: The locations sampled for radium-228 and thorium-228 and the locations of GEOSECS stations during the completion of Leg V of the Atlantic GEOSECS cruise

CHAPTER V. THE STUDY OF THE GEOCHEMISTRY OF RADIUM AND
AND THORIUM IN THE AREA OF THE NEW YORK BIGHT

The results of our past investigations of the distribution of radium-228 and thorium-228 in the oceans have indicated that the marine geochemistry of radium and thorium is most complicated, and therefore most interesting, in the shallow waters above the continental shelves. These shelf waters also constitute the marine environment most subject to pollution by human activities, and thus the area of the marine environment where potential radioactive tracers, such as radium-228 and thorium-228, might be of the most value in efforts to solve environmental problems. These considerations have led us to shift the main focus of our investigation to the shelf waters, and more specifically to the area of the New York Bight, the region of the continental shelf which is most accessible to us.

The oceanography of the New York Bight is quite complicated, but it is currently being studied intensively by several government agencies and research institutions. Perhaps the MESA Program of the Department of Commerce (NOAA) is the largest of these studies. The investigation of the marine geochemistry of radium-228 and thorium-228 in the New York Bight should both benefit from these other studies, and also offer complementary information to them. Our work in this area will also benefit from close cooperation between the Physical Oceanography and Geochemistry Sections of Lamont-

Doherty Geological Observatory.

It is planned that our investigations in the area of the New York Bight will follow three main lines of approach: a continuation of the type of water sampling which we have performed in the past, the separation and analysis of particulates suspended in the shelf water, and the measurement of rates of release of radium isotopes from sediments, using both field experiments and laboratory studies.

The Measurement of Water Samples for Isotopes of Radium and Thorium

During the course of our investigation a number of water samples for analysis of radium-228 and thorium-228 have been collected in the area of the New York Bight. Available results of the analysis of these samples are presented in Table 14, and the locations of sample collections are indicated in Figure 16. Most of these samples were collected in surface water, but during the past year we have begun using a submersible pump to collect subsurface samples as well. We plan to sample the waters of the New York Bight regularly over the course of several annual cycles of the seasons. This should yield a picture of the variations in concentrations of radium-228 and thorium-228 as a function of location relative to the shoreline and to the edge of the continental shelf, as a function of depth in the water column, and as a function of season of the year.

Table 14

Samples Collected in the area of the New York Bight

Sample Number	Collection date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
Ra0856	11 Nov. '67	36°55'N	71°04'W	0.45	3.8±0.4	0.63±0.02	0.17
Ra0862	4 Jan. '68	38°29'N	73°00'W	0.68	5.7±0.6	0.47±0.04	0.08
Ra1069	11 Aug. '70	40°58'N	73°28'W	3.02	25.6±2.6	-	-
Ra1070	12 Aug. '70	41°01'N	72°22'W	3.71	31.6±3.2	-	-
Ra1063	13 July '70	40°21'N	73°39'W	2.41	20.5±2.4	-	-
Ra1066	5 Aug. '70	40°08'N	73°42'W	2.37	20.2±2.0	-	-
Ra1062	18 June '70	39°56'N	73°09'W	1.79	15.2±1.5	-	-
Ra1064	14 July '70	39°42'N	72°34'W	1.41	12.0±1.2	-	-
Ra1060	17 June '70	39°29'N	72°23'W	1.06	9.0±0.9	-	-
Ra1067	6 Aug. '70	39°14'N	72°06'W	0.95	8.1±0.8	-	-
Ra1061	18 June '70	38°59'N	71°38'W	0.75	6.3±0.6	-	-
Ra1065	14 July '70	38°54'N	71°35'W	0.76	6.5±0.7	-	-
Ra1068	6 Aug. '70	38°52'N	71°26'W	0.50	4.3±0.4	-	-
Ra1121	26 Aug. '71	39°01'N	74°00'W	1.12	9.0±1.6	0.44±0.04	0.05
Ra1122	19 Sept. '71	40°16'N	73°15'W	1.08	8.6±1.5	0.37±0.04	0.04
Ra1123	19 Sept. '71	40°24'N	73°30'W	1.71	13.7±2.4	0.11±0.03	0.01
Ra1305	31 May '72	40°58'N	73°32'W	-	-	1.05±0.15	-
Ra1306	31 May '72	41°11'N	72°18'W	-	-	2.14±0.31	-
Ra1307	1 June '72	41°15'N	72°15'W	-	-	1.08±0.12	-
Ra1308	2 June '72	40°40'N	72°14'W	-	-	0.35±0.15	-
Ra1309	2 June '72	40°55'N	72°14'W	-	-	1.70±0.19	-
Ra1313	2 June '72	40°25'N	73°42'W	-	-	0.74±0.10	-
Ra1332	18 July '72	40°30'N	73°30'W	1.33	18.6±6.0	0.19±0.05	0.01
Ra1333	18 July '72	40°30'N	73°30'W	2.14	29.8±9.4	< 0.1	< 0.01
Ra1381	30 Oct. '72	38°41'N	74°56'W	2.24	17.8±3.1	0.36±0.04	0.02
Ra1624	31 Mar. '73	37°11'N	70°00'W	-	-	0.46±0.08	-
Ra1625	31 Mar. '73	38°05'N	70°56'W	-	-	0.85±0.07	-
Ra1626	1 Apr. '73	39°07'N	72°17'W	-	-	0.80±0.06	-
Ra1627	1 Apr. '73	39°31'N	72°47'W	-	-	0.49±0.05	-
Ra1629	1 Apr. '73	39°47'N	73°06'W	-	-	0.46±0.05	-
Ra1630	1 Apr. '73	40°02'N	73°26'W	-	-	0.36±0.04	-

Table 14 (continued)

Sample Number	Collection date	Latitude	Longitude	$\frac{\text{dpm } ^{228}\text{Ra}}{\text{dpm } ^{226}\text{Ra}}$	$\frac{\text{dpm } ^{228}\text{Ra}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$	$\frac{\text{dpm } ^{228}\text{Th}}{\text{dpm } ^{228}\text{Ra}}$
Ra1631	4 Apr. '73	41°00'N	73°23'W	-	-	0.94±0.08	-
Ra1632	4 Apr. '73	41°05'N	72°54'W	-	-	0.62±0.05	-
Ra1633	4 Apr. '73	41°08'N	72°40'W	-	-	0.49±0.04	-
Ra1634	4 Apr. '73	41°14'N	72°07'W	-	-	0.78±0.07	-
Ra1635	4 Apr. '73	41°16'N	71°43'W	-	-	0.46±0.05	-
Ra1636	4 Apr. '73	41°19'N	71°24'W	-	-	0.43±0.04	-
Ra1637*	4 Apr. '73	41°19'N	71°24'W	-	-	0.82±0.09	-
Ra1638	4 Apr. '73	41°22'N	71°08'W	-	-	1.84±0.19	-
Ra1639*	4 Apr. '73	41°22'N	71°08'W	-	-	0.89±0.15	-
Ra1879	27 Nov. '73	40°49'N	73°58'W	-	-	1.65±0.15	-
Ra1880	28 Nov. '73	41°34'N	73°58'W	-	-	3.01±0.23	-
Ra1883	15 Jan. '74	40°04'N	72°57'W	-	-	0.67±0.06	-
Ra1884	15 Jan. '74	40°04'N	72°57'W	-	-	0.54±0.05	-
Ra1885*	15 Jan. '74	40°04'N	72°57'W	-	-	0.36±0.04	-
Ra1886	16 Jan. '74	40°30'N	73°00'W	-	-	1.13±0.09	-
Ra1887	16 Jan. '74	40°15'N	73°46'W	-	-	0.72±0.09	-
Ra1888*	16 Jan. '74	40°15'N	73°46'W	-	-	1.30±0.11	-
Ra1910	13 May '74	40°15'N	73°47'W	-	-	0.32±0.03	-
Ra1911	13 May '74	40°15'N	73°47'W	-	-	0.34±0.04	-
Ra1912*	13 May '74	40°15'N	73°47'W	-	-	1.28±0.14	-
Ra1913	13 May '74	39°41'N	74°08'W	-	-	1.96±0.27	-
Ra1914	14 May '74	39°38'N	73°50'W	-	-	0.58±0.10	-
Ra1915*	14 May '74	39°38'N	73°50'W	-	-	1.10±0.12	-
Ra1916	19 May '74	40°15'N	73°46'W	-	-	0.18±0.03	-
Ra1917**	19 May '74	40°15'N	73°46'W	-	-	0.07±0.02	-
Ra1918	20 May '74	41°16'N	73°58'W	-	-	-	-

*Subsurface samples and their depths of collection are:

Ra1637 - 28m   Ra1639 - 30m   Ra1885 - 40m   Ra1888 - 55m   Ra1912 - 35m   Ra1915 - 25m

**Sample 1917 was centrifuged to remove particulates before it was processed

Figure 16. The locations sampled for radium-228 and thorium-228 in the area of the New York Bight.

Our initial expectation in beginning this repetitive sampling of the waters of the Bight is that we may find that radium-228 released from the shelf sediment accumulates below the thermocline layer during the summer, and then enters the surface waters mainly during the winter. On the other hand, it is possible that upwelling along the coast of New Jersey during periods of strong southwesterly winds introduces radium-228 into the surface water along this coast, and that it then is carried seaward by eddy diffusion within this surface layer. This might explain the steep concentration gradient across the shelf observed in surface samples collected in 1970 (Table 14). Individual storms may have a profound effect upon the distribution of radium-228 within the shallow shelf water, so it is anticipated that this study will have to extend through several complete seasonal cycles for its results to be valid. Careful attention will have to be paid to the hydrography at the time of sampling as well, to discern the effects of the tidal cycle as well as of discrete storm events.

In addition to continuing our measurements of radium-228 and thorium-228 in water samples, we expect to pay more attention to the measurement of radium-226 and thorium-232 in the shelf water. The thorium fractions of our samples, measured by alpha spectrometry for their thorium-228 content, are sometimes found to contain measurable amounts of thorium-232 also. The 4.01 Mev alpha peak characteristic of this

isotope has been found in the spectra of many samples collected in shelf water, which is probably not too surprising, but it has also been detected in the spectra of a few samples collected in the slope waters and in the Sargasso Sea. We will attempt to determine the conditions under which the thorium-232 is present in high concentrations and the conditions under which it is present in only low concentrations in shelf water, and the extent to which it is present in true solution or incorporated into suspended particulates.

Our technique of measuring radium-228 in water samples requires that we know the radium-226 content of that water, for this isotope is used as a natural tracer to determine our chemical yield for the radium-228 analysis. Consequently we have frequently collected water samples for analysis of radium-226 in conjunction with our collection of larger samples for the analysis of radium-228. The results of these measurements have indicated that the radium-226 content of near-shore water can be higher than that of surface water in the open oceans. This suggests that radium-226 as well as radium-228 may be released to the sea in significant amounts above the continental shelf, and we wish to pursue this possibility more fully.

The sediments of the continental shelf appear to be the only important source of radium-228 entering the surface waters of the ocean, but to verify this, as well as to anticipate the possibility of local anomalies at the mouths of

rivers in the New York Bight, we have begun some limited sampling of fresh water systems and estuaries. Table 14 includes three samples collected in the Hudson estuary, one collected in Peconic Bay, and a number collected in Long Island Sound. In conjunction with some other studies which were being performed on Lake Ontario, we collected three samples of lake water for analysis of radium-228 and thorium-228. The results of the thorium-228 analysis of these samples are given in Table 15. While Lake Ontario has no connection with the New York Bight, it is a part of a large hydrologic system which should give the type of results we can expect also in the smaller rivers which empty into the Bight.

The Analysis of Particulates Suspended in Shelf Water

As one new aspect of our study of the marine geochemistry of radium and thorium, we have undertaken the separation of the suspended particulates from 800 liter samples of water from the New York Bight using a continuous flow centrifuge. Our initial attempts at such separations in May 1974 were hampered by technical problems, and only one sample of particulates was obtained. This sample was distinctly green in color and appeared to contain a high concentration of phytoplankton. These, however, were too small to be resolved by the available microscope. Unfortunately the sample was contaminated and lost when a centrifuge tube containing it broke in a laboratory centrifuge, which had been turned to an

Table 15

Samples Collected Aboard the R/V KARLSEN on Lake Ontario in May 1972
and analyzed for Thorium-228

Sample Number	Collection date	Latitude (°N)	Longitude (°W)	$\frac{\text{dpm } ^{228}\text{Th}}{100\text{kg}}$
Kal641	1 May '73	43°19'	79°35'	0.35±0.04
Kal642	2 May '73	43°18'	77°02'	0.51±0.07
Kal643	3 May '73	43°36'	78°36'	0.44±0.05

unusually high speed in an effort to cause sedimentation of these small phytoplankton. It is our expectation that we will be able to collect and analyze successfully numerous samples of such suspended particulates during future months.

We anticipate analyzing samples of particulates ultimately for their content of organic matter and for their mineralogic composition. The chief purpose in collecting these samples is, however, the analysis of their content of radium and thorium isotopes. By comparison of the thorium isotope ratios and the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratios in the particulates to those in the water and to those in the bottom sediments, we would hope to be able to estimate the extent to which suspended particulates were preferentially removing thorium-228 from the water by adsorption. We hope in addition to use such data to evaluate the possibility that radium-228 might also be removed from shelf waters in part by adsorption onto particulates. We would expect the particulates to have a higher $^{228}\text{Th}/^{232}\text{Th}$ activity ratio than the bottom sediment as a result of the fairly rapid removal of thorium-228 from solution in shelf water (Broecker, 1973). If radium-228 is also being removed by adsorption, the $^{228}\text{Ra}/^{232}\text{Th}$ activity ratio should also be higher than that of the bottom sediment. Since much of the suspended particulate material may be unrelated to the bottom sediment, we anticipate sampling the suspended material in the rivers and estuaries which empty into the Bight as an alternative measure of the composition of

particulates before their exposure to the high radium-228 concentrations of the shelf water. We expect that some samples of particulates will contain high concentrations of organisms, as did that which we collected in May 1974, while others will consist mostly of non-living organic matter, and others mainly of inorganic minerals. We would expect that by identifying the nature of the particulate material with which we are dealing before analyzing it, we will be able to interpret our resulting data in terms of the actual processes which have affected the distribution of radium and thorium isotopes between the dissolved and adsorbed phases.

Estimating the Rate of Release of Radium-228
from Shelf Sediments

We anticipate using two basic approaches to estimating the rate of release of radium-228 into the seawater from shelf sediments. The first will consist of trapping radium in seawater as it leaves a mass of sediment, either in the field or in the laboratory, and the second will consist of measuring concentration gradients of radium in pore waters of sediment cores and calculating effective diffusion rates from these gradients.

We plan to perform field experiments to determine rates of radium release from sediments by emplacing open-bottom barrels on the sediment surface and allowing radium to accumulate in them for a number of days or weeks. The water will then be pumped continuously from the barrels and through an

extraction system (Moore and Reid, 1973) and back through the barrels for an hour or so. The sites for such emplacement will be selected based on accessibility and on the need to sample as much variety of sediment type as is possible, considering the predominance of sandy sediment on the shelf. Variations in mineralogy, and especially in the occurrence of monazite and zircon which would contain relatively high thorium concentrations, will be considered in site selection. Laboratory experiments will also be performed in which sediment collected on the shelf will be placed in barrels and seawater will be placed above it. The radium-228 and radium-226 will be allowed to accumulate in the water for a number of days or weeks, and will then be extracted and measured.

The second approach to estimating the rate of release of radium-228 from the shelf sediment will involve the collection of cores of sediment, and the measurement of radium-228 concentrations within the pore water as a function of depth within the core. A diffusion model will then be used to estimate the rate of flux of radium-228 out of the sediment based on the observed gradients in the pore water. Three cores to be used for such experiments were collected in the New York Bight in May 1974. A major difficulty with the experimental approach involves the problems in coring the sandy sediment which covers most of the shelf. Our cores were collected in the finer sediment which occurs in the Hudson channel, but such sediment is quite restricted in its occurrence, and is

not at all typical of most of the shelf sediment. It may prove to be quite difficult to obtain undisturbed cores of the more widespread sandy sediment. We may attempt to use cores of equivalent materials from shallow waters, such as Barnegat Bay, as substitutes for the shelf sands. In the proper area sand might be found in shallow water, but not subject to agitation by wave action, so that radium isotopes might have achieved diffusive equilibrium within its pore water. In such shallow water sampling might be accomplished by driving a coring tube into the sand by hand, and then digging it out to prevent loss of the sediment or draining out of the pore water.

CHAPTER VI. ADDITIONAL GEOCHEMICAL STUDIES

Our investigation of the marine geochemistry of radium-228 and thorium-228 has been broadened at times to include other radioactive isotopes and other environments which have been thought to offer promise of supplying useful information. Thus samples of water have been collected in Lake Ontario and in the Hudson River estuary for analysis of radium-228 and thorium-228, as discussed in Chapter V. At various times during this project, samples of seawater have been analyzed for lead-210 and polonium-210, and it is anticipated that such analyses will be continued. The analysis of seawater samples for plutonium was begun during the past year, but was suspended before any results were obtained. It is planned that the analysis of plutonium and some fission products will be performed on some samples of sediment, water and suspended particulates during the coming year, if such analyses are authorized. A limited number of experiments on the removal of various radionuclides from a fresh water lake were performed a year ago. The various additional geochemical studies are described briefly below.

The Analysis of Seawater Samples for Lead-210
and Polonium-210

The removal of lead-210 and polonium-210 from seawater by biological processes or by absorption onto particulates has been studied by several investigators (Rama et al., 1961;

Shannon et al., 1970; Tsunogai and Nozaki, 1971; Beasley et al., 1973; Turekian et al., 1973). Thompson and Turekian (in Turekian, et al., 1973) have concluded that, "Thorium-228 and polonium-210 have similar modes of particulate transport out of the surficial biologically productive zone but lead-210 has a longer mean residence time resembling that of the nutrients." By including lead-210 and polonium-210 in the scheme of analysis of some of our samples we can obtain additional evidence on the accuracy of this conclusion. The results of such analyses will add to our knowledge of the fate of reactive heavy metals in the shelf environment.

Lead-210 and polonium-210 have been analyzed as part of our research project at times in the past. Results are available for two series of samples collected for such analysis. One group of twelve samples was collected off the western coast of Africa in early 1970 for analysis of lead-210. The results of these analyses are given in Table 16. The interpretation of these data is complicated by the fact that samples were collected at a series of different locations and depths. It does appear, however, that in water of intermediate depth the lead-210 concentration ranges from 6 to 11 dpm/100 l. Broecker et al. (1967) determined that surface water in the Atlantic Ocean has a radium-226 content of about 9 dpm/100 l, and that deep water has a content about twice this value. While neither hydrographic nor radium-226 data are available for these samples, it would appear that they

indicate that lead-210 is depleted with respect to radium-226, if the data of Broecker et al. (1967) are applicable, for at least some of the water column. This set of data is apparently in agreement with the results of Craig et al. (1973) which showed depletion of lead-210 with respect to radium-226 in the deep water of the Atlantic and Pacific Oceans. The lack of radium-226 from the same stations and depths as our lead-210 samples leave this agreement in doubt, however. The most interesting aspect of the data is the wide range in surface water lead-210 concentrations, from 6 to 40 dpm/100 l. There is evidence to suggest that these variations are real. Shannon et al. (1970) measured lead-210 in surface waters off the coast of South Africa and found a range of 3 to 30 dpm/100 l. The addition to the sea of large surpluses of lead-210 (derived from the radioactive decay of radon-222) by rainfall, or the actions of organisms may have produced these variations.

A set of samples was collected for analysis of radium-226, lead-210 and polonium-210 near Bermuda in June 1972. Unfortunately the lead-210 analyses were lost due to an error in the analytical procedure, and so the radium-226 samples were not analyzed either. Results of the polonium-210 analyses are given in Table 17, however. This station is about 400 km from the North Atlantic station of Craig et al. (1973). From the data in Table 17, it can be seen that the concentration of polonium-210 rises sharply with increasing depth below the

Table 16

Lead-210 Concentrations Measured in Seawater Samples
Collected off the Western Coast of Africa in 1970

Latitude	Longitude	Depth (Meters)	^{210}Pb
			$\frac{\text{dpm}}{100\text{kg}}$
33°56'S	7°53'E	1	6.2
29°29'S	0°52'E	1	14.1
23°05'S	3°35'W	4700	13.8
18°31'S	1°37'E	950	11.4
16°32'S	3°54'E	460	9.0
10°05'S	11°26'E	100	6.6
7°26'S	10°00'E	2000	6.4
5°08'S	9°28'E	700	8.3
0°14'S	7°34'E	300	12.2
2°16'N	5°44'E	400	8.7
1°02'N	2°03'E	600	9.0
2°07'N	3°16'E	1	40.3

Table 17
 Polonium-210 Concentrations Measured in a Profile of Seawater Samples
 Collected near Bermuda in 1972

<u>Depth</u> <u>(meters)</u>	<u>dpm ²¹⁰Po</u> <u>100 l</u>
1	9.5
25	11.0
50	14.0
75	16.5
100	15.0
200	18.2
300	16.6
500	14.0
750	15.0
1000	10.0
1500	10.5
1750	11.2
2000	10.0

sea surface, and reaches a maximum at about 200 m. The hydrographic data show that the top of the thermocline is at approximately 200 m at this station. The concentration then decreases toward greater depths. For the bottom 1000 m the polonium-210 concentration remains fairly steady at 10 to 11 dpm/100 l, a value similar to that of the surface water. The sample from 2000 m is believed to have been collected within 100 m of the seafloor. The shape of the vertical distribution indicates that polonium-210 is being scavenged from surface water and carried into the thermocline layer. The work of Shannon et al. (1970) shows that polonium-210 is usually depleted with respect to lead-210 in surface waters, so we may expect that the lead-210 concentrations in the surface water at this station exceeded 9.5 dpm ^{210}Pb /100 l.

The Analysis of Water and Sediment Samples for Reactor Radionuclides

It may reasonably be assumed that the routine operation of nuclear reactors at offshore sites will result in the release of at least trace amounts of fission products and heavy metal radionuclides, such as plutonium and other transuranium elements, into the marine environment. Measurements of sediments from the Hudson River estuary made at this laboratory (Simpson, personal communication) have suggested that the fission products and plutonium in those sediments have come in part from fallout from nuclear bomb tests, but in part also from a nuclear reactor which discharges its cooling water into the

Hudson. It is certainly conceivable that a major accident at a nuclear reactor could release large amounts of fission products and transuranium elements into the marine environment. Clearly, then, it is important that information be accumulated which is relevant to the removal of fission products and transuranium elements from seawater by the particulate matter and organisms which are characteristic of the waters which overlie the continental shelf. We propose, therefore, to extend the study of radium and thorium isotopes in the shelf environment, which is discussed above, and which is primarily aimed at perfecting the use of radium-228 as a tracer of water motions, to include other radionuclides of interest. Specifically, it is planned to analyze samples of sediment, and perhaps later samples of seawater, suspended particulates, pore waters, and organisms for plutonium and for those fission products, such as cesium-137 and cerium-144, which can be analyzed by gamma spectrometry.

Plutonium-239 and fission products such as cesium-137 are by-products of nuclear fission reactors, and their distribution in the environment has been studied extensively and intensively. Nevertheless, the complexity of their behavior has limited the extent to which this behavior may be generalized. Bowen and coworkers, for example, have studied the distribution of fallout radionuclides in the marine environment for many years. They have suggested that the removal of plutonium from seawater may be involved with biological

processes, and that it concentrates in organisms to a greater extent than do cesium-137 or strontium-90. They have investigated the apparent enrichment of strontium-90 relative to cesium-137 in coastal seawater, the preferential removal of plutonium to the sediment relative to either cesium-137 or strontium-90, and the apparent post-depositional migration of these radionuclides within the sediment. Nevertheless, they have found that their studies have raised as many questions as they have answered. In view of the extent of work which has been done on these artificially produced nuclides by many investigators the world over, we will limit our investigation of them to the particular environment of the New York Bight-New Jersey coastal area which is relevant to offshore siting of nuclear reactors in the Metropolitan area.

We propose to center our study of the behavior of fission products and plutonium-239 in the marine environment in the area of the Forked River, N.J. nuclear reactor, which is operated by the Jersey Central Power and Light Company. Cooling water from this plant empties through Oyster Creek into Barnegat Bay, and from there is carried by tidal flow out onto the continental shelf. We have begun to collect samples of sediment from the Oyster Creek stream and estuary, from the various sediment facies in Barnegat Bay near Oyster Creek, and from the shelf sediments outside of Barnegat inlet. We hope that this survey will indicate whether there are

anomalously high concentrations of fission products and of plutonium in the vicinity of this plant, and if there are, whether they extend out into the shelf sediment. We expect to use gamma spectrometry to assay sediment samples for cesium-137, and we anticipate that such measurements will also reveal the presence in the sediments of other gamma emitting fission products and products of nuclear activation. It may prove to be impossible to detect any anomalies in radioactivity in the sediment attributable to the presence of the nuclear reactor, but since the plant is relatively old, and since its cooling water is discharged into relatively small waterways, it seems likely that a significant anomaly will be found. We believe that much of the bottom sediment of Barnegat Bay is similar to typical shelf sediment beyond the barrier island, so that the data we obtain should be generally applicable to the sediment-water interactions to be expected around reactors built at offshore sites. Moreover, if this anomaly exists and extends out into the shelf sediment, the data will be directly applicable to offshore siting problems. The extent to which this study will be pursued beyond this initial study will depend upon whether or not a useful anomaly is found. If it is, then additional nuclides, and especially heavy metals produced by nuclear activation, could be incorporated into subsequent studies. These future studies would also be expanded to include sampling of water and organism in addition to the sediment.

The Removal of Reactive Heavy Metals from a Lake

An intensive study of the geochemistry of fresh water lakes is being carried on in the Experimental Lakes Area, managed by the Fisheries Research Board of Canada, near Kenora, Ontario. One aspect of this study, which seems to have significance for our investigation of the marine geochemistry of radium and thorium, has been pursued in conjunction with our investigation.

As part of a eutrophication investigation of one small lake in this area, Lake 227, gas-exchange studies were performed using radium-226 as a radioactive tracer. In August 1970 9.7 mc of radium-226 were added to the lake, bringing the epilimnion concentration to about 200 dpm ^{226}Ra /liter. Within one month, most of the radium, which had been added as soluble RaBr_2 , had been removed from solution. Subsequent investigations have shown that it had been adsorbed by detrital algal material in the littoral zone (Emerson and Hesslein, 1973). Much of this detrital material has subsequently been redeposited in the deeper areas of the lake. This has permitted the use of the radium-226, and also of carbon-14 which had been added to the lake as part of another experiment, as a tracer in the determination of the rate of sedimentation and of sediment mixing in the lake.

A sediment core, collected at a point where the lake is nine meters deep, is being analyzed for its content of radium-226, carbon-14, lead-210 and polonium-210, and for its thorium

isotopic ratios. Profiles of concentrations of radium-226 and lead-210 and of relative concentrations of carbon-14 are plotted in Figure 17. It is evident that excess concentrations of radium-226 and carbon-14 extend 3 to 5 cm into the sediment. We may discount diffusion of these elements downward through the pore water to these depths since such diffusion would require much more time than has passed since these tracers were added to the lake. Thus this depth of 3 to 5 cm must represent the depth to which physical mixing of the sediment has occurred, either by the action of organisms or by the action of turbulence within the water itself. The sedimentation rate can be estimated from the profile of lead-210 concentrations. Lead-210 produced by the decay of radon in the atmosphere is deposited in the lake by rainfall. This creates an excess concentration of lead-210, relative to its long-lived radium-226 precursor, in the newly deposited sediment. With the passage of time this excess lead-210 decays, and the lead-210 concentration approaches radioactive equilibrium with the radium-226 in the core. In Figure 18 the radium-226 and lead-210 concentrations are plotted on the same scale. The plot of the logarithm of lead-210 concentration against depth is nearly linear, and corresponds to a sedimentation rate of 1 mm/yr.

Most members of the uranium-238 and thorium-232 decay series will be measured in this core. Table 18 contains

available results of measurements of relative polonium-210 concentrations and of thorium isotope ratios. It is hoped that a system of dating can be established using the nuclide pair, thorium-230-radium-226, which can be used in studies of marine sediments as well as fresh water sediments.

Figure 17. The vertical distributions of relative concentrations of carbon-14, and of concentrations of radium-226 and lead-210 in a sediment core from Lake 227.

Table 18

Thorium isotope ratios and relative Polonium-210
Concentrations measured in a sediment core from Lake 227

Depth (m)	$\frac{^{210}\text{Po}}{^{208}\text{Po}}$	$\frac{^{228}\text{Th}}{^{232}\text{Th}}$	$\frac{^{230}\text{Th}}{^{232}\text{Th}}$
0-1	4.91	1.93	0.82
1-2	3.04	-	-
2-3	1.94	-	-
3-4	1.18	1.23	0.65
4-5	1.22	1.14	0.75
5-6	0.73	-	-
6-8	0.62	1.44	0.88
8-10	0.19	-	-
10-15	0.08	1.02	0.64
15-20	0.08	1.00	0.73

Figure 18. The vertical distributions of concentrations of radium-226 and lead-210 in a sediment core from Lake 227.

References

- Beasley, T. M., R. J. Eagle and T. A. Jokela, Polonium-210, lead-210 and stable lead in marine organisms, U.S.A.E.C. report HASL-273, I2-35, 1973.
- Bhat, S. G., S. Krishnaswamy, D. Lal, Rama and W. S. Moore, $^{234}\text{Th}/^{238}\text{U}$ ratios in the ocean, Earth Planet. Sci. Lett. 5, 483, 1969.
- Broecker, W., A. Kaufman, T.-L. Ku, Y.-C. Chung and H. Craig, Radium 226 measurements from the 1969 North Pacific GEOSECS station, J. Geophys. Res. 75, 7682-7685, 1970.
- Broecker, W. S., A. Kaufman and R. M. Trier, The residence time of thorium in surface sea water and its implications regarding the rate of reactive pollutants, Earth Planet. Sci. Lett. 20, 35-44, 1973.
- Broecker, W. S., Y.-H. Li and J. Cromwell, Radium-226 and radon-222: Concentration in Atlantic and Pacific Oceans, Science 158, 1307, 1967.
- Craig, H., The GEOSECS program: 1970-1971, Earth Planet. Sci. Lett. 16, 47-49, 1972.
- Craig, H., S. Krishnaswamy and B.L.K. Somayajulu, ^{210}Pb - ^{226}Ra radioactive disequilibrium in the deep sea, Earth Planet. Sci. Lett. 17, 295-305, 1973.
- Emerson, S. and R. Hesslein, Distribution and uptake of artificially introduced radium-226 in a small lake, J. Fish. Res. Bd. Canada 30, 1485-1490, 1973.
- Kaufman, A., The Th^{232} concentration of surface ocean water, Geochim. Cosmochim. Acta 33, 717, 1969.

- Kaufman, A., R. M. Trier, W. S. Broecker and H. W. Feely,
Distribution of ^{228}Ra in the world ocean, J. Geophys. Res.
78, 8827-8848, 1973.
- Moore, W. S., Measurement of Ra^{228} and Th^{228} in seawater, J.
Geophys. Res. 74, 694, 1969a.
- Moore, W. S., Oceanic concentrations of radium-228, Earth Planet.
Sci. Lett. 6, 437-446, 1969b.
- Moore, W. S. and D. F. Reid, Extraction of radium from natural
waters using manganese-impregnated or acrylic fibers, J.
Geophys. Res. 78, 8880-8886, 1973.
- Moore, W. S. and W. M. Sackett, Uranium and thorium series
inequilibrium in sea water, J. Geophys. Res. 69, 5401, 1964.
- Rama, M. Koide and E. D. Goldberg, Lead-210 in natural waters,
Science 134, 98-99, 1961.
- Shannon, L. V., R. D. Cherry and M. J. Orren, Polonium-210 and
lead-210 in the marine environment, Geochim. Cosmochim.
Acta 34, 701-711, 1970.
- Somayajulu, B.L.K. and E. D. Goldberg, Thorium and uranium
isotopes in seawater and sediments, Earth and Planet. Sci.
Lett. 1, 102, 1966.
- Sverdrup, H. U., M. W. Johnson and R. H. Fleming, The Oceans:
Their Physics, Chemistry and General Biology, Prentice-Hall,
Inc., 1942.
- Trier, R. M., W. S. Broecker and H. W. Feely, Radium-228 profile
at the second GEOSECS intercalibration station, 1970, in the
North Atlantic, Earth Planet. Sci. Lett 16, 141-145, 1972.

Tsunogai, S. and Y. Nozaki, Lead-210 and polonium-210 in the surface water of the Pacific, *Geochem. J. (Japan)* 5, 165-173, 1971.

Turekian, K. K., D. P. Kharkar and J. Thomson, Uranium and thorium decay series nuclide abundances in marine plankton, Final Report on ARPA Contract N00014-67-A-0097-0022, 1973.